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WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 69

METEOROLOGY AND THE DESERT LOCUST

Proceedings of the WMO/FAO Seminar on Meteorology and the Desert Locust
Tehran — 25 November - 11 December 1963

WMO - No. 171. TP. 85

Secretariat of the World Meteorological Organization - Geneva - Switzerland

THE WMO

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It was created :

- to facilitate international co-operation in the establishment of networks of stations and centres to provide meteorological services and observations,
- to promote the establishment and maintenance of systems for the rapid exchange of meteorological information,
- to promote standardization of meteorological observations and ensure the uniform publication of observations and statistics,
- to further the application of meteorology to aviation, shipping, agriculture, and other human activities,
- to encourage research and training in meteorology.

The machinery of the Organization consists of the following bodies.

The *World Meteorological Congress*, the supreme body of the Organization, brings together the delegates of all Members once every four years to determine general policies for the fulfilment of the purposes of the Organization, to adopt Technical Regulations relating to international meteorological practice and to determine the WMO programme.

The *Executive Committee* is composed of 21 directors of national meteorological services and meets at least once a year to conduct the activities of the Organization and to implement the decisions taken by its Members in Congress, to study and make recommendations on matters affecting international meteorology and the operation of meteorological services.

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FOREWORD

The inter-regional training seminar on the relation between meteorology and the Desert Locust was held in Tehran from 25 November to 11 December 1963 at the kind invitation of the Iranian Government. The seminar was organized by WMO under the auspices of the United Nations Expanded Programme of Technical Assistance and with very considerable assistance from the Food and Agriculture Organization of the United Nations, especially through the Special Fund Desert Locust Project. Invitations were addressed to all countries liable to be affected by the Desert Locust.

The present publication contains the texts of the lectures given at the seminar, together with a general report on the proceedings by Dr. R.C. Rainey of the Anti-Locust Research Centre, London, who had been responsible for most of the technical planning of the seminar.

I should like to place on record my thanks to the Iranian Government for having made it possible to hold the seminar in Tehran, to Dr. M.H. Ganji, Director-General of the Iranian Meteorological Department, who served as director of the seminar, to Dr. R.C. Rainey and his fellow-consultants and invited lecturers, and to all the participants who have contributed towards these proceedings. Finally I wish to express my gratitude to the Director-General of FAO, Dr. B.R. Sen, for the provision of invaluable assistance in various ways, including the services of his staff, and to the Director of the Anti-Locust Research Centre, London, Dr. P.T. Haskell, for having provided the services of Dr. Rainey and other members of his staff.

D A Davies.

D.A. Davies
Secretary-General

Summary

The seminar began with an introduction to relevant aspects of the biology and behaviour of the Desert Locust (Schistocerca gregaria Forskål), followed by consideration of the evidence now available on the manner in which the migrations and distribution of the locusts are dominated by meteorological factors, particularly the wind-field, on the macro- and meso-scales. In addition to the transporting effects of wind on airborne locusts, the corresponding patterns of low-level convergence and divergence have been found of direct importance as factors in relation respectively to the concentration and dispersal of locust populations, as well as of major indirect importance in relation to the distribution of precipitation, which is essential for successful locust breeding. The main material presented on these points had already been published in full in WMO Technical Note No. 54 (used as the basic working document for the seminar) and is not repeated in the present Note.

Standard procedures for the study of the wind-field, including contours, streamlines, trajectories and methods for the quantitative treatment of the divergence fields, were described and applied to particular past weather situations associated with significant locust developments, and experience is presented on the application and further development of a number of the techniques under a range of conditions including equatorial latitudes and elevated continental terrain.

Reviews of the synoptic meteorology and climatology of the whole Desert Locust invasion area, comprising south-western Asia and most of Africa, are presented, with particular reference to wind-fields, rainfall and temperature. In addition, a series of synoptic studies by participants are included, relating to specific weather situations associated with recent locust developments affecting their own areas. Meso-scale wind-field systems and relevant aspects of atmospheric turbulence are reviewed in relation to the displacement, concentration and dispersal of airborne locusts.

The extensive material now available on seasonal and longer-term changes in the overall Desert Locust situation is briefly reviewed, and detailed evidence is presented on the manner in which an exceptional tropical cyclone, in southern Arabia, appears to have played a major part in bringing to an end the last major recession of the Desert Locust plague, in 1948-1949. An outline is given of the current strategy and tactics of locust control operations, with particular reference to points on which meteorological guidance is now needed and to the way in which such demands might develop in the future.

Résumé

Le cycle d'études a tout d'abord examiné quelques aspects de la biologie et du comportement du criquet pèlerin (Schistocerca gregaria Forskål), puis a étudié les indices dont nous disposons actuellement sur l'influence déterminante que les facteurs météorologiques à grande et à moyenne échelle, notamment le champ de vent, exercent sur les migrations et la répartition des criquets. On savait déjà que le vent exerçait des effets de translation sur les essaims de criquets en vol; on a constaté en outre que la configuration de la convergence et de la divergence dans les basses couches de l'atmosphère jouait directement un rôle important dans la concentration et la dispersion des populations d'acridiens, et qu'elle revêtait indirectement une grande importance dans ce domaine, du fait de son influence sur la répartition des précipitations qui constitue un facteur essentiel pour la propagation des criquets. La plupart des informations présentées à ce sujet ont déjà été publiées intégralement dans la Note technique N° 54 de l'OMM (utilisée comme document de base lors du cycle d'études) et ne sont donc pas répétées dans la présente Note.

Des procédures types pour l'étude du champ de vent (isohypses, lignes de courant, trajectoires et traitement quantitatif des champs de divergence) ont été décrites pendant le cycle d'études et appliquées à des situations météorologiques qui avaient été associées dans le passé à des aspects significatifs du comportement des criquets. La Note donne des précisions sur l'expérience acquise en matière d'application et de perfectionnement de diverses techniques pour toute une gamme de conditions différentes, notamment aux latitudes équatoriales et sur terrain continental élevé.

Elle passe en revue les conditions météorologiques et climatologiques dans l'ensemble de la zone envahie par le criquet pèlerin, qui comprend le sud-ouest de l'Asie et la plus grande partie de l'Afrique, et analyse plus particulièrement les champs de vent, la pluie et la température. Elle comporte en outre une série d'études synoptiques - présentées par des participants - sur les situations météorologiques spéciales associées à des mouvements de criquets survenus récemment dans les régions d'où provenaient ces participants. La Note étudie des champs de vent à moyenne échelle et les aspects correspondants de la turbulence atmosphérique, en fonction du déplacement, de la concentration et de la dispersion des essaims de criquets.

La Note résume brièvement l'abondante documentation dont on dispose actuellement sur les changements saisonniers et à plus long terme qui surviennent dans la situation générale des criquets pèlerins. Elle donne des précisions sur le rôle qu'un cyclone tropical exceptionnel semble avoir joué, dans le sud de l'Arabie, en mettant fin à la dernière grande récession du fléau des criquets pèlerins, en 1948-1949. Elle expose les opérations stratégiques et tactiques actuellement mises en oeuvre dans la lutte antiacridienne, en accordant une attention particulière aux problèmes dont la solution requiert des conseils météorologiques et à l'extension que pourrait prendre à l'avenir la demande d'assistance météorologique dans ce domaine.

РЕЗЮМЕ

В начале семинара была прочитана вводная лекция о биологии и поведении пустынной саранчи (**Schistocerca gregaria Forskål**), затем были рассмотрены вопросы, связанные с влиянием метеорологических макромасштабных и мезомасштабных факторов, в частности поля ветра на миграции и распространение саранчи. Кроме влияния ветра, как средства переноса перелетной саранчи, было обнаружено также, что факторами, непосредственно определяющими концентрацию и рассеяние стай саранчи являются соответственно конвергенция и дивергенция в приземном слое, оказывающие также важное косвенное воздействие на распределение осадков, влияющих на размножение саранчи. Основные материалы по этим вопросам уже опубликованы полностью вТехнической записке ВМО № 54 (на основе которой развернулась дискуссия на семинаре) и в настоящей записке не повторяются.

Стандартная методика изучения поля ветра, включая изогипсы, линии тока, так же, как и методы количественной оценки полей дивергенции, были описаны и применялись при исследовании конкретных условий погоды, связанных со значительными скоплениями саранчи; в Записке приводятся также данные о применении и дальнейшем развитии методов исследования в самых различных условиях, включая экваториальные широты и континентальные возвышенности.

В Записке дается обзор проблем синоптической метеорологии и климатологии всей области распространения саранчи, включающей юго-западную Азию и большую часть Африки, в частности даются сведения о полях ветра, осадках и температуре. Кроме того в Записке дается изложение ряда проведенных участниками семинара синоптических исследований по конкретным погодным условиям, связанным с наблюдавшимися в последнее время скоплениями саранчи в их странах.Проблемы мезомасштабных систем полей ветра и связанные с ними вопросы атмосферной турбулентности рассматриваются в связи с миграцией, скоплением и рассеянием стай перелетной саранчи.

В Записке дается также краткий обзор сезонных и более долговременных колебаний цикла появлений пустынной саранчи и в частности содержатся подробные сведения о тропическом циклоне исключительной силы, разразившемся на юге Аравийского полуострова и сыгравшем важную роль в ликвидации последнего крупного скопления пустынной саранчи в 1948-49 г.г.

Излагаются существующие в настоящее время "стратегические" и "фактические" методы борьбы с саранчой, в частности указываются области, в которых требуется помощь метеорологов и намечаются перспективы на будущее.

Resumen

El seminario se inició con una introducción sobre los aspectos particulares de la biología y el comportamiento de la langosta del desierto (Schistocerca gregaria Forskål), seguida de un estudio de los datos de que se dispone actualmente acerca de la manera en que influyen en las migraciones y en la distribución del acridio los factores meteorológicos, especialmente los sistemas de viento macroescalares y a escala media. Además de los efectos del viento como agente de transporte de los enjambres en vuelo, se ha encontrado una relación directa entre las correspondientes características de convergencia y divergencia que se registran a baja altitud, con la concentración y dispersión respectivamente, de las poblaciones acridianas, y se les atribuye asimismo una relación directa importante con la distribución de la precipitación, elemento que es indispensable para la reproducción de la langosta. La documentación básica que se presentó al seminario ha sido ya publicada íntegramente en la Nota Técnica de la OMM No. 54 - que sirvió de documento de trabajo principal del seminario - y no hay por tanto objeto de reproducirla en la presente Nota.

Se describieron los procedimientos corrientes para estudiar los sistemas de viento, con inclusión de topografías, líneas de corriente, trayectorias y métodos para el estudio cuantitativo de los campos de divergencia, siendo aplicados a situaciones meteorológicas particulares observadas en el pasado y asociadas con proliferaciones significativas de langostas, siendo asimismo expuestas las experiencias recogidas en la aplicación de nuevos procedimientos de diferentes técnicas bajo diversas condiciones, que iban de las latitudes ecuatoriales a los elevados relieves continentales.

Se analiza la meteorología y la climatología sinópticas de toda la zona de invasión de la langosta del desierto, inclusive el Sudoeste de Asia y casi todo el continente de Africa, refiriéndose esencialmente a los sistemas de viento, a la precipitación y a la temperatura. Se incluye además una serie de estudios sobre situaciones meteorologicas determinadas, que algunos participantes asocian con proliferaciones recientes que se han producido en sus regiones. Se estudiaron los sistemas de viento a escala media y ciertos aspectos pertinentes de la turbulencia atmosférica con relación al desplazamiento, concentración y dispersión de las langostas en vuelo.

La abundante documentación disponible ahora sobre los cambios de carácter estacional o de largo plazo en la situación general de la langosta del desierto es objeto de un breve repaso y se presentan numerosas comprobaciones acerca de la manera en que un ciclón tropical excepcional en Arabia Saudita parece haver contribuido largamente a coartar la más reciente disminución de importancia de la plaga de langostas del desierto, en 1948-1949. Se resumen la estrategia y las tácticas a que obedecen hoy las operaciones de la lucha antiacridiana, destacándose los aspectos en los cuales es necesario contar con orientación meteorológica y sobre la manera en que puede evolucionar tal necesidad ulteriormente.

PROGRAMME OF SEMINAR

Opening ceremony

The seminar was opened by Dr. M.H. Ganji on the morning of 25 November 1963 at the University of Tehran. He welcomed the participants and, after outlining the scope and objectives of the seminar - including reference to personal experience of earlier locust invasions of Iran - introduced H.E. Dr. H. Shalchian, Minister of Roads and Communications. The Minister said that the desert Locust had from time immemorial been a devastating plague to the agricultural economy of Iran, where it is often known as the "Marine Locust" because it frequently attacks from the direction of southern seas. On behalf of the Government of Iran, he welcomed the scientists and scholars, and expressed his good wishes for the success of the seminar and for every happiness during the members' stay in Iran.

Dr. E. Esfandiari, Technical Under-Secretary of the Ministry of Agriculture, referred to the heavy Desert Locust invasion of Iran only the previous year, particularly in the Ostans of Khorasan, Kermanshah and Lorestan. He said that Iran was one of the countries in which the importance of weather to the migration of locusts was first recognized by Predtechensky and his Iranian colleagues, more than thirty years ago. Iran had always played a leading part in the development of international co-operation against the Desert Locust, and was at present a major contributor to the United Nations Special Fund Desert Locust Project. Emphasizing the support of the Ministry of Agriculture for the seminar, he welcomed the inclusion in the programme of other practical aspects of locust control.

Dr. M.H. Mahdavi, Dean of the Agricultural College of Tehran University, reviewed the wide scope of the Desert Locust problem, and expressed the happiness with which the University of Tehran placed its premises and facilities at the disposal of the seminar.

Mr. O.M. Ashford, Chief of WMO Research Section, speaking on behalf of the Secretary-General of WMO, outlined the assistance which WMO had provided in the development of the use of meteorology in locust control, particularly by the work of the 1955-1961 WMO Technical Assistance Mission for Desert Locust Control; and expressed appreciation for the invitation of the Government of Iran and for the support of the UN Technical Assistance Board and of FAO which had made the seminar possible.

Mr. A.M. Mustafa, FAO Country Representative in Iran, speaking on behalf of the Director-General of FAO, referred to the importance which FAO had always attached to the meteorological aspects of the Desert Locust problem. In the UNSF Desert Locust Project, for example, for which FAO was Executing Agency, specific provision for meteorological work was made under the chapters of the Ecological Survey, the Desert Locust Information Service, and the Operational Research Air Unit.

Concluding the opening ceremony, Dr. R.C. Rainey, in charge of the FAO Desert Locust Information Service at the Anti-Locust Research Centre, London, emphasized the extent to which utilization of the professional experience of forecasters in many countries had contributed towards an understanding of the role of meteorological factors in locust migration. He recalled in particular the impressive manner in which swarm movements, which he had himself been shown, in Kermanshah and Lorestan the previous year, had subsequently proved to have been associated with the passage of the frontal systems recorded at the time, entirely independently, on the synoptic charts of the Iranian Meteorological Department at Mehrabad.

Technical programme

The technical programme consisted of a series of lectures by consultants, guest lecturers and other participants, combined with some practical exercises and demonstrations. The main features of the programme are discussed by Dr. R.C. Rainey in the following section of this publication. Most of the lectures are published in full.

Conclusions and recommendations

In response to the wishes of many participants, the further development of applications of meteorology to locust control was discussed at the end of the technical programme, and as a result of this discussion, the following informal recommendations were agreed.

(a) There should be close liaison between the national Meteorological Services on the one hand and the national organizations responsible for locust control on the other;

(b) A basis should be worked out for an improved exchange of information between neighbouring countries about the breeding and movements of locusts, not only for anti-locust operations but also for meteorological research;

(c) Ways and means should be publicized for obtaining more complete and reliable information on the size, structure and movements of swarms. Wherever aircraft are available for crop-spraying, they should be used to obtain information, so that major swarms do not go untracked;

(d) Meteorological Services should be encouraged to take the following steps wherever they have not been taken already :

- (i) Preparation of divergence charts, on a routine basis for levels up to 3 km, during periods of actual or threatened infestations. Other synoptic studies pertaining to rainfall, thunderstorms, etc. should be undertaken so as to establish precisely the relationship between these phenomena and the movement and development of locust swarms. The assistance of the basic meteorological observational organization should be sought for closer reporting on swarm movements as well as the associated meteorological situations as observed on the spot;
- (ii) Meso- and micro-meteorological studies should be stepped up. It should be considered whether it would be feasible to organize mobile units, equipped with instruments, to visit infested areas and carry out detailed observations on the spot;
- (iii) Where weather radar sets are available, they should be used whenever possible for locust tracking, and a programme of photographing any locust radar echoes observed should be instituted;
- (iv) The phenomena known variously as the ITCZ, ITF, equatorial trough and the monsoon discontinuity should be investigated more fully;
- (v) The Meteorological Services of maritime countries should be reminded of Recommendation 16 (CMM-III) calling for reports of locusts by ships;

(e) The establishment of a WMO/FAO Working Group on Locust Meteorology should be considered. The initial tasks of this group might include :

- (i) Recommending the most efficient way in which Meteorological Services can report locust swarms;
- (ii) Preparing guidance material on the best ways for implementing the various suggestions in sections (a), (b), (c) and (d) above.

At the formal conclusion of the seminar, Dr. K.U. Siddiqi, Deputy-Director of the Pakistan Meteorological Department, on behalf of participants, and Mr. O.M. Ashford and Dr. R.C. Rainey, as co-directors, expressed appreciation to all who had contributed to the work of the seminar. Particular reference was made to the unfailing co-operation of the Iranian Meteorological Department; the hospitality of the University of Tehran; the invaluable assistance of the Ministry of Agriculture, the Royal Iranian Air Force, and the FAO Operational Research Air Unit; and to the "magic carpet" with which Iranian Airlines had enabled a memorable day in Isfahan to be included in so full a programme.

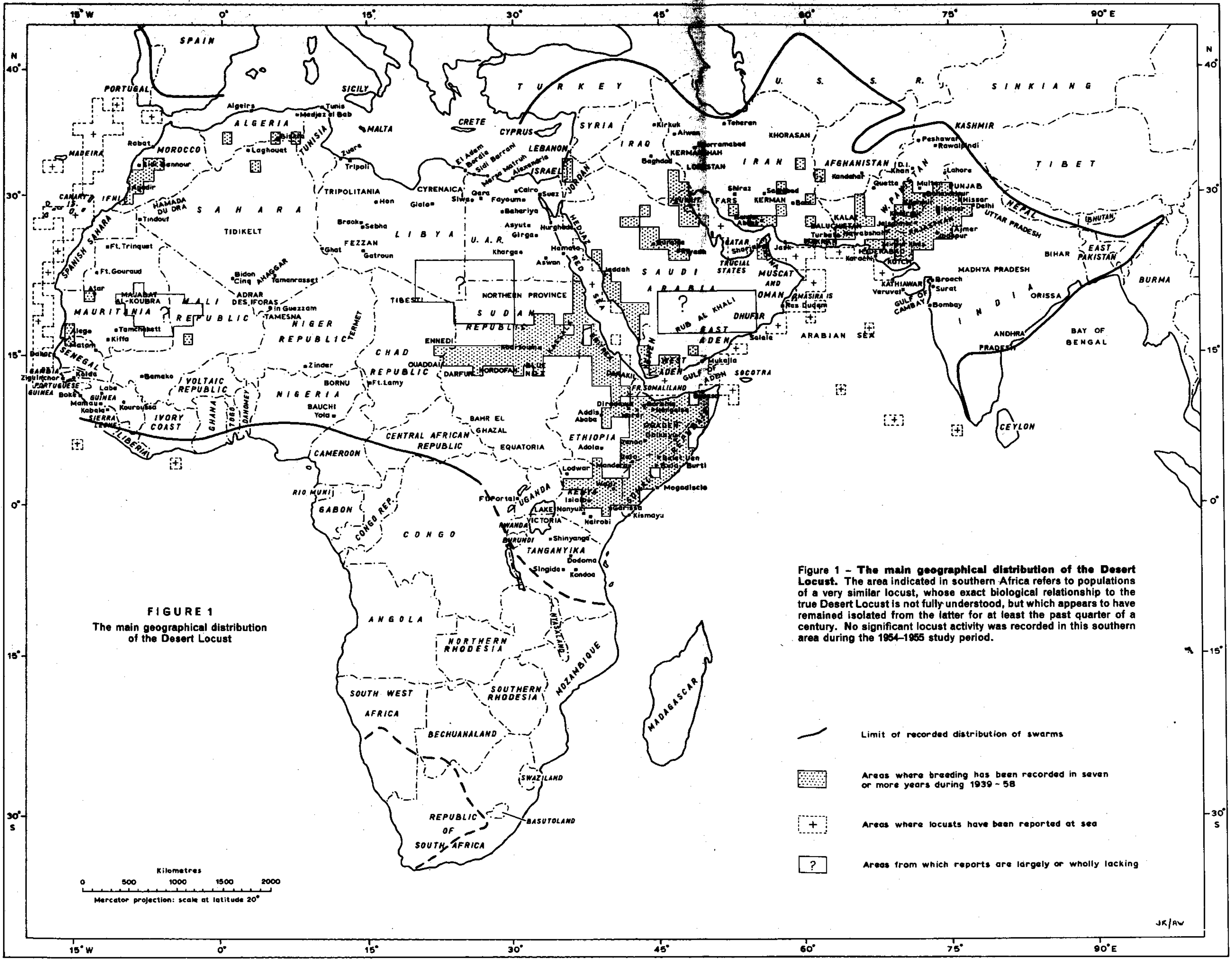

FIGURE 1
The main geographical distribution
of the Desert Locust

Figure 1 - **The main geographical distribution of the Desert Locust.** The area indicated in southern Africa refers to populations of a very similar locust, whose exact biological relationship to the true Desert Locust is not fully understood, but which appears to have remained isolated from the latter for at least the past quarter of a century. No significant locust activity was recorded in this southern area during the 1954–1955 study period.

TECHNICAL REPORT ON THE SEMINAR

by

R.C. Rainey

The seminar was planned with the primary object of helping participants to provide, in their own countries, the kind of meteorological guidance which has already been found of direct practical value in locust control operations in a number of different countries (see Chapter 4 of WMO Technical Note No. 54*) through the medium of national Meteorological Services. The International Desert Locust Information Service likewise utilizes current synoptic charts to assist in interpreting and in forecasting developments of the current locust situation over the whole area concerned (Figure 1). It was also hoped that it would be possible, at the seminar, to take advantage of the specialized professional experience of participants to help in the analysis and interpretation of particular synoptic situations associated with specific recent locust developments concerning their own countries.

The seminar began by introducing the Desert Locust initially as a flying machine, with a flight performance and operating limitations which can be expressed in terms similar to those applied to man-made aircraft. This was illustrated by a film by Torkel Weis-Fogh and Martin Jensen, showing in detailed slow motion, by stroboscopic photography, the flight of an individual locust on an aerodynamic balance in a wind-tunnel. The film incorporated a presentation of the corresponding variations in the lift and thrust developed by the wing-systems in the course of a complete wing-beat cycle, indicated by superimposed vertical and horizontal arrows varying appropriately in length and sense. It was thereby hoped to begin to provide the same kind of acquaintance with the flight performance and operating limitations of the Desert Locust which most participants were already likely to have with the corresponding characteristics of the aircraft they have long served.

Consideration of the relevant specifically biological characteristics of the locust followed, illustrated by live Desert Locusts of all stages - eggs, wingless nymphs or "hoppers", and winged adults - demonstrated by Ing. Gh. Farahbakhsh of the Iranian Ministry of Agriculture. The display included locust eggs brought from the Anti-Locust Research Centre in London, which hatched on the last day of the seminar, some 27 days after they had been laid in London. From this fact and the evidence available on the effects of soil temperature on egg-development [1] [2], it is incidentally possible to provide an approximate estimate of 23°C for the mean temperature to which they had been subjected in the course of their subsequent vicissitudes.

Following this introduction to the flight-performance and biology of the individual locust, research results were presented showing the behaviour of locusts in numbers in the field, in marching bands of hoppers and in flying swarms of adults, with details of a number of specialized techniques of observation, visual and photographic, and illustrated by cine sequences from ground and air. The results demonstrated the relative unimportance of the orientation or heading of the individual flying locusts in relation to the displacement of

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* A copy of Technical Note No. 54 - Meteorology and the migration of Desert Locusts - had been supplied in advance to each participant, together with a provisional French text where appropriate.

the swarm as a whole, by reason of the extreme diversity of orientation shown from point to point and from time to time between different groups of flying locusts in every swarm so studied.

Detailed evidence was next presented on the routes followed by individual swarms in relation to the corresponding wind-fields, providing nearly fifty estimates of the instantaneous velocity of complete swarms and of the corresponding winds. These estimates demonstrated a consistently downwind direction of displacement, implying movement directed on balance towards and with zones of low-level convergence of the wind-field. Further consideration of meteorological implications introduced streamline analysis, trajectories, and techniques for the analysis of the divergence field. A practical exercise in isogon analysis, introducing the construction of streamlines, was followed by exercises in streamline analysis and in the assessment of divergence. Participants carried out these assessments by two different methods (one using separate scalar analyses of northerly and easterly wind components, and the other using multiple trajectories), using for both methods the data of an actual case-study (late June 1961 in Pakistan and India). This study (in course of preparation for publication elsewhere) has provided evidence not only of the transport of swarms by the corresponding winds but also of the concentration of initially scattered solitary-living locusts, by highly convergent wind-fields, and possibly leading to the formation of additional swarms.

The consideration of effects of wind-fields on locusts on the meso-scale, already introduced by detailed hour-by-hour tracks of individual swarms with the corresponding winds, led to discussions of frontal structure and of convective and topographical effects, including thermal bubbles, turbulence eddies and clear-air turbulence, sea-breezes and coastal fronts, and anabatic circulations together with other aspects of the airflow over hills and mountains. One novel suggestion was that since locusts are constrained, often by temperature, to fly at relatively low levels, they might tend to be concentrated in the wake of thermal bubbles, instead of necessarily tending to be dispersed by turbulence. Previous work had directed attention to the continued cohesion of individual swarms (found in some cases to retain their identity and even their approximate plan-area for periods up to weeks and displacements up to hundreds of kilometres - see e.g. Figure 9 in Technical Note No. 54), despite potentially disruptive effects both of atmospheric turbulence and of the diversity of orientation shown between different groups of flying locusts within the same swarm. Direct observations, photographic and visual, provided evidence on which this continued cohesion was attributed primarily to the active behaviour of the flying locusts, turning back on arrival at the perimeter of the swarm; but clearly full consideration must also be given to any physical factors which might have the same effect - taking into account all available evidence of the scales of time and distance on which these phenomena are observed and on other orders of magnitude involved [3, 4].

Passing on to synoptic-scale effects of wind and other meteorological factors, the synoptic meteorology of Africa and south-western Asia was reviewed, with particular reference to low-level wind-fields, precipitation and temperature as especially significant in relation to the distribution, movements and breeding of locusts. Associated practical exercises dealt with the synoptic analyses (using mean sea-level isobars and streamlines of wind at 600 m above surface, together with 850 mb and 700 mb contours) of past synoptic situations which had proved important in relation to locusts. The situations chosen related to the periods 25 May to 14 June 1954, 24 to 30 January 1955, and 21 to 29 March 1962, for which the observational data had been assembled at the Anti-Locust Research Centre in London with the co-operation of WMO and of the Meteorological Services concerned, and plotted on working charts at the Centre's Desert Locust Information Service under the guidance of Mr. D.H. Johnson; a set of these plotted working charts for two days in each of the periods studied was provided to each participant at the seminar for analysis. Participants were shown the distribution of locusts at the beginning of each study-period, and, after a discussion of the completed analyses, led by Mr. Johnson, participants were able to see the corresponding changes in the locust situation which had occurred during each study-period - respectively, movements of swarms, mainly from Arabia, into the vicinity of the inter-tropical discontinuity in Africa; movements of swarms across northern Africa, including the invasion of Tunisia, under the influence of an Atlas-lee depression; and movements of swarms across north-eastern Iran and into the Turkmeniyan S.S.R., together with an eastward movement of swarms across India, associated with the passage of westerly disturbances. For the first two study-periods, the results of special synoptic analyses undertaken by a WMO Technical Assistance Mission, together with the corresponding locust history, appear in WMO Technical Note No. 54, and some very useful supplementary upper-air analyses for the second period were prepared by one of the participants at the seminar. For the third study-period, it is hoped to be able to arrange for the future publication of the master-analyses undertaken for the seminar.

Furthermore, all participants whose attendance was known in advance had been asked to arrive prepared to comment on particular recent synoptic situations, selected at the Desert Locust Information Service, when there had been significant locust movements affecting their own countries. Most participants had in fact done so, and presented their material in short talks, subsequently made available with the corresponding analyses for publication in these proceedings. With these participants' papers, and the chart discussions, the seminar provided invaluable opportunities (informal as well as formal) for the exchange of synoptic experience by practising forecasters; and it is hoped that these all-too-short discussions in Tehran, and these proceedings, may prove to be of general synoptic interest even apart from their relevance to locust problems. In order to provide effective technical discussion, all participants (including consultants and other lecturers) were encouraged to express, develop and finally to publish in these proceedings their own individual ideas, on locusts as well as on meteorology; the organizers of the seminar can accordingly accept neither credit nor responsibility for the views so expressed.

On a still longer time-scale, the synoptic climatology of northern and equatorial Africa, and of southern Asia, was reviewed, and the extensive evidence now available on seasonal and longer-term changes in the overall Desert Locust situation was outlined; this included evidence of the manner in which meteorological factors appear to have played a major part in bringing to an end the last major recession of the Desert Locust plague, in 1948-1949.

In order to indicate to participants the kind of meteorological guidance needed by locust control organizations, and the manner in which these needs might be expected to develop in the future, the logistics and strategy of locust control were described in a paper presented by the Director of the International Desert Locust Control Organisation for Eastern Africa, and the organization of Desert Locust control was described by the Chief of the FAO Operational Research Air Unit, with particular reference to the place of aircraft, since it is especially in relation to the increasing use of aircraft, for reconnaissance as well as for spraying, that locust control organizations may be expected to make increasing demands on their national Meteorological Services.

During the planning of the seminar, the Iranian authorities had indicated the importance which they attached to the practical aspects of these problems. Accordingly, in addition to lectures on locust control techniques, a very successful demonstration of ultra-low-volume spraying methods, from ground and air (which deliberately exploit both wind and atmospheric turbulence for the distribution of insecticides, and within the last decade have become part of current anti-locust practice in many countries), was given at Doshan Tapeh aerodrome, with the co-operation of the Royal Iranian Air Force, the Iranian Ministry of Agriculture and the FAO Operational Research Air Unit, and under the technical direction of Mr. Sayer, who has made major contributions to the development of these methods. One of the standard exhaust-nozzle sprayers of the Iranian Ministry of Agriculture, mounted on a light four-wheel-drive reconnaissance vehicle, was first demonstrated. This simple device, designed by Mr. Sayer and successfully used in more than a dozen countries, operated by the exhaust system of the vehicle, applies special concentrated formulations of persistent insecticide to the sparse wild vegetation on which locust hoppers feed, in the form of a fine spray with a mass median diameter of about 70μ at dosages of the order of a few decilitres per hectare. By way of contrast, a Piper PA 18A agricultural aircraft, fitted with standard agricultural boom-and-nozzle spray-gear and flown by Y.M. Afshar, next demonstrated standard crop-spraying practice (as in general use against other pests), spraying from a height (recorded photographically) of less than one metre, and applying dilute aqueous emulsion at a dosage of about 27 litres per hectare over a swathe of 20 m. Finally, a Cessna 185 aircraft, fitted with rotary atomizer spray-gear and flown by Birgir Jonsson, at a height photographically recorded as 11 to 14 metres and on a heading at right-angles to the very light wind (about 3 kt), demonstrated an effective swathe of more than 200 m with dosages again of the order of decilitres per hectare of concentrated oil solution in a non-volatile solvent. Such spray-lines, applied up to 1 km apart in FAO field trials in India and in subsequent operations by the Pakistan locust control organization in 1962, were found to represent probably the most effective method yet available for the control of extensive infestations of locust hoppers.

As a final exercise, participants were grouped into syndicates and each syndicate was invited to envisage itself as the technical staff responsible for planning air operations to deal with a particular locust situation, of which all relevant biological and operational details were provided. Syndicates were asked to prepare an outline plan for air reconnaissance to assess, with minimum flying hours, the adult locust population escaping from the breeding area concerned (as the first step in enabling appropriate spraying operations to be mounted), taking advantage of the high constancy of the wind-field to be expected in the area and season concerned. The solutions were submitted for general discussion by the chairman of each syndicate, and showed a considerable degree of agreement with each other and with the plan which had actually been used in the particular situation concerned (eastern Africa in December 1953, when air contact with the leading locusts had been established on the Juba river on the day after the reconnaissance programme had been started). The main difference between the plans prepared by the syndicates and that adopted in practice was the larger number of moves of the main base which we envisaged at the seminar.

Desert Locust populations are now (December 1964) at a very low level; it is hoped that the Tehran seminar will have demonstrated the vital role of the application of synoptic and meso-scale meteorology in helping to maintain this situation, particularly in assisting locust control organizations to establish and maintain contact with the surviving locust populations. Moreover, there is reason to believe that a similar approach may well be of value in dealing with problems of the movement and distribution of other airborne organisms, such as the spores of the wheat-rust (Puccinia) of Pakistan and India, the migratory sunn-pest (Eurygaster) of the Near East and even birds, for all of which the wind-field must at least provide an important component of their displacement relevant to the ground. In addition, convergence or divergence of the wind-field must necessarily contribute to the concentration or dispersal, respectively, of all organisms or other material constrained in any way to remain in the lower levels of the atmosphere.

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RELEVANT ASPECTS OF THE BIOLOGY AND BEHAVIOUR OF THE DESERT LOCUST

by

R.C. Rainey

The lecture given under this title was an account of Chapter 1 of Technical Note No. 54, Meteorology and the migration of Desert Locusts (WMO-No. 138.TP.64/ Anti-Locust Memoir 7).

BEHAVIOUR OF LOCUSTS IN FLYING SWARMS, WITH PARTICULAR REFERENCE TO ORIENTATION

by

H.J. Sayer

The fundamental problem of the desert locust, which makes it one of the most devastating insect plagues, is the fact that it can appear in very large numbers at high densities which can move rapidly over thousands of miles. Much work has, therefore, been undertaken on the study of these flying swarms of locusts in order to determine (a) the mechanism which holds them together and (b) their migration. Regarding the former, the concentrating effect could be either the result of gregarious behaviour, or, in certain circumstances, due to the wind. Studies of the behaviour of locusts in swarms have shown that the movement of swarms is controlled by the weather, the only contribution from the locusts being a daily cycle of flight which is mainly temperature controlled.

A week or so after fledging, adult locusts become relatively strong flyers with an endurance based on their supply of fuel, which is their body fat. The maximum powered flying possible is around 20 hours but, of course, longer airborne periods are possible if gliding is also adopted. Normally, continuous flying of the individual locusts in a swarm is rare, except in exceptional circumstances such as passage over the sea; there are generally a large number of locusts temporarily settled under a flying swarm. A swarm progresses, then, by the intermittent flight of the millions of individuals composing it.

The diurnal temperature cycle determines the flying time each day, since the locust does not normally fly at all when its body temperature is below about 20°C. Owing to the early morning basking behaviour of locusts in which they tend to expose the maximum surface to the sun on the ground where there is the minimum wind, their body temperatures can soon be higher than the surrounding air, but the cooling effect of wind or flight will soon reduce their temperature to near that of the air. In flapping flight, the metabolic heat produced by flying can maintain the body temperature above that of the air, a fact which is very obvious towards the end of the day when a large proportion of a swarm may still be actively flying in air which is rapidly cooling to well below 20°C. As the temperature rises in the morning, the number of locusts airborne and the length of individual flights gradually increase until by mid-afternoon a swarm is, under normal circumstances, most actively flying. The reverse process, that is, settling on the roost site, takes place much more rapidly, and sometimes very dramatically. Thus, a large swarm flying up to a thousand feet or more at 17.30 hours can be virtually all settled within one hour.

The flight performance of a locust has been studied in both the laboratory and the field, and the cruising flying speed in both cases is about 3.8 - 4.3 m/sec (13 - 15 km/hr). This speed of flight is often less than the wind speed, when it would be impossible for locusts to progress upwind. But since observations on swarms together with the evidence of hundreds of vertical photographs taken systematically during the passage of a swarm have shown that the orientation of locusts within a swarm is effectively random, the net result of the randomly orientated flight of millions of locusts is a drifting downwind of the swarm. This downwind movement of swarms has been confirmed and is described elsewhere.

If one observes the passage of a flying swarm, several characteristics become apparent. Looking upwind towards an approaching swarm, it is common to be surrounded suddenly by descending gliding locusts heading upwind before the arrival of the leading low-flying locusts. Looking upwards, one sees similar upwind orientated locusts, the leading edge of a swarm being typified by locusts gliding back towards the main body of the swarm. During the passage of the main body of the swarm, one sees streams of locusts all flying in nearly the same direction, each successive stream having a different orientation, and weaving in and out across the swarm. At one moment, a stream directly over the observer may be moving eastwards followed a few minutes later by a stream moving westwards. At the rear of the swarm, there is more common orientation of downwind towards the departing swarm. As the swarm passes by, the settled locusts around the observer take off rapidly, heading downwind after the swarm. Under the common desert bush conditions, the passage of a swarm is very clean, there being very few stragglers left behind. Only in those areas of dense vegetation or tall dense grass, more typical of non-desert vegetation, do stragglers occur in any large numbers.

If there was only random flight of all the locusts in a swarm, under stable wind conditions, one would expect dispersion of the locusts for two additive reasons. Firstly, considering the locusts as inanimate particles such as dust or smoke, they would be dispersed under the effect of wind turbulence, and secondly, random flying even under still air conditions would again result in dispersion. Observations on swarms moving in a steady wind over periods of days have shown that swarms change very little in size through the whole period and certainly do not double their size every six hours of flight as might be expected from the dispersive effects. There is clearly another factor at work.

It has been pointed out above that the locusts at the front and rear edges of a swarm are seen to be orientated inwards. Similarly, observations have been made both visually and photographically at the sides of swarms. Groups of outward flying locusts have been observed turning back into the swarm at the sides and a series of vertical photographs taken at 20 second intervals from three camera stations during the passage of swarms have shown a predominance of similar inwardly directed flight at the swarm edges. This edge effect in which locusts are seen to be turning in towards the swarm can only be attributed to their gregarious behaviour and is, therefore, a most important factor. Under conditions of near zero wind divergence, when the net effect of the wind is to disperse locusts, there is a balance between the gregariousness of the locusts and the dispersive forces of the wind. Under some conditions of high turbulence usually associated with high temperature, swarms are so dispersed as to become unrecognizable as a swarm, whereas conversely, where the convective turbulence is low, as on high plateaux, the swarms fly very dense and low.

Photographic records of flying density have shown that recognizable swarms can have densities between 0.001 and 1.0 per cubic metre. It would seem, therefore, that locusts generally prefer to fly not closer than about one metre to their neighbours and not much further than ten metres. Investigations as to the mechanism of this behaviour have shown that there is little likelihood of sound being the operative sense-organ. It has been shown that locusts under field conditions are unlikely to respond to the sound of another locust beyond a distance of two metres, which limits this sense-organ to the high density flight. The locust eye has been shown to respond to a movement of a light source of 0.1° which is the angle subtended by the length of a locust at 30 metres, which corresponds with the low-density flight. A great deal of investigation is still needed into the mechanism of gregariousness.

Locusts have repeatedly been observed taking off and landing into wind. This would be expected to give a common upwind orientation of those locusts near the ground and may, in the past, have given the impression to observers that locusts prefer to fly upwind. However, upwind orientation is very soon abandoned after take-off and a curved flight is often assumed. This low-altitude common orientation may explain the sometimes observed phenomenon of low-flying swarms over highlands appearing to be flying against the wind.

Under conditions of negative wind divergence, the gregariousness of the locusts is reinforced by the wind, and under extreme conditions exceedingly high flying densities can occur. At low levels the convergent winds bring the locusts together, the only dispersive directions being upwards or along the line of convergence. Since locusts tend to cease flapping flight with altitude owing to the lapse rate, then the main dispersion is that along the convergence zone. Under such conditions, swarms become long and narrow with the topmost locusts several thousand feet above ground.

DISPLACEMENT OF INDIVIDUAL LOCUST SWARMS IN RELATION TO WIND

by

R.C. Rainey

The lecture given under this title was a summarized account of Chapter 2 of Technical Note No. 54, Meteorology and the migration of Desert Locusts (WMO-No. 138.TP.64/ Anti-Locust Memoir 7).

THE METEOROLOGICAL IMPLICATIONS OF DOWNWIND MOVEMENT

by

D.H. Johnson

1. INTRODUCTION

From the many locust studies summarized by Dr. R.C. Rainey [4] and from the lectures which he and Mr. H.J. Sayer have given, it is seen that the weather elements play an important part in each phase of the life-cycle of the desert locust. Meteorologists can expect to be asked by locust control workers to supply information about winds, temperatures convection and turbulence in the lowest 2000-3000 metres of the atmosphere, about temperatures amongst vegetation, at the surface, and in the upper 10 cm of the soil, about rainfall, about moisture stored in the upper 10 cm of soil, about solar radiation or at least about sunshine and cloud, about convergence and about vertical motions. It is possible that physiological studies will lead in time to an interest in relative or absolute humidity as well. The information sought may relate to the climatic normal to current conditions or to conditions over the next few hours, or days, or even months.

2. ANALYSIS METHODS

Once a swarm or an infestation of locusts has been reported, control operations may require spraying aircraft to keep in touch with swarms over periods of days or weeks. Operational circumstances prevent a continuous watch being kept on the locusts themselves, and the problem of making contact with swarms previously sighted requires their probable movement to be estimated. This is a tactical problem. There are longer-term requirements as well. Dr. Rainey has pointed out that every one of the 60 countries subject to invasion is attacked from time to time, by swarms produced thousands of kilometres beyond its own borders, although even the most frequently afflicted countries can be free of swarms for several years. Forewarning of impending invasion is therefore of great importance for alerting and mobilizing the available control teams. In these circumstances we can understand the great significance for the application of meteorology in locust control, of the hypothesis, tested and substantiated by Dr. Rainey using data accumulated over the past ten years or so, that migrating locust swarms are simply displaced in the direction of the low-level wind. It will be recalled that the swarm as a whole usually progresses at a speed which is substantially less than that of the wind, because the locusts fly mainly by day and even then they spend part of their time on the ground. If they are carried out to sea however, they have to stay airborne until they strike land or until they fall exhausted.

It has also been pointed out that warmth is an important control on flight activity: flight activity is reduced if the temperature drops below about 23°C in cloudy weather or below 15°C in sunshine. Temperature then has to be taken into account in deciding whether the locusts will begin or continue their migration and also at what levels they may fly.

The depth of swarms varies considerably, but over low ground the locusts are usually located between the surface and 850 mb. However, over high ground and hot places they may extend above 850 mb, maximum height often being attained during the afternoon when the topmost locusts sometimes approach the limit of dry convection on the ground [4].

Migrating swarms respond to atmospheric motions on all scales. The seasonal and annual patterns of their movements can be related to the general circulation, as shown by Professor H. Flohn and Dr. Rainey. Migrations over periods of days take place within the circulation of the weather disturbances which are revealed by synoptic analysis : the lectures of Mr. J. Cochemé, Mr. S. Mazumdar and the writer, and a large part of the practical work, are concerned with such motions. Swarms also become involved in convection and in meso-scale circulations, the latter being systems of diameter between 10 km and about 500 km such as a line squall or sea breeze, which may affect some of the observations plotted on a synoptic chart, but cannot adequately be defined in the synoptic analysis : Professor R.S. Scorer, Mr. H.J. Sayer and Dr. Rainey deal with the effects and importance of systems of this size.

The synoptic analysis programme at the main analysis centres within the desert locust area normally includes charts for surface, 850 mb and 700 mb. Together with tabulations showing the variation of wind with height in detail at individual stations (or wind sheets as they are sometimes called), and tephigrams or other thermodynamic diagrams, these provide material for assessing the synoptic-scale steering currents which the locusts have encountered or are likely to encounter. For some locust studies /5/ an additional chart has been introduced, which gives the wind field at a height of 600 metres above ground level. This chart is particularly valuable in very low latitudes where there is no simple and general way of deducing the wind above the surface friction layer from the surface pressure pattern. It is also useful over high ground in other parts of the desert locust area, where similar difficulties may arise due to problems of barometric reduction and due to the effects of the mountains on wind and pressure patterns. It is of course quite logical in locust meteorology to analyse the wind in a surface which follows the contours of the ground because the paths of the migrating locust swarms must also follow the general level of the terrain. Since the surface of 600 metres above ground level (AGL) does not correspond either to a constant level or to a constant pressure, the wind field must be analysed directly using a form of streamline analysis.

3. STREAMLINE AND ISOTACH ANALYSIS

Several techniques for the direct analysis of the wind field have been devised, but in the system most generally applied the wind field is represented by two sets of isopleths, namely, streamlines and isotachs. V. Bjerknes and J.W. Sandström /2/ were the first to advocate the technique but C.E. Palmer /3/ has been primarily responsible for its recent use especially in tropical meteorology. For those who have no practice in the streamline technique the remainder of this lecture will be devoted to an account of the method as given for example by C.E. Palmer and collaborators /3/, A.T. Bath and W.J. Gibbs /1/ and H.Riehl/6/. It is from the first two works that the illustrations for this lecture have been taken, i.e. Figures 1 to 11 from Palmer and collaborators /3/, Figures 12 to 15 from Bath and Gibbs /1/

3.1 The direct method

Figure 1 shows a streamline and isotach analysis. Two sets of isopleths completely specify the horizontal wind field. The streamlines, represented by continuous curves with arrowheads, enable the wind direction to be deduced by interpolation at any point of the map and the isotachs, drawn as pecked lines, give a field representation of the wind speed. It is important to note that although the flow is parallel to the streamlines, in this type of streamline analysis the wind speed is not proportional to their distance apart. In streamline analysis, as in surface pressure or upper-contour analysis, there are a number of common distinctive configurations, or models. In Figure 1 there are several asymptotes, that is streamlines along which neighbouring streamlines tend to converge, and two kinds of singular points. Singular points are points into which more than one streamline can be drawn or about which the streamlines form a closed curve. Figure 1 contains two singular points : in its south-west quadrant there is a neutral point, that is a point at which two asymptotes, one of confluence and one of diffluence, intersect; in the north, there is a cyclonic indraft, "cyclonic" describing the sense of rotation of the flow.

Figure 2 shows pure indraft, pure outdraft and the various types of vortex. The bottom two are possible kinematically, but they rarely, if ever, occur in the lowest part of the troposphere although they may well occur in special circumstances at higher levels.

The development of a low latitude wave into a cyclonic indraft is illustrated in Figure 3. The wave amplifies and passes through the cusp-point stage before the vortex and an associated neutral point form simultaneously and progressively separate as the vortex grows. The cusp is a transitional feature, rarely properly observed.

When a vortex is embedded in a uniform current, invariably there is an associated neutral point. Where the neutral point lies, relative to the vortex, is a matter of simple geometry depending upon the direction of the uniform current and the kind of vortex. This is demonstrated in Figure 4.

Typical relations between the isotach and streamline patterns are shown in Figure 5. The major currents have elongated wind maxima near which the isotachs tend to parallel the streamlines. At every singular point there is a speed minimum : clearly there can only be a zero flow, that is a calm, at a point where streamlines intercept. Near a neutral point the speed minima tend to be elongated along the asymptotes. When singular points occur in a closely-spaced chain they are usually associated with a band of relatively light winds.

At most of the centres where training in tropical analysis is given, the construction of isogons (isopleths of wind direction) is usually recommended as a preliminary to the drawing of the streamline field : isogon analysis is discussed below. However, the process is too laborious for routine use over large areas and in day-to-day practice the so-called direct method is applied. The first stage consists of sketching a few key streamlines and isotachs in regions where the observations are fairly dense, as in Figure 6. Figure 7 shows the relation of the completed streamlines to the wind observations. There is no limit to the number of streamlines which can be drawn, but there is no point in drawing more lines than are sufficient to portray the character of the flow unambiguously. It is a common tendency of beginners to distort the streamlines so that they pass through the points of observation and this is a fault to be avoided. In Figure 8 isogons have been added to the analysis, bearing in mind the relations previously discussed. The spacing of 5 kt for the isotachs is suitable for low levels in the tropics, but at higher levels and in the subtropics this may be too small an interval, 10 kt or 20 kt being more convenient. As in all forms of synoptic analysis, continuity in time and in the vertical should be maintained.

3.2 The isogon method

Isogon analysis is a scalar method of depicting the field of wind direction. Isogons are lines joining places having the same wind direction. The isogons for 090, 180, 270 and 360 degrees are known as the cardinal isogons. Figure 9 shows the cardinal isogons sketched to the wind observations of Figure 8. Isogons are interpolated between the observations in much the same way as isobars, but they have one very important characteristic which isobars, isotherms and most other isopleths of scalar fields do not have : isogons of different values may intercept. They do this at singular points. Two special properties of singular points to be noted are that each singularity is a point of interception of all isogons, and that on passing through a singularity the value of an isogon changes by 180 degrees. In Figure 10, the analysis begun in Figure 9 is completed. Note that the isogons are drawn at intervals of 30 degrees. There are often areas of the chart where it is convenient to add additional isogons drawn at 10-degree intervals.

The process of deriving a streamline field from the isogons is a simple one. Using a ruler and protractor, short-line elements are ruled across each isogon, in a direction corresponding to its indicated value. The asymptotes should then easily be recognized and streamlines can be sketched in to be everywhere tangential to the short-line elements. Figure 11 illustrates the elevation of the streamlines from the isogon pattern of Figure 10.

Singularities can be divided up into two families on the basis of the isogon patterns. In the first family, known as positive singularities, the isogon values increase in a clockwise direction around the singular point. Figure 12 shows the relation between streamlines and isogons for several kinds of singularity which include cases of pure rotation, pure indraft or outdraft and intermediate states. Figure 12F shows how the type of the singularity varies according to the quadrant in which the 360-degree isogon is located. The second family consists of positive singularities in which the isogon values decrease in a clockwise direction around the singular point. As Figure 13 indicates, negative singularities all correspond to neutral points, and the general shape of the streamline pattern is unaffected by the orientation of the isogons. The lower part of Figure 13 shows the streamline patterns associated with parallel isogons; isogons orientated in their own directions are lines of convergence or divergence.

Figure 14 is an isogon analysis made by Bath and Gibbs [1] which shows the general character of the patterns which emerge when an analysis is made for a large area. Note that positive and negative singularities occur in pairs; this corresponds to the observation previously made that every vortex has an associated neutral point. Bath and Gibbs [1] mention that a good deal of reference to the surface pressure chart was made in producing this analysis, upper-wind observations within the area being too sparse to define the isogon field by themselves. The corresponding streamline analysis is shown in Figure 15.

Streamline and isotach analysis are clearly capable of representing the wind field with high accuracy, but therein lies a difficulty. Palmer and collaborators [3] who were able to work in the central Pacific with a fairly close network of radar winds, have remarked that "The interpolation (analysis) is complete and correct when the analyst recognizes that every wind arrow plotted is strictly tangential to the streamlines, and that no streamline turns too abruptly, and that there is a general smoothness and elegance to the pattern difficult to define, but easy to recognize." Analysts who have attempted to make such accurate streamline and isotach analyses for the desert locust area at low levels, where there are many pilot-balloon observations, have found the flows apparently complicated by an embarrassing number of asymptotes, singularities and small waves, which have poor continuity with previous and succeeding analyses, and most of which seem to have little relevance to the pattern of weather. On most overland charts a number of wind observations are unrepresentative of the general synoptic-scale flow to a greater or lesser degree, due to errors of observation and transmission, or to the effects of local convection or orographic circulations. Streamline analyses drawn for the desert locust area usually incorporate a degree of smoothing. However, when assessing the effect of winds on locust movements taking place over a few hours only, the analyst must use his experience to judge very carefully whether apparent departures from the synoptic-scale circulation represent real small-scale circulations or whether they are more likely to be the result of errors of observations.

4. LOCUST CONCENTRATION

In earlier sections the importance for locust control operations of the hypothesis of downwind displacement was discussed. Dr. Rainey [4] has also pointed out that the downwind movement takes place towards regions of low-level wind convergence. This process serves to concentrate the locusts in regions which are favourable for rain : in Dr. Rainey's words "It accounts for the close and apparently purposeful association between swarm movements and the distribution of rainfall which is essential for successful breeding".

The concept of divergence is best understood quantitatively from its formulation in terms of natural co-ordinates :

$$\nabla_H \cdot V = \frac{\partial v}{\partial s} + V \frac{\partial \Psi}{\partial n}$$

The first term on the right is known as the longitudinal component of the divergence ("vergence"). The second term on the right is the transverse component ("fluence"). Their significance and the meanings of confluence and diffluence are demonstrated in terms of streamline and isotach representation of the wind field. It is important to note that the two terms are usually of opposite sign so that the total may be an order of magnitude less than that of the individual terms.

Mr. Cochemé deals in detail with the effects of convergence and divergence and with methods of measuring them (p. 23).

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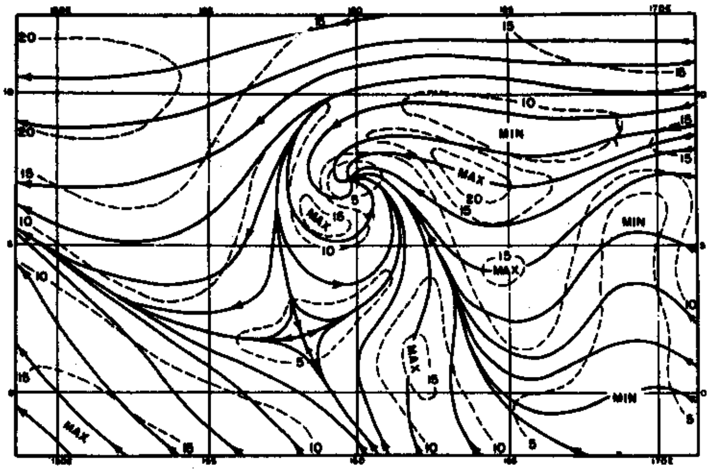
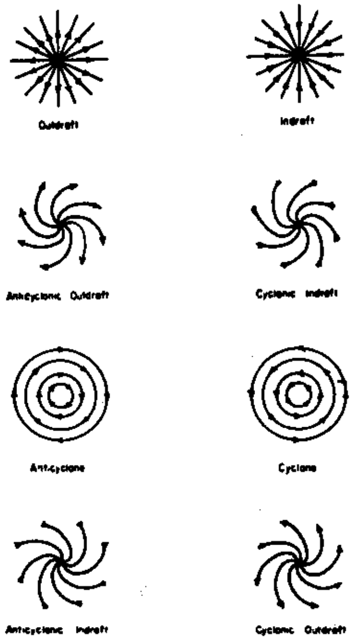


Figure 1 - The streamline-isotach method of wind analysis. Streamlines represent only the wind direction. Isotachs represent the speed.



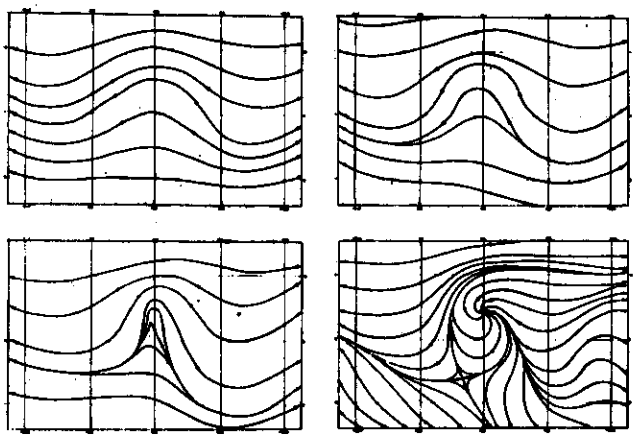


Figure 3 - The transition from a wave to a vortex-neutral-point pair through the cusp-point stage.

Figure 2 - Vortices in the streamlines. The cyclonic and anticyclonic classification applies to the northern hemisphere.

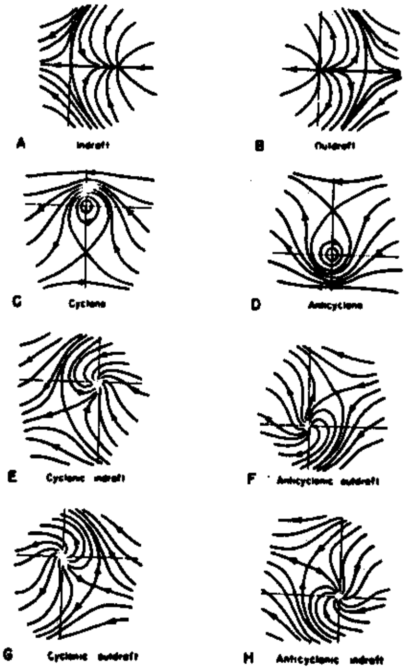


Figure 4 - Orientation of the vortex and its associated neutral point in an easterly current in the northern hemisphere.

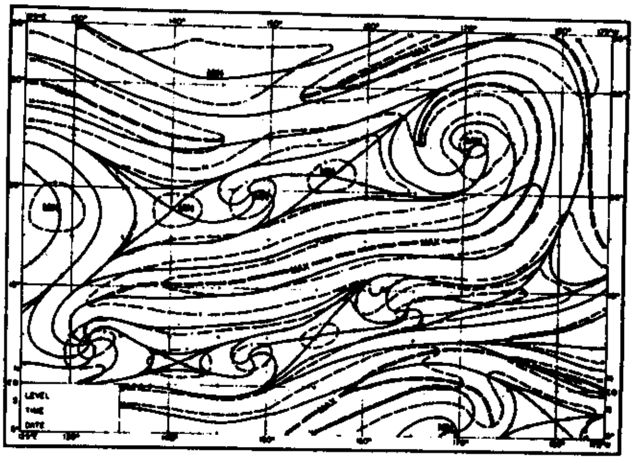


Figure 5 - Isotach patterns associated with typical streamline patterns over a large oceanic area.

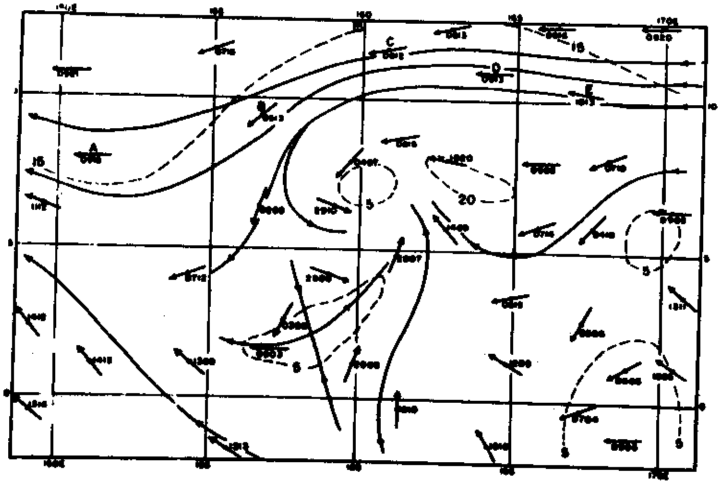


Figure 6 - A preliminary sketch of the streamlines and isotachs.

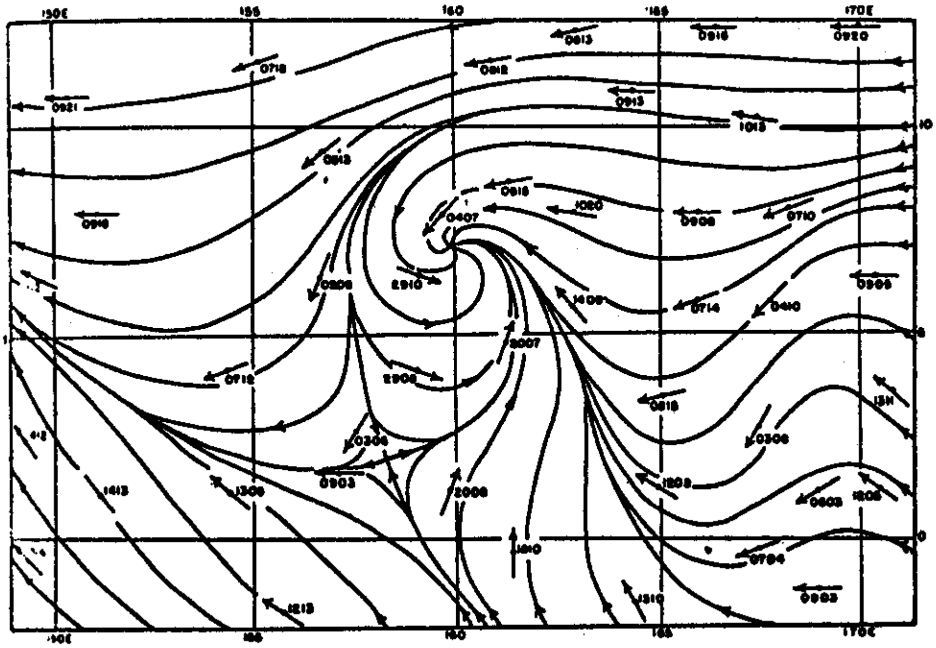


Figure 7 - The completed streamline analysis.

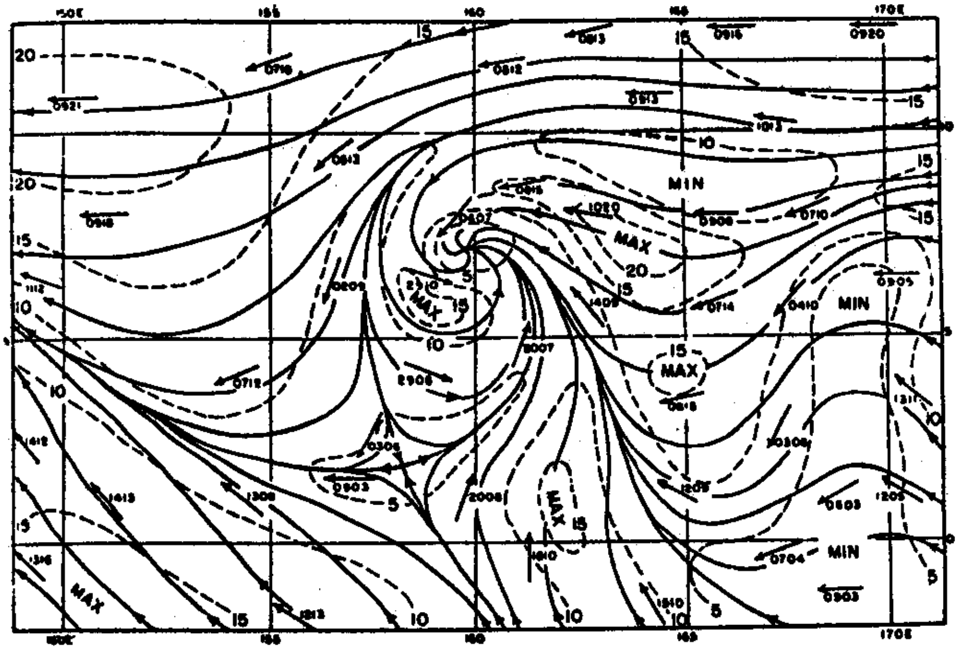


Figure 8 - A complete streamline-isotach analysis.

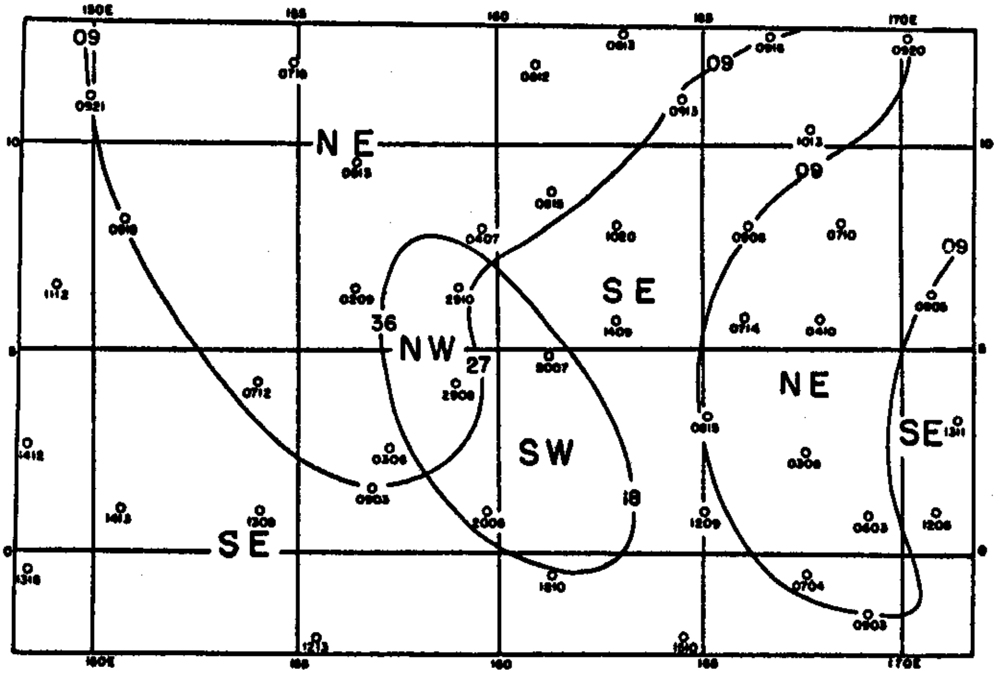


Figure 9 - A preliminary sketch of the cardinal isogons.

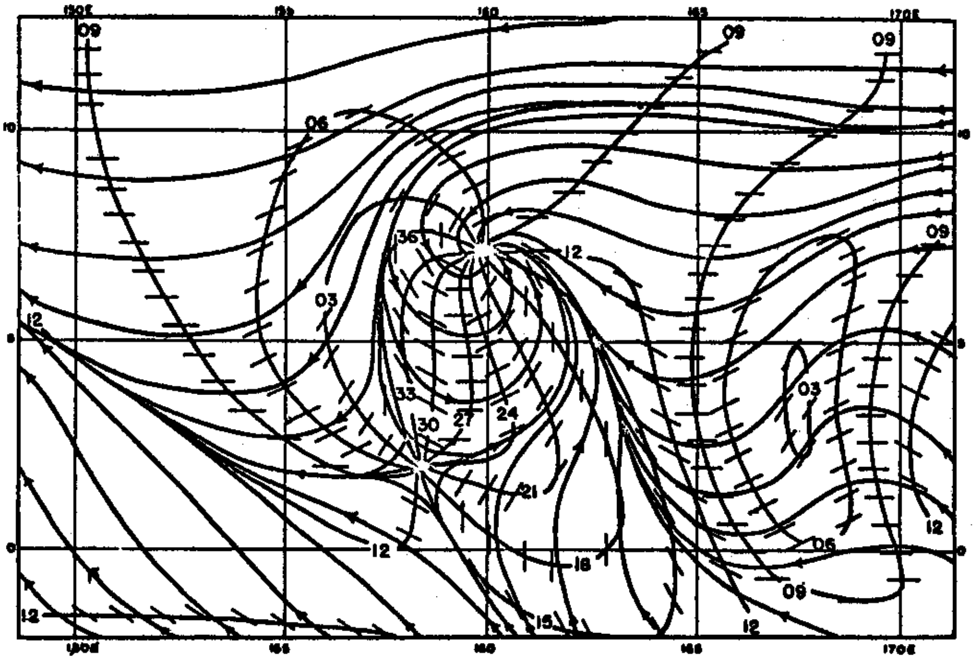


Figure 11 - Streamlines drawn with the aid of the isogon line elements.

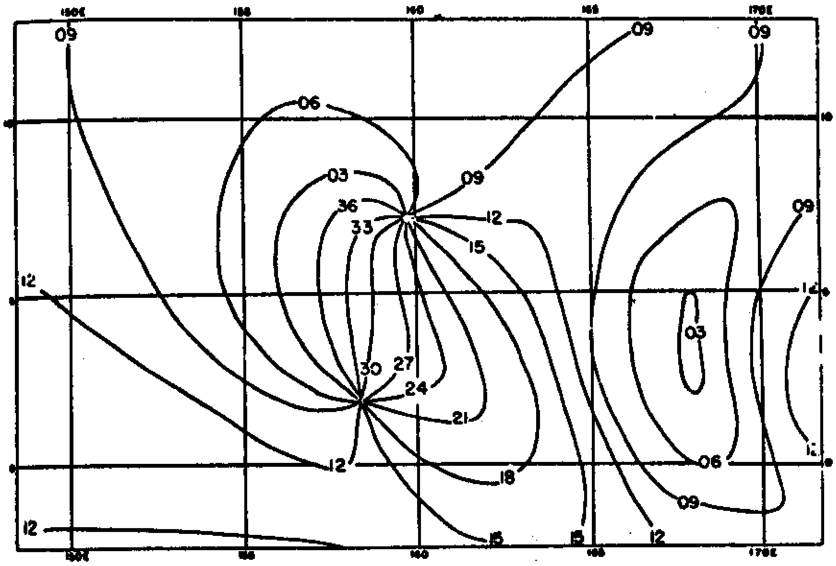


Figure 10A - A complete isogon analysis illustrating singular points and a closed curve in the isogons.

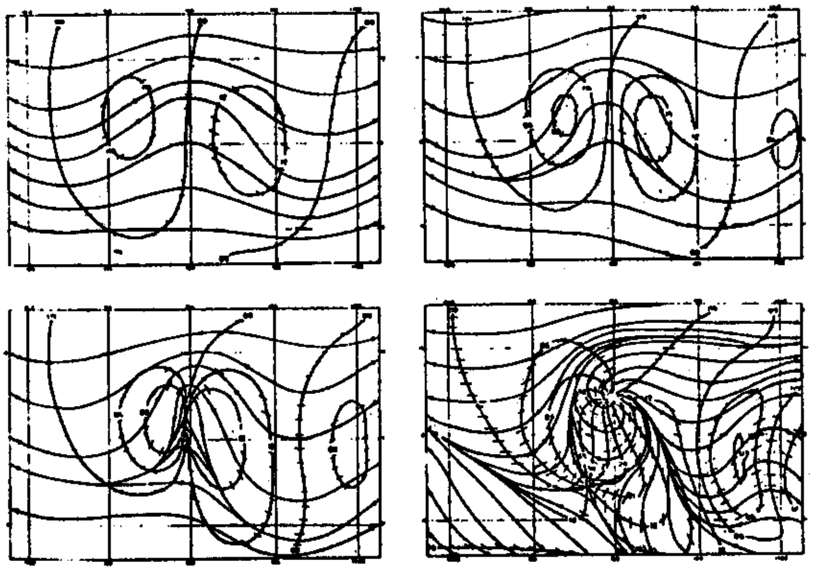


Figure 10B - Isogon patterns associated with common streamline patterns.

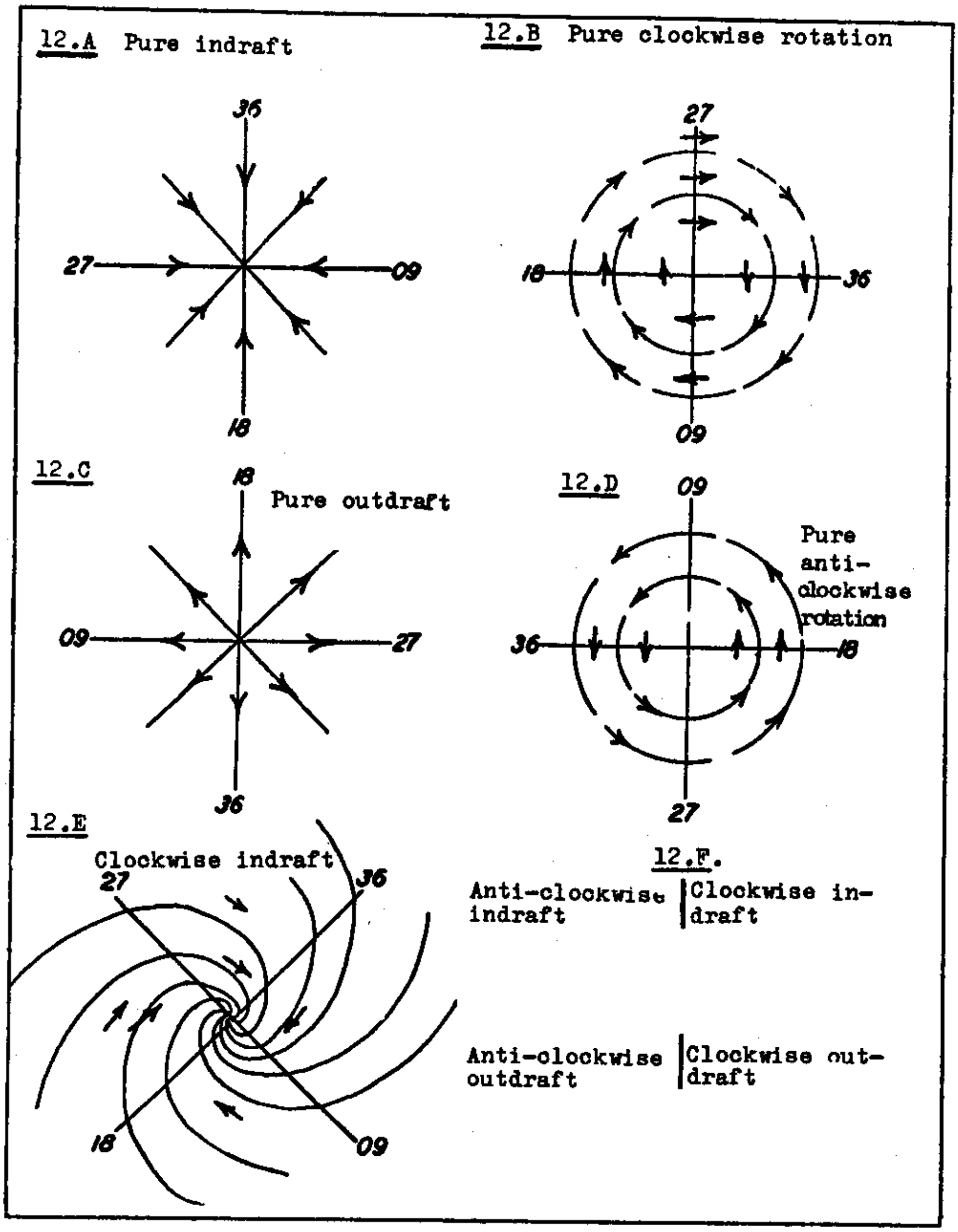


Figure 12 - Showing relationship between streamlines and positive isogon singularities. For description of 12.F, see text.

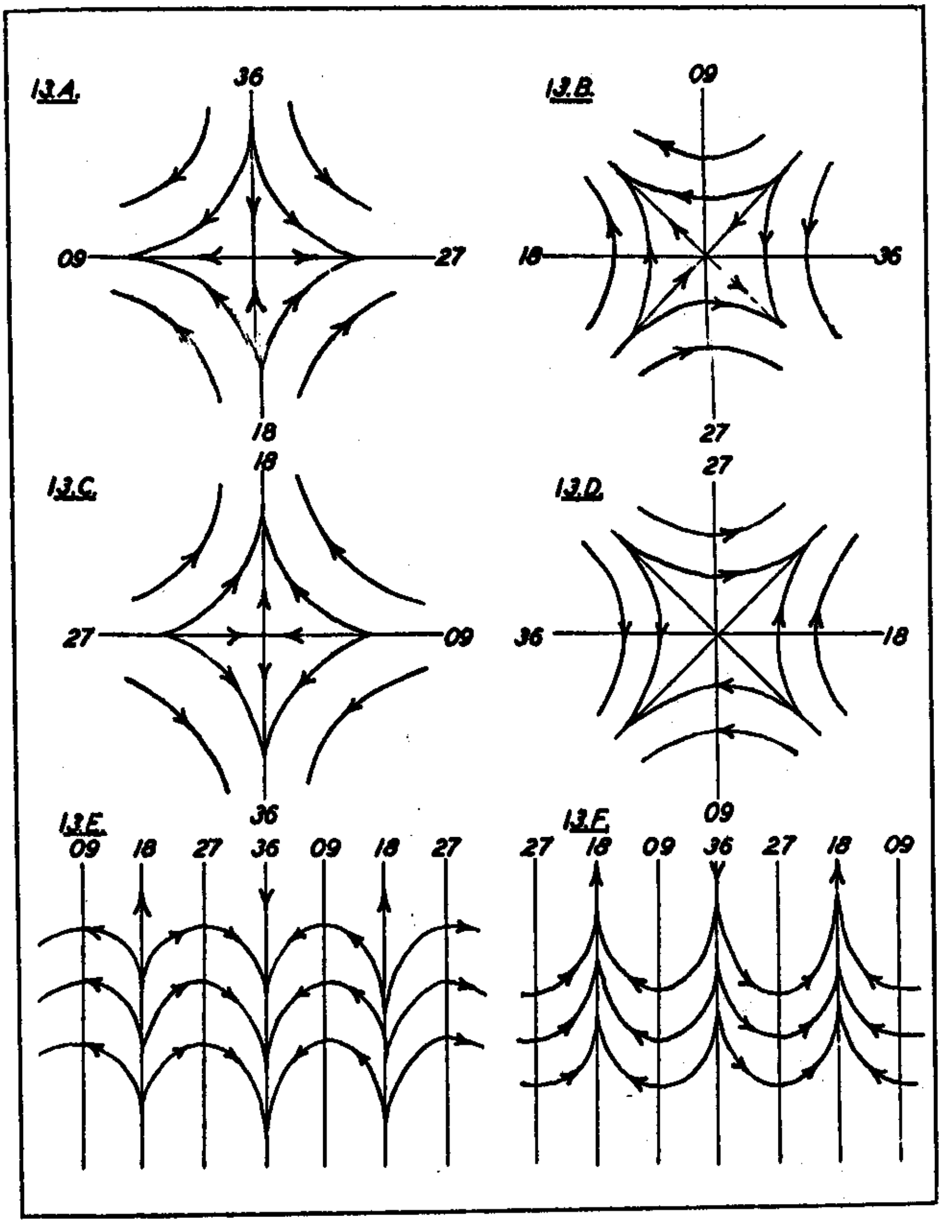


Figure 13 - Showing relationship between streamlines and negative singularities (13.A to 13.D)

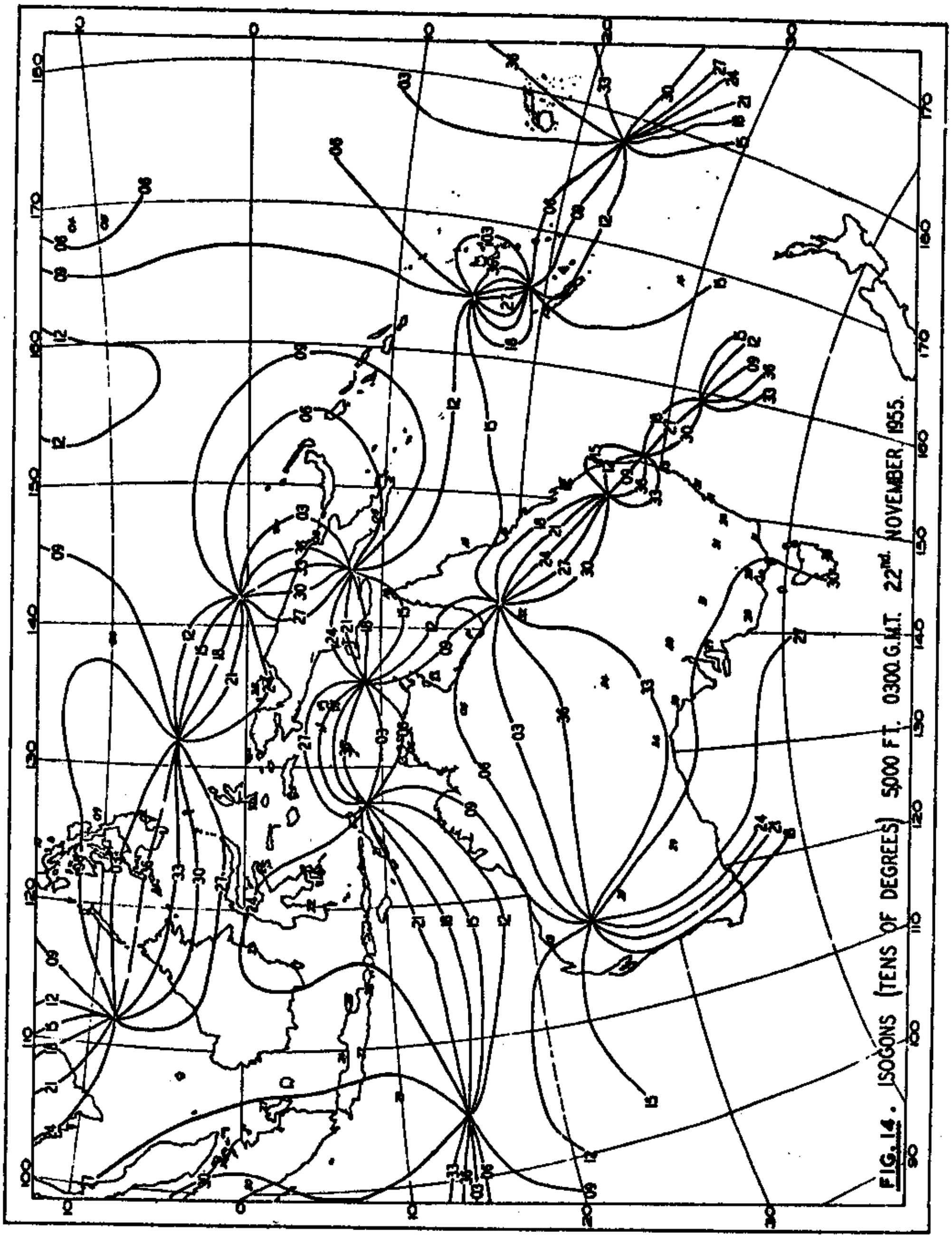


FIG. 14. ISOGONS (TENS OF DEGREES) 5000 FT. 0300 G.M.T. 22nd NOVEMBER 1955.

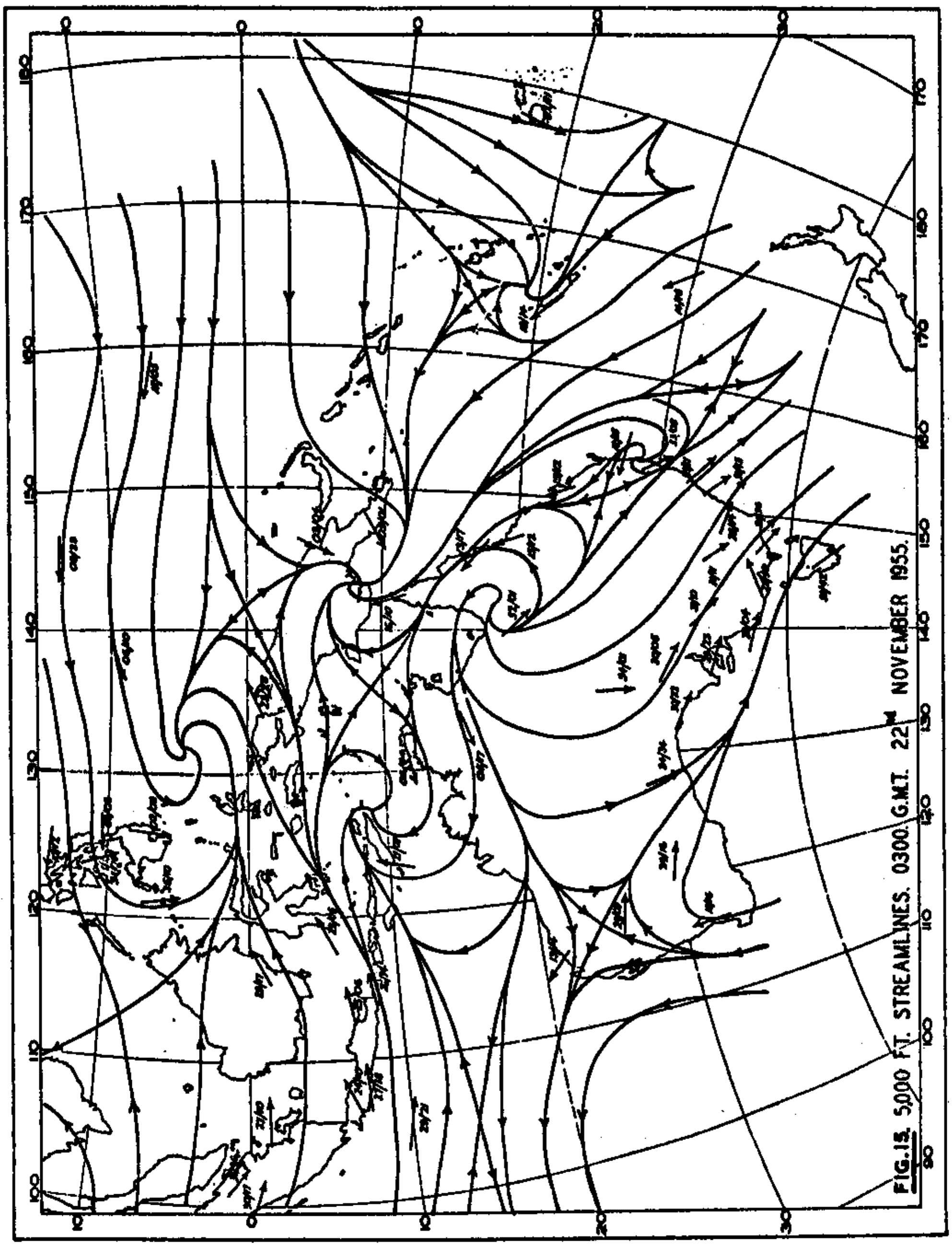


FIG.15. 5000 FT. STREAMLINES. 0300 G.M.T. 22nd NOVEMBER 1955.

LOCUST MAPPING TECHNIQUES

by

Elizabeth Betts

For more than thirty years a continuous record of the current infestation of the principal species of the locusts of Africa and south-western Asia has been maintained at the Anti-Locust Research Centre in London. The greater part of this information has been in the form of weekly, fortnightly or monthly reports from the agricultural departments, plant protection departments or locust control organizations of the countries of Africa and south-western Asia, supplemented by occasional reports from travellers, and, following a recommendation of the WMO Commission for Maritime Meteorology, by reports of locusts seen at sea, the number of the latter having increased during 1961. The greater part, and indeed the most useful part, of the basic locust record consists of lists of reports of swarms of adult locusts, bands of hoppers (young locusts) or scattered locusts of known species, on standard forms which are now printed and distributed by the Food and Agriculture Organization. When completed, the data on these forms include the date and time of observations, the locality infested, with latitude and longitude, and estimates of the size and density of the swarms or hopper bands. Swarm reports include information on the maturity of the locusts (pink or immature, yellow or sexually mature), and whether laying or copulation has been observed. In hopper reports, the date of hatching is recorded if known, and the instars (stage of development) present at the time of observation, as well as the date of fledging. Locusts not in swarms or bands are classified as isolated (seen singly) or in groups (two or more seen together). Some reports also contain references to the weather and the state of vegetation at the time of observation, and to any control operations carried out, or damage caused to vegetation or crops.

In order to visualize and to assess these records at the Anti-Locust Research Centre, all such reports are plotted on topographical maps of a medium scale, 1:1,000,000, 1:2,000,000 or 1:4,000,000.

A series of conventional symbols together with the day of the month represents on these maps all the known infestations of one species of locust throughout one calendar month: either of swarms, groups of adult locusts or isolated adult locusts, with different colours indicating their state of maturity; or, on a transparent overlay, of hopper bands, groups of hoppers or isolated hoppers. A second basic series of monthly locust maps of the entire Desert Locust area on a scale of 1:11,000,000 is also maintained. Despite the inevitable loss of detail, particularly in the better reported areas, this second series of maps allows a comprehensive view of the locust situation throughout the whole invasion area, showing clearly the major displacements of swarms and the onset of maturation, laying, hatching and fledging over wide areas.

Although this substantial body of data on, and maps of, the geographical and temporal incidence of locusts is probably better than that for any other species, it has a number of limitations. First it is incomplete : at the height of a swarming period more than a thousand individual swarm records may be received in a month, but in most areas this is substantially less complete than the corresponding synoptic data; there are, for example, some three hundred meteorological stations, each reporting several times daily, within the Desert Locust area, even though the latter includes the Sahara and Arabia, where meteorological stations are themselves comparatively sparse. Large variations occur in the number of locust reports from country to country; these usually reflect the level of the human population and the efficiency of the locust reporting organization, and not necessarily the intensity of the infestation. A daily plot of the locust records gives no indication of the extent of the locust infestations, and shows areas which are known to be infested, that is where swarms may have been recorded a few days previously and are recorded again within the next few days, with no reason to suppose that the locusts have departed and returned, as apparently completely clean

In years of heavy and widespread infestations it is possible to draw simple isochrones of the successive displacement of swarms over distances of the order of thousands of kilometres and sometimes spread out across a width of the same magnitude. With movements of this scale, which are usually the simplest to relate to weather changes, the missing of swarm reports even in a substantial number of localities is not usually significant.

But in the consideration of minor movements of locust swarms, such omissions in the data can often be misleading, particularly if the arrival of a swarm in a new area was missed or regarded as unconfirmed, because reported by an uneducated local person, and not seen by a locust official until a day or so later. In this context too, the recorded direction of flight has been shown to be frequently misleading; photographs taken during the passage of a swarm have shown numerous groups of locusts, each group in the interior of the swarm flying in an apparently purposeful but separate direction, and the ensemble of groups randomly orientated within the swarm. Thus it is often impossible for a ground observer looking directly at only a part of a swarm to determine the direction of the whole swarm [4, 5]. Consequently, it is necessary to stress that the meteorological conditions relevant to a particular locust invasion are those during the period immediately prior to the arrival of the first reported swarm, not necessarily those at the time when a swarm was first seen by a responsible member of the locust control organization, which may not be until some days later.

But in spite of these limitations, much can be drawn from maps of locust data, which can be presented in a variety of ways. Major swarm displacements can be shown by isochrones, as described above; by a series of maps showing the total distribution of swarms during successive periods, either as in the pentad/degree-square maps used by Rainey [3] to provide evidence both of the spread of swarms and of their remaining static, or as maps of selected periods showing initial distribution of swarms in one or more areas, the localities visited during a major migration and the final redistribution of the swarms. In addition, the basic locust maps have been used both in the compilation of maps of the frequency of incidence of locust swarms and hopper bands, which have been used in the planning of locust control strategy [1, 2], and which can be related to climatic factors [6]; and the basic locust maps have also been used to classify the very varying periods of egg-incubation and hopper development, which are also associated with the weather [7].

Many problems on the relationship between locusts and weather remain to be studied, some during periods of locust movement and breeding, and others during periods when locusts remain effectively static despite synoptic observations suggesting conditions suitable for movement.

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ASSESSMENTS OF DIVERGENCE IN RELATION TO THE DESERT LOCUST

by

J. Cochemé

An important corollary of the now generally accepted thesis of the downwind movement of locusts is that they accumulate in areas of horizontal convergence in the velocity field of the winds.

Here the word convergence means negative divergence which is a term in more general use in physics and mathematics.

Though positive divergence itself may also play a significant part in the evolution of locust infestations, convergence effects seem to be more common and important.

It should be clearly realized that we are here dealing with horizontal or two-dimensional divergence. In three dimensions, at the scale at which we are working, divergence is invariably nil in accordance with the equation of continuity. Thus divergence along the two horizontal axes is compensated by air movements along the vertical; convergence is maintained by ascending air currents which themselves lead to compensating supernatant divergence. If the locusts followed these currents all the way they would not therefore accumulate in areas of low-level convergence. However, through some physiological mechanism which appears to be controlled by temperature, locusts generally remain in the lowest layers of the atmosphere just as if sieves of too fine a mesh for them had been put across the rising air currents.

An obvious development of this notion is to approach it quantitatively : to measure the divergence associated with known locust occasions and estimate that likely to occur during locust developments.

This is all the more important since qualitative estimates resulting from merely looking at synoptic charts or other representations of air currents may be very much in error because convergence can be due to a flowing together or confluence of the winds, which is obvious, or to a slowing down of these winds,which is less obvious. The two effects may act together or, as is frequently the case, in opposition.

These quantitative assessments of divergence are worth attempting at the several scales in space and time at which locust movements are being studied. These studies of the effect of wind on locust regrouping might be divided as follows :

(1) Synoptic analyses of occasions which have significantly affected the development of locust infestation.

(2) Estimates of wind climatic averages or normals on a monthly or fortnightly basis to provide a useful background against which to examine the significant occasions and a tool for anti-locust strategy.

Together these two studies should make it possible gradually to evolve a locust synoptic climatology which would provide classified models of significant occasions together with the frequency of their occurrence.

Precise measurements of divergence are not easy to make since they are derived from observations of wind strength and direction which exhibit quasi-random fluctuations. Furthermore, in the tropical and equatorial regions of the locust area, no help can be expected from vorticity, a more conservative element and one which is advected and which, in higher latitudes, can usefully be related to divergence.

Work done so far implies that divergence estimates based directly on wind observations, however crude, are providing valuable information. Much more evidence is needed, however, and it is hoped that it will come from meteorological studies done in the countries of participants of this seminar.

Divergence is of dimensions T^{-1}. It is a rate at which something is happening. At a point it can be expressed mathematically in two ways :

(1) In terms of Cartesian co-ordinates, when

$$\text{Div}\ V_H = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \qquad (1)$$

where u and v are the component velocities, and two partial derivatives are their changes along the co-ordinate axes x and y.

(2) In terms of streamline or natural co-ordinates, when

$$\text{Div}\ V_H = \frac{\partial v}{\partial s} + v\frac{\partial a}{\partial n} \qquad (2)$$

where v is stream velocity and s stream distance, a is the angle of stream direction measured relative to some fixed direction, and the second term the advection of the change in that angle along a co-ordinate n at right-angles to the stream direction. This term expresses the diffluence of the stream whereas the first term expresses its acceleration.

It can easily be verified that both these expressions are of dimensions T^{-1}. They will both yield the same values of divergence for the same point at the same instant, but when averaging or integration is carried out for areas and over intervals of time they differ in the information they give on the effects of divergence.

Physically the process in which we are interested may be visualized in two ways which are related to the two mathematical expressions.

(1) The rate at which air is leaving an area (fixed relative to the ground) in excess of that entering it.

(2) The rate of increase in area of a surface bounded by air particles moving with the stream.

Both changes are expressed as fractions of the area or original area per unit of time.

The unit most commonly used in meteorology is one hundred-thousandth per second, 10^{-5}/sec. Values of two to four of these units can be recorded in an active westerly depression.

The information we need is integrated divergence over periods of time and representative of selected areas or air masses. In the first manner integration with respect to time will yield OUTFLOW out of a fixed area and in the second EXPANSION relative to the stream. Both these quantities are dimensionless since they are the product $T^{-1} \times T$.

These integrations are not easy to achieve and a first approach will be the use of average divergence for periods of time or even the assumption that instantaneous values are representative of conditions during these periods. This use of large finite intervals is a device to which meteorologists often have to resort.

Having obtained inflow or contraction we shall try to relate it to changes in density of particles airborne at a constant level, and then compare these changes with locust regrouping.

Different density thresholds in locusts may bring about different significant events, some irreversible, some not. Most of these thresholds have yet to be estimated but it can already be suggested that a change in density of about 10^3 would be necessary to yield swarm densities from scattered populations, whilst a change of 10 might be sufficient significantly to assemble swarms. The quantitative difference between these two events is so great that it is conceivable that whereas the former is patently achieved mechanically by convergence, the latter is beyond the means of wind-field changes known to us.

Some methods of assessing divergence will now be described. They all have their advantages, their limitations, and their particular uses in this context.

The winds at 600 metres above the ground appear to be the most applicable. This means that horizontal winds are used to calculate divergence along a surface which is not strictly horizontal. But the gradients involved are very small indeed in almost all cases and the errors introduced are much smaller than those inherent in the calculations.

The first method described is given by J.C. Bellamy [1]. In its essentials it had first been published by Bennet in 1907 in an appendix to a classical paper by Sir Napier Shaw called "The life history of surface air currents".

It yields average divergence for an area fixed relative to the ground.

It is an objective method in as far as it does not involve the drawing of isolines, and it is simple.

The horizontal divergence within a triangular area from the corners of which wind observations are available is the sum of the ratios between the components of the winds along the corresponding triangular heights and these heights.

$$\text{Div } V_H = \sum \left(\frac{u}{h} \cos \theta \right) \qquad (3)$$

Where u is wind speed, h length of triangular height, θ angle between wind direction and triangular height and consequently $u \cos \theta$ is the component along the height, positive or negative depending on whether it is directed out of or into the triangle.

It is assumed that variation in wind direction and speed from corner to corner is on the average linear. This type of assumption is common to meteorology.

The fineness of the divergence picture obtained depends on the size of the triangles. The best possible pattern of observations would be one giving a network of equal small equilateral triangles, though the smaller the triangle the more vulnerable it is to random fluctuations of the wind.

Figure 4 shows a collection of triangles which were measured for an estimation of divergence along the Inter-Tropical Convergence Zone (ITCZ) in Africa. Daily values at 1200 GMT were worked out for the month of October 1954 and from those a monthly mean pattern was calculated shown here together with the mean surface position of the observable front (Figure 5).

Here the speeds are in knots and the distances in nautical miles and the answer is therefore in number of times per hour, one such unit being $\frac{1}{3.6} \times 10^{-3}$/sec. I have used in the plotting 10^{-2} and 10^{-3}/hour, which correspond to 2.8 and 0.28×10^{-5}/sec.

To gain time computation tables were prepared. There are four variables in the calculations and three calculations per triangle for each estimate. Two of the variables, the length of the triangular height and its orientation, are fixed for each triangular apex. Thus it is possible to construct tables where the last two remaining variables, the observed wind speed and its direction, can be entered, there being a book of three tables per triangle (Figure 6).

These calculations can be made by computer. Programming for doing this on an electronic Mercury computer showed that if the wind data had to be punched on a tape specially for these divergence estimates then it was just as quick to enter them in tables. If, on the other hand, the winds are punched on cards as a matter of routine then there is everything to be said for using a computer.

Another method of measuring average divergence within an area uses quadrilaterals bounded by a pair of streamlines and two boundaries across the flow (Figure 7).

The average divergence is given by

$$\frac{b_2 v_2 - b_1 v_1}{A} \qquad (4)$$

where b_1 and b_2 are the length of the boundaries, v_1 and v_2 the mean wind speed across them, and A the area of the quadrilateral which can be measured with a grid.

This method is rapid especially if the streamlines are drawn as a matter of routine but it does not easily lend itself to adding up and averaging since the areas from different charts do not coincide.

If lines of equal divergence are drawn on each chart then these contour lines can be added graphically, the result being average divergence or inflow relative to the ground and not the stream.

A method of calculating divergence relative to the ground which is more detailed but also more subjective is a graphical estimation and averaging of formula (1).

This method is described by A.G. Forsdyke [2].

First the observed winds are split into their components and the northerly and easterly components are plotted on two separate charts.

Then isotachs are drawn on both charts. The velocity gradients which we need are the slopes between these contour lines along the y axis for the northerly components and the x axis for the easterly components.

These gradients can be measured with a reciprocal scale or by drawing cross sections. The values at significant points and at grid points are noted. The addition of these two derivatives at corresponding points on both charts can be either arithmetical or graphical, by drawing on transparent paper contour lines of the gradients, superimposing, and then adding the values where the lines cross.

From these point values, however they are obtained, lines of equal divergence can be drawn.

In Figure 8, I have shown the results of convergent estimates obtained by this method for an area in West Pakistan and north-west India during a period of 11 days at the end of June 1961 whilst locust swarms were invading the area. The velocity gradients were in knots per degree and the resulting unit is equal to $.5 \times 10^{-5}$/sec approximately, taking into account the length of a degree of longitude at the average latitude of 25° for the area. Inflow for the whole period is represented, it being assumed that convergence at 1200 GMT was representative of what took place during a 10-hour period of each day. The total inflow is shown together with the reported positions of swarms at the end of the period. Before the 20th no swarms had been reported from anywhere in this area and it is thus seen that swarms have moved towards areas of convergence and assembled there.

Let us now see how convergence can be related quantitatively to the grouping or density of particles airborne at a constant level. With an area fixed relative to the ground and out of which air is not flowing, if we start with a uniform density β_o in particles per unit area, a constant convergence $\underline{c}$, acting during time $\underline{t}$, will bring about an inflow $\underline{ct}$, an increase in density $\beta_o \times \underline{ct}$ and thus a new density

$$\bar{\beta}_g = \beta_o \ (1 + ct) \qquad (5)$$

assuming that the particles continue to enter the area at density β_o (Figure 9).

The resultant density is an average for the area within which it is not uniform since the time during which individual particles have been acted upon by convergence varies between $\underline{t}$ for those originally in the area and $\underline{o}$ for those in the act of crossing the boundary at the end of the interval. Thus the particles in the centre of the area will be most tightly packed and those near the rim least.

In the case of a surface moving with a stream of steady convergence $\underline{c}$, and accordingly decreasing in area, it can be shown that at the end of interval $\underline{t}$ the density will be

$$\beta_s = \beta_o e^{ct} \qquad (6)$$

Whereupon

$$\frac{d\beta_s}{dt} = \beta_o C e^{ct} = \beta_s C \qquad (7)$$

Whilst in the first case

$$\frac{d\beta_g}{dt} = \beta_o C \qquad (8)$$

In both cases the rate of increase in density is proportional both to the convergence and the density, recalling the continuity equation $\frac{d\rho}{dt} = \rho \operatorname{div} V$, but in the first case it is the original density which is involved and in the second the density achieved at any instant, the increase being exponential.

Thus with an average convergence of 1 per day of 10 effective hours (about 3 units of 10^{-5}/sec), a density within the stream β_s of 10^3 times the original β_o can be achieved in a week. At the end of the same period and with the same convergence the average density within a fixed area $\bar{\beta}_g$ would only be 8 times β_o, but of course, locally, much higher densities would be obtained.

Moreover, in the case of a fixed area, if the inflow is a net inflow compounded of air entering and leaving the area or, in other words, if the air is flowing steadily through a convergence pattern fixed relative to the ground, $\beta_g = f(t)$ becomes constant after a certain interval of time when t ceases to operate as an independent variable. This can easily be seen in the simple case of a rectangular area bounded by two streamlines and two cross-flow lines where there is no confluence and convergence is uniform throughout, being due solely to the steady slowing down of the stream (Figure 11), where s_1, s_2 are the streamlines, b_1, b_2 the cross-flow lines and v_o and v_e the entrance and exit velocities.

There, after an interval of time equal to that needed for a particle to cross the area, the average density inside it will settle down to a constant value, the particles then leaving the area at the same rate as they are entering it, the entrance and exit densities being inversely proportional to their respective speeds.

It can be shown (see footnote*) that in this case

$$\beta_g = \beta_o c \cdot \frac{V_o}{a} \tag{9}$$

which is independent of t and where a is the retardation.

The exit density β_e, inversely proportional to the exit velocity, is also equal to the density obtained by considering the contraction of a small surface crossing the area

$$\beta_e = \frac{V_o \beta_o}{V_e} = \beta_o e^{ct} \tag{10}$$

An area similarly bounded by two streamlines and two cross-flow lines can also be constructed (Figure 12), so that convergence is uniform and entirely due to confluence, the velocity being uniform. Then $v_o = v_e$ and in (2) $\frac{dv}{ds} = 0$ and the convergence $c = \frac{da}{dn} v$ is made constant by assuming that $\frac{da}{dn}$ is constant.

There again the average density for the whole area will eventually settle down to a constant value, the entrance and exit densities being then inversely proportional to the length of the cross-flow lines.

$$\beta_e = \beta_o \frac{b_1}{b_2} \tag{11}$$

---

* Let T be the time taken for a particle to cross the area, travelling distance S along a streamline.

From (2), since $\frac{da}{dn} = 0$, the convergence

$$C = \frac{dv}{ds} = \frac{\Delta v}{S} = \frac{aT}{V_oT - \frac{1}{2}aT^2} = \frac{a}{V_o - \frac{1}{2}at}$$

The density β_g after time T, when all the particles originally there will have cleared the area and none of the new ones come out, will equal $\frac{\text{particles entered}}{\text{area}}$. Assuming unit width

$$\beta_g = \beta_o \frac{V_oT}{S} = \frac{B_oV_o}{V_o - \frac{1}{2}aT}$$

and substituting for C

$$\beta_g = \beta_o c \frac{V_o}{a}$$

In this case the particles are approaching each other along the cross-flow lines whilst they remain equidistant along the streamlines, assuming uniform initial distribution, β_0, whereas in the first case the inverse was taking place.

Patterns can be visualized where the two types of divergence are acting concurrently, not necessarily with the same sign. If the net result is convergence, the effect will be to increase the density in particles in the air traversing the patterns rather than accumulating them progressively in the areas concerned.

Such patterns are quite common in nature and may carry locusts over density thresholds, some of which may be significant or irreversible, without their remaining in the area.

Conversely, convergence patterns may move through a field of uniform particle density and regroup themselves in certain characteristic ways without bringing about much general advection.

We have already seen that a stationary cyclonic vortex would tend to collect particles at its centre. Such a vortex moving at a speed of the same order of magnitude as that of the circulation would leave a trail of more densely grouped particles parallel to the path of its centre on the side where the wind and the centre are moving together, the density and the position of the trail varying with the ageostrophy of the winds, and the relative speeds of the centre and the winds.

Since the fraction locust transport/air displacement decreases as the wind increases, the effect of convergence on locust concentration must increase with increased ageostrophy and consequently decreased latitude.

A certain amount of convergence and corresponding ageostrophic displacement of air will be more effective at lower latitudes than at higher latitudes where such ageostrophy will correspond to a greater movement of air along the isobars and consequently higher wind speeds which the locusts will be unable to follow.

Thus an assessment of the effect of the winds of a cyclone on the regrouping of locusts demands careful consideration of these several features.

It seems that the most informative estimates of convergence for locust studies would be given by a method yielding cumulative results relative to the stream provided it were possible to locate the resultant concentrations relative to the ground.

For this a double integration needs to be carried out :

First with respect to displacement along a given streamline pattern;

Secondly with respect to change with time in the pattern itself. Symbolically

$$\iint ds\, dt$$

A graphical solution of this double integration can be effected by moving imaginary particles along air trajectories. Their regrouping will represent changes in density and their displacement transport by advection. Useful analogies can thus be provided with locust movements and concentration.

Multiple air trajectories which represent the successive changes of the streamline pattern are needed for this graphical solution.

What we can prepare in the first place are sets of streamlines and some representation of attendant air speeds for the times at which upper-air information is available. Graphical interpolation between these sets can be carried out to obtain trajectories but the work involved, easy enough with fragments of simple patterns, becomes extremely laborious when dealing with the complex features of air movements over a large area.

If a sequence of streamline charts is used then the integration with respect to time is replaced by a consideration successively of conditions representative of finite intervals. Using trajectories, however, the double integration would be satisfactory, since integration with respect to distance is reasonably accurate by this graphical method.

When using successive streamline patterns inspection will show if there is logical sequence and some trajectories may be drawn to smooth out sharp transitions.

In practice it was found that speed was best represented by the length of displacement vectors rather than by isotachs. The time covered by the vectors would be the interval between two charts or the locust flying time, whichever was shortest, and certain assumptions can be introduced to take into account locust flying times and to represent the complex relation between air speed and swarm ground-speeds to increase the analogy between the moving dots and the locusts (Figure 13).

A start is made with particles regularly spaced at grid points and then made to move along streamline bared trajectories for distances derived from the displacement vectors. In practice it was found that a set of five consecutive daily charts was as much as could be dealt with before having to start afresh with regularly spaced dots.

This method was found useful in analysing the locust invasion of India and Pakistan in June 1961. This investigation provided the published material used at the seminar during the practical exercises (see page 37).

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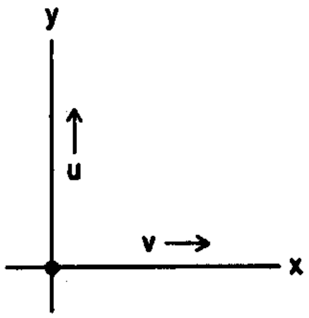

Figure 1 - Convergence at a point, cartesian co-ordinates.

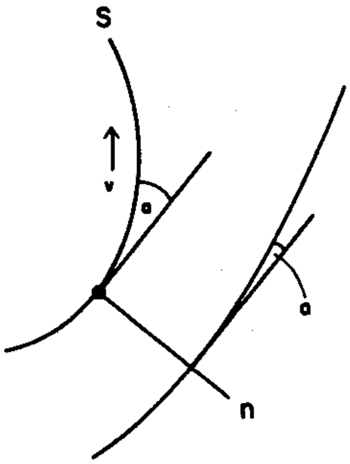

Figure 2 - Convergence at a point, natural co-ordinates.

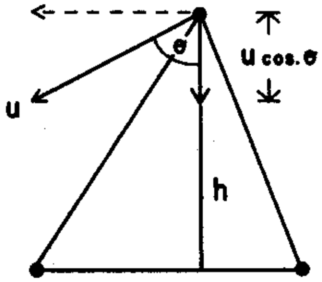

Figure 3 - Average convergence within a triangular area with wind observations at apices.

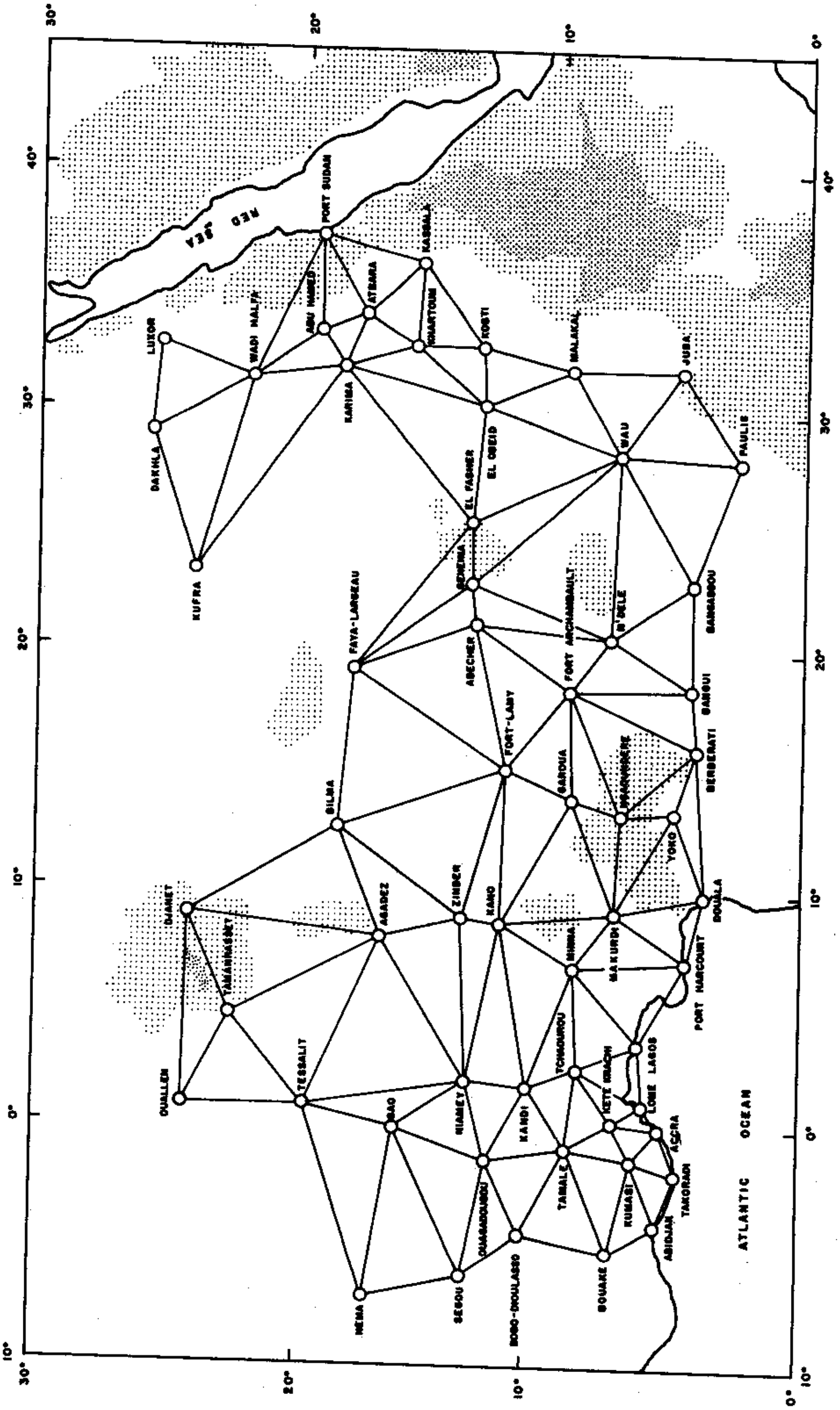

Figure 4 - Wind triangulation of area south of the Sahara.

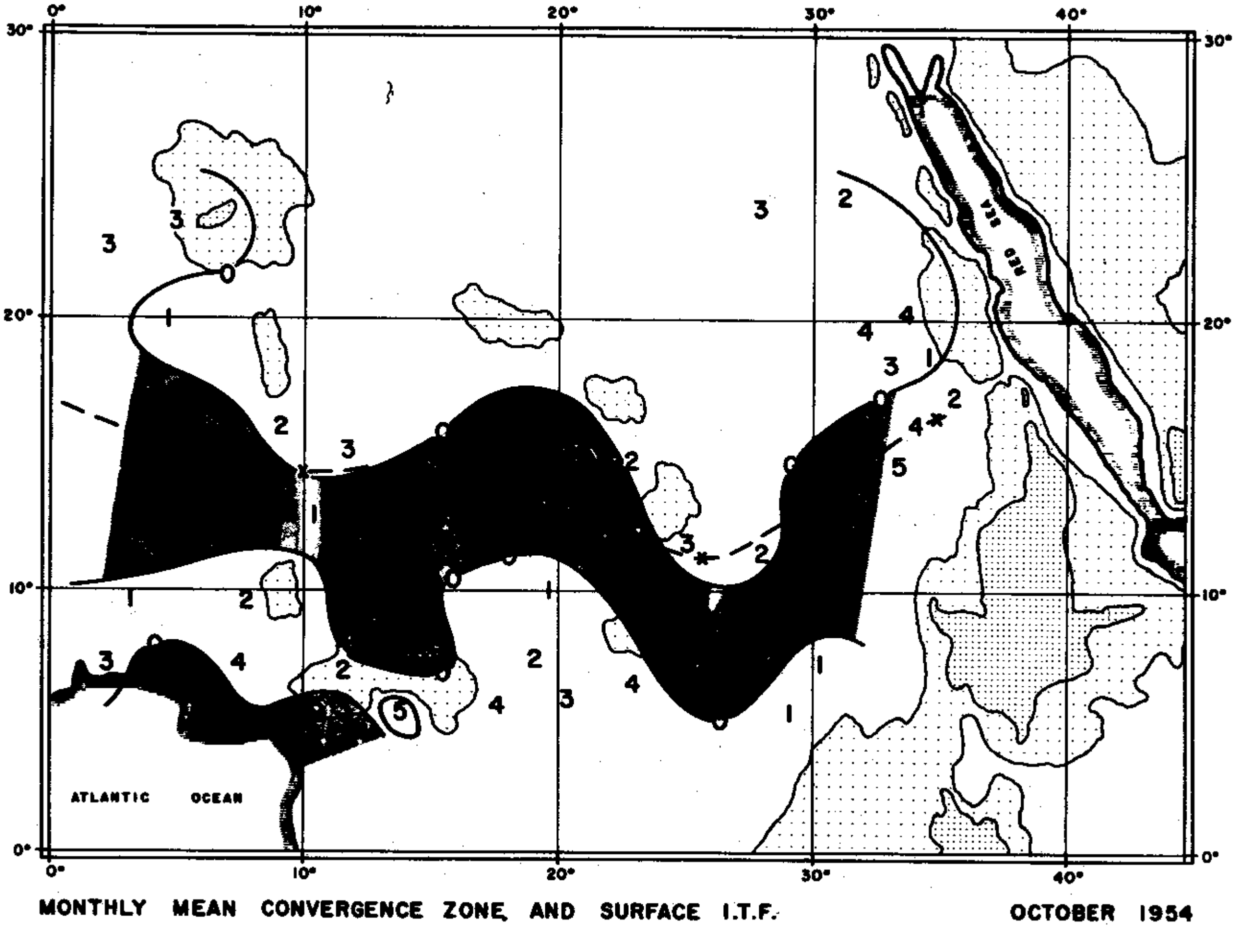

Figure 5 - Monthly mean convergence at 600 metres, mornings, October 1954. Figures give divergence in 10^{-2}/h, shaded areas are negative.

FORM I VORTICITY AND DIVERGENCE IN 10^{-3} PER HOUR

TRIANGLE No. 89 ⟶ GAO → SEGOU → NEMA HEIGHT 390 mi
Components for Gao 61 226 61 272 61 219 ANGLE 255°

Vorticity +		Divergence +		Knots									Divergence —		Vorticity —	
				1	2	3	4	5	6	7	8	9				
345		255		2·6	5·1	7·7	10·3	12·8	15·4	17·9	20·5	23·7	075		165	
340	350	250	260	2·6	5·1	7·7	10·2	12·8	15·3	17·9	20·4	23·0	070	080	160	170
335	355	245	265	2·5	5·1	7·6	10·1	12·6	15·2	17·7	20·2	22·7	065	085	155	175
330	360	240	270	2·5	5·0	7·4	9·9	12·4	14·9	17·3	19·8	22·3	060	090	150	180
325	005	235	275	2·4	4·8	7·2	9·6	12·0	14·5	16·9	19·3	21·7	055	095	145	185
320	010	230	280	2·3	4·6	7·0	9·3	11·6	13·9	16·3	18·6	20·9	050	100	140	190
315	015	225	285	2·2	4·4	6·7	8·9	11·1	13·3	15·5	17·8	20·0	045	105	135	195
310	020	220	290	2·1	4·2	6·3	8·4	10·5	12·6	14·7	16·8	18·9	040	110	130	200
305	025	215	295	2·0	3·9	5·9	7·9	9·8	11·8	13·7	15·7	17·7	035	115	125	205
300	030	210	300	1·8	3·6	5·4	7·3	9·1	10·9	12·7	14·5	16·3	030	120	120	210
295	035	205	305	1·7	3·4	5·1	6·8	8·5	10·2	11·9	13·6	15·3	025	125	115	215
290	040	200	310	1·5	2·9	4·4	5·9	7·4	8·8	10·3	11·8	13·2	020	130	110	220
285	045	195	315	1·3	2·6	3·8	5·1	6·4	7·7	9·0	10·3	11·8	015	135	105	225
280	050	190	320	1·1	2·2	3·3	4·3	5·4	6·5	7·6	8·7	9·8	010	140	100	230
275	055	185	325	0·9	1·8	2·6	3·5	4·4	5·3	6·1	7·0	7·9	005	145	095	235
270	060	180	330	0·7	1·3	2·0	2·7	3·3	4·0	4·6	5·3	6·0	360	150	090	240
265	065	175	335	0·4	0·9	1·3	1·8	2·2	2·7	3·1	3·6	4·0	355	155	085	245
260	070	170	340	0·2	0·4	0·7	0·9	1·1	1·3	1·6	1·8	2·0	350	160	080	250
255	075	165	345	0				0				0	345	165	075	255

Figure 6 - The stations at the corners of the triangle are given clockwise beginning with the one to which the table applies. There are three such tables per triangle. The angle is the azimuth of the triangular height. The speed is entered under knots and the direction first allocated to the half circle which determines the sign is then entered under divergence. The table was also used to obtain vorticity.

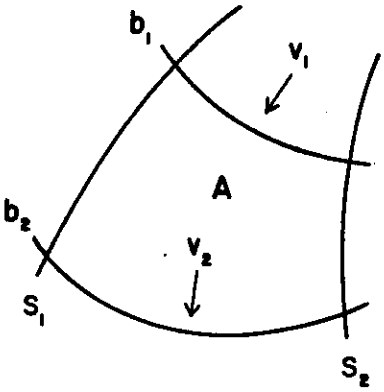

Figure 7 - Average divergence within an area A, bounded by streamlines S_1, S_2 and crossflow lines b_1, b_2.

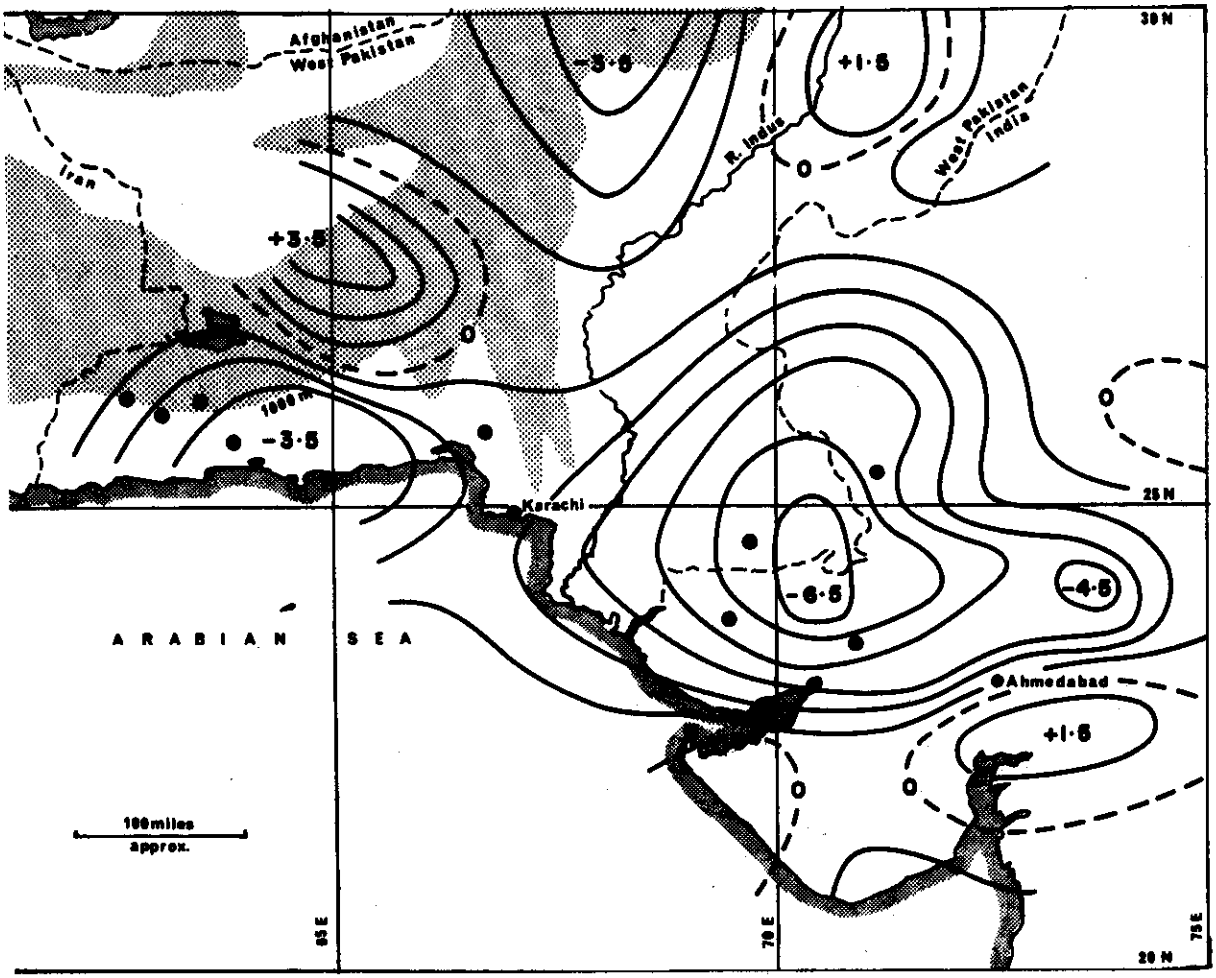

Figure 8 - Total inflow during assumed flying times in 11 days and associated distribution of swarms which have entered the area during the period. Black dots represent swarms observed during the last two days.

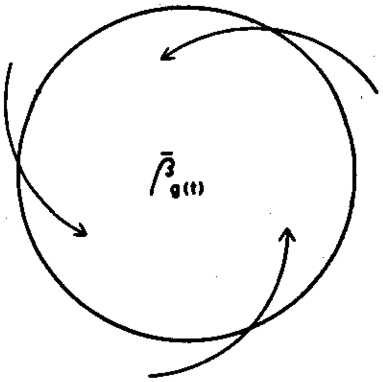

Figure 9 - Average particle density within an area fixed relative to the ground.

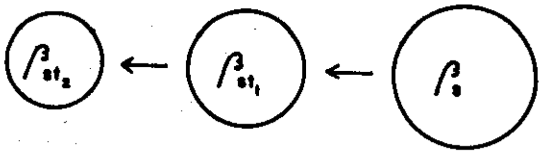

Figure 10 - Average particle density, within a surface moving with the stream.

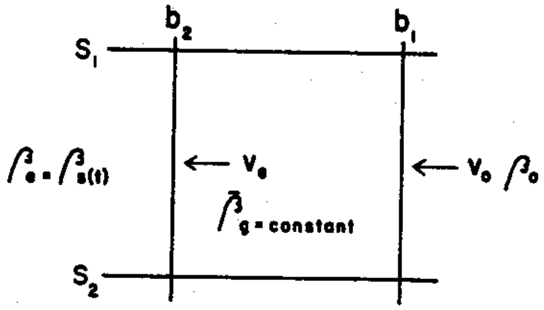

Figure 11 - Convergence between parallel streamlines due to a slowing down of the stream.

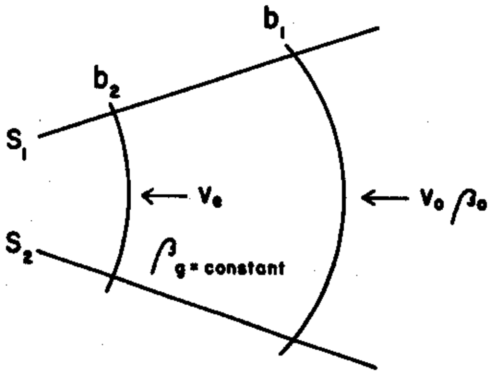

Figure 12 - Convergence in a stream of uniform velocity between converging streamlines.

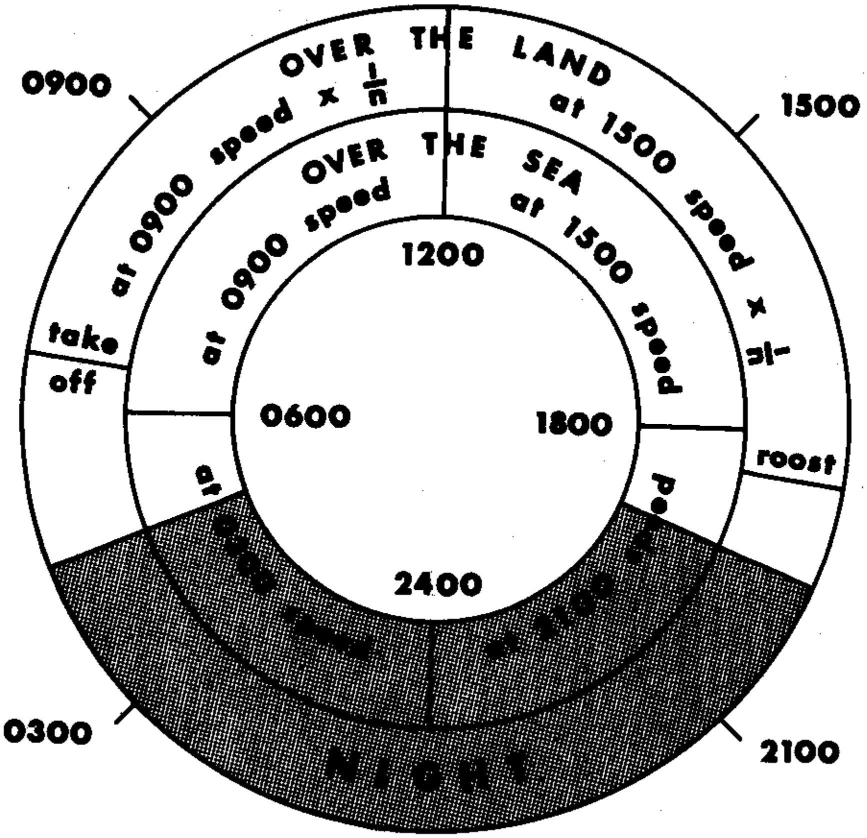

Figure 13 - Suggested schedule for the moving of locust analogue particles.

PRACTICAL EXERCISES IN ASSESSMENTS OF DIVERGENCE

Exercise 1

Computation of convergence relative to the ground according to relation

$$\text{Div } V_H = \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y}$$

Participants were supplied with chart 1, Mercator projection, scale 6 million, of north-west India and West Pakistan on which the northerly components, v, of wind observations at 1200 GMT on 20 June 1961 had been plotted (values framed). A grid of a mesh of one degree was outlined on the same chart. Reciprocal scales graduated in knots per degree and based on dimensions at 25°N were also supplied. The steps of the estimation went as follows :

1 - Draw contour lines of v five knots apart.

2 - Using the scale, estimate $\frac{\delta v}{\delta y}$, by measuring along the meridians, that is from north to south, the gradients being inversely proportional to the distances; the scale to be used rather like a geostrophic scale except that it has to be kept strictly parallel to the sides of the sheet. Estimated values in knots per degree in the vicinity of the grid points are written down with due regard to sign as shown on Chart 1.

3 - Estimate $\frac{\delta y}{\delta x}$ in a similar way on another chart measuring from west to east.

4 - Add the two values at respective grid points with due regard to signs, thus obtaining point values of $\frac{\delta y}{\delta x} + \frac{\delta v}{\delta y}$, from which contour lines of divergence may be drawn as on Chart 2.

If thought necessary, values for one of the gradients may be obtained at special points other than on the grid but it then becomes necessary to obtain a corresponding estimate on the other sheet.

At 25°N one knot per degree is $\frac{1 \times 100\,000}{54.4 \times 3\,600}$ or $.05 \times 10^{-5}$/sec

Exercise 2

Estimation of displacement and concentration of locust analogues.

Participants were supplied with Chart 3, same scale and date as Charts 1 and 2, on which 10-hour wind displacement vectors have been plotted based on the 1200 GMT observations. Steps were :

1 - Draw streamlines based on these winds as shown on Chart 3, where circles are used for inflowing cyclonic vortices and triangles for outflowing anticyclonic vortices.

2 - Draw 10-hour horizontal trajectories for particles originally at grid positions deriving the path from the streamlines and the distance from the displacement vectors, Chart 4.

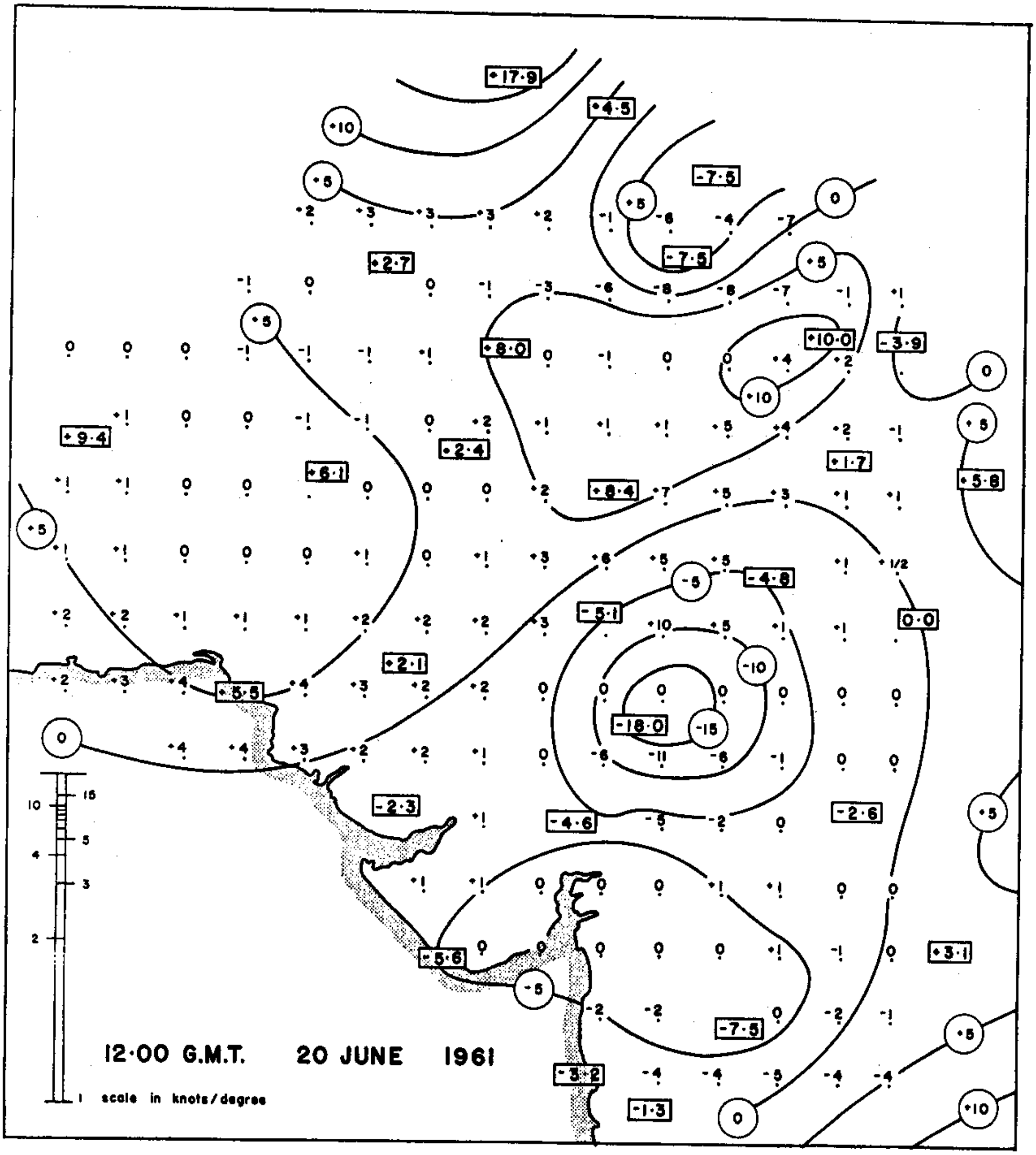
12·00 G.M.T. 20 JUNE 1961
scale in knots/degree
+17·9
+4·5
-7·5
-7·5
+2·7
+8·0
+10·0
-3·9
+9·4
+6·1
+2·4
+8·4
+1·7
+5·8
-4·8
-5·1
0·0
+2·1
+5·5
-18·0
-2·3
-4·6
-2·6
-5·6
+3·1
-7·5
-3·2
-1·3

Chart 1

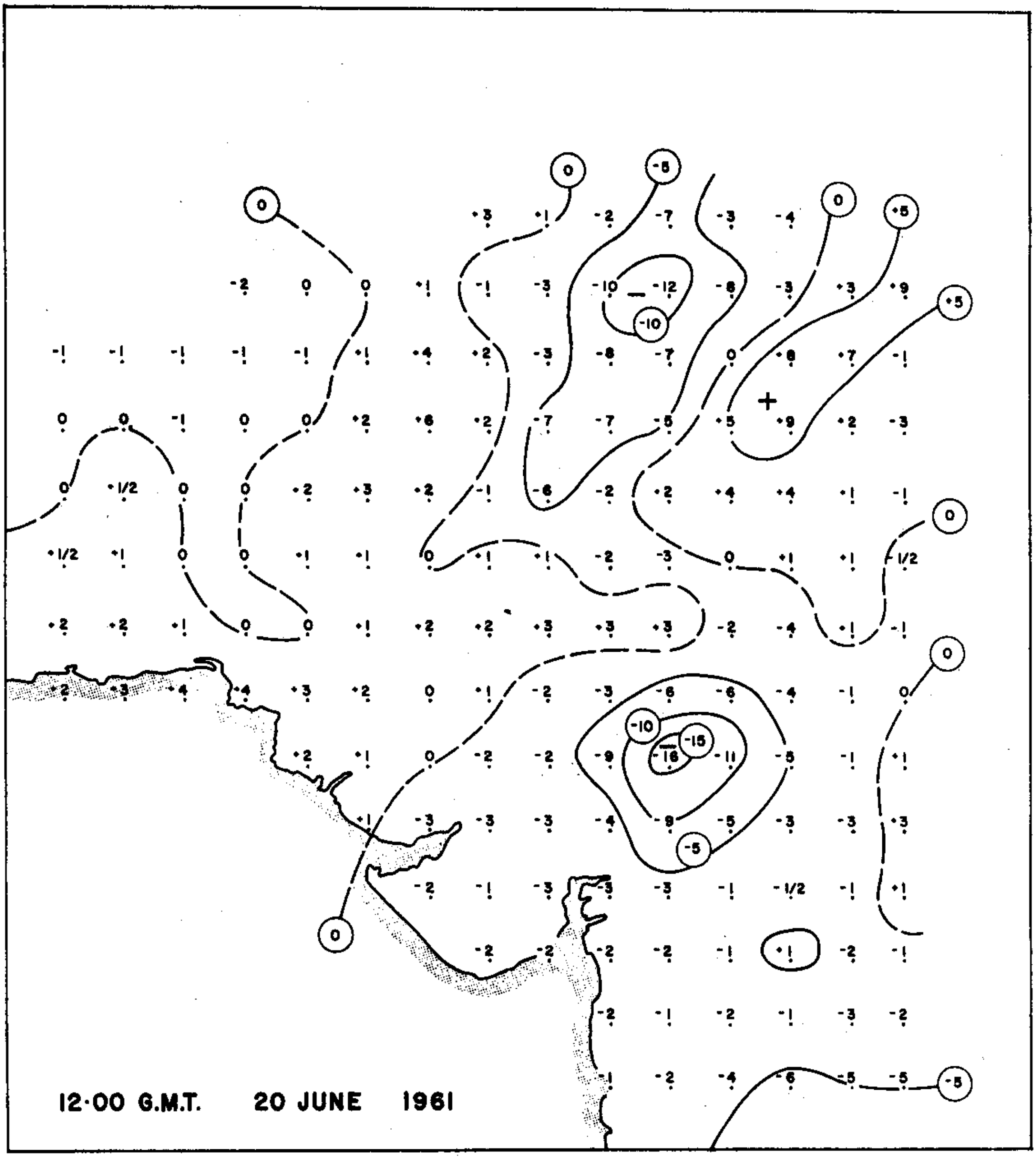

Chart 2

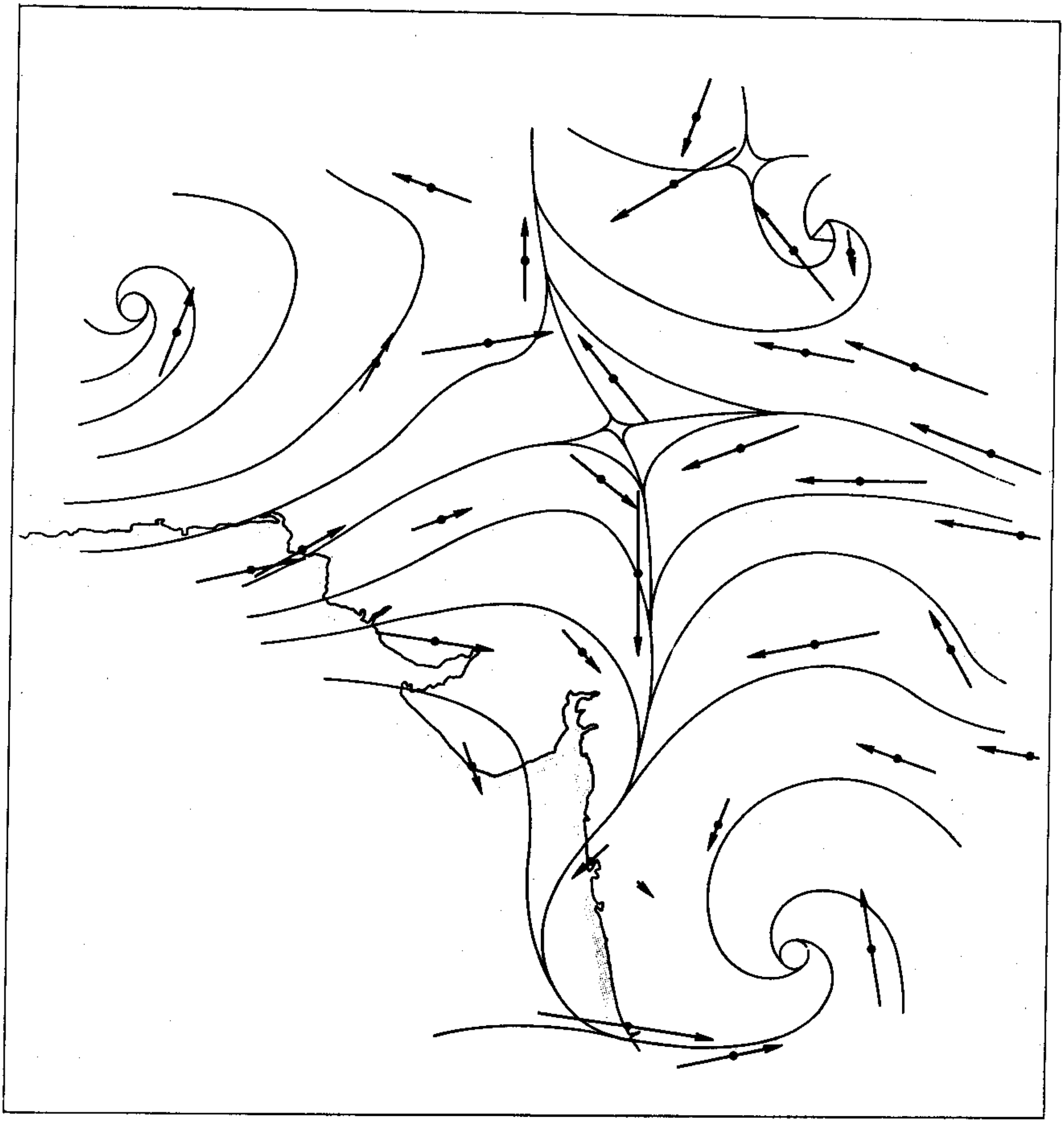

Chart 3

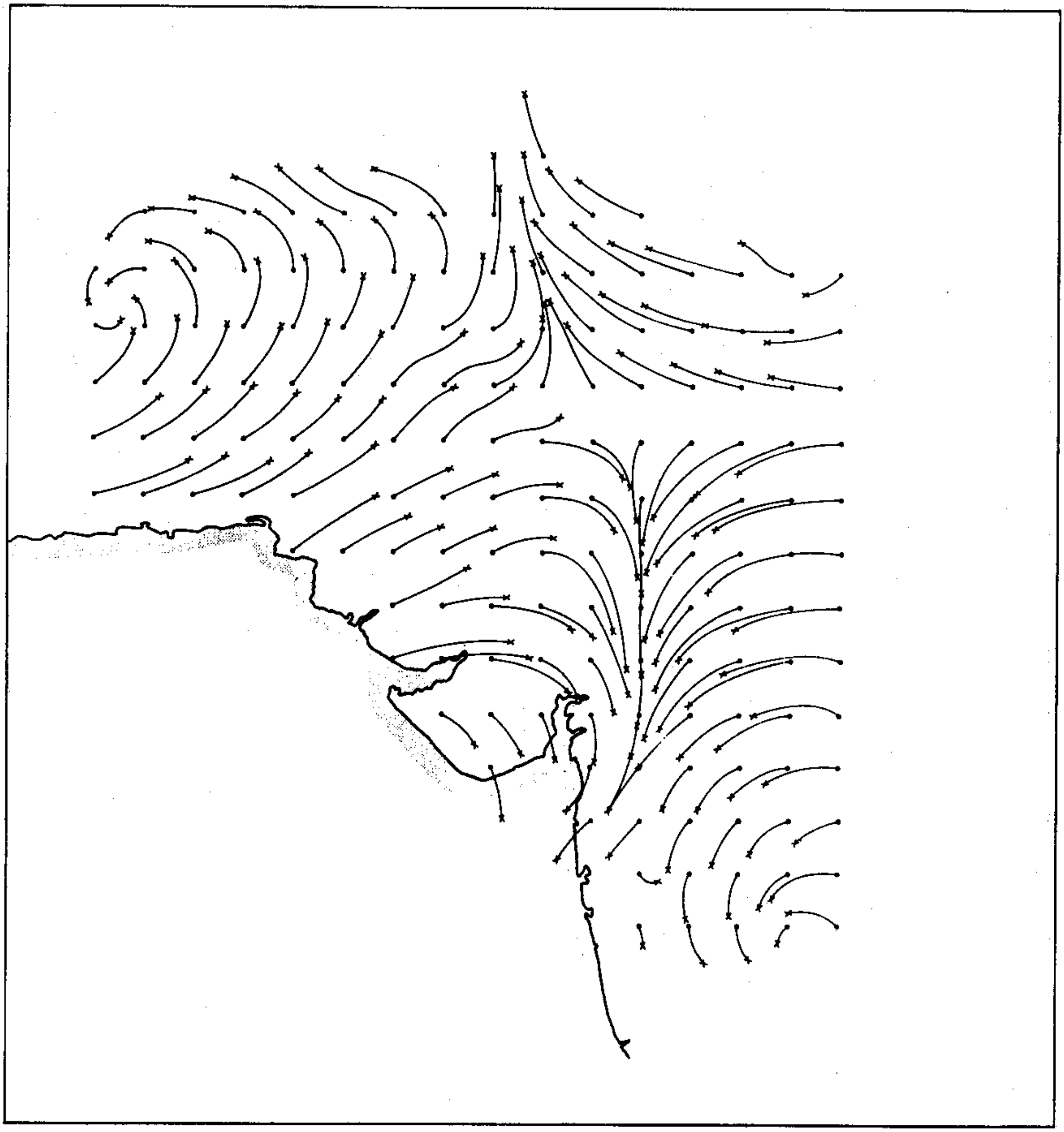

Chart 4

PARTICLE TRAJECTORIES IN LOW LATITUDES

by

A.H. Gordon

After many years of neglect the methods of particle dynamics, which are based on the integration of the primitive equations of motion rather than on the vorticity equation, are again assuming importance. The pioneer work of Grimes [7], Crossley [2], Forsdyke [4], Gordon and Shaw [6] in this field serves as a useful starting point for a further development of such techniques. In particular, the objections of many workers that such methods are unrealistic and therefore of little practical value have been refuted by the results of the transosonde constant level balloon trajectories. Such trajectories have shown specific evidence of inertial oscillations and other features of the actual wind flow which are masked by the conventional contour or streamline analysis techniques.

With regard to the subject of the seminar, the most reliable method for analysing and predicting the movement of locust swarms is to construct trajectories of the air streams in which they are embedded. It is logical to assume that the insects will be carried along with the air parcels themselves rather than along the contours which presuppose geostrophic or gradient flow, or streamlines which presuppose a steady state in time. Only trajectories give position as a function of time for unsteady motion. The simplest trajectory formula is given for a parcel projected horizontally from the origin of a Cartesian system of co-ordinates along the y axis with initial velocity V_o, in the absence of any pressure gradient, frictional or other external forces, and assuming a constant Coriolis parameter.

The solution of the second order differential equation gives

$$
\begin{aligned}
x &= \frac{V_o}{f}\,(1-\cos ft) \\
y &= \frac{V_o}{f}\,\sin ft
\end{aligned}
\qquad (1)
$$

The above equation defines the circle of inertia of radius R, where $R = \sqrt{x^2+y^2}$. f is the Coriolis parameter.

Now suppose we put the Coriolis parameter, $f = 2\Omega \sin \phi = \frac{2\Omega y}{a}$ where a is the radius of the earth.

Then the differential equations can be resolved into the form

$$
\begin{aligned}
u &= \frac{\Omega}{a}\,(y^2 - y_o^2) + u_o \\
v^2 &= v_o^2 - u^2
\end{aligned}
\qquad (2)
$$

where u, v are the component velocities along the x and y axes and the subscript o refers to the initial conditions. A strictly mathematical solution of the trajectory cannot be obtained from Equation (2). A solution can, however, be obtained by numerical integration.

We can first calculate the westerly velocity for different values of y, say in steps of 2°of latitude. It is then relatively simple to calculate the northward velocities from the second relation of (2). Trajectories can then be plotted from the calculated positions of the parcels at the 2° degree latitude steps.

Thus $\frac{dy}{dx} = \frac{v}{u}$

and $\Delta x = \frac{u}{v} \quad \Delta y$

$\Delta x = 2\,\frac{u}{v}$

where Δx is measured in degrees of longitude, which are assumed to be equal to degrees of latitude near the equator.

$$x_{t_1} = x_{t_o} + \frac{2\,(u_{t_o} + u_{t_1})}{v_{t_o} + v_{t_1}} \tag{3}$$

Trajectories have been plotted in Figures 1-3. Figure 1 shows a family of trajectories of parcels projected northwards from the equator with different velocities ranging from 5 to 30 metres per second. Figure 2 shows a family of trajectories followed by parcels projected northwards from different latitudes with a fixed initial velocity of 10 metres per second.

The solution of the equations for parcels projected in any direction can be obtained by the inclusion of the initial velocity conditions.

The special case where $v_o = 0$ and the parcel is projected with an initial velocity due east or west is of particular interest. If the parcel is projected due west u_o is negative while if it is projected due east u_o is positive. A family of trajectories of particles projected due east and west from different latitudes with an initial velocity of 10 metres per second is shown in Figure 3.

All of these trajectories are a form of constant absolute vorticity trajectory. They are, of course, different from the usual constant absolute vorticity trajectories which have been computed for initially balanced geostrophic flow.

We may now turn to the case where a uniformly horizontal and linear pressure gradient exists. If the Coriolis parameter is assumed constant, the trajectories are cycloid family curves given by the expression

$$\begin{aligned} x &= \frac{G}{f}\left(t - \frac{1}{f}\sin ft\right) + u_o t + x_o \\ y &= \frac{G}{f^2}\left(1 - \cos ft\right) + v_o t + y_o \end{aligned} \tag{4}$$

where G is the pressure gradient acceleration. In isobaric co-ordinates $G = -g\,\frac{\partial z}{\partial y}$ where $\frac{\partial z}{\partial y}$ is the slope of the isobaric surface in the meridional direction.

If the pressure gradient is radially divergent, that is, if the isobars are concentric circles around an anticyclone, equally spaced apart, the resulting trajectories emanating from the origin are cardioid type curves. The equations in polar co-ordinates are

$$r = \frac{4G}{f^2}\left(1 - \cos\frac{ft}{2^2}\right)$$

$$\theta = \frac{-ft}{2} \qquad (5)$$

where $G = -\frac{1}{\rho}\frac{\partial p}{\partial \Omega}$

If the parcel starts from some distance r_o from the centre of the anticyclone the equations become

$$\dot{\theta} = \frac{f}{2r^2}\left(r_o^2 - r^2\right) + \frac{r_o^2}{r^2}\dot{\theta}_o$$

$$\dot{\Omega}^2 = 2G(r - r_o) - \frac{f^2}{4r^2}\left(r_o^4 + r^4\right) + \frac{f^2 r_o^2}{2} \qquad (6)$$

where the dot notation represents a first order derivative with respect to time.

Equation (6) cannot be readily integrated except by numerical methods. However, the angular and radial velocities may be computed and trajectories plotted through points at specified intervals of r by means of the relation

$$\Delta\theta = \frac{\dot{\theta}}{\dot{\Omega}}\Delta r$$

Let us now consider the case of Equation (4) in which we allow the Coriolis parameter to vary according to the relation $\sin\phi = \frac{y}{a}$.

We must solve the equations

$$\dot{u} - \frac{2\Omega\dot{y}}{a} = 0$$

$$\dot{v} + \frac{2\Omega u}{a} = G \qquad (7)$$

Integration yields

$$u = \frac{\Omega}{a}\left(y^2 - y_o^2\right) + u_o$$

$$v^2 = -\frac{\Omega^2}{a^2}\left(\frac{y^4}{2} - y_o^2 y^2 + \frac{y_o^4}{2}\right) + G(y - y_o) + v_o^2 \qquad (8)$$

The component velocities of the trajectory motion can thus be calculated and the trajectories found by application of Equation (3).

Figure 4 illustrates the family of trajectories for the case where parcels start from rest from different latitudes travelling through a pressure gradient acceleration of 10^{-3} metres per sec^2.

It is interesting to note that the trajectories converge as they move northwards.

The evaluation of these equations needs an electronic computer for any routine calculations. Such facilities are even more necessary to meet the case when the pressure gradient is not meridional. In the latter case the integration of the primitive equations of motion requires advanced mathematical techniques.

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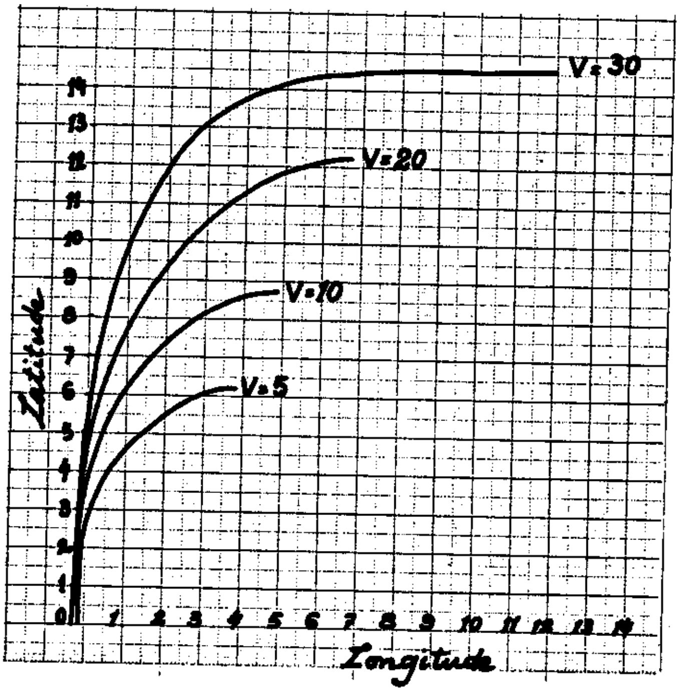

Figure 1 - Family of trajectories projected northwards from the equator with varying velocities.

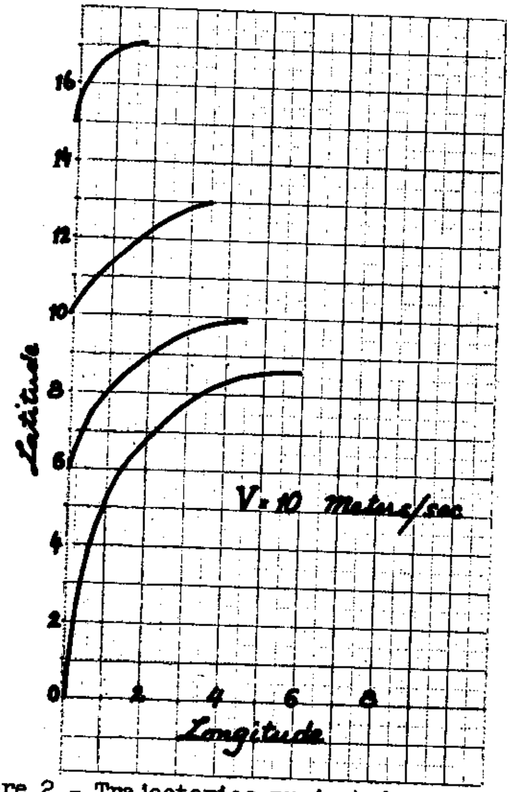

Figure 2 - Trajectories projected northwards form different latitudes with velocities of 10 metres per second.

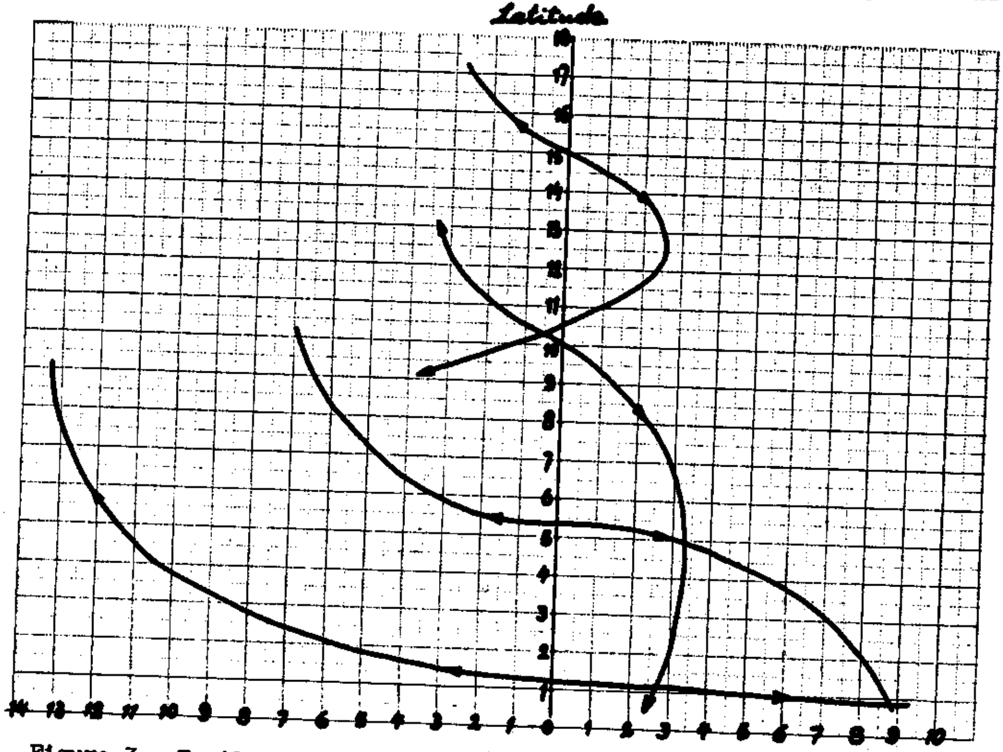

Figure 3 - Family of trajectories projected zonally with an initial velocity of 10 metres per second.

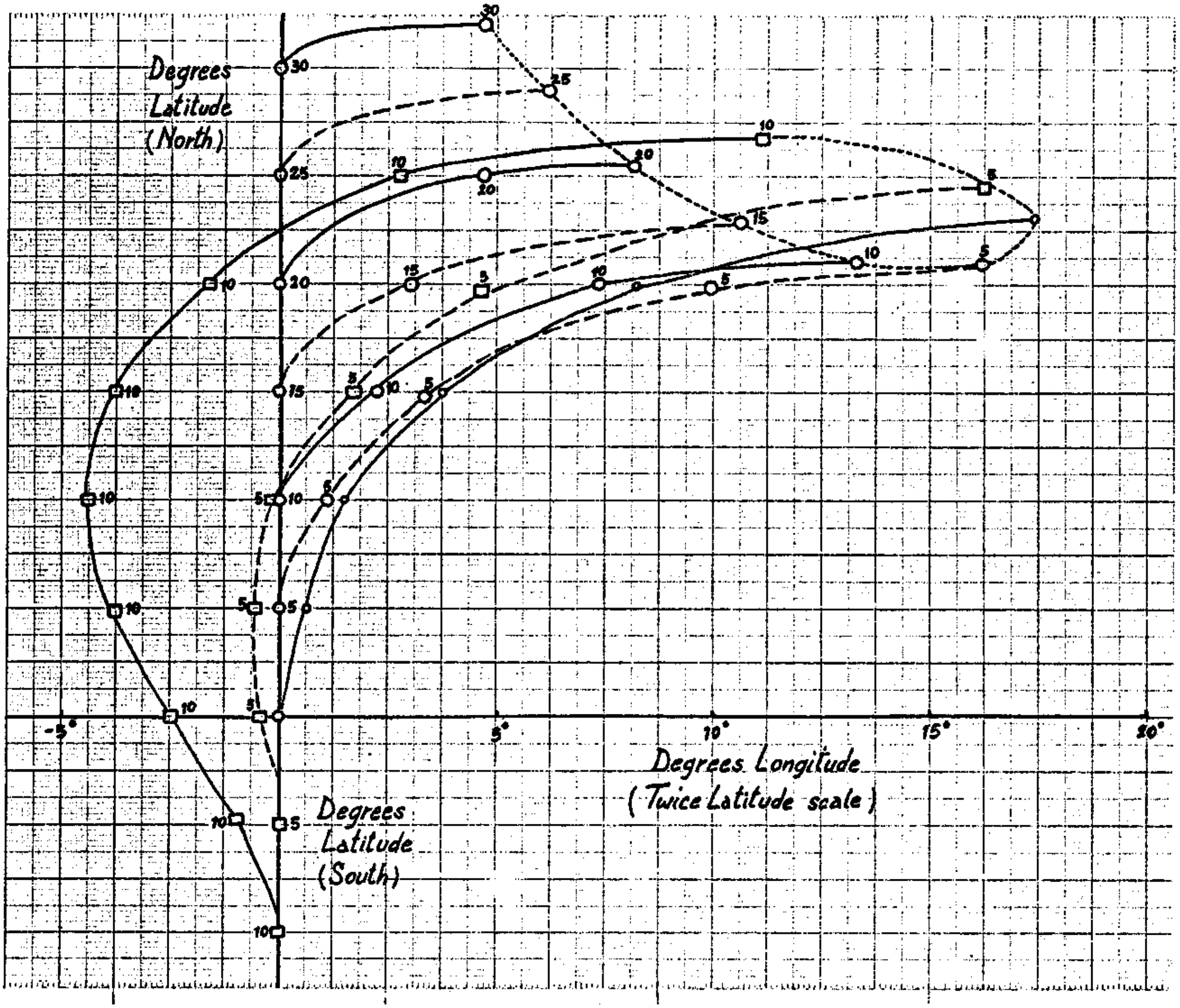

Figure 4 - Trajectories of air parcels starting from rest at successive intervals of 5° latitude under a meridional pressure gradient of 10^{-3} metres per sec^2.

AFRICAN SYNOPTIC METEOROLOGY

by

D.H. Johnson

1. INTRODUCTION

One of the purposes of this seminar is to encourage co-operation between locust control and meteorological services in making studies of the effects of weather systems on swarm movement and on swarm formation and dispersal. Case history studies would be of great value, and not only for anti-locust operations or for locust meteorology. Weather systems of the desert locust area as a whole are poorly documented and there are some parts for which the synoptic meteorology is virtually unknown.

In the three lectures summarized here our knowledge of systems which affect eastern, central, western and northern Africa is reviewed. Some of these are already known to be important for locust migration, but the relevance of others has yet to be established.

2. THE INTER-TROPICAL FRONT (ITF)

One of the most significant features on surface synoptic charts for Africa, north of the equator, is the boundary between the hot, dry easterly or north-easterly flow on the southern side of the North African subtropical anticyclones and the cooler, moist equatorial air to the south. The boundary is known in most of the countries through which it passes as the inter-tropical front (ITF). A typical July situation is shown in Figures 1 and 2. The ITF is a region of relatively low pressure but not all Saharan lows are located at the ITF itself. On most days, the ITF can be defined readily, except near the coast, by the difference in surface dew point between the two air masses. Above the surface, north-easterly or easterly air overrides the moist south-westerly current which lies in a wedge pointing northwards. Near the boundary the southern air may be modified considerably by convective mixing with the drier air aloft. The ITF itself is usually a region of fair or fine weather, and the rainy zone in which convective storms are normal begins three or four hundred kilometres to the south. In areas of organized convection, the easterlies become saturated as well as the westerlies. It is a reasonable inference that the rainy zone is associated with convergence in depth, through the lower troposphere, but to maintain the well-marked surface dew-point discontinuity despite the vigorous convection due to solar heating, there must also be persistent, though shallow, convergence in the lowest layers at the surface position of the ITF.

Figures 3 (a) and 3 (b) (Clackson [3]) illustrate the range of the seasonal and day-to-day migrations of the surface boundary of the dry northern air over West Africa. Differences from year to year are appreciable : compare, for example, the southern limits reached by the boundary in the early months of each year. It is notable that the ITF, as we have described it, does not follow the sun into the southern hemisphere. French meteorologists working in equatorial Africa have recognized two inter-tropical fronts, "Le front intertropical (FIT) nord" and "Le front intertropical (FIT) sud". A scheme suggested by Tschirhart [28] (Figure 4) shows the positions of the ITF in the extreme seasons. During the northern summer, when it is most marked, "Le FIT sud" divides the southern boundary of the humid westerlies from the drier easterlies of the Kalahari Desert region, but it is generally a less well-defined system than "Le FIT nord".

The mean sea-level pressure patterns for January, April, July and October, computed by Weickmann /29/, are given in Figure 5. The patterns must be interpreted very carefully, since there are serious objections to the reduction to mean sea-level of high-level observations; for example, it is doubtful whether much weight can be given to the analysis drawn over the Ethiopian Highlands which rise above 3,000 metres over a wide area. Nevertheless Figures 4 and 5 illustrate certain features which are borne out by daily synoptic surface and 850 mb analyses. For example, the surface trough of low pressure over northern Africa moves southward between July and January with the ITF, but it too does not cross the equator. A trough of low pressure exists south of the equator in association with "Le FIT sud" in July : it intensifies and moves south with the development of the Angola - Kalahari low during July - January, but according to Tschirhart /28/ "Le FIT sud" becomes progressively more feeble during this period and he does not include it in his scheme of fronts for the southern summer. The structure of the Angola - Madagascar trough, which is an extension of the oceanic inter-tropical convergence zone, as can be seen from Figure 5, is entirely different from the structure of the North African ITF. The ITF is marked by a clear-cut air-mass boundary and the trough with which it is associated is displaced equatorwards with height, normally (though not quite invariably) reaching the equator by 700 mb, so that the low-level westerlies are overlain by easterlies from 700 mb upwards. On the other hand, the air at low levels in the vicinity of the Angola - Madagascar trough is generally humid, there being no sharp air-mass boundary, although there may be an asymptote of convergence, and the trough frequently extends vertically upwards from its surface position to 700 or 500 mb. Rain falls along the length of the southern trough; unlike the ITF it is not a region of mainly fair or fine weather.

The author of Figure 5 has marked the Inter-Tropical Convergence Zone (ITCZ) along various trough-lines. This use of the term is much too general for day-to-day synoptic work, where we must recognize the very significant differences between the structures of the ITF and the southern hemisphere summer trough. Tschirhart /28/ has suggested that the term ITCZ be used only for the primarily oceanic region where the trade winds of the two hemispheres meet. In the WMO "Provisional guide to synoptic meteorological practices" the name "inter-tropical discontinuity" is recommended for a discontinuity separating very hot and dry continental air from the cooler moist air from equatorial regions. This term has not replaced ITF in everyday use in Africa, so far.

The July chart in Figure 5 illustrates other problems. What happens over Arabia, where any confluence there is takes place between north-westerly flow from northern Arabia and the moist south-westerlies which reach the southern coasts? The nature of the convergence zone here, if there is convergence, must be different from that of the North African ITF and the southern hemisphere summer trough (or ITCZ). Note also that over the Congo the equatorial belt, which has a high rainfall, is occupied by relatively high surface pressure throughout the year.

Very little has been written about the perturbations of the ITF. According to Clackson /3/, day-to-day changes in its location may be due either to a bodily north-south movement or to an east-west movement of a disturbance along it. An example of bodily movement is given in Section 4 below. Nevière /23/ has reported a diurnal movement of the ITF, which evidently tends to shift southwards during the morning and northwards in the afternoon.

3. DISTURBANCES IN THE ZONE TO THE SOUTH OF THE ITF

The best-known of the disturbances which contribute to the weather of the rainy zone to the south of the ITF are the disturbance lines (lignes de grains). They have features in common with squall lines encountered in several parts of the tropics. The West African variety consists of a line of thunderstorms orientated roughly north-south moving westwards against the low-level moist south-westerlies. A short way ahead of the line weather is usually normal for the time of day and season but as it approaches the wind falls to a calm and soon afterwards the squall itself, due to outflow from the Cumulonimbi, comes from a direction between north-east and south-east. Near the coast, gusts in the squall are of order 30-40 kt, but they reach up to 60 kt in the north, where with a dry surface they sometimes raise a curtain of dust similar to that encountered in the Haboobs of the Sudan. A few minutes after the squall, thunderstorms with very heavy rain begin and the cloud base lowers. At this stage it is often reported as Stratus or Nimbostratus of base about 120 m. Cloud tops are usually above 6 km and sometimes reach 15 km. The period of heavy rain lasts for about an hour before the cloud base rises and rain decreases. Slight rain may continue to fall from medium cloud for several hours, during which the wind direction remains easterly before the wind and weather return to normal. In the latitudes of the West African coast, the most vigorous squalls occur in May - June and September - October, being rare in July and August. Further north, for example in the Lake Chad area, peak frequency is reached in July.

Figure 6 shows part of the synoptic chart for 1200 GMT on 19 May 1959 when a disturbance line was crossing Nigeria. Typically, it was associated with high pressure; there may be a jump of several millibars in the barograph trace at the passage of the squall. At present, forecasting the passage of line squalls relies primarily upon recognizing their development at an early stage, from the observations, and then tracking them with the help of deterioration and improvement reports. They seem nearly always to move at a speed of about 25 kt, which is greater than that of the easterlies in the lower and middle troposphere. Their average length is 300-500 km, but the intensities of the thunderstorms vary both with time and with distance along the line. Disturbance lines have been discussed by Hamilton and Archbold [10], Dhonneur [4], Eldridge [5] and Tschirhart [27].

A larger-scale system than the disturbance line has recently been shown to occur fairly commonly over West Africa by Gilchrist and Mathews [9]. It consists at 850 mb of a westward moving low (Figure 7) with a well-defined cyclonic circulation. It is not easy to trace in the surface pressure pattern except in intense cases. The closed 850 mb circulations are overlain at higher levels by an open wave pattern in both contours and streamlines, the amplitude of the wave decreasing with height until at 300 mb it is difficult to detect. This structure requires a weak cold pool in the lowest 1,000-2,000 m to be surmounted by a warm core aloft. Erickson [6] has described the development into a hurricane of one such low as it moved out over the Atlantic. According to Gilchrist and Mathews [9] the lows are accompanied by a high level of thunderstorm activity and they are often, but not always, preceded by a squall line as indicated by the dash-dot line in Figure 7. With the passage of the 850 mb lows, the moist south-westerly current over southern parts of West Africa deepens, and the deepening of the westerlies, as discussed by Gilchrist, is generally accompanied by outbreaks of the so-called "monsoon rain". The morning monsoon rain is notable for its steadiness and non-convective character; it falls from widespread layered cloud usually reported as Nimbostratus or Altocumulus/Altostratus. The weather shown in Figure 2 is typical. During the day the layered clouds break up and thunderstorms build, especially inland. The area affected during the morning of 28 July 1960 is cross-hatched in Figure 7. A correlation between the zonal component of the tropospheric wind and rainfall has been reported for several parts of the tropics, as discussed by Flohn [7] and others.

In the scheme illustrated in Figure 4, Tschirhart [28] has marked a feature which he terms "Le front équatorial africain (FEA)". It is indicated as dividing moist westerlies (Atlantic air) from moist easterlies. It has also been called the boundary of the monsoon (Jeandidier and Rainteau [11]) and it could no doubt be identified with a line sometimes drawn by East African analysts to mark the "boundary of Congo air". In each of these terms there is the implication of the existence of an air-mass boundary. Jeandidier and Rainteau state that thundery systems often develop near this boundary, but occasionally they occur within the westerly flow as a result of a surge in the monsoon (strengthening of the westerlies). Figure 8 (Johnson [14]) shows the evolution of an eastward-moving thundery disturbance which crossed the Congo region during 21-23 March 1960. Comparing especially the three 1200 GMT charts, it can be seen that during 21-22 March an isallobaric low, as indicated by the dotted 24-hour isallobars drawn at intervals of 1 mb/24 hour, developed to the east of the trough which lay over the eastern Congo at the beginning of the sequence. At the same time an incipient isallobaric high appeared to the rear of the trough, the whole system being mobile. At 1200 GMT on 22 March the isallobaric low was a region of fair weather and high temperatures but to the rear of the trough thunderstorms had developed, associated low noon temperatures being typical of a widespread outbreak. From 22 to 23 March the system continued to move eastwards, the isallobaric low declining and the isallobaric high growing along with the associated ridge. The thundery outbreak spread eastwards quickly, the storms leaving in their wake overcast skies of layered cloud from which slight rain fell (illustrated best at 0600 GMT on 23 March). It seems reasonable to suppose that developments of this kind are responsible for the eastward-moving Congo rainfall patterns first described by Bultot [1].

Between 1200 GMT on 22 March and 1200 GMT on 23 March thunderstorms spread eastwards at a rate of 10-15 m/sec. It is significant that westerly winds of that speed were not reported at any of the standard upper levels; in fact winds aloft in the vicinity of the disturbance were easterly except in a band south of the equator at 850 mb. The evidence shows that the thunderstorms were not simply carried along in an eastward-moving monsoon air-mass, but rather that some form of perturbation propagated through the air itself. The involvement in the thundery system on 23 March of air which during 22 March was travelling westwards in the region of fair weather was probably important for the maintenance of the vigour of the disturbance, since conditional instability in such air is normally high, whereas the aftermath of an intense thundery outbreak is a more stable, saturated troposphere with lapse-rates near moist adiabatic and skies of dull, layered aspect, screening insolation. The mechanism by which such systems are propagated awaits investigation but it may be that once a relatively small thundery outbreak has been triggered, it spreads of its own volition in favourable circumstances at a speed related to the intensity of the cold outflow from peripheral storms or to the surface pressure gradients created by the build-up of a low-level cold dome in the thundery area. The same suggestion might be made, of course, in respect of the cold-low line-squall system shown in Figure 7.

As often happens, it is not easy to locate precisely the boundary of the surface westerlies on each of the charts of Figure 8. Jeandidier and Rainteau remark that this is best done by reference to winds at a few hundred metres above the surface. However, north of the equator it probably coincides with the trough lines at 1200 GMT on 22 and 23 March. Examination of synoptic situations of the kind just described suggests that the *front equatorial africain*, even when it is well-defined, is better regarded as a dynamical feature similar to a stream-line asymptote, which may be translated relative to the air, than a front in the normal air-mass sense.

4. DISTURBANCES OF THE ZONE TO THE NORTH OF THE ITF

The evidence so far available suggests that movements of locusts northwards away from the neighbourhood of the ITF, which take place especially in October, eastward movements of locusts across North Africa during the northern winter and the northward movements of locusts from Ethiopia and Somalia, which take place in May, are all brought about by disturbances which develop and travel eastward or north-eastwards with troughs in the upper-subtropical westerlies.

Figure 9 shows a development reported by Mathews [22]. It is essentially middle-latitude in character, although it occurred in a region which is beyond the southern edge of the temperature-latitude analysts' normal working chart. A surface depression developed on the forward side of a well-marked upper trough and ran north-eastwards. A substantial anticyclone built up to the rear of the trough as it moved from the west. The dotted curves in Figure 9 are isallobars drawn at intervals of 2 mb/24 hours. These events took place, of course, over a region where the air-flow at low levels is normally controlled by the subtropical high-pressure cells. During 24-26 December the ITF shifted several hundred kilometres northwards of its average seasonal position, towards the developing Saharan low and unseasonable thunderstorms broke out over northern Nigeria and over the Sahara as the upper-cold trough approached. On 27 December, the surge of pressure to the north drove the ITF southwards again until during 28-29 December it moved clear of the West African coast. According to Mathews the increase of thundery activity over Nigeria with the passage of troughs in upper westerlies to the north is a fairly frequent occurrence in the winter months. The December 1960 case must be a fairly extreme one since we have already seen that in some winters the ITF does not cross the Nigerian coast at all.

The passage of baroclinic waves across northern Africa is most likely during those winter periods when the temperate-latitude westerlies are blocked over Europe. In many cases the associated surface lows track eastwards over, or a little to the south of, the Mediterranean and the surface belt of subtropical high pressure may be weakened but not broken down. At 500 mb too, it is perhaps more typical for the troughs not to penetrate south of the 20°N parallel, so that high pressure is maintained in latitudes 10°N to 20°N. These higher latitude progressions facilitate the eastward movement of locusts along and inland from the North African coast. Incidentally, they are also still important for West African weather; the tendency for pressure to build to the rear of the troughs (as in Figure 9) and for the pressure gradient to strengthen to the north of the ITF frequently results in the onset of Harmattan haze over northern Nigeria and adjacent territories (Gilchrist [8]). Burns [2] has shown that the surface pressure gradient across the southern Sahara, or more directly the speed of the surface wind, is critical for the raising of Harmattan dust.

During 21-24 March 1960 a low-latitude upper trough moved over the Sahara from the Atlantic and activated a Saharan heat low. The normal structure of the ITF broke down, the dry surface north-easterlies being replaced for two or three days by moister westerlies from the Atlantic. Air which originated in the lower troposphere to the south of the ITF flowed northwards over the Sahara. Developments of this type are probably of great significance for swarm movements. It has been described in detail elsewhere (Johnson [15]). During the same period a notable development of the same kind took place over Arabia ahead of a downstream trough. Rainey [25] has analysed the movement of locusts northwards from eastern Ethiopia in mid-March 1962. He concludes that the movement began during a brief spell of warm southerlies, interrupting cooler northerlies, associated with the passage to the north of disturbances of the type described above for 21-23 March 1960. Figures 10 and 11 show the relevant 700 mb situation and locust reports.

5. WEATHER OVER EAST AFRICA : WIND AND PRESSURE FIELDS

East Africa is the only region in which locusts are known frequently to cross the equator. This fact alone suggests that the synoptic meteorology and climatology of the area are different from those of the other tropical regions with which we have been concerned so far. Before analysing the wind and weather systems of eastern Africa, however, it is necessary to discuss the relations between air-flows and pressure fields near the equator.

Although the practical difficulties in mapping the upper-pressure fields in low latitudes has led in past decades to a concentration on methods of analysing the flow using wind observations alone, most tropical meteorologists have acknowledged the theoretical desirability of making upper contour analyses and the need for knowledge of the interactions between the flow and pressure fields at levels above the surface friction layer. Even though the geostrophic approximation has less general validity near the equator and the wind-field cannot be inferred from the pressure pattern by the methods in use in higher latitudes, we still must recognize that the development of weather, and changes in the wind-field, depend upon interactions between the wind and pressure fields in the tropics no less than they do in higher latitudes.

Following the improvements in the African radiosonde network at about the time of the International Geophysical Year (IGY) daily contour analyses were attempted in East Africa for a region which includes all Africa and part of Europe. Streamlines were added as necessary in low latitudes. Daily experience of the upper-air analyses led to the recognition of a number of typical synoptic states or models. The 700 mb level was found to be particularly suitable for studying low-latitude contour wind relations over equatorial Africa because it is the lowest standard level which is free from small-scale, orographically tied distortions of the flow; it is reached by many of the pilot-balloons; and the random and systematic errors in the radiosonde observations are not generally so large as to mask the broad-scale contour patterns when well-organized flows prevail.

One of the commonest and most important models is the equatorial duct, illustrated in Figure 12A. In this case there are large subtropical anticyclones in each hemisphere with the lowest pressure in any given longitude at the equator itself. In such situations the broad-scale flow approximately parallels the contour lines. There is a region of confluence in the east and diffluence in the west but the flow is nearly zonal in central longitudes. The meridional pressure or contour gradient decreases towards the equator. The V-shaped appearance of the contour lines which cross the equator is a natural geometric consequence of the relatively small zonal component of contour gradient along the equator and there is no implication that the trough in the meridional-pressure profile is sharp. Johnson and Mörth [18, 19] have pointed out that for zonal flow to approximately parallel the contours in a steady state, the pressure and Coriolis forces must be of the same order of magnitude down to very low latitudes, and it is suggested that in the case of the duct, the geostrophic approximation provides a useful guide to the pressure gradients in the free atmosphere to within at least three or four degrees of the equator. Tschirhart [28] has made much the same deduction and observation from studies made independently in countries of former French Equatorial Africa : Figure 13 is a diagram taken from his paper. This does not apply, of course, in the layer affected by mechanical surface friction where, near the equator, the winds blow sharply across the isobars. Figure 14 shows the bowl-shaped meridional pressure profiles proposed for the duct model; the pressure gradients vanish at the equator. Palmer *et al.* [24] have drawn attention to some six-day mean surface pressure profiles across the central Pacific trades which are similar to those given in Figure 14, and have demonstrated from a study of radar and radiosonde data in the central Pacific during June 1956 that for monthly mean flow at least, the pressure and Coriolis forces are of the same order down to 4°N.

Figure 12B shows a second case in which flow can parallel the contour lines. Over Africa, at high levels it is not so common as the duct but it is believed to occur occasionally at high levels when deep troughs in the westerlies of the two hemispheres penetrate simultaneously and in the same longitude, to the equatorial zone. There is evidence that it is a common state at 700 mb over the Indian Ocean in July-August. The meridional pressure profile for this case would take the form of a broad ridge, flat at the equator.

The third possibility for low-latitude quasi-geostrophic flow arises if the meridional pressure profile has an inflexion at the equator, where the pressure gradient vanishes and the flow is zonal. This model, called "step", is illustrated in Figure 12C. It very rarely occurs at low levels over Africa, although, as will be seen, situations in which there is a subtropical high cell in one hemisphere and a low-latitude low at the same longitude in the other hemisphere are commonplace.

What is commonly observed when there is a high to the north of the equator and a low to the south is shown in Figures 12D to 12F. The model given in Figure 12D is the simple cross-equatorial drift. The flow in this case is far from geostrophic near the equator; it leaves the northern hemisphere as a north-easterly current and recurves south of the equator into a westerly. Johnson and Mörth /19/ have suggested that in the simple drift there is a marked meridional pressure gradient at the equator which is absent in the quasi-geostrophic cases. They have shown that, for a linear variation of pressure with latitude, zonally orientated isobars, and initial zonal flow, for a given pressure gradient there is a critical latitude equatorwards of which any small geostrophic departure is sufficient to cause air particles to stream across the equator. From Figure 12D it will be seen that the flow crossing the equator from the north forms a confluence with the flow from the south. In the east of the pattern the two currents meet as far south as 10°S to 15°S and the northern flow has an east component at 5°S. Figure 12E shows another type of drift in which the confluent westerlies are located nearer to the equator and the recurving flow from the north acquires a west component before it reaches 5°S. It will be shown later that it is important to distinguish between the two variations when considering equatorial weather. The latter case appears to arise when the southern flow is strong and especially when there is a component of pressure gradient at the equator directed from west to east. In Figure 12E the low pressure south of the equator takes the form of a closed low with a zonal trough extending westwards; Figure 12F shows how a similar situation arises when there is a meridional trough to the south.

There is a stage intermediate between the duct and the drift when the trough, which lies along the equator in the case of the duct, is displaced polewards, but not sufficiently far for drift flow to occur. This stage is illustrated in Figure 12G; this state might be described as a "displaced duct" although between the equator and the trough is a region of highly ageostrophic flow. If the poleward displacement of the trough were continued, the shear line type of flow illustrated in Figure 12H might be expected to occur. There are some cases which can be analysed in this way over limited regions but usually the zonal trough is broken up into cells which allow meridional components of flow, as shown in Figures 12D to 12F.

Very commonly, the various kinds of duct and drift occur in adjoining longitudes, and it is most instructive to see how the models then fit together. Figure 12I shows a common form of duct exit with a meridional trough to the south-west. The north-easterly flow, which occupies the centre of the figure, is flowing parallel to the contour of the high in the east, but it consists of ageostrophic flow of the drift type in the west. Figure 12J illustrates a synoptic situation which has drift flow in the east, and a kind of well-displaced duct entrance in the west : in this case, as in the previous examples, it is not difficult to see where the asymptotes would be drawn in a continuous streamline analysis of the wind-field.

In the example of Figure 12L, a bridge lies to the east of a duct entrance, but the duct entrance differs from that shown in Figure 12A in having a relatively large zonal component of pressure gradient at the equator. In the case illustrated in Figure 12A, it is the Coriolis force which deflects the flow into an easterly current as it moves into the duct entrance, although there may be some lateral exchange of momentum between the currents of the two hemispheres at the equator itself. In the Figure 12L example, however, due to the zonal component of pressure gradient, the air tends to approach the equator, to the east of the high pressure, at an obtuse angle and the pressure force gains an ascendancy, deflecting the meridional current eastwards into the entrance of the bridge. The problem of how much zonal gradient can be imposed at the duct entrance before the typical flow breaks down, and westerlies appear, is solved by the atmosphere each year at 700 mb over East Africa and the Indian Ocean : during early April, when ducts are a common feature, they take the form shown in Figure 12A, but as the month advances, zonal components of pressure gradient along the duct axis increase (in a statistical sense) and in late April or May the continued fall of pressure over the Indian Ocean results in the appearance, at first spasmodically and locally, of westerly components as shown in Figure 12L.

Figures 15 to 20 show how the models which have been discussed arise in the course of the evolution of the upper flow and pressure fields of the tropics and subtropics. In Day 1 (Figure 15), the subtropical anticyclones are well-developed, forming a duct over eastern Africa. The northern anticyclonic belt is broken by a confluent trough with tilted axis and air-streams across the equator to the south of Lake Chad. By Day 2 the northern trough has relaxed and contour height has risen in the northern anticyclonic belt, removing the break in the zonal flow along the equator. The trough over South Africa on Day 1 has moved east and tilted by Day 2 and a sympathetic weakness has developed to the north. On Day 3 an extensive anticyclone is well-established in latitude 10°N, but south of the equator contour height has fallen in the col between the two high cells so that a low has formed over central Africa and the eastern cell of high pressure has degenerated; there is a drift over eastern Africa. A ridge has built eastwards across South Africa in the rear of the mobile trough. North of the equator on Day 4, the old trough in the westerlies which had been relaxing has redeveloped, perhaps sympathetically with the trough-ridge pair in the west. South of the equator the drift has consolidated and the low pressure is now zonally orientated. The high pressure over South Africa on Day 3 continues to extend eastwards on Day 4, the subtropical high-pressure belt having been effectively displaced southwards by events during the period Day 1 to Day 4. On Day 5 there is continued mobility in the subtropical wave-train. South of the equator the zonal trough has split into two but the cross-equatorial flow continues. By Day 6 a significant development has taken place south of the equator, the splitting of the zonal trough on Day 5 being a precursor to the growth of a small high cell which interrupted the drift and set up confluent easterlies over Lake Victoria. Meanwhile the progressive separation of the high cells in latitude 35°S has allowed a fresh link to be formed between the southern westerlies and the low off Madagascar. Figures 15 to 20 are based upon actual situations, but they were drawn to illustrate as many features as possible in a limited number of diagrams. The pace of development is quick, but not unrealistically so (see for example, Johnson /15/). The sequence shows how contour analysis potentially can provide a basis for a synoptic method of forecasting changes in the low-latitude wind-fields analogous to those in use in middle latitudes. Following the initial analysis the probable changes in the temperate and subtropical contour patterns must be assessed using tendencies, trends, wavelength indications, middle latitude models and the guidance provided by the subjective or numerical forecast analyses issued by higher latitude centres. The reactions on the tropical contour patterns are then gauged, again with the help of tendencies, extrapolation and synoptic experience. Finally, application of the low-latitude contour-wind models enables the probable future low-latitude streamline patterns to be assessed. The method clearly calls for a good deal of experience in its application, experience, that is, in forecasting middle latitude developments as well as a knowledge of the behaviour of the subtropical cells.

6. EAST AFRICAN WEATHER : SYNOPTIC SITUATIONS AND LOCUST MOVEMENTS

Disturbance lines and mobile systems of the scale encountered in West Africa contribute little to the weather of the eastern parts. Study of the synoptic-scale rainfall systems of East Africa has shown that they are mainly quasi-stationary. They develop in the course of two or three days over areas of radius 300 to 600 km, perhaps persisting for another two or three days before shifting rather abruptly elsewhere or declining in situ. Experience has shown that there is a useful correlation between the rainfall patterns and synoptic types illustrated in the previous section.

Figure 21 shows the location of various geographic features to which reference is made below. The term "East Africa" is used in the present context to comprise Kenya, Uganda, Tanganyika and the offshore islands.

From late May to early October, East Africa is overlain at low levels by a persistent diffluent airstream which flows from the south-east. Figure 22 shows an 850 mb chart for 24 September 1959 which is typical of the period. The ridge extending from the south over Tanganyika, the Uganda low and the low pressure to the north-east, over Arabia, are all permanent features. One branch of the south-easterly stream crossed the equator to recurve over Somalia as a south-westerly, a second branch turned westwards towards the Congo, whilst the remainder of the current flowed on each side of the Kenya Highlands (which rise above 850 mb) into the Uganda low. The northerly flow from the Sudan into the Uganda low is a rather less persistent feature and may be replaced by a southerly at times when the Uganda low becomes a trough extension of a deeper low over the southern Sudan. Small east-west shifts in the coastal ridge and changes in the orientation of the south-easterly over the Indian Ocean are believed to be related with occasional outbreaks of rain on the Tanganyika coast, but these associations have yet to be studied systematically. Showers occur in Uganda throughout this season and also in the Kenya Highlands, which rise above the influence of the diffluent 850 mb flow, but elsewhere the weather is predominantly dry. Figure 23 shows that at 700 mb on 24 September 1959 there was a large-scale duct with an entrance in longitudes about 35°E; this feature is typical of September - November rather than June - August. A very different type of situation could be seen on the charts for 25 June 1959 displayed at the seminar. In the case shown in Figure 23, part of the south-easterly stream from Madagascar recurved over Somalia in sympathy with the 850 mb flow, although a north-easterly stream from Arabia flowed to the east of the Ethiopian Highlands. This juxtaposition of the two flows frequently occurs at 700 mb in May to September and aircraft pilots confirm that there is a sharp wind shear between them.

During late September and early October contour height rises at 850 mb over Arabia. Figure 24 shows the situation at 850 mb on 12 October 1959. A high cell had already replaced the September low over Arabia and there were north-easterlies over the Gulf of Aden. The ridge over Tanganyika persisted, however, and part of the south-easterly flow from the south Indian Ocean still recurved across the equator into westerlies. Thus a shear line had developed over the Horn of Africa. This situation persisted until 18 October when the recurving westerlies over Somalia became disorganized, and by 21 October (Figure 25) a confluence was established in latitude 5°N over eastern Africa. The location of the ridge over Tanganyika was unchanged despite a substantial shift in the location of the southern high centre between 12 and 21 October. The establishment of the confluence over Somalia and East Kenya within a few days of 20 October appears to be a normal seasonal feature. As long as the 850 mb south-easterly current crosses the equator and recurves over Somalia, the weather remains dry over east Kenya. In 1959 and 1960 the first outbreaks of the second rains occurred over northern Kenya simultaneously with the establishment of the confluence. The persistence of the confluence is unreliable, however, and if pressure falls again to the north the recurving flow may be re-established. This happened in both 1959 and 1960 and in consequence the rain over Kenya stopped. The success of the second rains over east Kenya requires that the ridges of high pressure from north and south should achieve a nice balance. If the establishment of the northern high pressure is too fitful, or if the southern ridge recedes too soon, substantial rains are unlikely.

Note the persistence of low pressure and convergent winds over Uganda. It is to this low pressure that Uganda owes its economy and the Nile its source. The low itself is probably partly thermal and partly orographic in origin. Sansom /26/ has shown that it tends to shift diurnally towards the Kenya Highlands during the day.

The persistence of low pressure over Arabia and to the east, until late September, is important for the climate of Somalia. Monthly mean rainfall charts show that the Horn of Africa remains dry during September, although to the west over the Congo the rains are shifting south. It is not until October that rain falls over Somalia.

Once high contour height is permanently established to the north of East Africa at 850 mb and 700 mb there follows a season from November to April when the rainfall patterns over East Africa are sufficiently well correlated with the 700 mb contour and wind-fields for the models described in Section 5 above to have a useful weather forecasting value.

Figure 26 shows a duct at 700 mb on 23 November 1959. This case has been discussed in detail by Johnson and Mörth [20]. There was a confluence over East Africa. At 850 mb (Figure 27) a ridge extended south-westwards from the Arabian high and a second ridge extended northwards from the high over South Africa. Contour height was low over the Lake Victoria basin and there was a well-developed east Congo high. The latter cell presents a considerable problem. (High-level stations which report 850 mb contour heights instead of mean sea-level pressures are indicated by dots in Figure 27 : there are many of them and it is to these that the detailed pattern is drawn.) It is a semi-permanent feature, well substantiated by reported surface pressures, but the relative levels of pressure between the Lake Victoria basin and the Congo may not be correct; the gradient between the high and low coincides with a mountain range which is also a boundary between two networks of observations. The important feature in the present case is the confluences at the equator in the flow over East Africa.

Figure 28 shows the rainfall distribution over East Africa for 23 November 1959. There was a large rain area near the equator along the axis of the 700 mb duct and the 850 mb confluence. During the period November to April 700 mb ducts are typically associated with rain near the equator. Johnson and Mörth (in preparation) have classified the 700 mb patterns of December 1958 to April 1959 and November 1959 to April 1960 into a number of synoptic types, and derived the corresponding mean-rainfall patterns. The rain was very frequently not distributed symmetrically as that shown in Figure 28; the type of flow occurring at 850 mb has a considerable influence on the rainfall distribution as might be expected. Markedly diffluent flow at 850 mb is usually associated with a much reduced rainfall. It is always necessary to consider the flow and contour patterns throughout the lower troposphere when trying to assess their significance for East African weather. The appearance of control by the 850 mb patterns at the time of onset of the Kenya second rains described earlier is to some extent misleading because a favourable 700 mb pattern, in the form of a simple duct entrance, is normally already established early in October. The charts for 11 November 1959, displayed at the seminar (Figures 29 and 30), show another duct situation, briefly described and compared in WMO Technical Note No. 64 (Vol. II, pp. 21-22).

Returning to Figure 12A, which shows the equatorial duct schematically, it will be appreciated that the acceleration of air into the duct entrance requires a component of flow across the contours towards the equator. True convergence (and not merely confluence) thereby results. This is one reason why the duct is favourable for rain near the equator, but any form of frictional effect, perhaps caused by the vertical transport of momentum in the convection cells, may also result in a component of flow towards the equator, and thus convergence. The potential for rain is greatest when pressure rises within the subtropical anticyclones, increasing the pressure gradients and unbalancing the geostrophic control, with resultant flow, again towards the equator. Simultaneous rises of pressure to north and south of East Africa have long been taken to foreshadow rain.

The weather associated with the displaced duct (Figure 12G) is similar to that of the duct, except that, as would be expected, the rainbelt is on average shifted somewhat south. Duct exits are associated with very low rainfalls.

Weather over East Africa with 700 mb equatorial drifts varies according to the location of the confluent westerlies. In the synoptic classification of Johnson and Mörth (Figure 12), the drifts were divided into two categories depending upon the direction of the flow at 5°S. The drifts in which the flow was east of north at 5°S, as in Figure 12D, were associated with notably dry weather except in southern Tanganyika. The drifts in which the flow was west of north at 5°S, as in Figures 12E and 12F, were much wetter by contrast. A number of these drifts, associated with appreciable, meridional components of pressure gradient, had westerlies along parts of the equator. The ducts have more significance for coastal rain than the drifts.

A synoptic example of a drift is given in Figure 31, which contains the 700 mb contour chart for 15 January 1959. A very narrow ridge, well substantiated by the winds and by the heights reported from Addis Ababa and Nairobi, extended across Ethiopia and Somalia. There was a deep trough over Madagascar, and a characterless area of slack pressure gradients over Angola and the Rhodesias. Outflow from the northern ridge streamed across the equator, down gradient, meeting little opposing flow from the south. Winds were generally north-easterly at 5°S, and well organized. At 850 mb, the patterns over East Africa were much more confused than at 700 mb, but along the coast there was simple recurvature of the flow. Figure 32 is the rainfall chart for this case.

Synoptic charts for the drift of 20 January 1960 displayed at the seminar (Figures 33 and 34) are briefly described in WMO Technical Note No. 64 (Vol. II, p.22).

The situation shown in Figure 12J, when it arises at 700 mb, is associated with even drier conditions than the drift. There is some tendency to confluence in the southwest and care should be taken to distinguish between cases of the Figure 12J kind, in which the confluence is well south, with others in which the south-western high pressure is better developed and the confluence is near the equator; the latter cases often give considerable rain in the west of East Africa, although the east remains dry.

Figures 35 A-J give the distribution of the Desert Locust in selected months of 1953-1954. During April - May 1953 the locusts were evacuated from East Africa with the low-level monsoon flow. They returned with the north-east monsoon between October 1953 and February 1954. A similar cycle was observed in 1954 but in that year the locusts did not all leave East Africa : many remained in the Kenya Highlands and in eastern parts of Uganda. It is significant that they remained in the region of East Africa affected by the Uganda low, where low-level convergence and rain is experienced during May - September. It may be even more significant that they were located mainly in the Highlands region since, as mentioned above, the morning Uganda low shifts diurnally towards the higher ground in the east : locust flight activity would be confined to the afternoon in this region, where the nights are cold. Why the locusts remained in East Africa in one year and not in the other remains unexplained. This example of unexplained swarm behaviour* is one of many which would provide material for investigation, the results of which would be of benefit in locust control and meteorology alike.

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* During March-September 1954 the locusts not only remained in East Africa but passed through two successive generations of breeding, instead of evacuating this area as in 1953.

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Useful additional information on the meteorological characteristics of Asmara, including a number of points of importance in relation to locusts, has since been published by the Ethiopian participant at the Seminar, Mr. Gizaw Attlee, in "Weather at Asmara", Imperial Ethiopian Government Civil Aviation Administration Meteorological Service, May 1964.

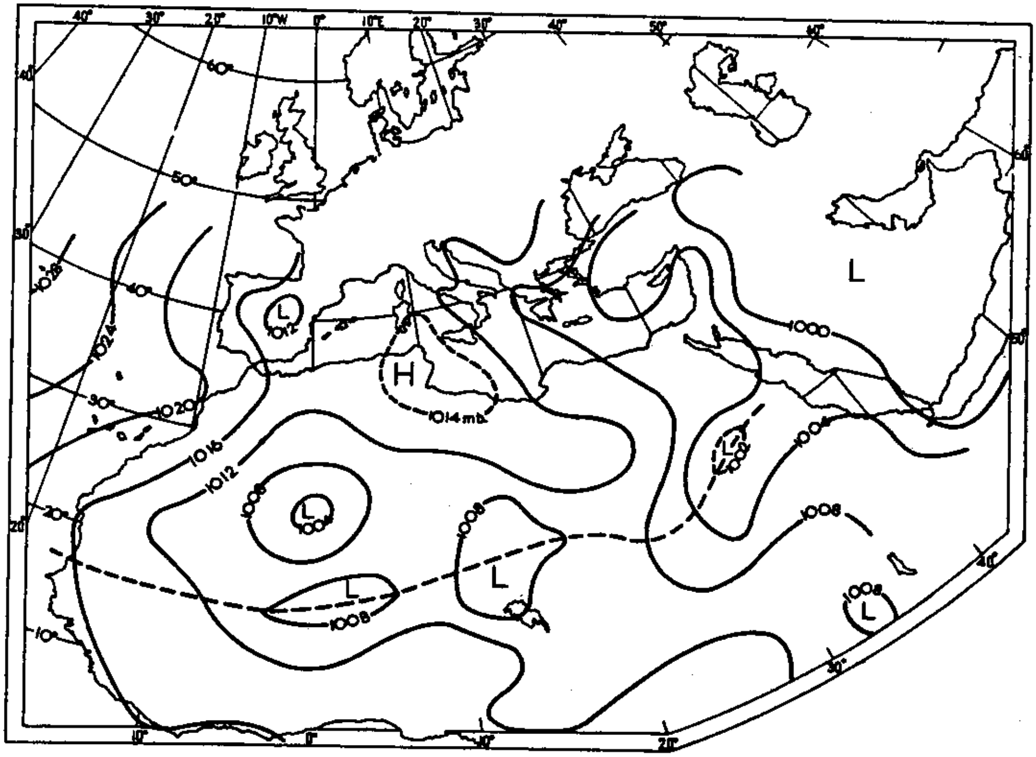


Figure 1 - Large-scale surface synoptic situation, 1200 GMT, 22 July 1959. The broken line extending from West Africa to the Red Sea is the Inter-Tropical Front (Inter-Tropical Discontinuity). After Gilchrist [8].

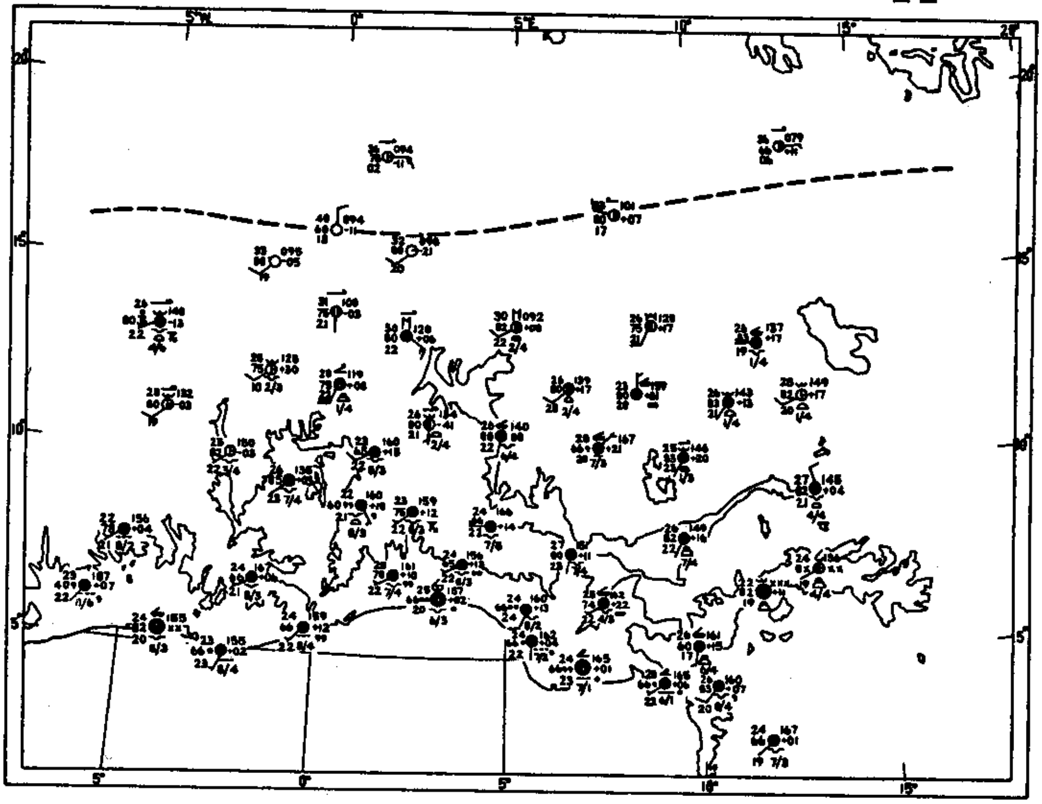


Figure 2 - Monsoon rain. Surface chart for parts of West Africa, 0900 GMT, 22 July 1959. The broken line is the Inter-Tropical Front (Inter-Tropical Discontinuity). After Gilchrist [8].

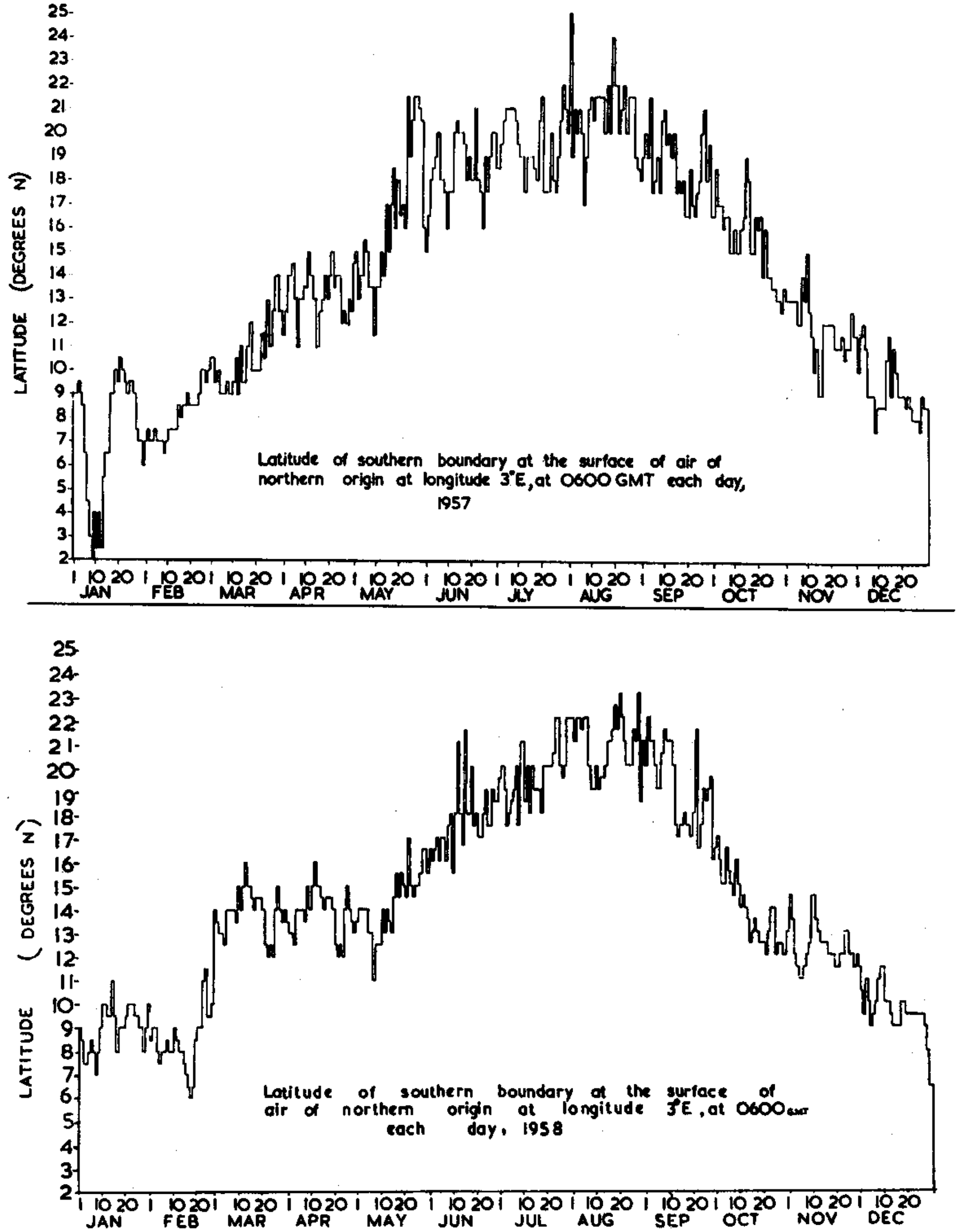
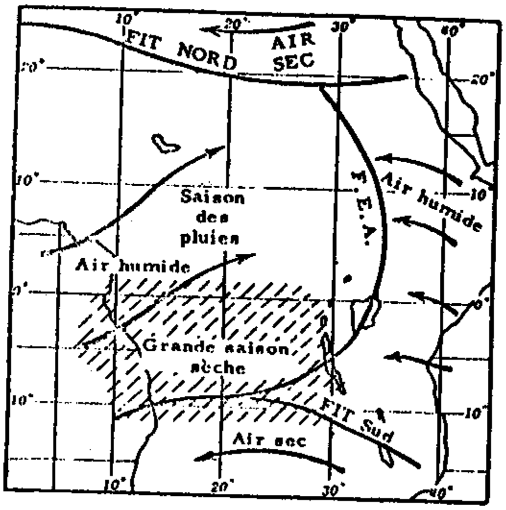
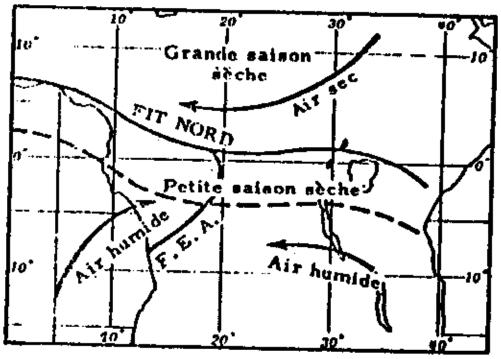


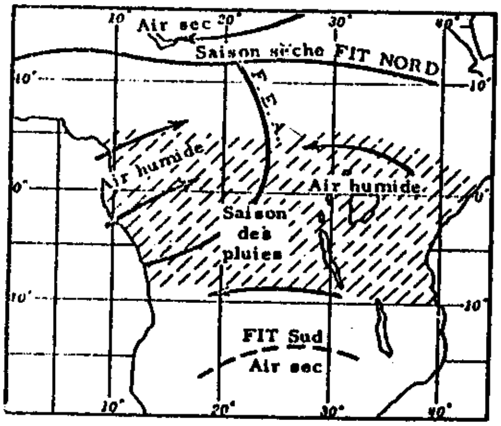
Figure 3 - The latitudes at 0600 GMT each day of the Inter-Tropical Front (Inter-Tropical Discontinuity) along the 3 E Meridian. After Clackson [3].



Southern winter - The Northern and Southern FIT are very far to the North; the Southern FIT is very marked during this period. The "front équatorial africain" oscillates around a longitude far to the East. The Atlantic air masses flowing, in the lower layers, over Gabon and Middle Congo are very stable (radiative type). These territories have a major dry season.



Southern summer - The Northern FIT is at its most southerly position in the year. The Southern FIT is indistinct. The "front équatorial africain" oscillates around longitudes far to the West.



The FIT occupy intermediate positions, slowly shifting southwards from September to December, and northwards from February to July. The "front équatorial africain" oscillates very widely in the centre of Equatorial Africa, which has a rainy season.

Figure 4 - Tschirhart's scheme of three African fronts (Tschirhart, [28]).

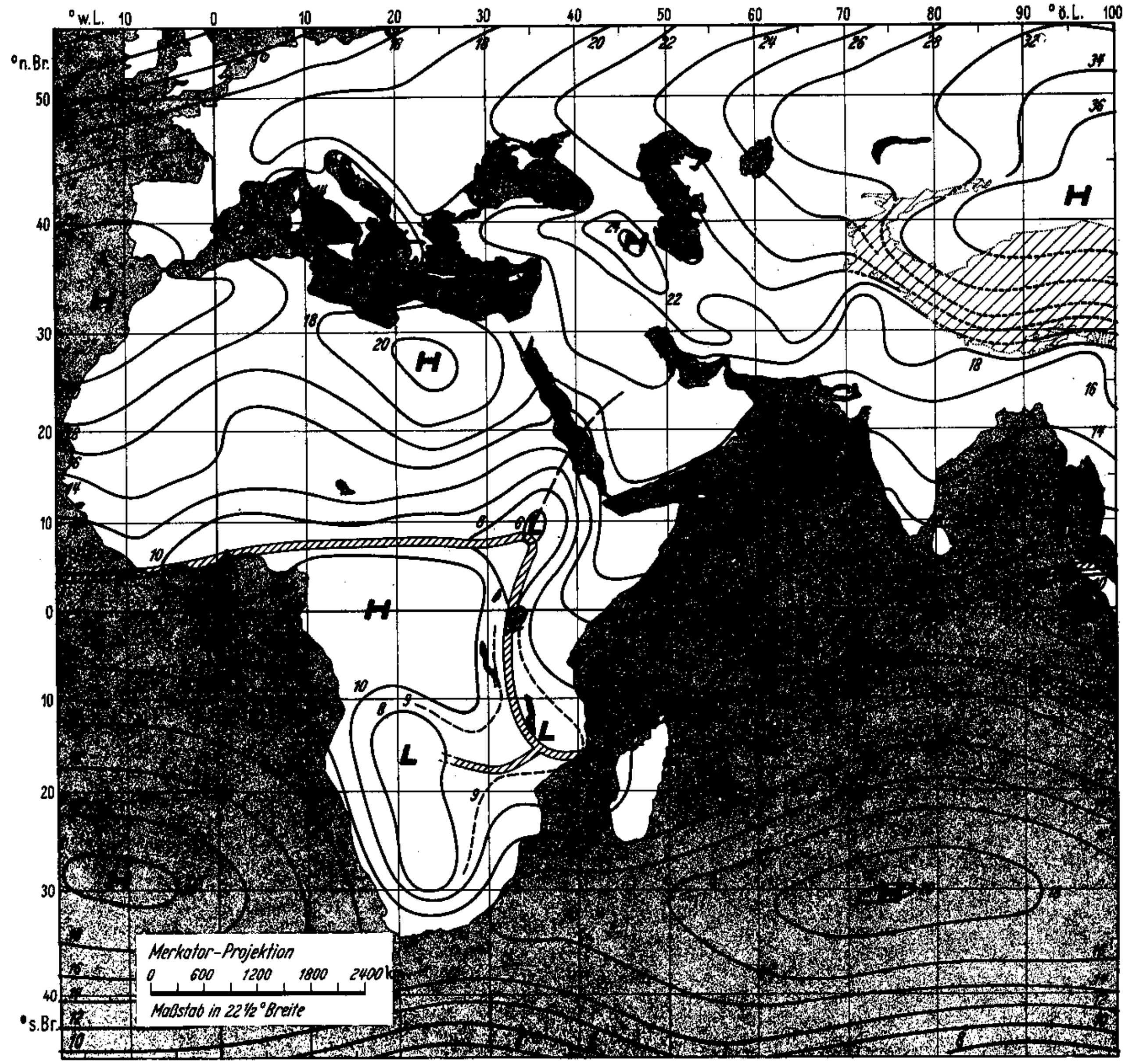


Figure 5 (a) - Mean sea-level pressure, patterns for January computed by Weickmann [29].

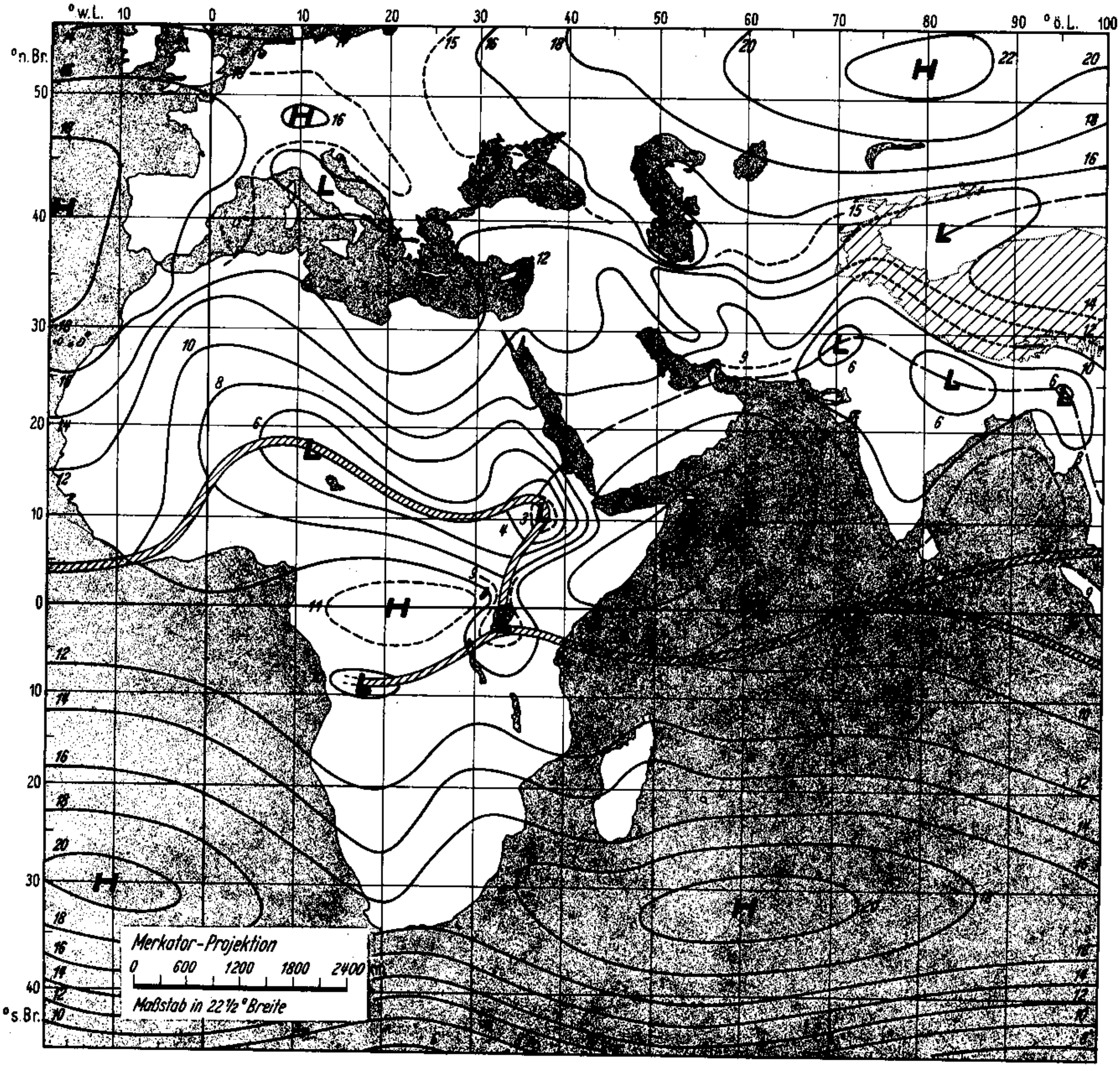


Figure 5 (b) - Mean sea-level pressure, patterns for April computed by Weickmann [29].

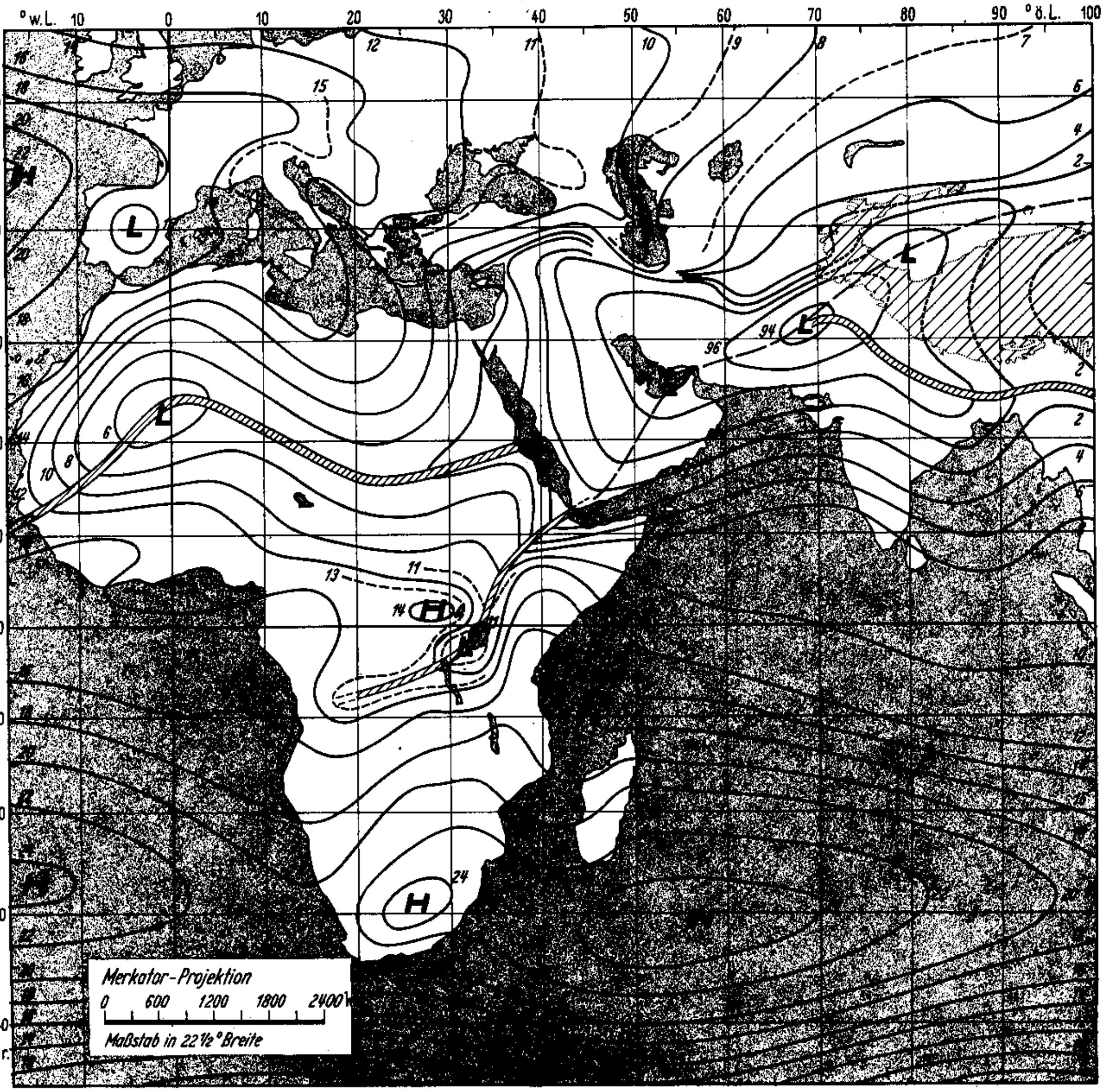


Figure 5 (c) - Mean sea-level pressure, patterns for July computed by Weickmann [29].

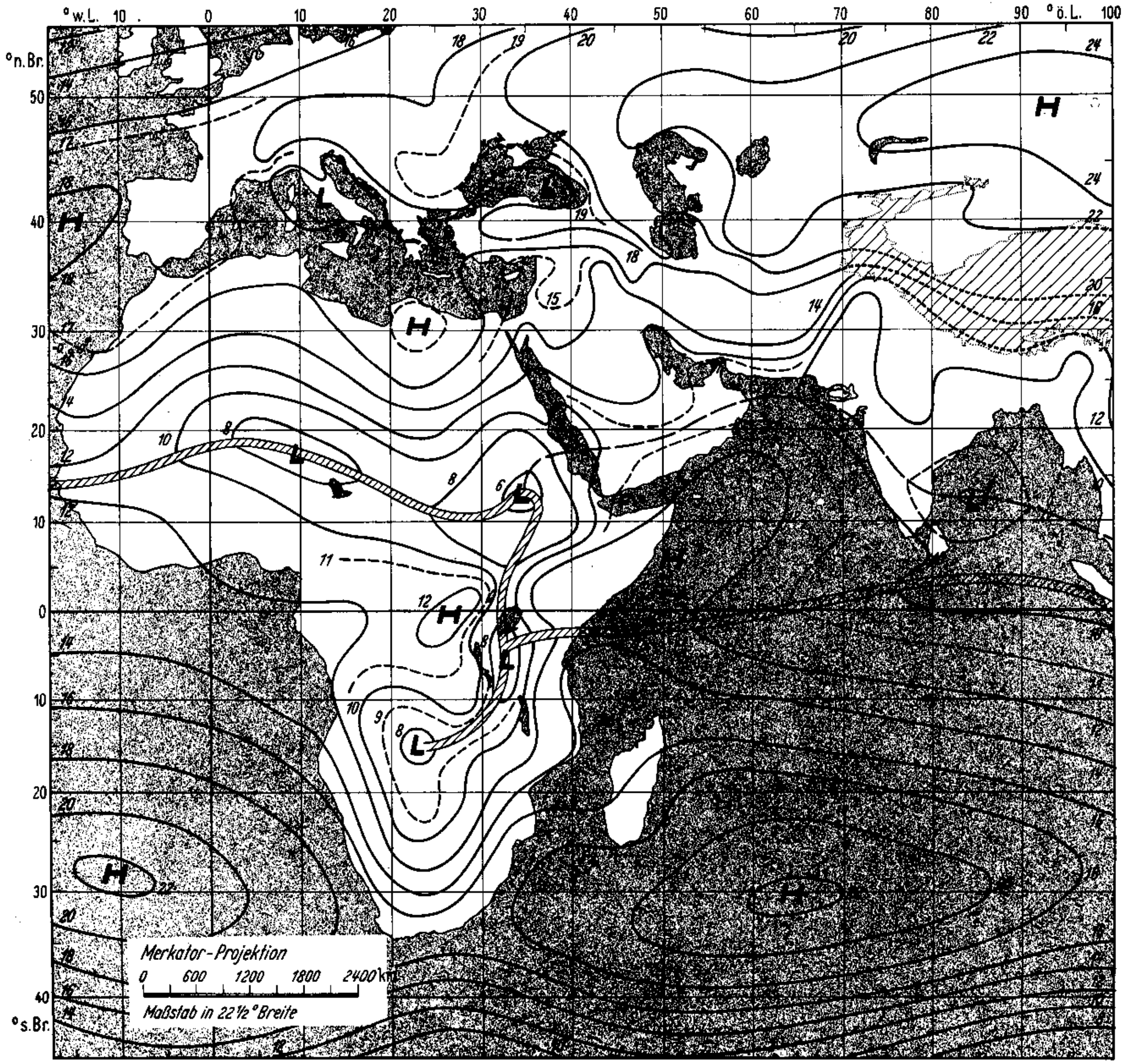


Figure 5 (d) - Mean sea-level pressure, patterns for October computed by Weickmann [29].

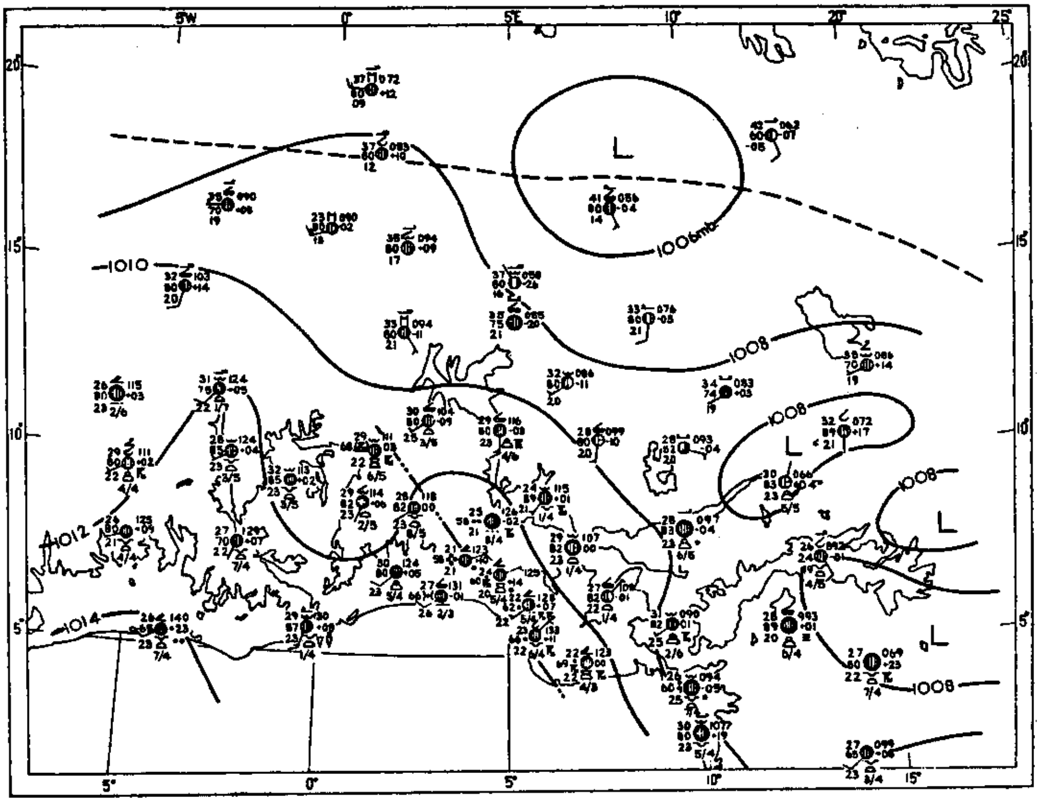


Figure 6 - Disturbance line. Surface chart for parts of West Africa, 1200 GMT, 19 May 1959. The broken line is the Inter-Tropical Front (Inter-Tropical Discontinuity). After Gilchrist /8/.

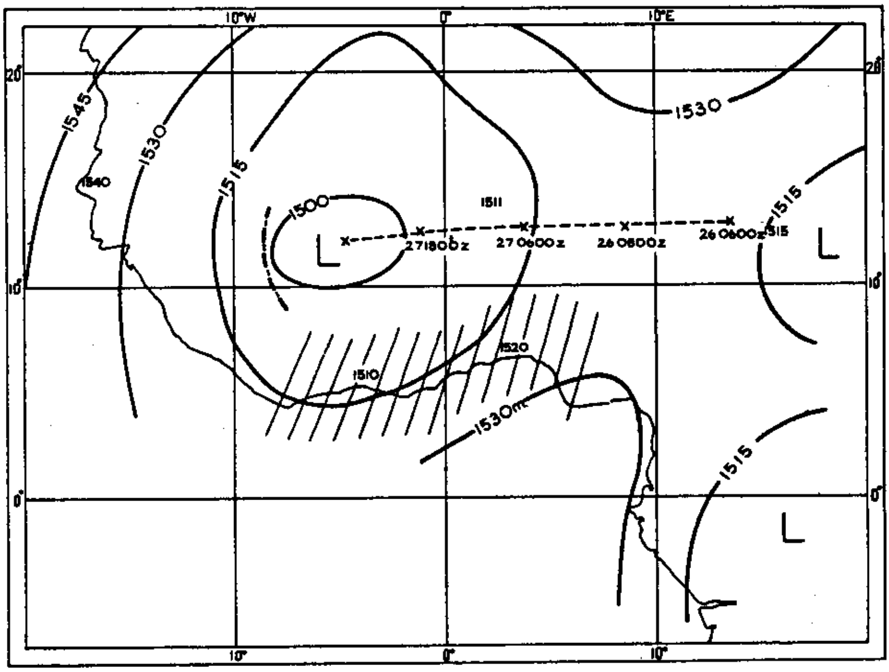
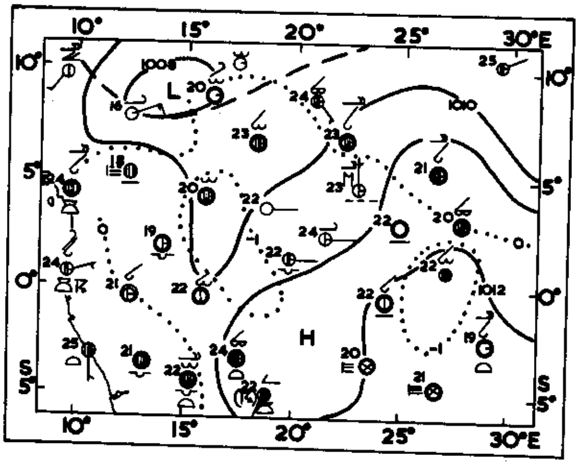
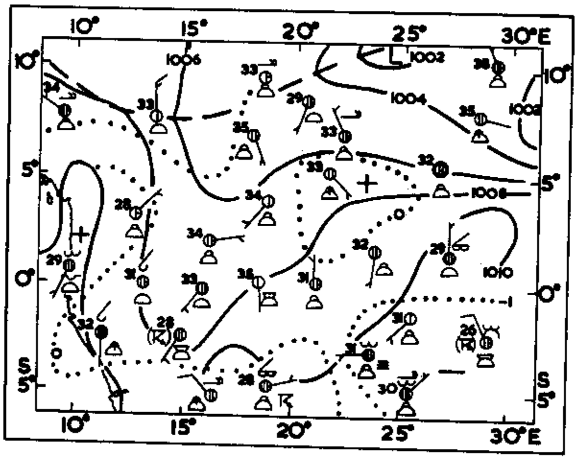


Figure 7 - 850 mb contour analysis, morning, 28 July 1960. Crosses mark the positions of the 850 mb low at 12-hourly intervals during 26-28 July. Monsoon rain fell within the area hatched. The dash-dot curve shows the surface position of a disturbance line. Based upon Gilchrist and Matthews /9/.



21st. March 1960 0600 G.M.T.



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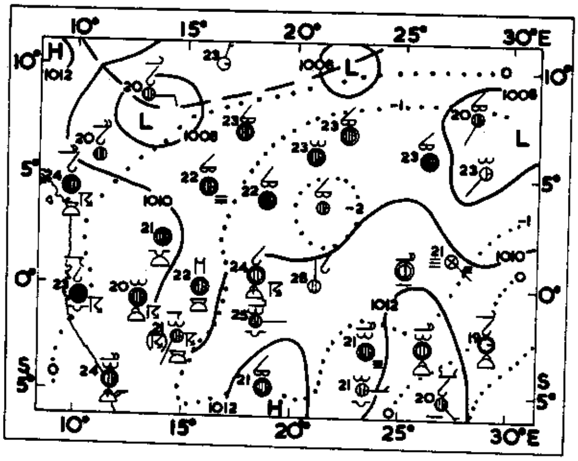

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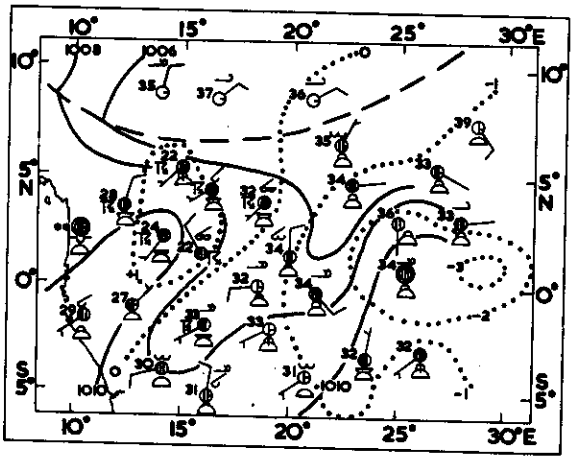

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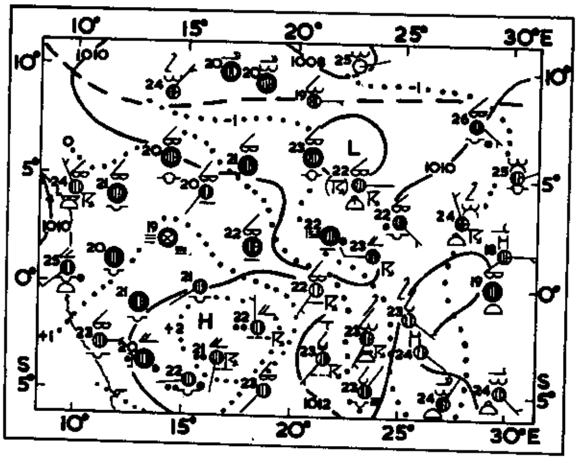
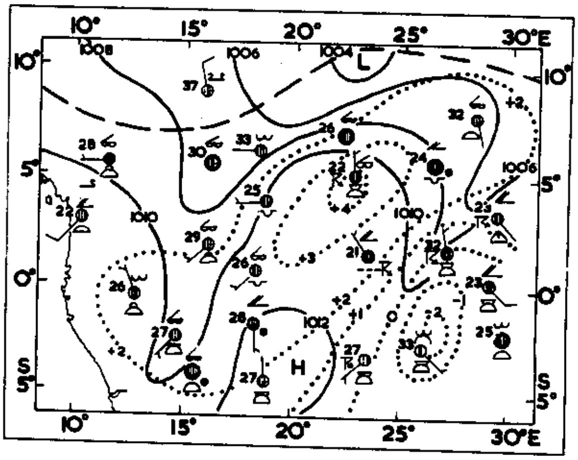
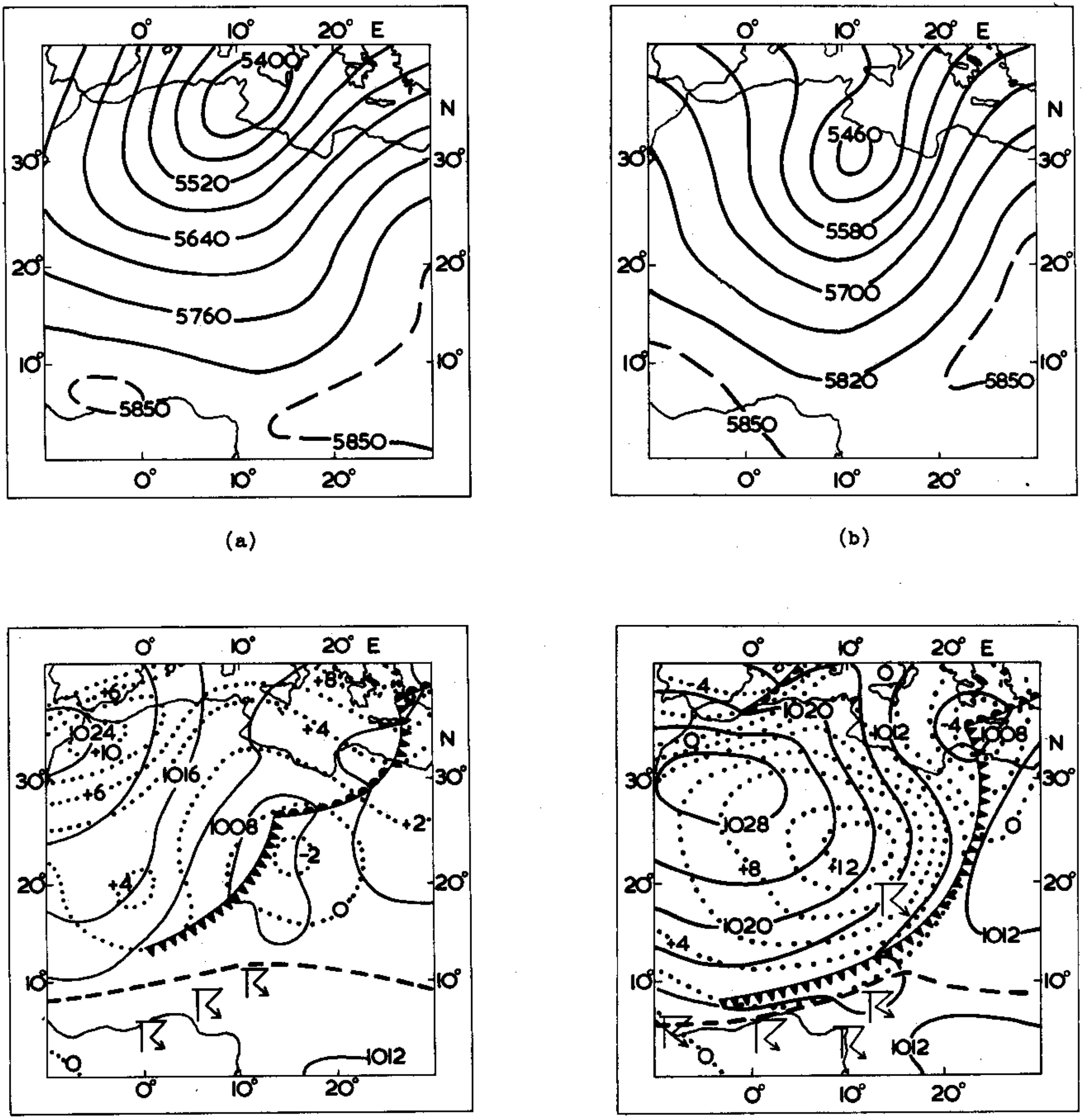


23rd. March 1960 0600 G.M.T.



23rd. March 1960 1200 G.M.T.

Figure 8 - The passage of a thundery disturbance across the Congo region, 21-23 March 1960.



(a) (b)

(c) (d)

Figure 9 - Synoptic situation for the Nigeria storms of Christmas, 1960. The dotted curves in Figures 9 (c) and (d) are isallobars drawn at intervals of 2 mb/day. After Matthews [22].

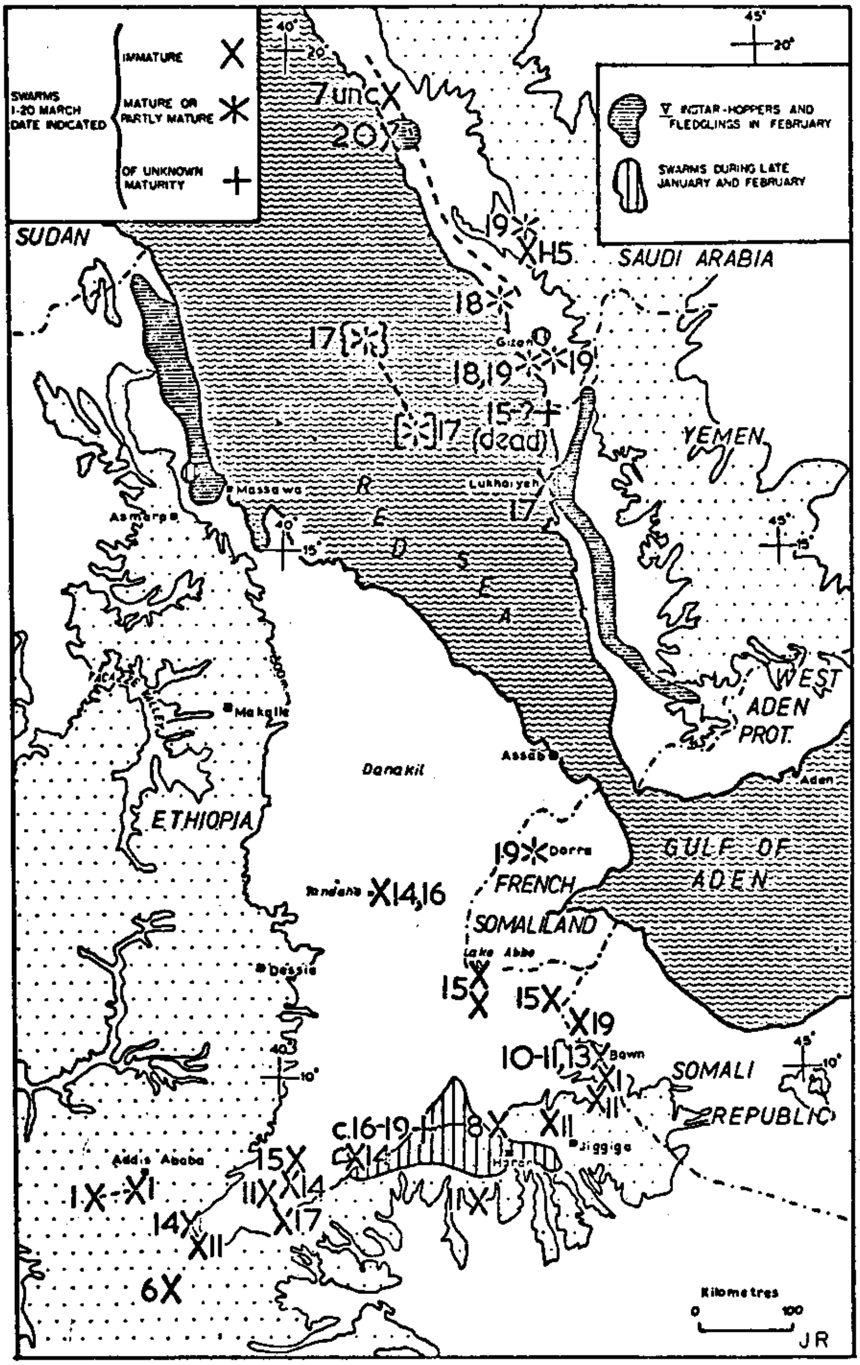


Figure 10 - Locations of locust swarms reported during March 1962. After Rainey [25].

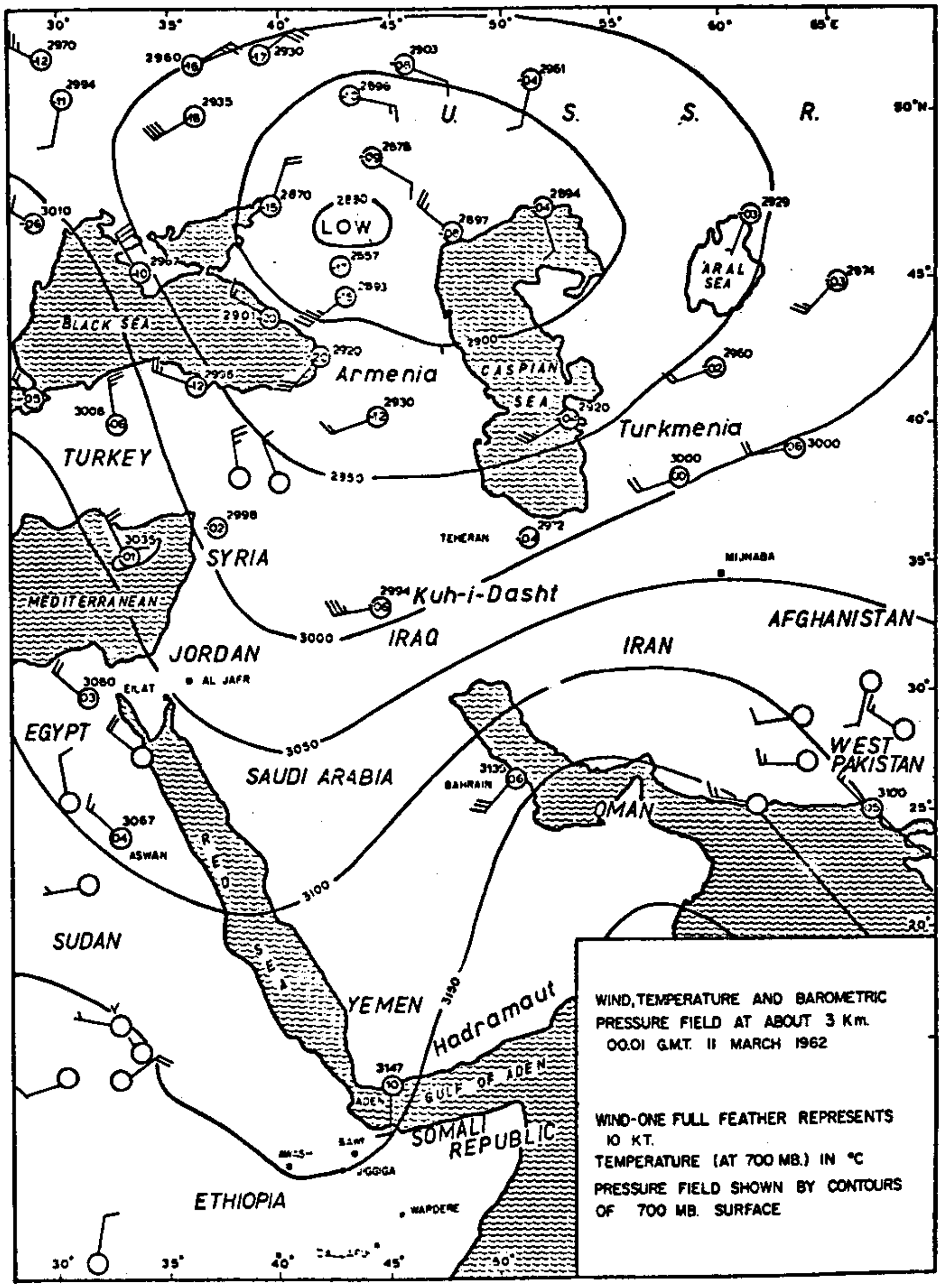


Figure 11 - 700 mb contours and winds near 700 mb, 0001 GMT, 11 March 1962. After Rainey [25].

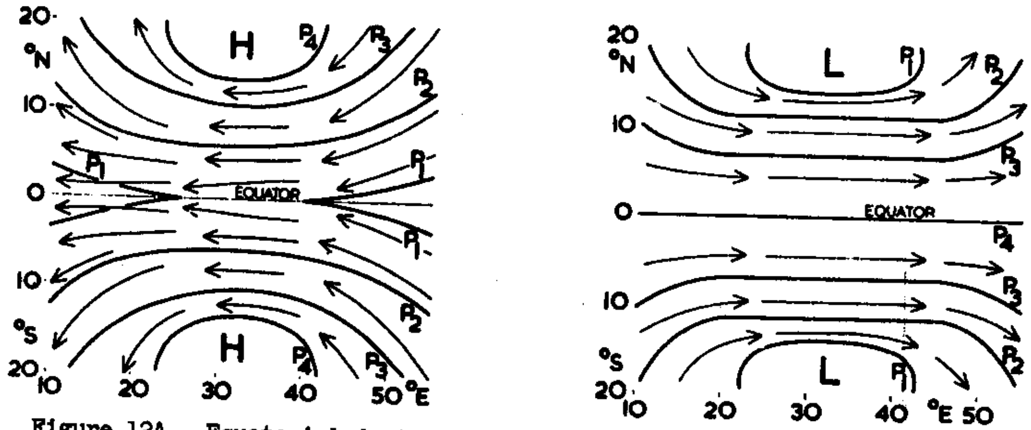


Figure 12A - Equatorial duct

Figure 12B - Equatorial bridge

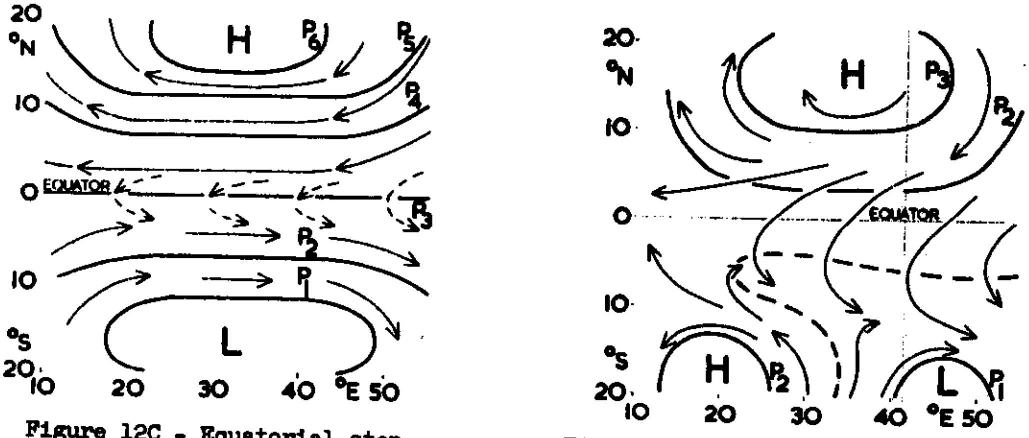


Figure 12C - Equatorial step

Figure 12D - Cross-equatorial drift

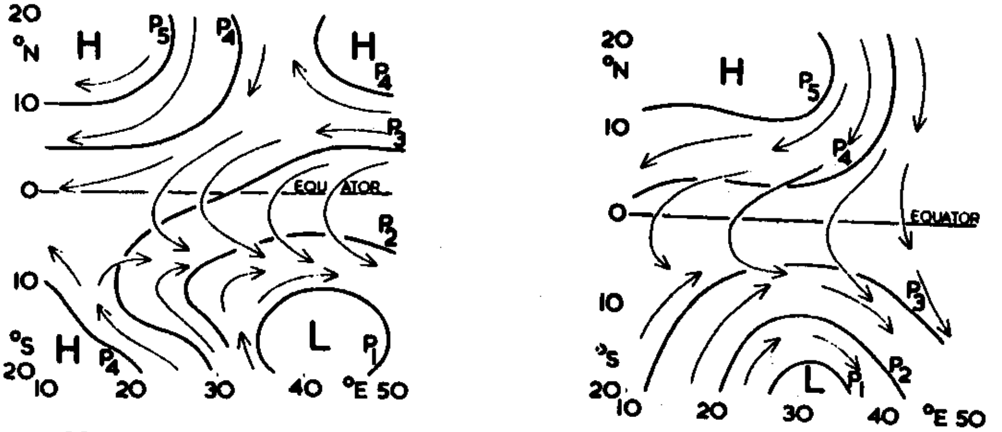


Figure 12E - Cross-equatorial drift

Figure 12F - Cross-equatorial drift

Figure 12 - East African synoptic models formulated by Johnson and Mörth [21]

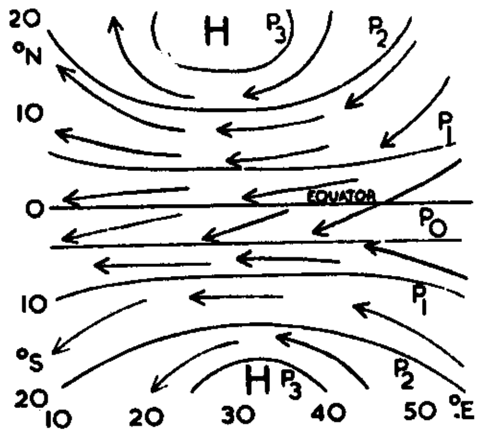


Figure 12G - Displaced duct

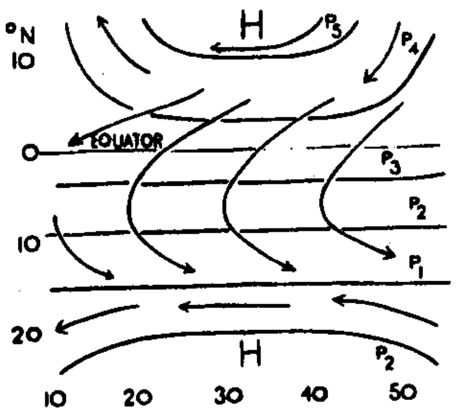


Figure 12H - Shear line

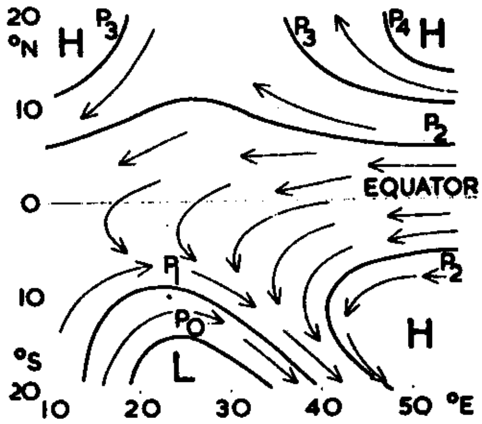


Figure 12I - Duct exit

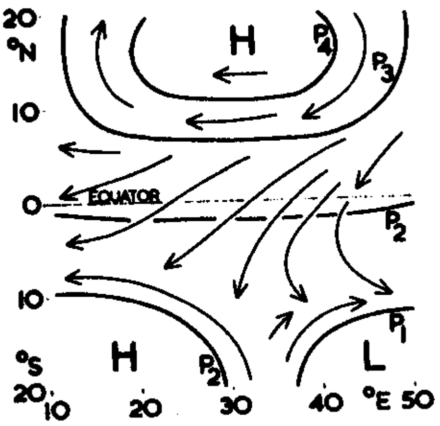


Figure 12J - Ageostrophic neutral point

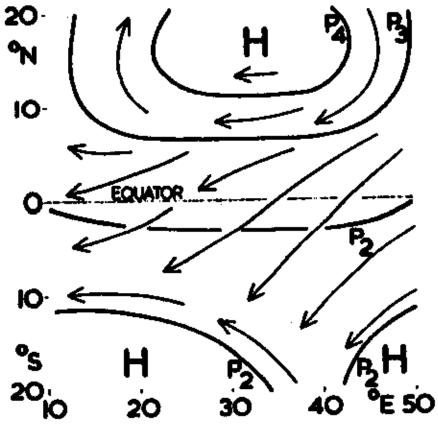


Figure 12K - Weak displaced duct

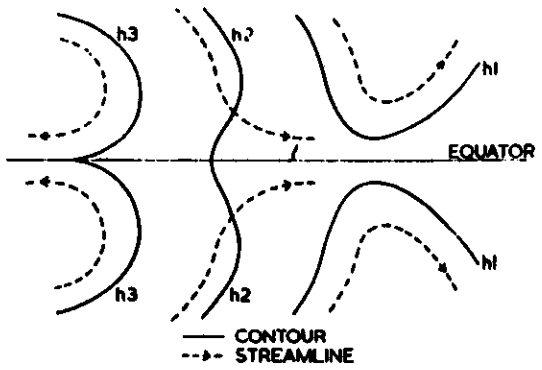


Figure 12L - Duct and bridge

Figure 12 - East African synoptic models formulated by Johnson and Mörth [21].

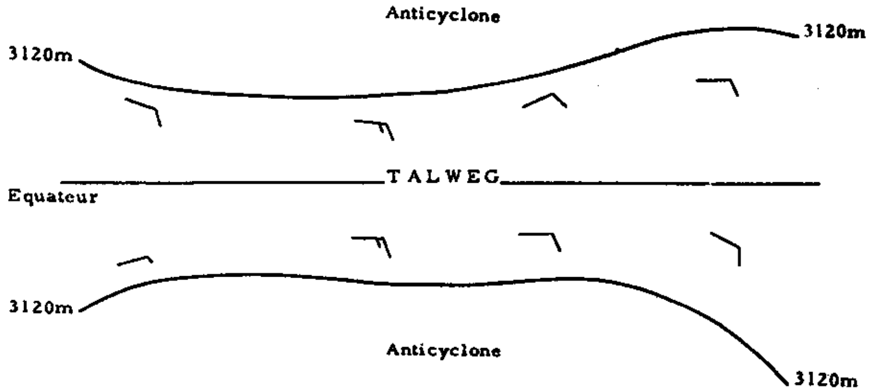


Figure 13 - Tschirhart's example of equatorial flow with winds blowing along the contours. After Tschirhart [27].

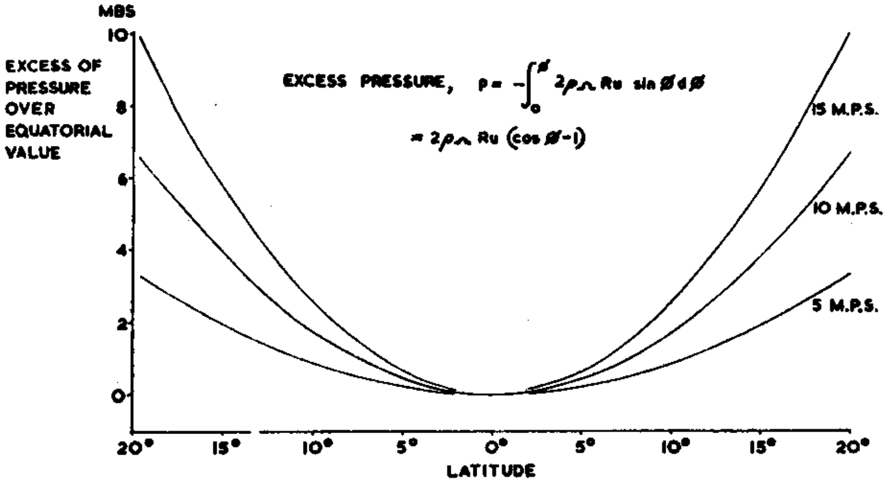


Figure 14 - Variation of pressure with latitude in a model duct. After Johnson and Mörth [19].

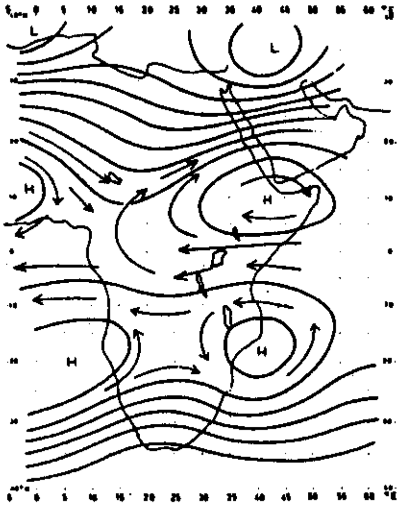


Figure 15 - Day 1.

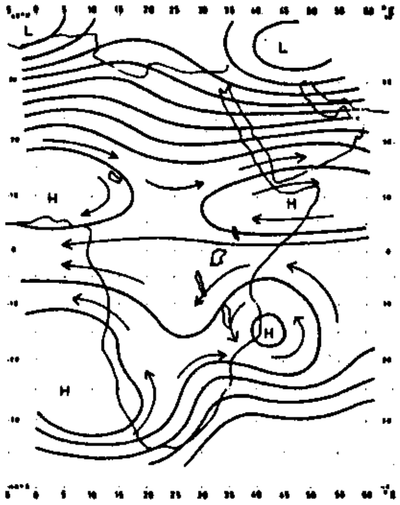


Figure 16 - Day 2.

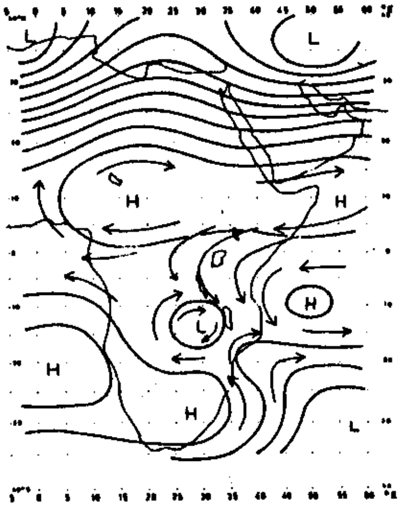


Figure 17 - Day 3.

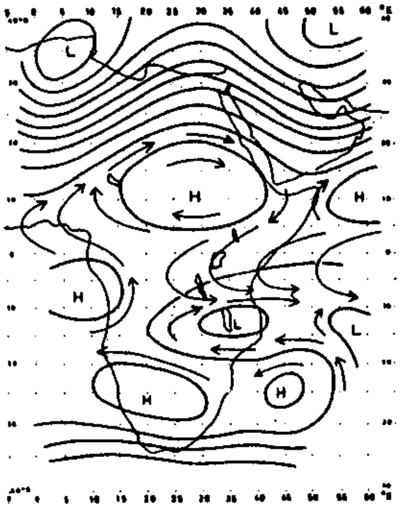


Figure 18 - Day 4.

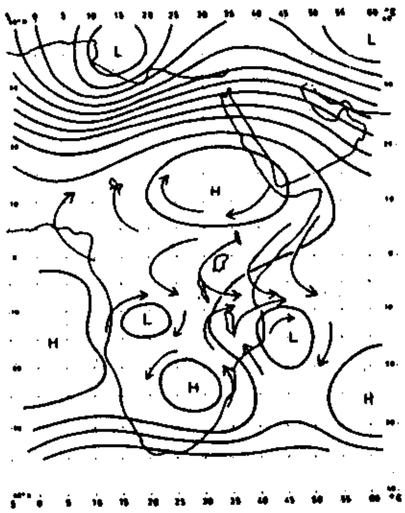


Figure 19 - Day 5.

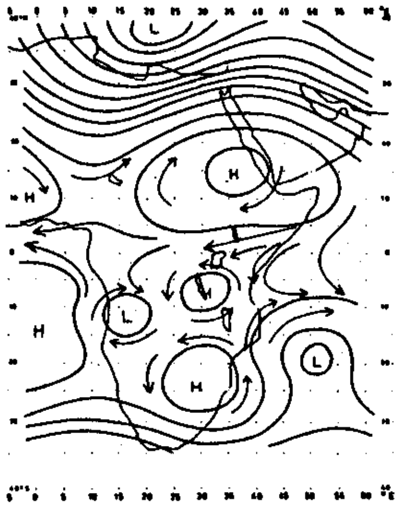


Figure 20 - Day 6.

Figures 15 to 20 - A six-day evolution of contour and flow patterns. Full lines are contours. Arrows represent segments of streamlines.

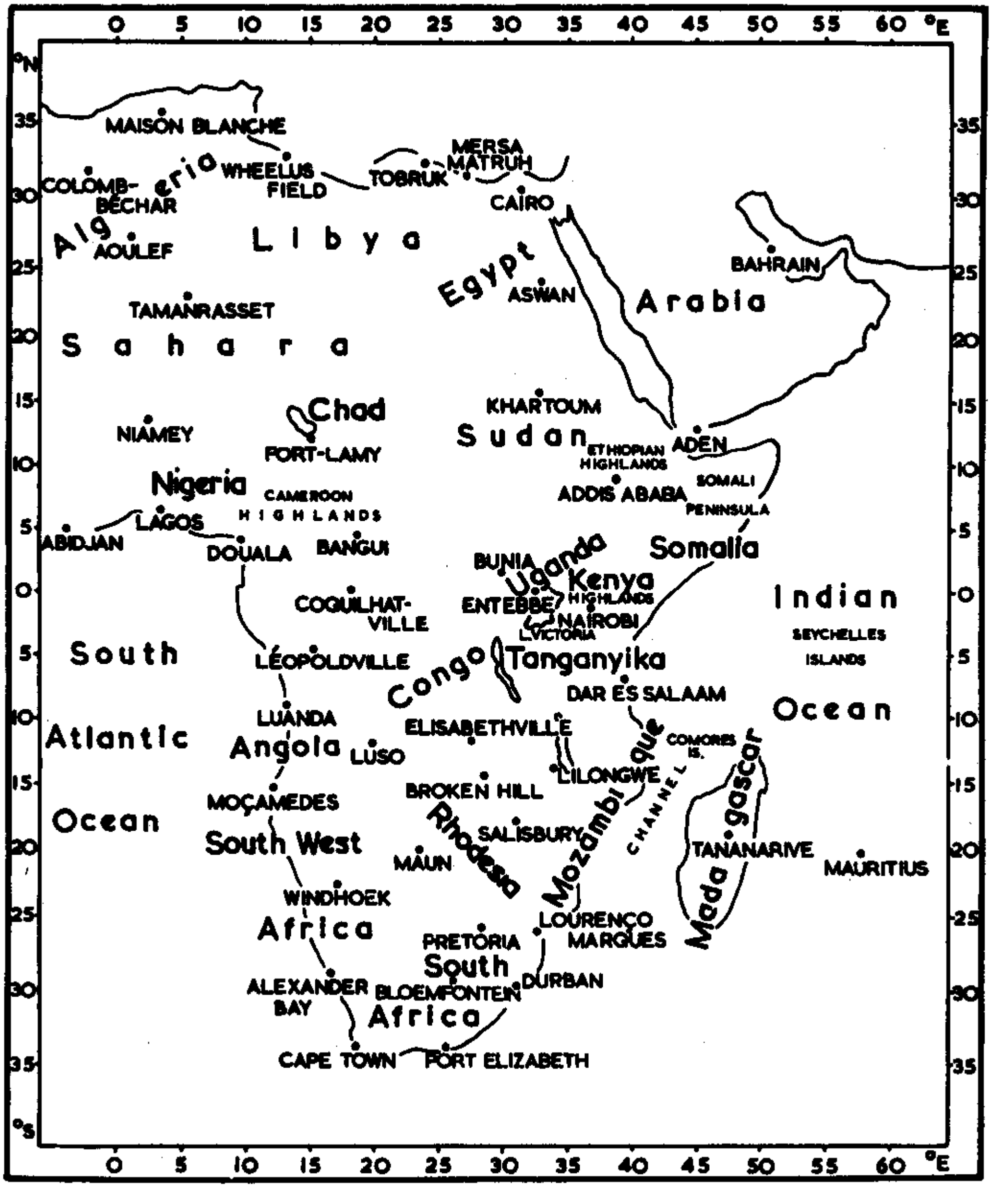


Figure 21 - African key map.

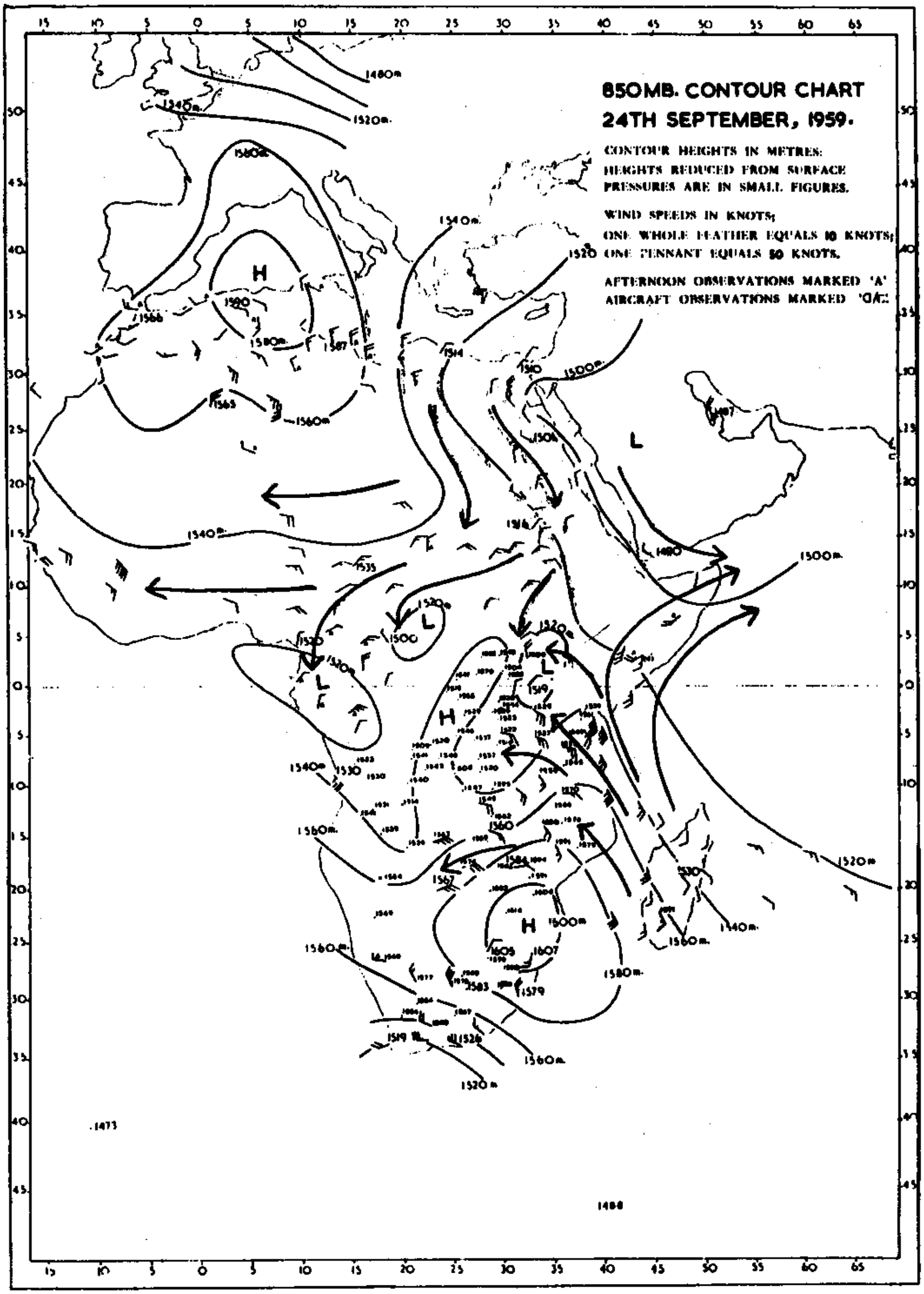


Figure 22 - 850 mb contour chart, 24 September 1959.

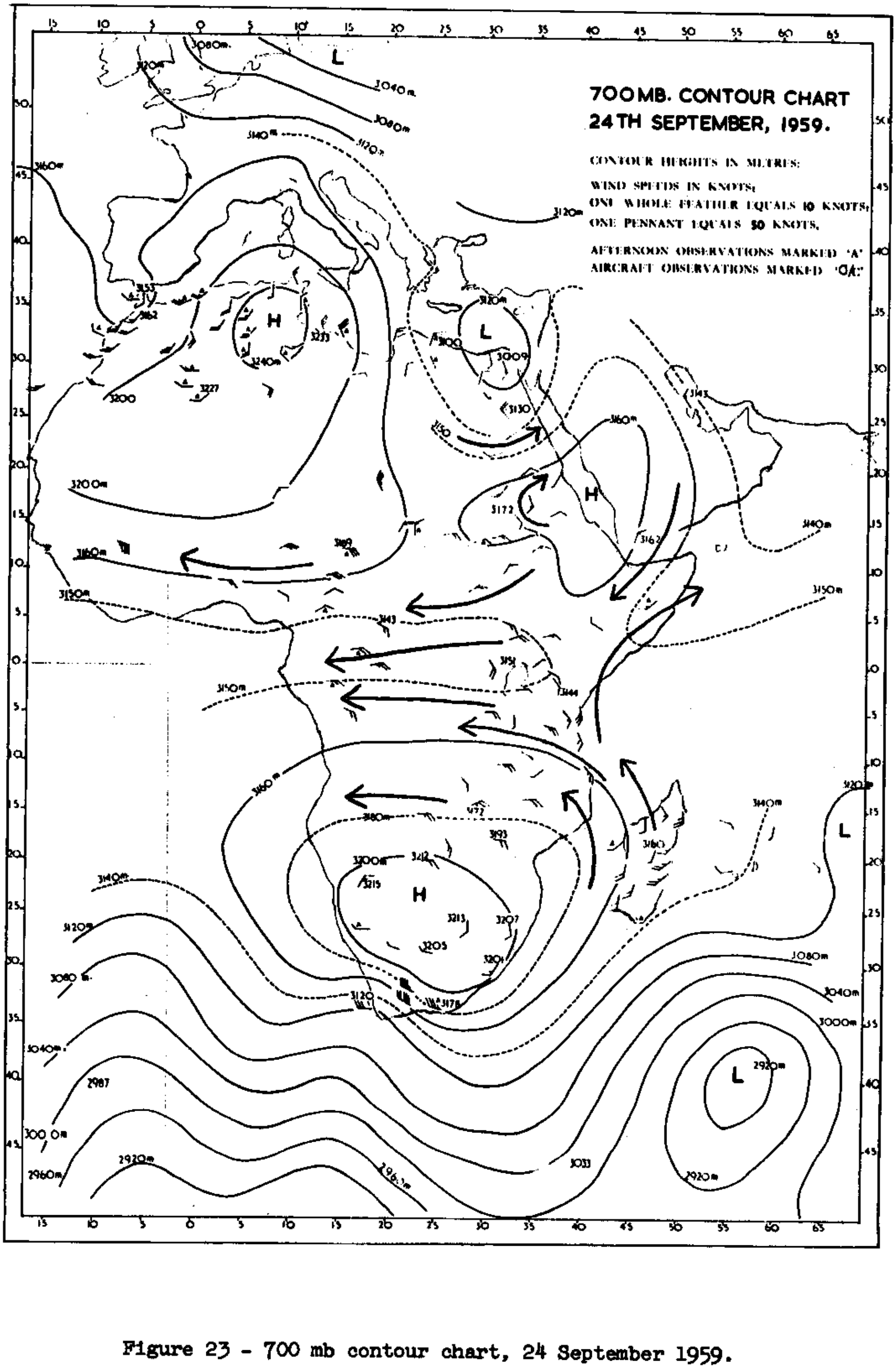


Figure 23 - 700 mb contour chart, 24 September 1959.

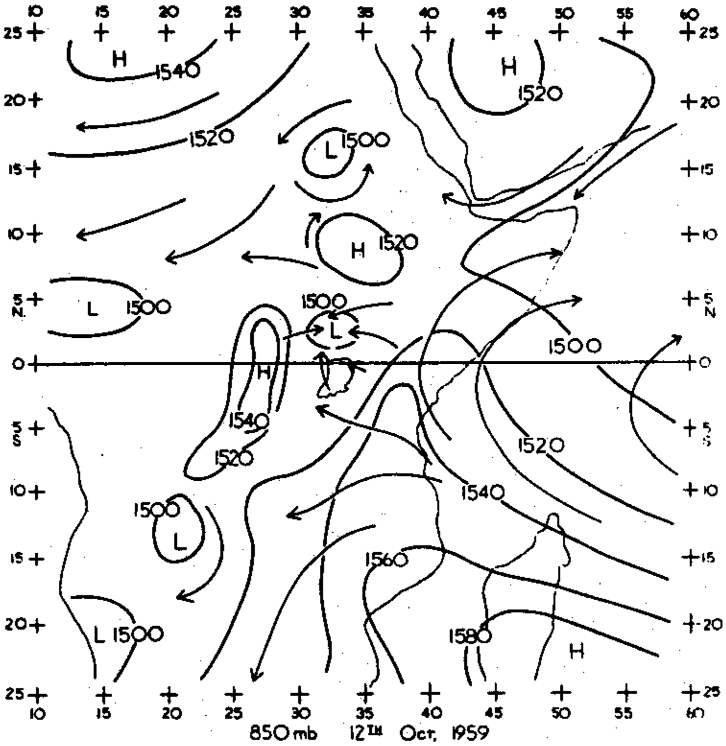


Figure 24 - 850 mb contour chart, 12 October 1959. Arrows represent segments of streamlines.

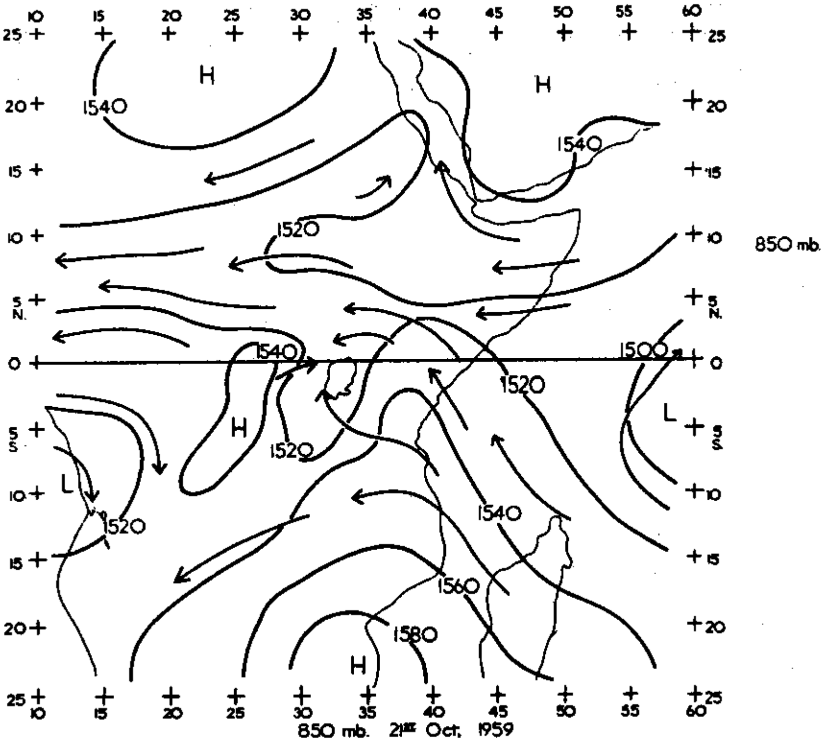


Figure 25 - 850 mb contour chart, 21 October 1959. Arrows represent segments of streamlines.

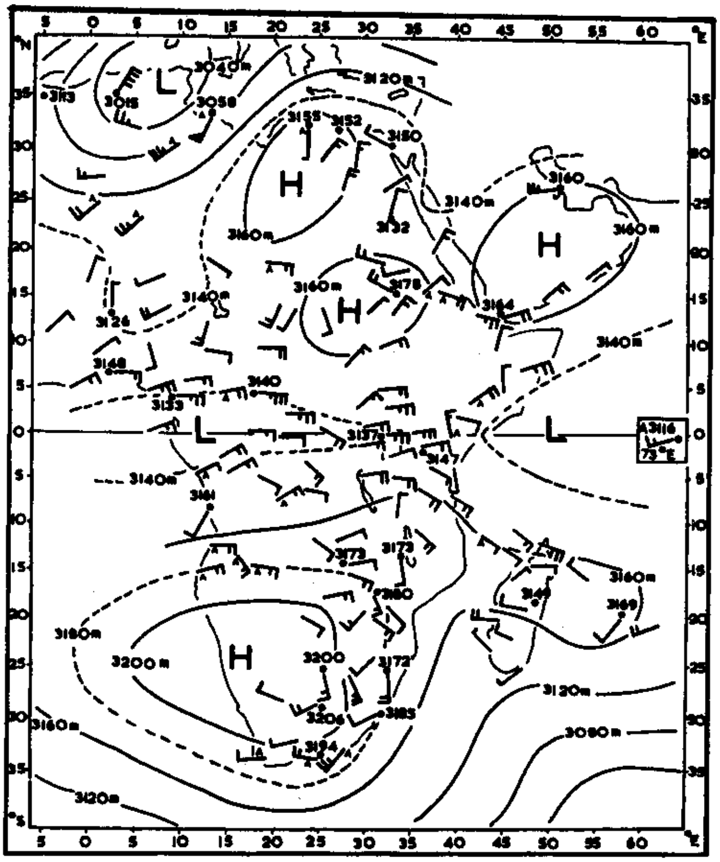


Figure 26 - 700 mb contour chart, 23 November 1959.

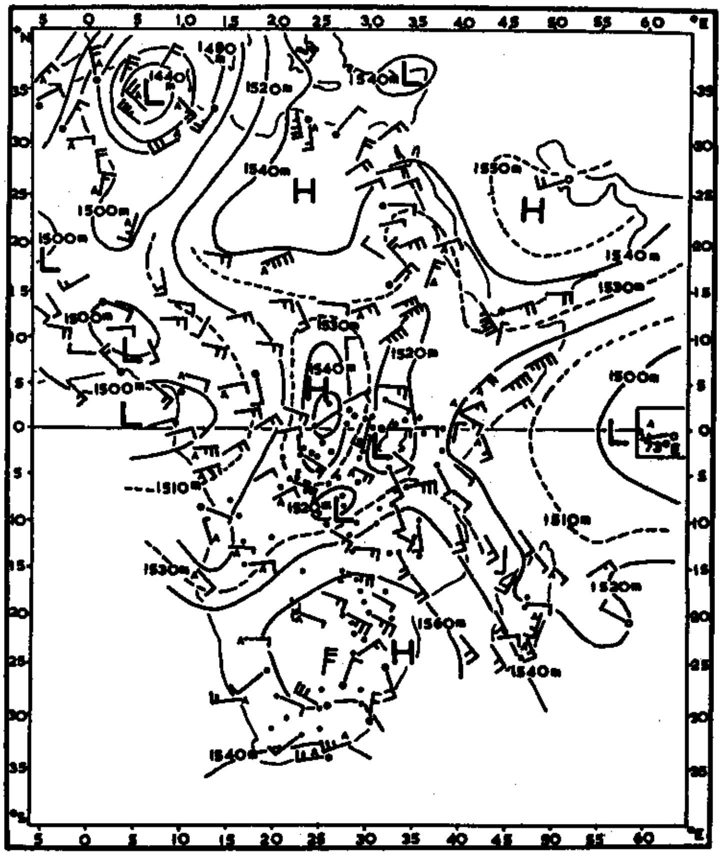


Figure 27 - 850 mb contour chart, 23 November 1959.

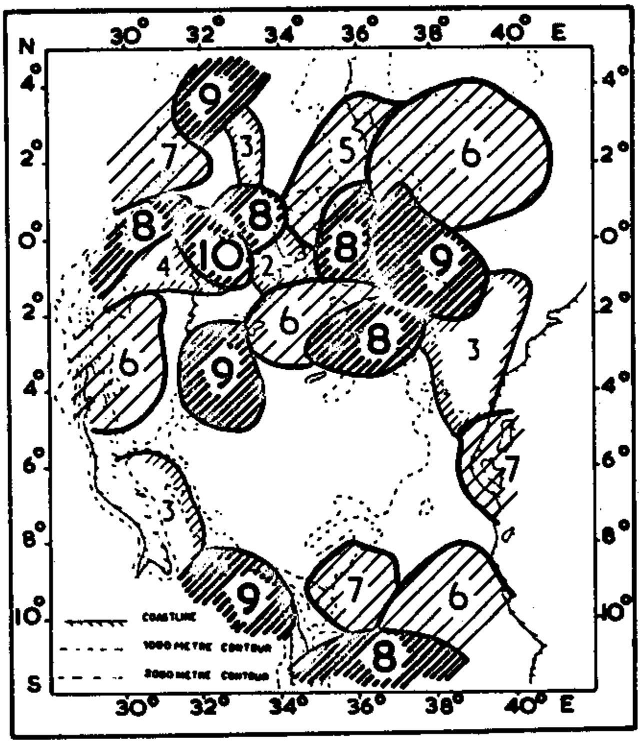


Figure 28 - East African rainfall, 23 November 1959. The figures give the percentage, in tens of per cent, of stations reporting rain for each marked area, according to the 24-hour rainfall totals.

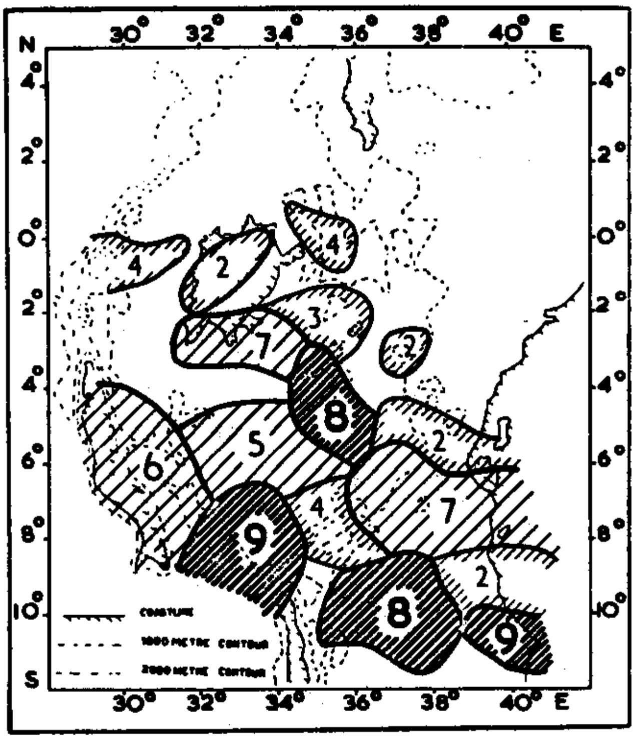


Figure 32 - East African rainfall, 15 January 1959. The figures give the percentage, in tens of per cent, of stations reporting rain for each marked area, according to the 24-hour rainfall totals.

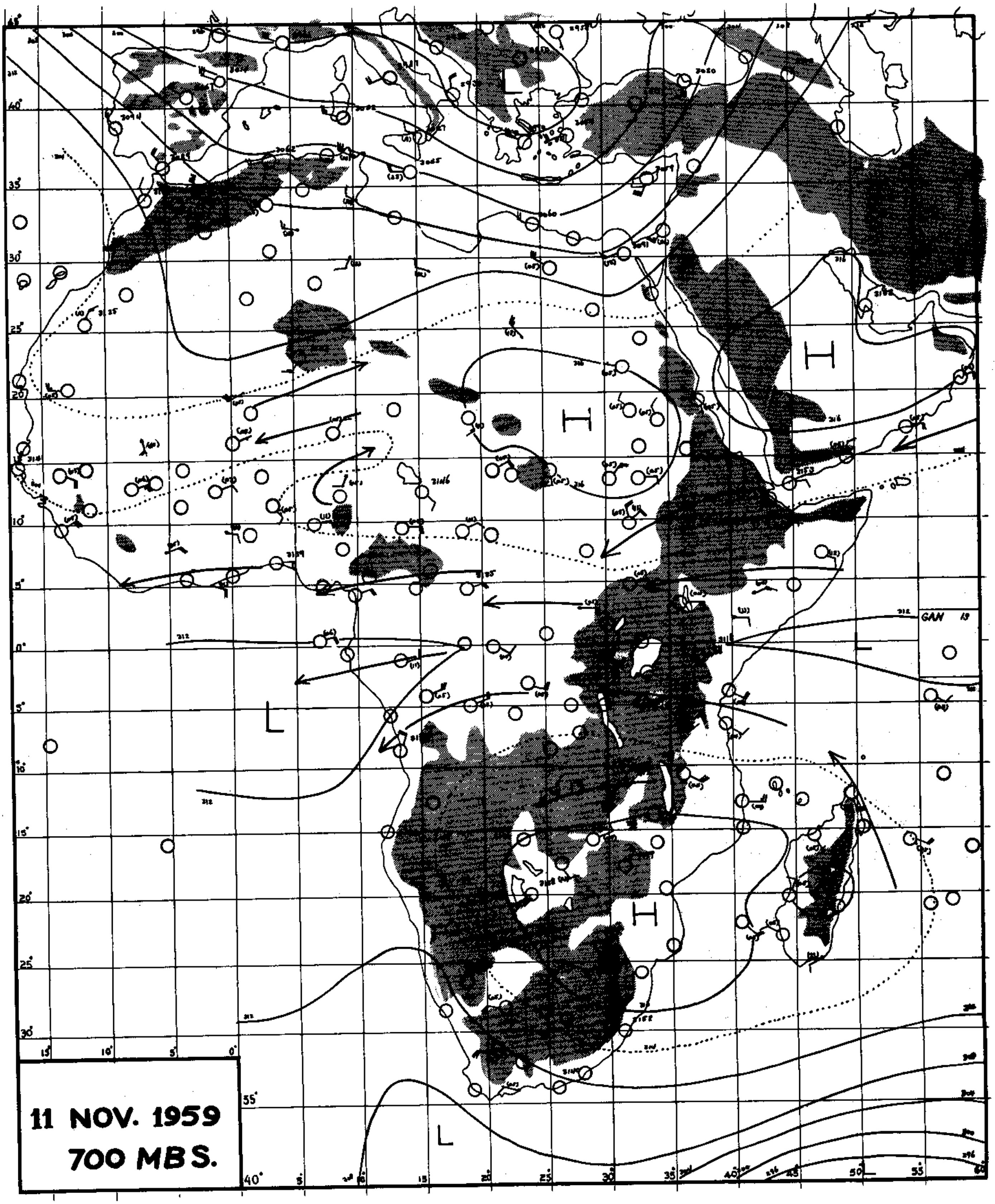


Figure 29 - 700 mb contour chart, 11 November 1959.
Arrows represent segments of streamlines.

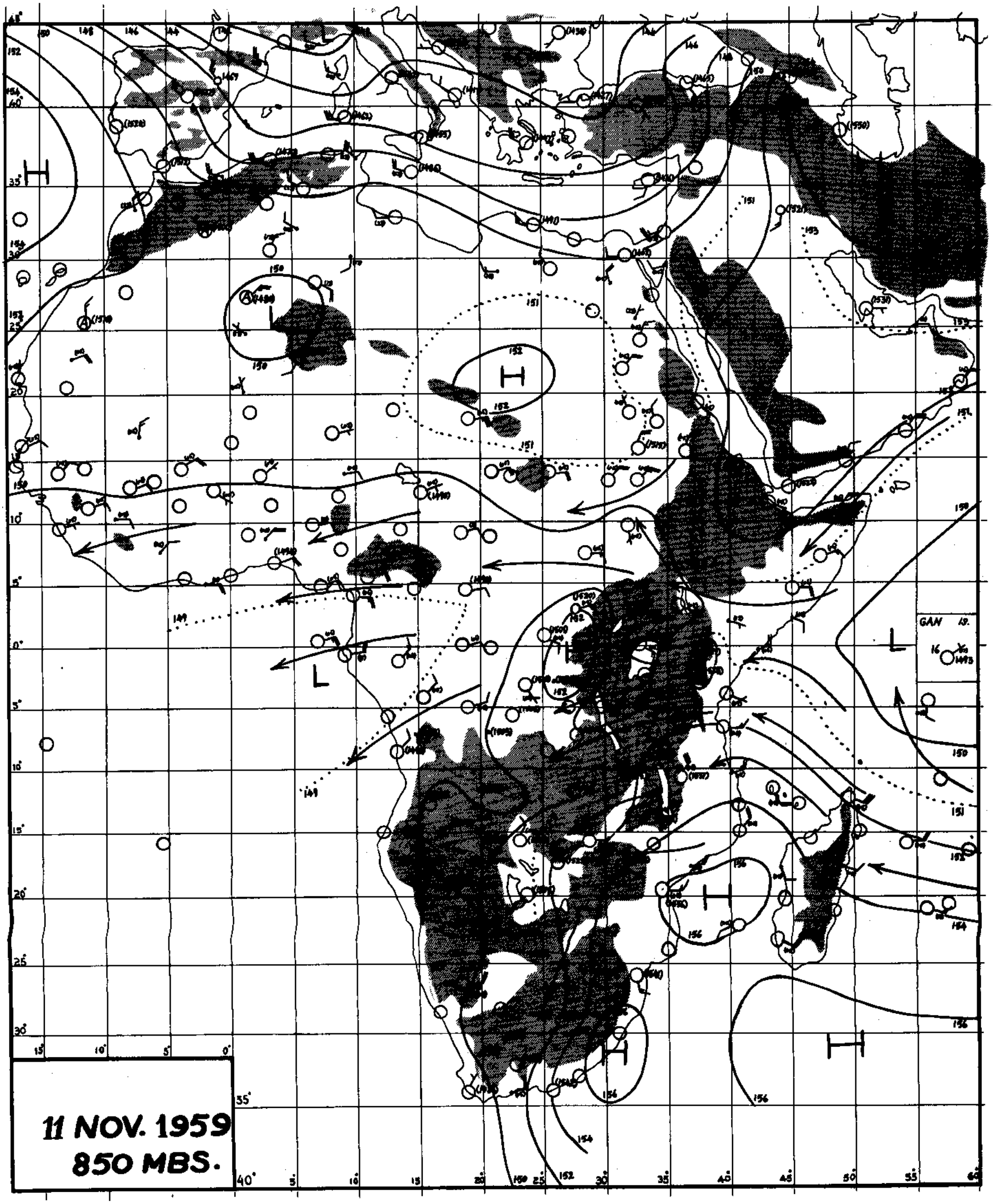


Figure 30 - 850 mb contour chart, 11 November 1959.
Arrows represent segments of streamlines.

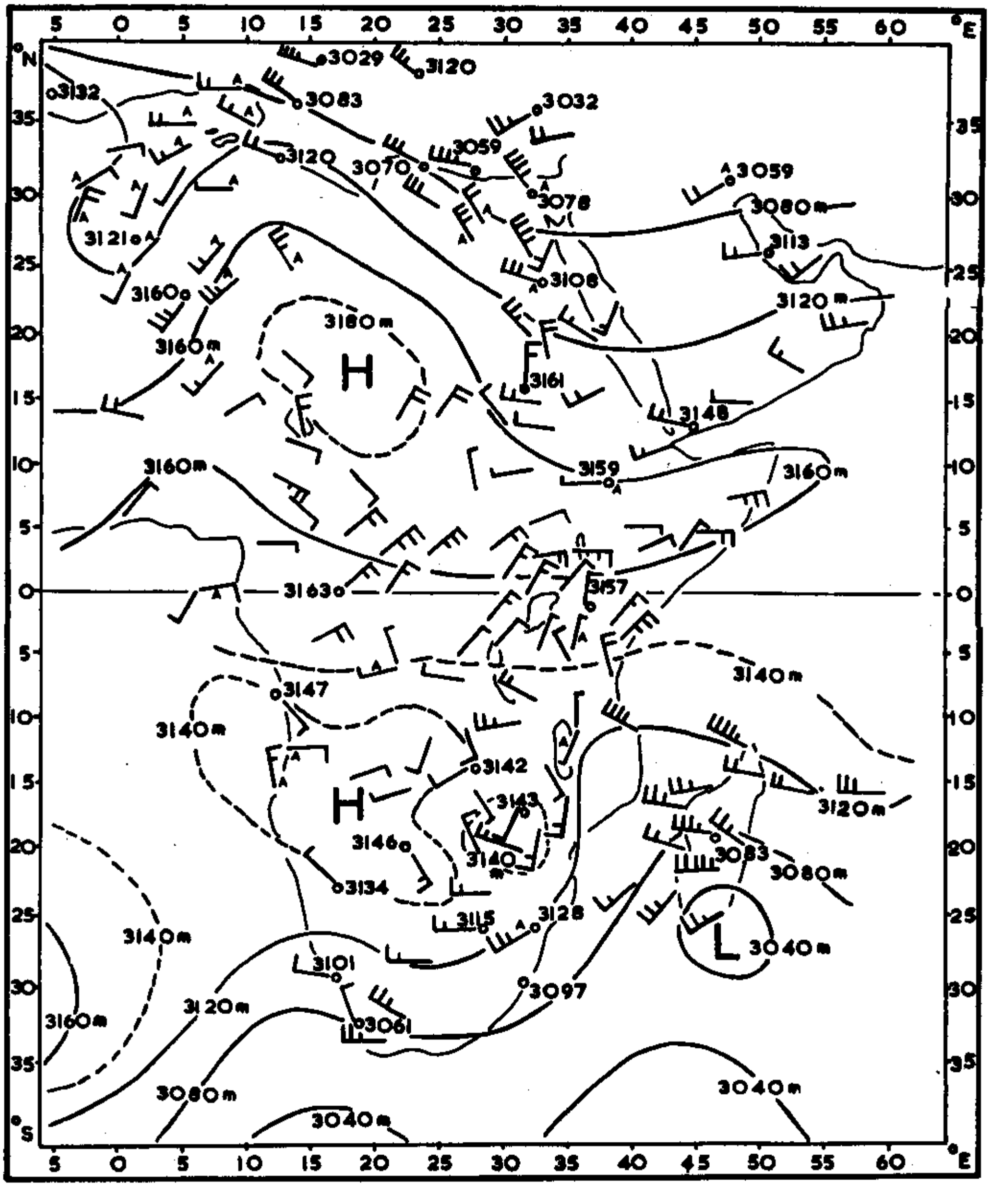


Figure 31 - 700 mb contour chart, 15 January 1959.

Figure 32 - See page 81.

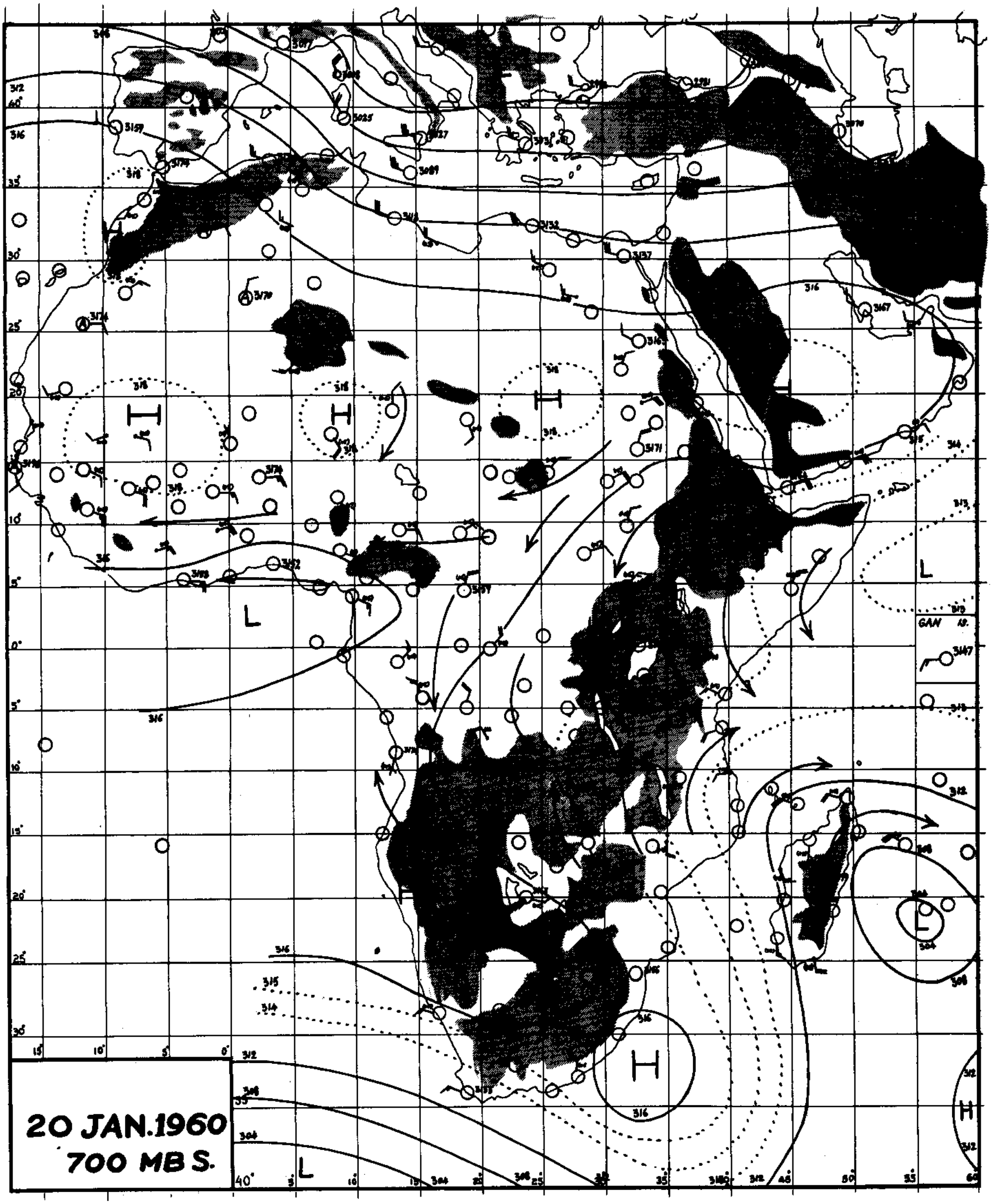


Figure 33 - 700 mb contour chart, 20 January 1960.

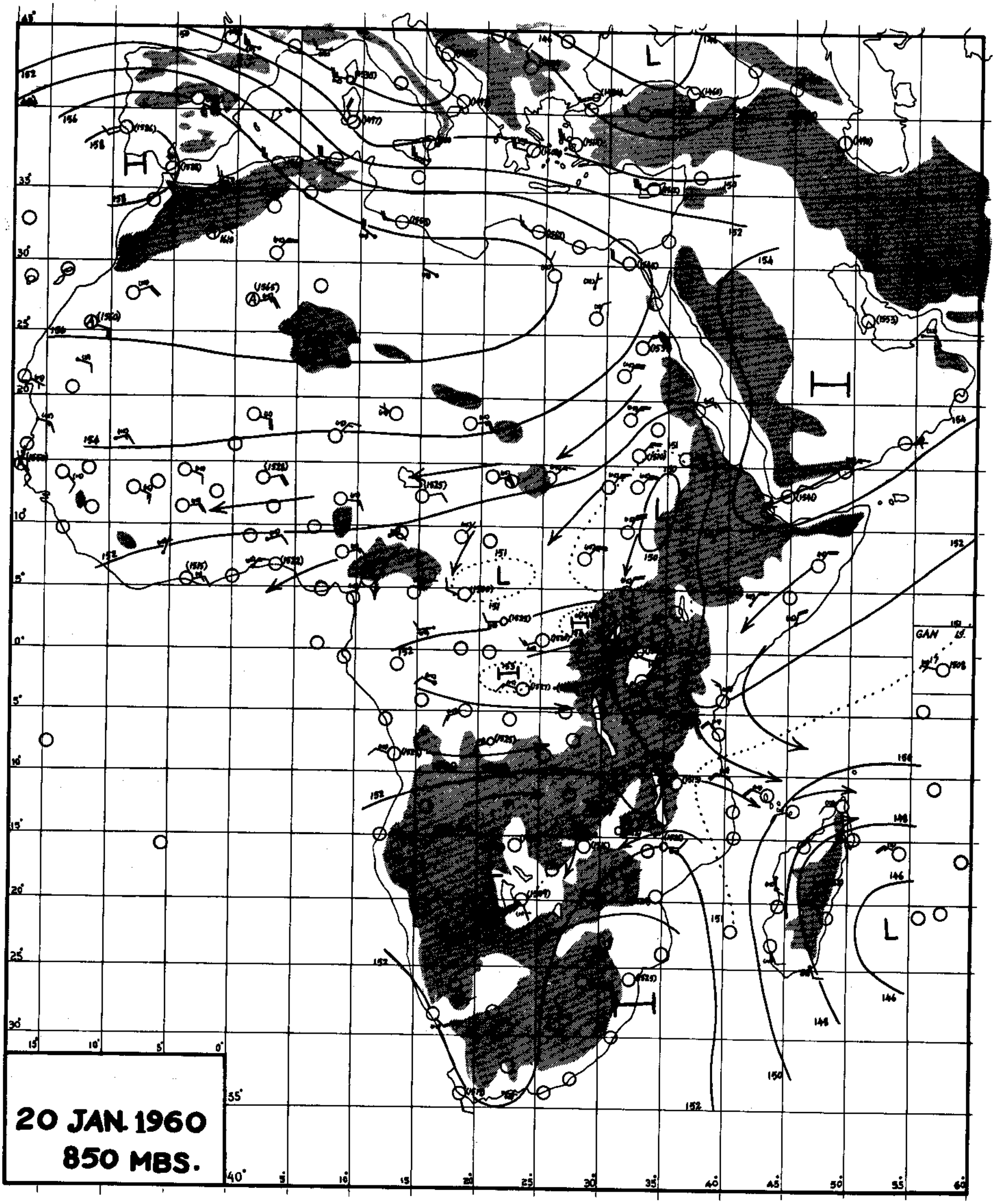


Figure 34 - 850 mb contour chart, 20 January 1960.

Figure 35 A-J - The distribution of the Desert Locust during 1953-1954. Crosses denote swarms and circles locate hoppers or eggfields.

MOVEMENTS OF THE DESERT LOCUST, 1953-1954

SWARMING LOCUSTS

- O Egglaying or eggfields
- • Hoppers
- X Adults - immature
- ✱ Adults - mature or partly mature
- + Adults - maturity not reported

LOCUSTS NOT IN SWARMS

- { } In groups
- ( ) Isolated
- [ ] Unspecified

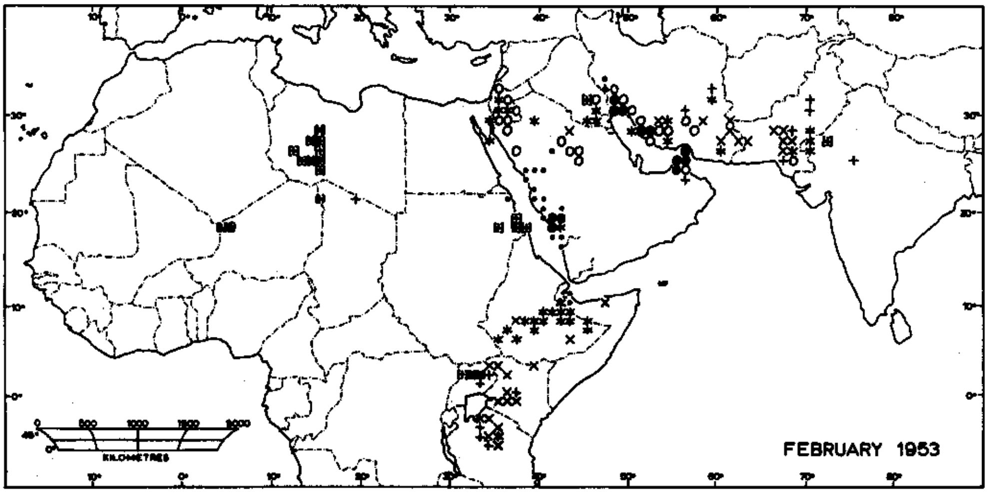


Figure 35A

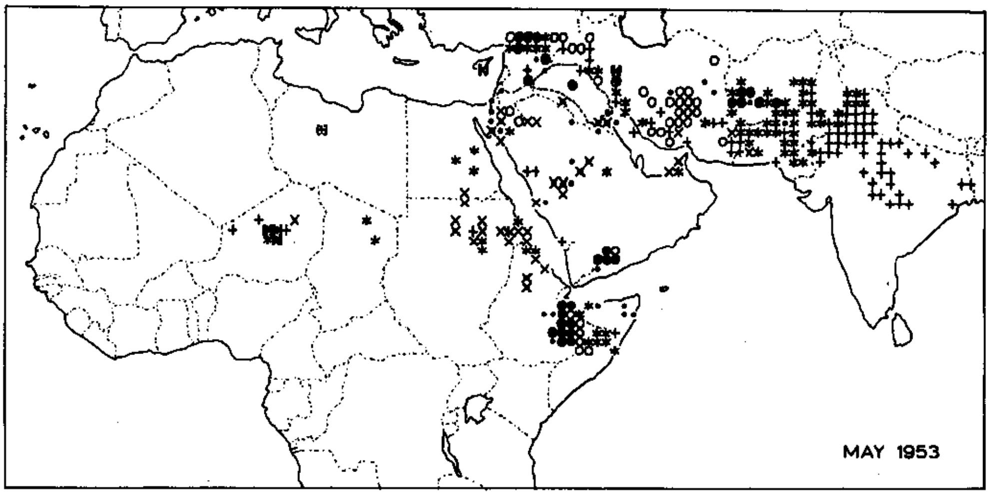


Figure 35B

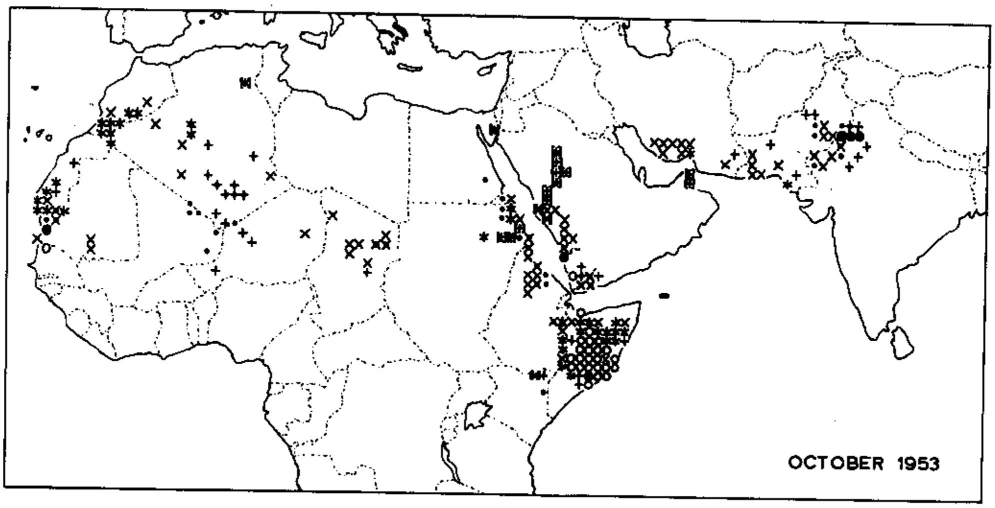


Figure 35C

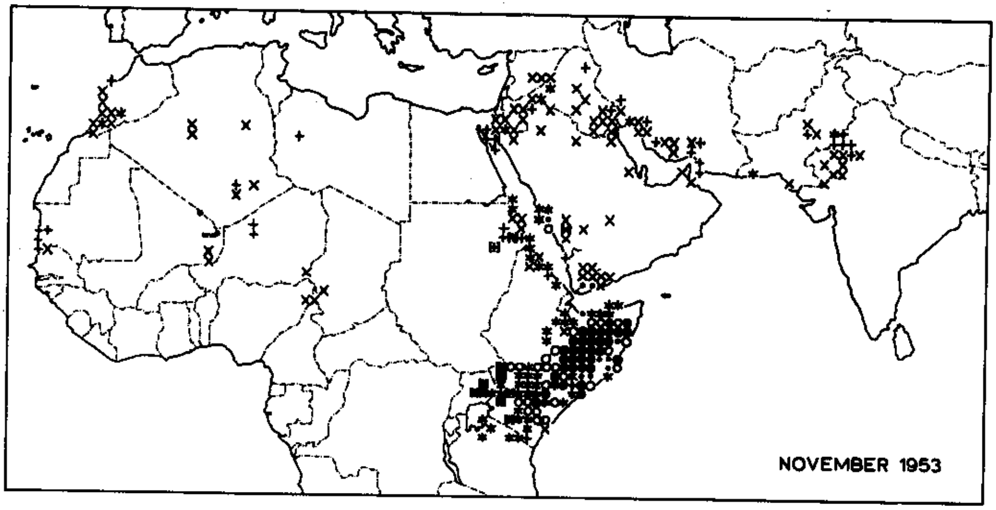


Figure 35D

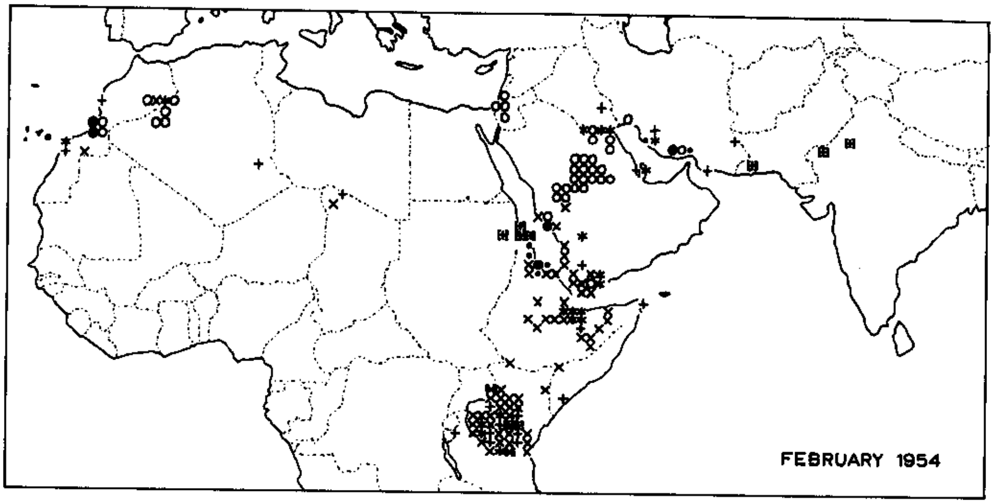


Figure 35E

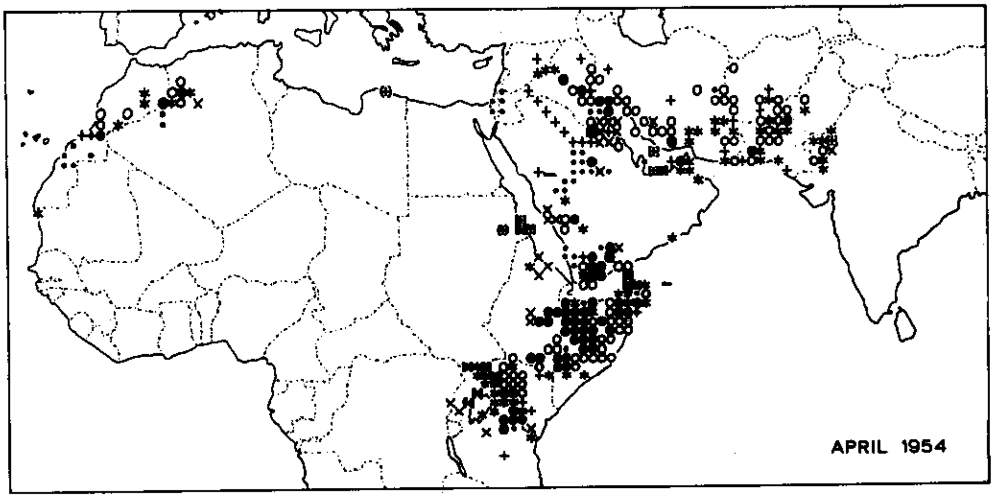


Figure 35F

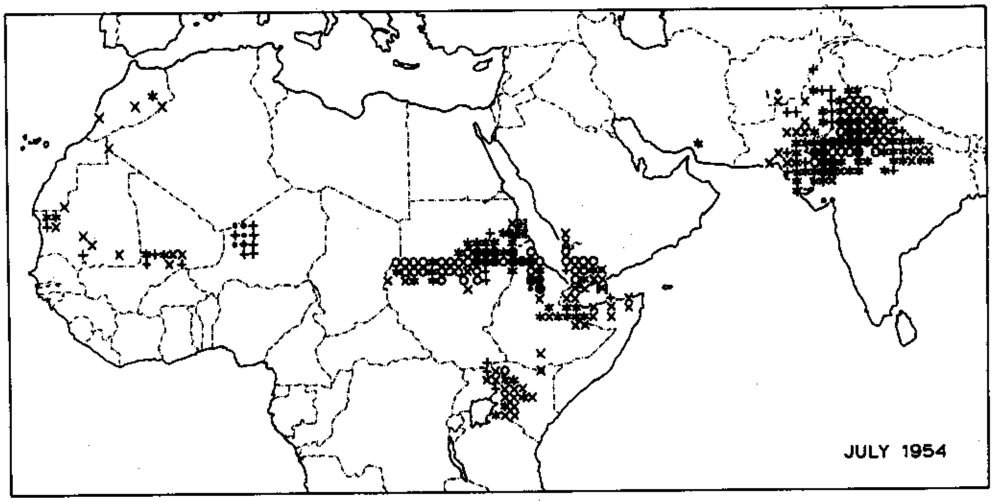


Figure 35G

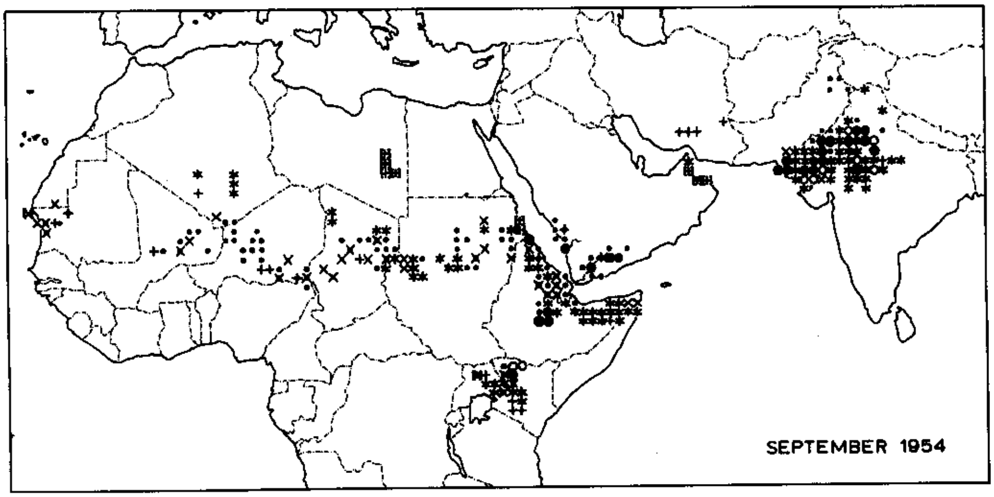


Figure 35H

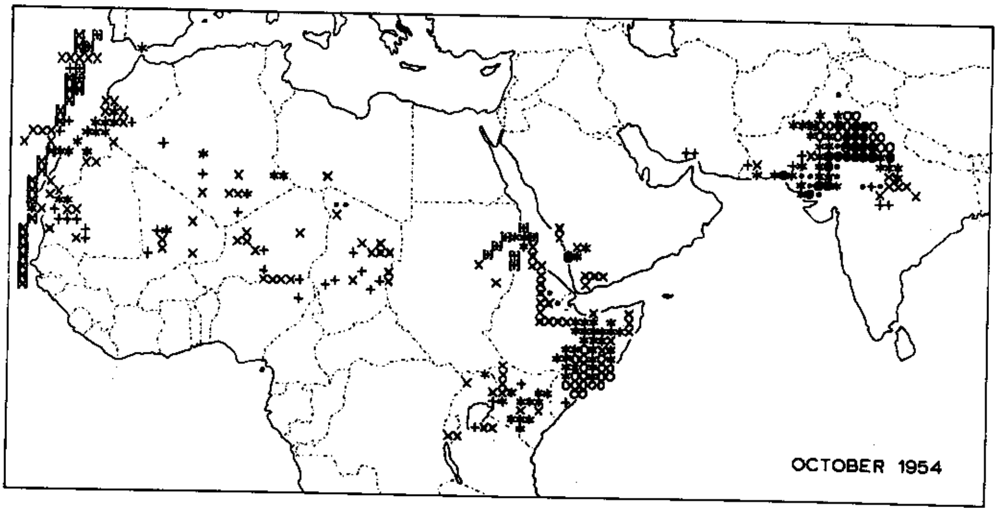


Figure 35I

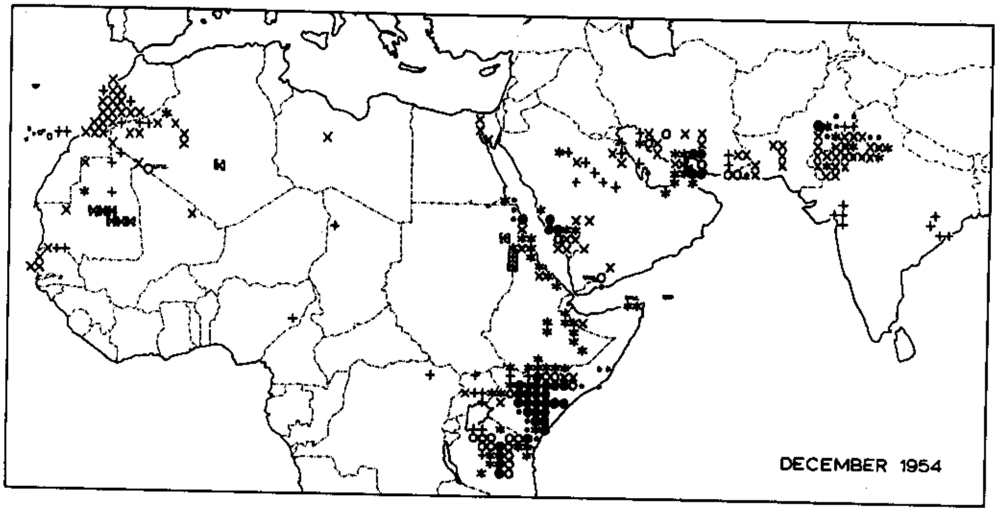


Figure 35J

THE STRUCTURE AND BEHAVIOUR OF THE INTER-TROPICAL CONVERGENCE ZONE (ITCZ)

by

H.W. Sansom

1. INTRODUCTION AND NOMENCLATURE

There are few topics more likely to cause controversy amongst meteorologists than the so-called Inter-Tropical Front (ITF) or Inter-Tropical Convergence Zone (ITCZ). At one time most tropical meteorologists were believers in the concept of an ITF or ITCZ, but now, in many parts of the world, there has been a strong reaction, and while only a few meteorologists will go so far as to deny its existence, the majority recognize that it is only of limited value in day-to-day forecasting.

The terms Inter-Tropical Front (ITF), Inter-Tropical Convergence Zone (ITCZ) and Equatorial Trough will appear frequently in this paper. At the onset, we will define these terms, following the definitions given in the "Glossary of meteorology" (Huschke /8/).

Inter-Tropical Front

A front presumed to exist within the Equatorial Trough separating the air of the northern and southern hemispheres.

It has been generally agreed that this front, if one exists, cannot be explained in the same terms as the front of higher latitudes. However, the extent to which frontal theory is to be modified and the nature of the modifications are as yet very controversial questions.

Inter-Tropical Convergence Zone

The axis, or a portion thereof, of the broad trade-wind current of the tropics. This axis is the dividing line between the south-east trades and the north-east trades (of the southern and northern hemispheres, respectively).

At one time it was held that this was a convergence line along its entire extent. It is now recognized that actual convergence occurs only along portions of this line.

Equatorial Trough

The quasi-continuous belt of low pressure lying between the subtropical high pressure belts of the northern and southern hemispheres. This entire region is one of very homogeneous air, probably the most ideally barotropic region of the atmosphere. Yet, humidity is so high that slight variations in stability cause major variations in weather.

The position of the Equatorial Trough is fairly constant in the eastern portions of the Atlantic and Pacific, but it varies greatly with season in the western portion of those oceans and in southern Asia and the Indian Ocean. It moves into or towards the summer hemisphere.

> It has been suggested that this name be adopted as the one general term for this region of the atmosphere. Thus, the Equatorial Trough would be said to contain regions of doldrums, portions of it could be described as inter-tropical convergence zones; and within it there might be detected inter-tropical fronts. However, one weakness of this nomenclature is that it alludes specifically and only to the existence of a trough of low pressure. Perhaps an even more general term might be preferable, for example, "atmospheric equator".

These definitions will be adhered to as far as possible within this paper; thus "Equatorial Trough" will be used as a general term, and when the pressure trough is the main distinguishing feature; "Inter-Tropical Convergence Zone" (ITCZ) will be used only when there is evidence of low-level convergence between the easterly trades of the two hemispheres; and "Inter-Tropical Front" (ITF) will be used only when there is an obvious air-mass discontinuity. The shortcomings of these definitions will become apparent later on, and some proposed new terminology is given in the Appendix.

2. HISTORICAL SURVEY

Thompson [23] describes the concept of the ITF as being "the child of the enormous enthusiasm which followed the successful application of the frontal theory in extra-tropical latitudes soon after the First World War". In a detailed review of the development of tropical meteorology, Palmer [12] shows that the idea of a front in the tropics was first propounded by Brooks and Braby [3] who described a zone of convergence between the two trade winds in the western south Pacific, and suggested, in a footnote, the name "equatorial front" by analogy with the polar front which had very recently been described by Bjerknes.

At this stage synoptic meteorology in the tropics was in its infancy, and climatological data (as opposed to synoptic data) was used to develop the concept. It is certainly true that on climatological charts for the Sudan and West Africa there is excellent evidence for the existence of an air-mass discontinuity along the axis of the surface Equatorial Trough. To the north of this front there are warm, dry north-easterly winds, whereas to the south of it there are cool, moist south-westerlies. The typical climatological charts for different months (see Figures 1, 2), after Sawyer [19] clearly suggested that there was an annual migration of this front following the movement of the sun, and there seemed to be some correlation between the position of the front and the seasonal occurrence of rain. Soliman [21] has pointed out some of the errors in the picture, particularly for the southern summer. Thompson [23] emphasizes the point that the whole concept of the ITF was based on "a sketchy climatological interpretation of unstudied pressure systems and surface winds" together with "little knowledge of upper-level airflows or of the nature and detail of tropical rain and allied synoptic processes". The generalized conclusion that the ITF encircled the globe and was the explanation of the seasonal rainfall pattern of the tropics, was accepted, more or less without question, until the Second World War, which brought many meteorologists into the tropics for the first time.

During the war it soon became apparent in Africa and elsewhere that the simple theory of the ITF left much to be desired. In the northern summer it was usually quite easy to detect the ITF as an air-mass discontinuity on synoptic charts, but it was usually not associated with any rainfall. At other seasons it was seldom easy and often impossible to detect the ITF at all, except in West Africa where the air-mass discontinuity still existed. The result was that different forecasters used different techniques for locating the front, and there seemed to be little or no continuity in its movement or in its relation to the weather. In many areas a double front seemed to exist, in others none at all. Palmer (loc. cit.) quotes some of the many conflicting statements about the ITF which were published during the 1940's, but although confidence in the usefulness of the ITF as a forecasting tool rapidly waned, the concept was not abandoned entirely. It was realized that there was not always any significant temperature discontinuity across the front, and Garbell [7] states: "The discontinuity between the two tropical air masses coming from the two hemispheres usually consists not so much in a difference in surface temperatures as in a difference mainly in the vertical distributions of temperature, moisture, stability and wind velocity between the two easterly air streams." At this point it is worth recalling that in their classic paper some twenty years ago Brooks and Braby [3] had remarked on the evident absence of any temperature contrast across the equatorial front in the Pacific. Attention now turned more to the wind flow, and it was assumed that horizontal convergence of the trade winds was the main factor occurring at the ITF. This led to the gradual adoption of the term Inter-Tropical Convergence Zone as an alternative to Inter-Tropical Front. The name might equally well have been suggested by Brooks and Braby whose original paper had been entitled "The clash of the trades in the Pacific". It must be noted, however, that, by definition, the term ITCZ is restricted to the trade-wind régime, whereas there are quite often westerlies on the equatorward side of the Equatorial Trough.

The growing emphasis on wind flow and the need to locate zones of convergence led to streamline analysis being widely adopted in tropical meteorology, and at the same time the realization that there must be a three-dimensional study of the tropical atmosphere led to attention being focused less and less on the surface position of the ITF, which need not necessarily be a line of convergence. Streamline analysis also showed that although the mean asymptote of confluence found on maps of average winds coincides closely with the Equatorial Trough, this is by no means always true on day-to-day synoptic charts. La Seur [11], for example, states that "On synoptic charts an asymptote of confluence may or may not exist in the region of the Equatorial Trough".

The wartime period enabled one or two meteorologists to make detailed analyses of the day-to-day structure of the Equatorial Trough in parts of the world where there was a reasonably dense upper-air observational network (e.g. Sawyer [18]); see Section 4.2 below. The growing volume of climatological data available also enabled meteorologists such as Flohn [5] to deduce some important facts regarding the mean structure of the Equatorial Trough. Section 4.1 describes this work.

The vastly improved network of radiosonde stations over Africa has now led to the adoption in East Africa and some other equatorial countries of contour analysis, as described by Johnson and Mörth [9 and 10], instead of streamline analysis, but there has been little new detailed study of the ITF as such. Except during the northern summer it may not even appear on the daily synoptic charts prepared in many meteorological offices, and little or no use is now made of the concept as an aid to short-period weather forecasting in the tropics. In fact, were it not for the important work of Rainey [15], who showed the marked association between the occurrence of locust swarms and the position of the ITF, the ITF might no longer be worthy of consideration. It is noteworthy that Riehl's textbook on Tropical Meteorology [16] lists only a single mention of the ITCZ or ITF in its subject index, and this only in a review of earlier theories. Palmer et al. [13] in their "Practical aspect of tropical meteorology" give it even more scanty mention. They do, however, admit that the Equatorial Trough is shown up on mean streamline patterns as "a line of convergence in the streamlines in the vicinity of the equator".

3. RELATION OF EQUATORIAL TROUGH TO LOCUST SWARMS

Rainey [15] was the first to discover the marked association between the occurrence of locust swarms and the ITCZ. He postulated that locusts, whose still-air flying speed is only 7 to 11 mph, and which are therefore essentially wind-borne insects, should be blown from areas of divergence towards areas of convergence. The hypothesis was tested by a comparison of swarm records with the corresponding synoptic charts, and a remarkable association between reports of locust swarms and the surface position of the ITF was found (see

Figure 3). Although Rainey used the term ITCZ, this is not in accordance with the current definition, since in the example illustrated the convergence is not between the NE and SE trades.

This hypothesis led indirectly to the establishment of the WMO Technical Assistance Mission for Desert Locust Control, whose findings have strongly confirmed the original hypothesis; see Aspliden and Rainey [1]. Figure 4, taken from Aspliden and Rainey's paper, demonstrates clearly the importance of the ITCZ/Locust relationship. It is perhaps noteworthy that both Figures 3 and 4 relate to July, when the Equatorial Trough is in its northernmost position, and when it is most clearly defined on the synoptic charts for Africa both as an air-mass discontinuity (ITF) and also as a zone of low-level windflow convergence.

It is thus evident that meteorologists should study carefully the movements of the Equatorial Trough in order to provide assistance to the Locust Control teams in the area, even if the information derived from the study will not be of great value in the preparation of routine weather forecasts.

4. THE STRUCTURE OF THE EQUATORIAL TROUGH

4.1 Climatological studies

The pioneer work in the climatological field has been done by Flohn [4, 5], who drew attention to the association between precipitation and cloudiness at the Equatorial Trough and winds with either a westerly or poleward component. Johnson and Mörth [9] have also commented on the tendency for upward transport of moisture to develop in westerly flow, whereas downward motion tends to result from easterly flow. This relationship can be seen from the equations of motion for vertical acceleration,

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{dp}{dz} - 9 + 2\Omega\cos\phi.u$$

where the symbols have their usual meaning. In this equation, the term $2\Omega\cos\phi$ has its maximum at the equator ($\phi = 0$), and although the term $2\Omega\cos\phi.u$ is small in magnitude in comparison to the other terms, it may nevertheless be of real significance when compared to the small difference between the pressure gradient and gravity terms which almost cancel one another out. A positive u, i.e. wind blowing *towards* the east, thus tends to produce a vertical upward acceleration, whereas a negative u, i.e. wind blowing towards the west, tends to produce a downward acceleration.

Flohn has also investigated the mean patterns of vertical motion and divergence in the regions of the trade winds and the Equatorial Trough and has shown that, to the north of the Equatorial Trough, the convergence observed at the surface changes everywhere into divergence at a height of 1.3 to 1.8 km whereas south of the trough the convergence is not only stronger, but also extends upwards to a greater height (3-5 km). Figure 5 represents his results. It can be seen that the vertical wind component is at its maximum some 500-600 km south of the Equatorial Trough.

Flohn [4] has also drawn attention to a difference between the ideal surface wind patterns to be expected at the Equatorial Trough over oceans and over continents (see Figure 6); but the simple oceanic pattern is, however, only borne out when the trough is within 5° latitude of the equator. The normal flow over the Indian Ocean, where the Equatorial Trough moves a considerable distance on either side of the equator, resembles that depicted by Sawyer [19] in Figure 7.

Soliman [21] suggested that the term ITF should be used over land areas, where there may be a genuine air-mass difference, while the term ITCZ should be reserved for the oceanic areas where there is little or no air-mass difference, but where there may be real convergence between the trades. Although it is probably quite true that over the open oceans the ITCZ seldom, if ever, has any frontal structure there is, however, certainly not always any significant air-mass difference over the continents.

Thompson /24/ by studying monthly mean charts for standard pressure levels over the whole of Africa was able to produce a rather more detailed vertical picture of the structure of the Equatorial Trough over the African continent. Figure 8 shows the mean surface chart for July and Figure 9 shows a cross-section along the Greenwich meridian between the equator and 30°N during July. It is seen that the axis of the Equatorial Trough, which,as the windfield reveals, is here also a definite convergence zone, is situated on the surface at approximately 22°N, whereas at 850 mb it is 15°N, and at 700 mb at approximately 5°N. This represents a mean slope of about one in 500. To the north of the trough winds at all levels are easterly, whereas to the south of it the low-level winds are south-westerly or westerly. The mean rainfall for July is negligible at the latitude of the surface trough but increases southwards from 18°N to a maximum at about 10°N. The corresponding charts for January are shown in Figures 10 and 11. The cross-section in this case is along the 25°E meridian and differs from the July chart in that surface pressure data cannot be given, since the African plateau is at a level close to the 850 mb pressure surface. The mean January surface pressure chart (Figure 12) shows the ITF quite clearly defined in the Equatorial Trough near 5°N between the west coast of Africa and 30°E, and it reappears south of the Equator east of 35°E. On the vertical cross-section the Equatorial Trough at 850 mb is situated at about 15°S, and slopes northwards (at approximately one in 100) to approximately 10°S at 500 mb. The rainfall distribution in January shows its peak at about 12°S, but the rain area is much more spread out than in July. Since, even on the mean charts, it is difficult to locate the ITCZ on the surface over Africa south of the equator, it will be appreciated that on the daily synoptic charts it is often an impossible task. It is, in fact, of no meteorological importance in this area, being neither a significant air-mass boundary, nor even often an active convergence zone, and consequently no attempt is usually made to locate it.

A similar cross-section through the Equatorial Trough over the Indian Ocean in January (Figure 12) reveals that it has an almost vertical structure. The pressure and contour gradients are very slack, and there is no evidence of any strong horizontal windflow convergence on the mean chart.

Solot /22/ has described the structure of the ITF across the Sudan and West Africa where a warm northerly continental air mass overlies a cooler southerly maritime airstream. He shows how this structure inhibits the formation of rain at the front, since any cloud forming in the lower maritime air mass and penetrating through the frontal boundary will become desiccated. "Only in those regions far enough removed from the front to possess sufficiently deep layers of moist unstable air, can Cumulonimbus clouds become fully developed. Thus there exists a line approximately 200 miles south of the front which makes the northern limit of precipitation."

Soliman /21/ has drawn attention to the inaccuracies in the classical climatological picture of the windflow in the southern summer; he pointed out that "the north-east winds over northern Africa do not penetrate far south in the heart of the continent and never cross the equator to 20°S. The current normally penetrates only to about latitude 20°N, where it turns to easterly". This new picture of the average January flow agrees with that of Thompson (contrast Figures 1 and 10); Soliman, however, introduces a second front, which he calls the subtropical front, separating the easterly air in the thermal low that forms over the Sudan. This subtropical front is a zone of marked baroclinity and there is a close relationship (on seasonal charts) between its location and the position of the subtropical jet stream over Africa. Soliman also maintains that it is incorrect to draw the ITF through the centres of the closed-isobar heat lows that form over the Sudan and West Africa, since such thermal lows must consist of hot air surrounded by cooler air. However, this seems to introduce an unnecessary complication, and most meteorologists still prefer to consider the ITF as lying within the Equatorial Trough.

4.2 Synoptic studies

Sawyer /18/ carried out a classical study of the Inter-Tropical Front over northwest India during the northern summer. Sawyer was, however, careful to point out that, because of the large air-mass contrasts that exist over NW India, "the results obtained from analysis of the weather of NW India cannot be expected to apply without modification to similar latitudes where air-mass differences are smaller, and still less should the structure of the ITF in this region be regarded as indicative of its structure elsewhere". From temperature soundings in the two air masses on either side of the front, Sawyer calculated that there was a mean slope (to the south) of about 1/350 in the layer 1000-900 mb, steepening to about 1/200 in the layer 900-800 mb, and 1/100 from 800-700 mb. Above 700 mb there was no temperature contrast, but the air-mass boundary slopes back towards the north. This structure gave the ITF a "nose" at approximately 700 mb, some 300 miles south of the surface position of the ITF. Figure 13 shows the structure Sawyer depicted. The position of the "nose" represents the approximate northern limit of the rain area south of the ITF. There is, however, no evidence for this "nose" structure existing over the African continent.

4.3 Locust studies

Sayer /20/ has studied movements of locust swarms in the vicinity of a convergence zone over the northern region of the Somali Republic, and has used this information to deduce facts concerning the structure of the convergence zone. There seems, however, considerable doubt whether Sayer was really dealing with the Inter-Tropical Front. Many of the features which he describes fit perfectly with the idea of a sea-breeze front, which would undoubtedly exist in this area.

A further study by Paskin and Sayer /14/ over the Eritrean Escarpment also appears to deal with a local convergence zone caused by a sea-breeze effect accentuated by the topography. Such local convergence zones may, at times, merge with and intensify any convergence zone associated with the Equatorial Trough, but it would be unwise to generalize concerning the behaviour of the ITCZ from the behaviour of these local convergence zones.

Any convergence zone, whether caused by a sea-breeze front, by topography, or by purely meteorological factors, will naturally tend to produce a concentration of locust swarms in the same way as the ITCZ.

5. THE BEHAVIOUR OF THE ITCZ

5.1 Its movement

Sayer /20/ has commented on "three distinct and superimposed movements of the Inter-Tropical Convergence Zone differing in both amplitude and duration". These are : (i) seasonal, (ii) diurnal, (iii) an intermediate oscillation.

(i) Seasonal

The seasonal movement has already been mentioned in Section 2, and is due to the seasonal movement of the surface Equatorial Trough. This trough, being thermally induced, normally moves through a greater distance over the continents than over the oceans, but in areas such as West Africa its movement is restricted by the absence of any land mass south of the equator. Thus in West Africa the Equatorial Trough always remains north of the equator, oscillating between about 7°N in January and 20°N in July. Over central and eastern Africa the movement is very much greater (see Figures 1 and 2), but as previously pointed out, it is often very difficult to locate the ITCZ precisely over the eastern half of the African continent in July.

(ii) Diurnal

Sayer has described a diurnal movement consisting of a southward movement during the morning followed by a northward movement during the late afternoon, the total amplitude being of the order of a few tens of miles. This small-scale movement resembles the land/sea breeze effect, which adds weight to the suggestion that Sayer was not dealing with the true ITF but with a sea-breeze front. Diurnal movements of the Equatorial Trough may, however, undoubtedly occur in some areas, since differential heating can cause marked local diurnal changes in the surface pressure distribution, as has been noted over Lake Victoria and Western Kenya by Sansom /17/. The diurnal movement of the ITF over the Sudan, described by Solot /22/, differs somewhat from that described by Sayer. There is, of course, no reason why the diurnal movement should be the same in all areas.

(iii) Intermediate oscillations

This is a movement with an amplitude of the order of 100 miles or so around a mean position, and lasting several days. It is associated with the changes of pressure on a synoptic scale. In some areas an association between the direction of movement of the ITF and the weather has been observed, but it cannot usually be applied elsewhere. For example, Solot /22/ accounts for heavy rains in the Sudan by a surge of the south-westerlies pushing the ITF northwards; whereas Paskin and Sayer /14/ report that periods of rainfall in Eritrea are normally associated with the southward movement of the ITF.

5.2 Its relation to the weather

Attention has already been drawn to the occurrence of maximum rainfall 200 miles or more south of the Equatorial Trough when it is in its northern position. Solot /22/ described the rain-inhibiting tendency of the ITF structure in this area (see Section 4.1). Thompson /24/ has, in fact, pointed out that there is no necessary connexion between the movements of the ITF as seen on a surface chart, and the development or movement of rain areas. Referring to Thompson's cross-section (Figure 10), we see that the area of maximum rainfall lies approximately midway between the position of the trough at 850 mb and 700 mb. Rainfall cannot normally occur at the surface position of the trough because this lies beneath a region of subsidence dominated by anticyclones at 850 mb and 700 mb; however, these pressure systems are not stationary, and rainfall increases whenever the trough assumes a more vertical structure between 850 mb or 700 mb and 500 mb, thus allowing convergence and vertical motion to develop through a reasonable depth of the atmosphere. Such movements of the upper troughs can occur with little or no movement of the surface trough, and consequently there may be no connexion at all between the position of the ITF or ITCZ as shown on a surface chart and the area in which rain falls to the south of it.

6. FORECASTING THE INTER-TROPICAL CONVERGENCE ZONE

6.1 Movement

Forecasting the movement of the ITCZ at the surface is basically forecasting the position of the Equatorial Trough. Changes in the location of the Equatorial Trough are the result of change in the surface pressure pattern, and it is therefore essential to study the probable changes in the general pressure field, and particularly in the high pressure cell distribution. Isallobaric charts may be helpful, but it must be remembered that they only show changes which have happened, and cannot usually be used to indicate future changes since there is little time continuity in isallobaric patterns.

The forecasting of pressure changes has hitherto relied on the forecaster's experience accumulated from the study of repetitive synoptic sequences; but extensive research into pressure control mechanisms in low latitudes has recently yielded promising results and their application to forecasting is at present being tested. There is thus hope of a considerable improvement in the forecasting of pressure changes, and so in the forecasting of movements of the Equatorial Trough, in the near future.

6.2 Convergence

Forecasts of low-level convergence near the Equatorial Trough are of obvious importance to Desert Locust Control organizations, since convergence tends to lead to a concentration of locust swarms. Estimates of convergence should be made from upper-wind observations at a constant height, 600-1500 m above ground-level; this eliminates the effect of friction and also of varying topography, and represents the average heights at which locusts fly. Convergence may be estimated qualitatively by inspection of the streamline and isotach patterns, or it may be estimated quantitatively by Forsdyke's graphical method (see Forsdyke [6]), or by a simple objective method, such as described by Bellamy [2]. If the terrain varies greatly in height, Bellamy's method does not give very satisfactory results, even when using winds at constant height above ground-level, because of the local channelling of the wind by the topography.

A method has been described by Palmer [13] which can give quite rapid results at selected points, once a streamline chart has been drawn up. The procedure is as follows :

(i) Measure along a streamline through the selected point, P, a distance of 1° latitude both upwind and downwind. Mark the points P^{1} P^{11}.

(ii) Algebraically subtract the wind speed (knots) at P^{1} from that at P^{11} and divide the difference by 2 to obtain the speed divergence. If the speed is increasing downstream, this term is positive.

(iii) Take a transparent curvature scale prepared by ruling a set of concentric arcs, labelled with a number which is the reciprocal of the radius of the arc in degrees of latitude (according to the scale of the chart being used); at P carefully fit an arc on this scale so that it cuts the streamline through P, as well as the streamlines on either side, at right-angles. Read off the value on the arc, and multiply their value by the wind speed at P. If the streamlines are divergent at P, this term is positive.

(iv) Add the result of (2) to that of (3), having due regard to the sign. The result is the divergence in "practical units" (i.e. per 60 hours). A negative result indicates convergence. In these units, values from -1 to -5 represent moderate convergence, -5 to -8 strong convergence, and beyond -8 is very strong.

6.3 Precipitation

Forecasts of precipitation near or associated with the ITCZ can only be made by a three-dimensional study of the windflow. Low-level convergence will not result in precipitation if it is overlain by divergence a few thousand feet up. Contour charts for the standard levels (850 mb, 700 mb, 500 mb and 300 mb) are necessary, and by estimating (a qualitative estimation is usually adequate) the convergence or divergence at each level it is possible to deduce the nature and extent of any vertical currents. Consideration must also, of course, be given to the stability and moisture content of the air masses involved.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of main conclusions

The terms "Equatorial Trough", "Inter-Tropical Front" and "Inter-Tropical Convergence Zone" should not be used in a slipshod fashion. They are, however, far from satisfactory as they stand, and a new terminology is desirable. In particular the term ITCZ, as at present defined, has a very restricted use; and since it is always located in the Equatorial Trough, the term ITCZ could be dropped.

The "Equatorial Trough" can normally be located on both climatological and synoptic charts over land and ocean. Over the continents, it may, however, be found at a considerable distance from the geographical equator during the solstice periods. Thus the adjective "equatorial" can be misleading.

Within the Equatorial Trough there may exist a genuine air-mass discontinuity, i.e. an Inter-Tropical Front, but over Africa this can only be detected north of the equator, and is most marked west of the Kenya/Ethiopia plateau. In this area, the ITF could be defined as the northern limit of the south-westerly air stream.

Over the oceans, the Equatorial Trough does not usually contain any air-mass discontinuity, but convergence may occur in "duct" type situations (see Johnson and Mörth /9/), where two anticyclones face one another across the equator.

Over Africa west of 30°E the ITF remains north of the equator throughout the year.

Although there may be low-level wind convergence at the Inter-Tropical Front over Africa, this is usually confined to a shallow layer. Precipitation is almost exclusively on the equatorward side (i.e. the south) of the ITF and may be 200 miles or more south.

The movements of the surface position of the ITF bear no relation to the movements of the area of precipitation.

South of the equator and over eastern Africa the ITCZ is diffuse and difficult to locate, and seldom has any frontal structure. Precipitation may occur either at the surface Equatorial Trough or to the equatorward side of it.

There is a close relationship between the movement of locust swarms and the position of the Equatorial Trough particularly during the northern summer and equinoctial periods.

Movements of the Equatorial Trough are controlled primarily by pressure changes on either side of it.

In addition to its seasonal movement, the Equatorial Trough may undergo a small diurnal displacement, and also has an intermediate irregular oscillation of a period of several days.

Estimates of convergence can only be made if there are adequate pilot-balloon wind observations.

Forecasts of precipitation associated with the Equatorial Trough require consideration of the three-dimensional structure of the Equatorial Trough, and the estimation of the vertical distribution of horizontal divergence through the troposphere.

7.2 Recommendations

New terminology for the Equatorial Trough, Inter-Tropical Convergence Zone and Inter-Tropical Front are required to remove the present ambiguities. Some proposals are shown in the Appendix.

Meteorological services in the tropics should make every effort to increase their network of surface meteorological stations (including barometric pressure), and of upper-air stations.

In the vicinity of the Equatorial Trough low-level pilot-balloons, up to 1500 m above ground-level, or even less, can give valuable information, and meteorological services should instruct their observers to endeavour to make wind observations at least twice daily, even in cloudy weather.

An increased network of rawinsonde stations is essential for any further improvement in forecasting in the tropics.

ACKNOWLEDGEMENTS

I am grateful to Mr. B.W. Thompson, Director of the East African Meteorological Department, for the loan of a manuscript copy of his "Climate of Africa", and for helpful comments and suggestions; to the Director of the Desert Locust Control Organization for Eastern Africa for useful discussions and for access to unpublished manuscripts; and to my colleague, Dr. H.T. Mörth, for the proposed new definitions which appear in the Appendix.

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APPENDIX

SUGGESTED NEW TERMINOLOGY

The following draft definitions have been submitted by the chairman of the Working Group on Methods of Analysis and Prognosis in the Tropics of the WMO Commission for Synoptic Meteorology for consideration by the members of this group.

Thermal Equator Trough (TET)

(A) zonal trough(s) at or immediately above the surface of the earth along the belt(s) of highest daily mean surface temperature (thermal equator).

> Migrates annually with the inclination of the sun and is therefore principally confined to the tropics. A double structure can occur in a region of approximately zonal distribution of land and sea (e.g. coastline of southern Arabia and southern Asia) where a heat trough may form over the land in the summer hemisphere whilst the heat trough over the sea maintains its identity.

Thermal Equator Convergence Zone (TECZ)

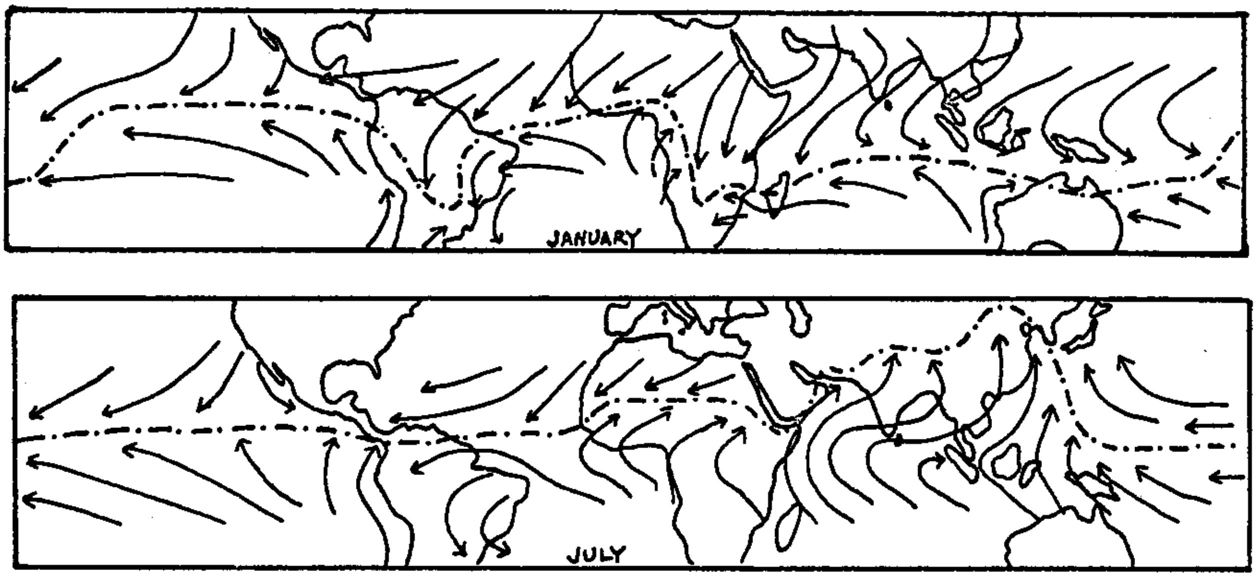
A belt of wind convergence produced by the TET, the converging winds generally originating from both hemispheres.

> This zone is located in the TET when the thermal equator is near the geographical equator but is displaced equatorward from the TET when the thermal equator is far distant from the geographical equator (solstice position over land). In the former case north-east and south-east trades converge, while in the latter case monsoon winds originating from the winter hemisphere converge with westerlies on the equatorward side of the TET.

Inter-Tropical Weather Zone (IWZ)

Zonal concentration of predominantly convective cloud and weather in the summer hemisphere at, or displaced equatorward from, the TECZ.

> The displacement equatorwards of the IWZ from the TECZ can amount to several hundred miles over land areas in the period around the solstice position. This occurs because the TECZ is then often overlain by subsiding air preventing cloud development in spite of maximum surface convergence; instead, optimum kinematic conditions for cloud development exist further equatorwards where cloud development is not hampered by subsiding air aloft, despite the smaller degree of surface convergence.



Figures 1 and 2 - Mean position of ITF and mean surface winds in the tropics, as commonly given. (After Sawyer /19/).

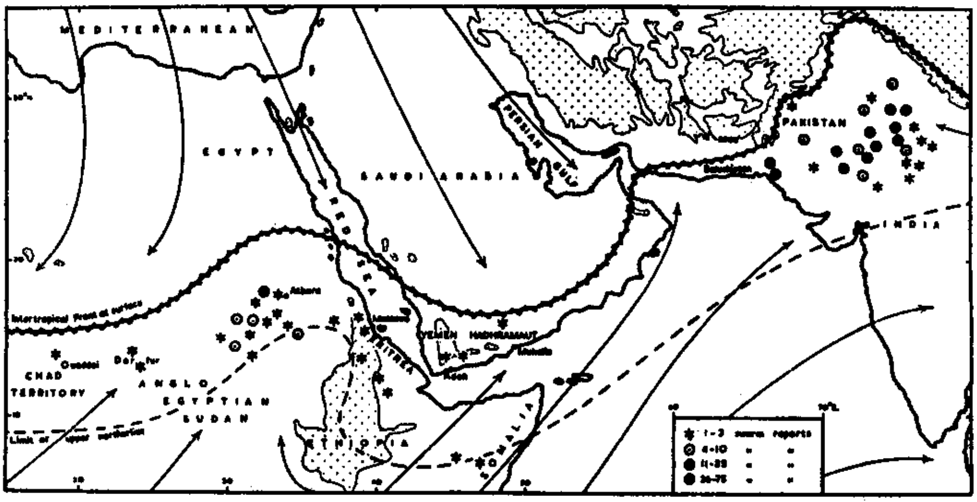


Figure 3 - The position of the ITF and the distribution of locust swarms, July 12-31 1950. (From Rainey /15/).

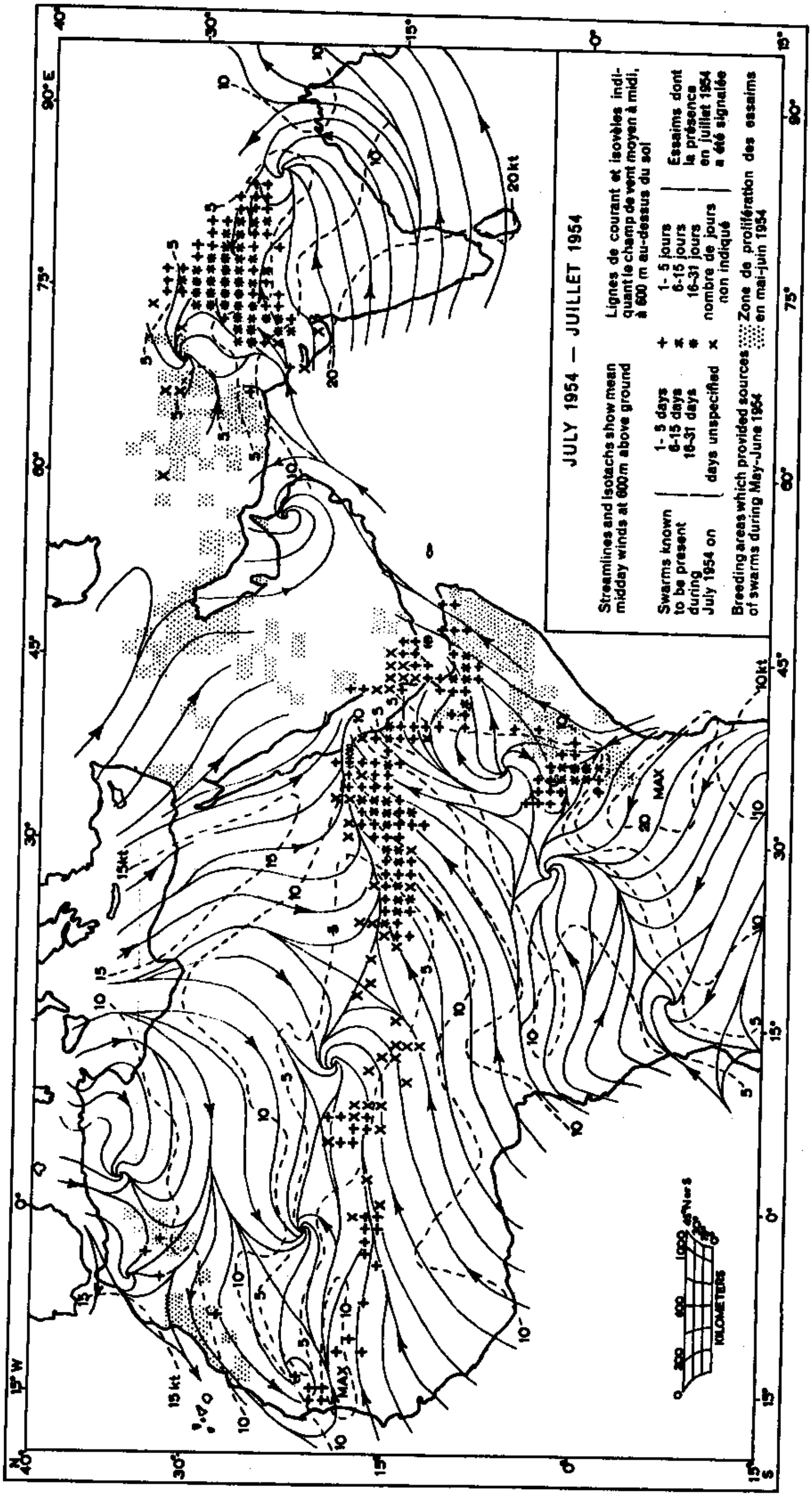


Figure 4 - The position of the ITF and the distribution of locust swarms during July 1954.
(From Asplíden and Rainey [1].

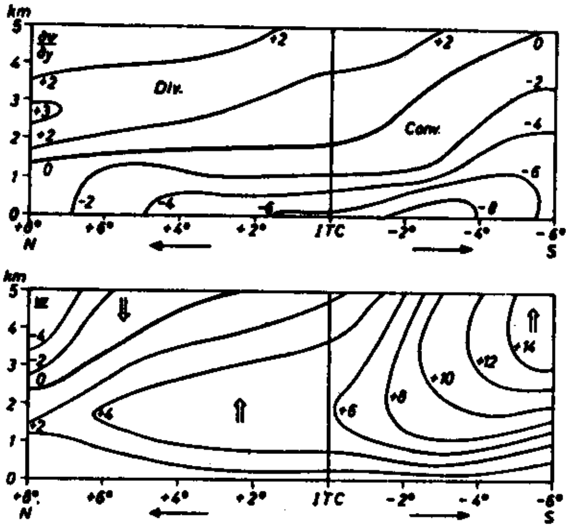


Figure 5 - Approximate horizontal divergence in 10^{-6} sec^{-1} (above) and the vertical wind component w in mm / sec^{-1} (below) in a vertical cross-section at both sides of the Equatorial Trough. (From Flohn [5]).

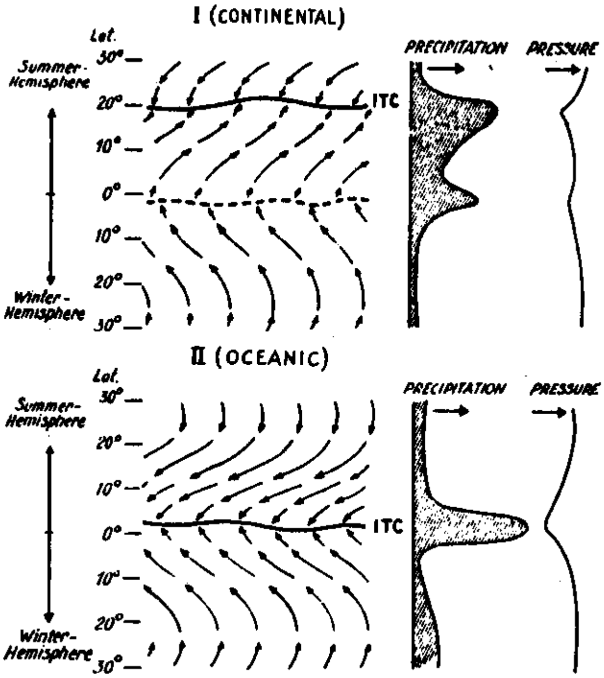


Figure 6 - Ideal continental and oceanic patterns of windflow, precipitation and pressure at the Equatorial Trough. (From Flohn [5]).

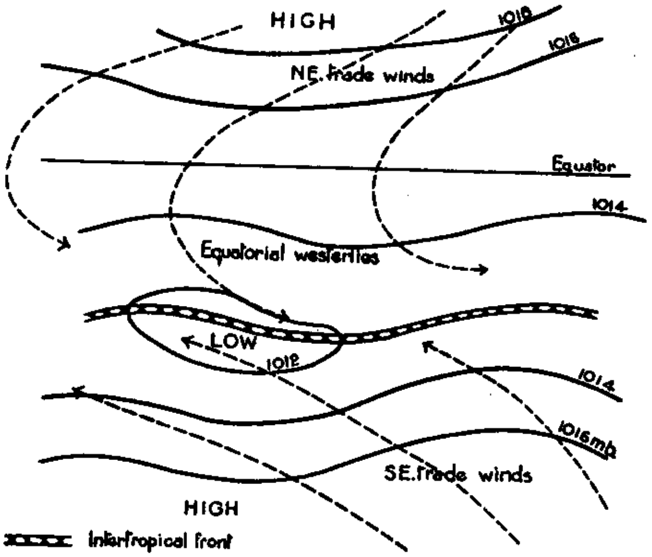


Figure 7 - Actual windflow and pressure pattern over the ocean when the Equatorial Trough is more than 5° from the equator. (From Sawyer [19]).

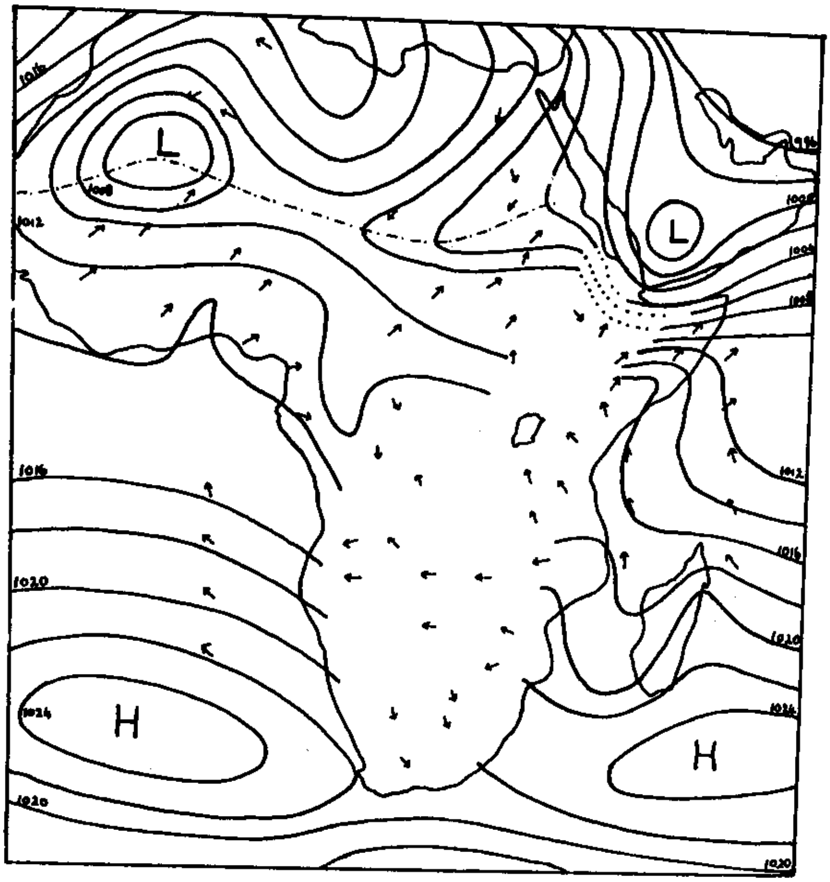


Figure 8 - Mean surface chart for July.

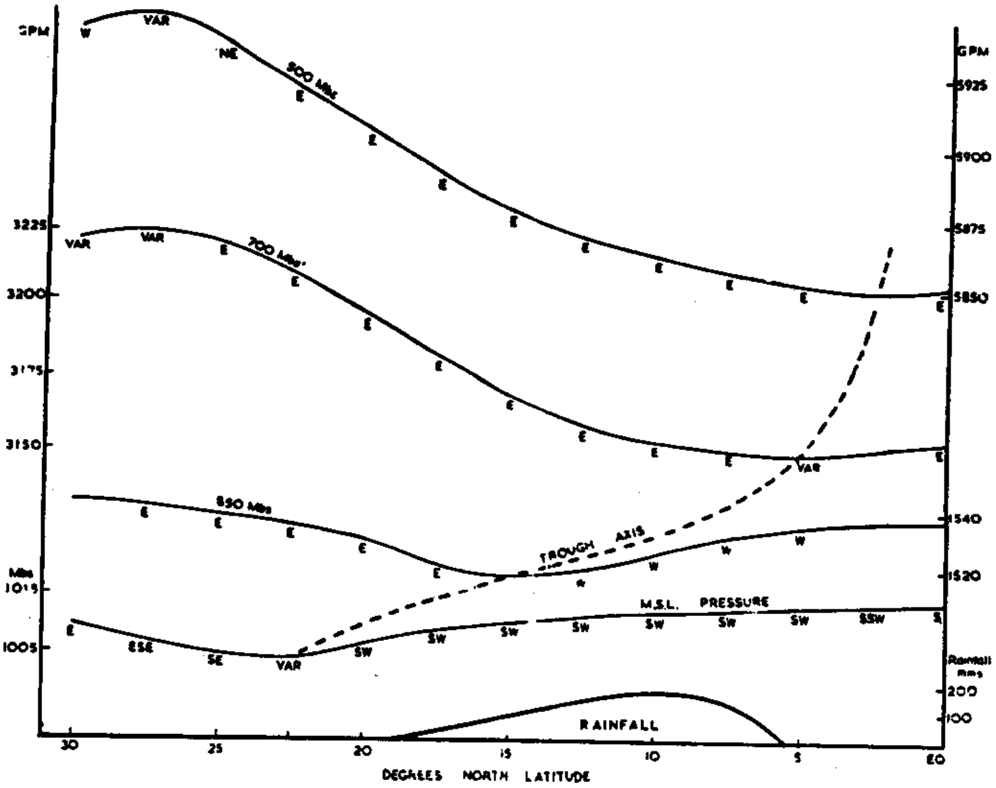


Figure 9 - Cross-section along the Greenwich meridian between the equator and 30°N during July. (From Thompson [24]).

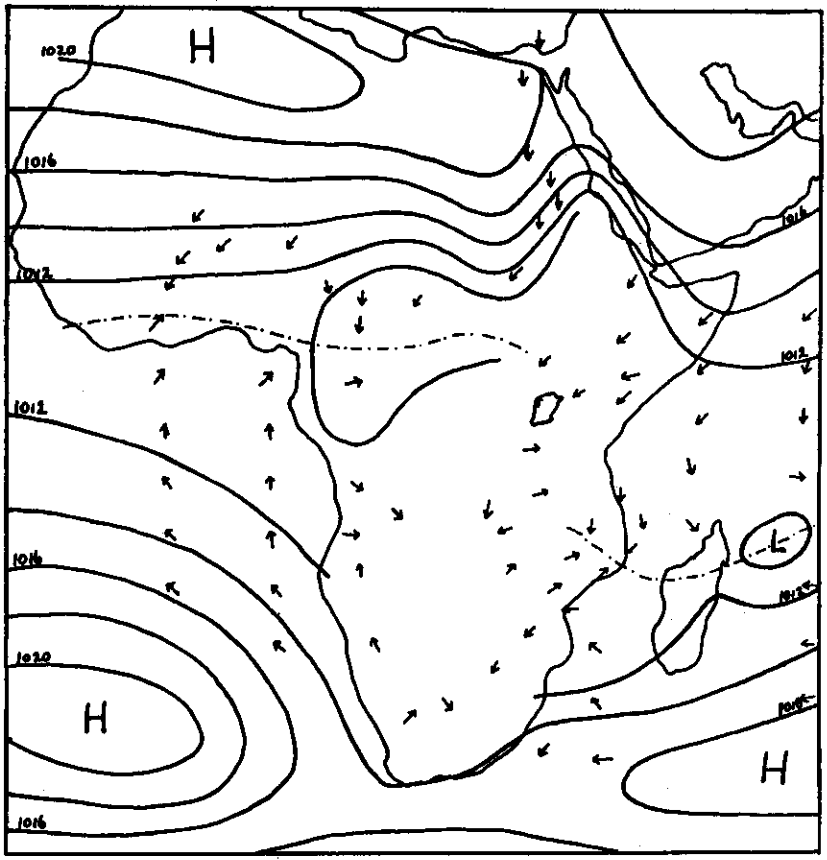


Figure 10 - Mean surface chart for January.

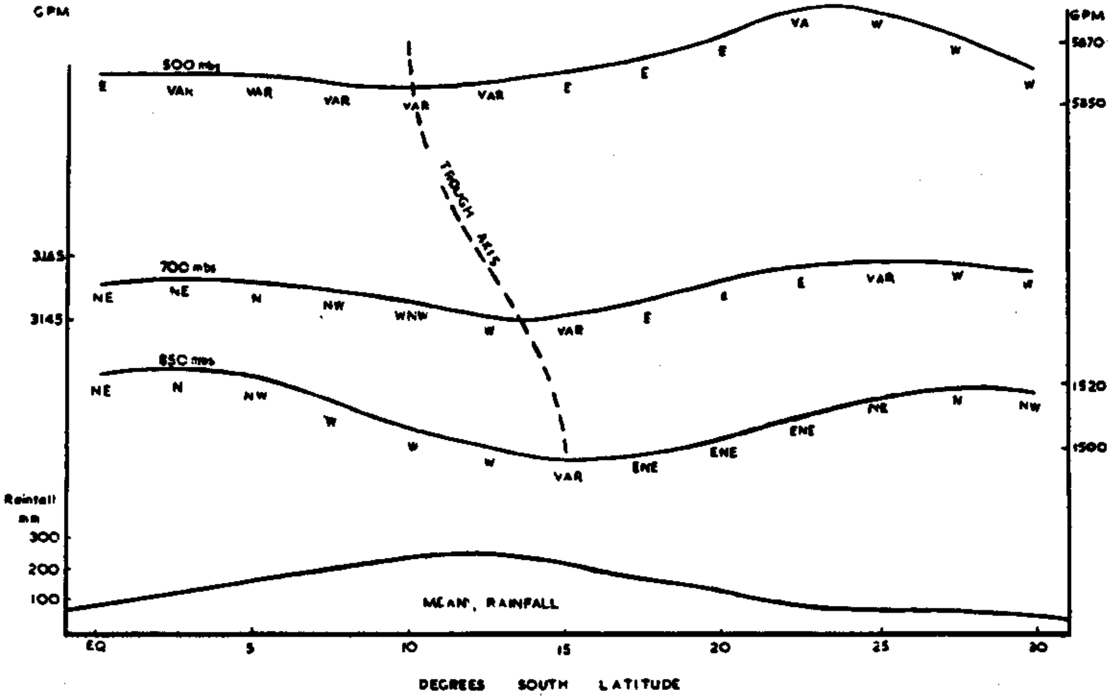


Figure 11 - Cross-section along 25°E between the equator and 30°S during January. (From Thompson [24]).

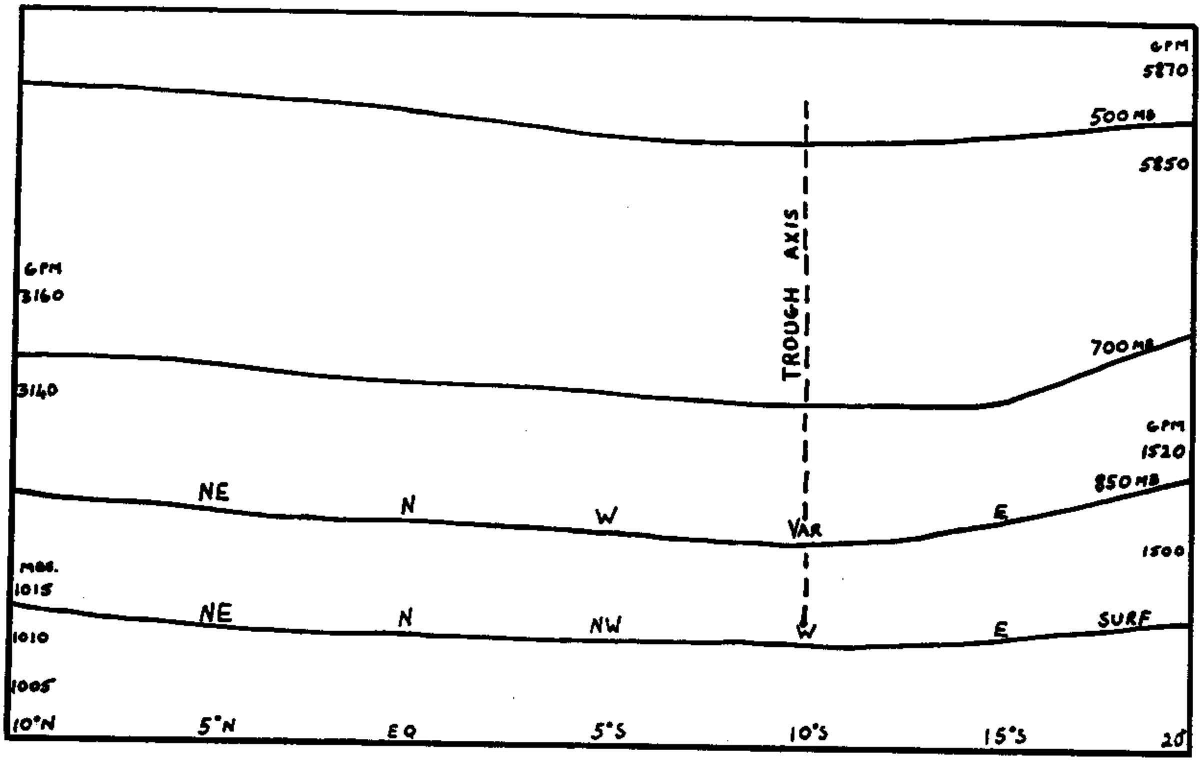


Figure 12 - Cross-section through Equatorial Trough over Indian Ocean (60°E) during January.

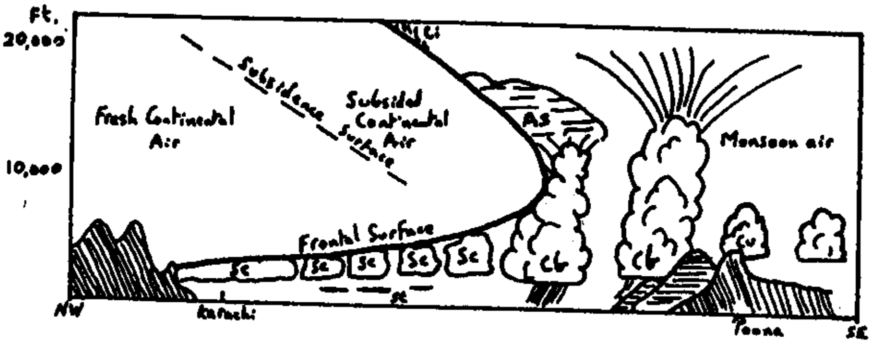


Figure 13 - Cross-section through the ITF over coastal regions of NW India and Pakistan. (After Sawyer [18]).

LE FRONT INTERTROPICAL (FIT) ET SES PERTURBATIONS EN AFRIQUE DE L'OUEST

par

B. Haudecoeur

En hiver boréal, la position moyenne du front intertropical (FIT) sur l'Afrique de l'Ouest se trouve entre le 5ème et le 8ème parallèle. C'est la saison sèche. Seule une étroite bande littorale reçoit quelques averses. Il y a par contre de fortes précipitations au large du golfe de Guinée. En été au contraire la position moyenne du FIT est autour du 20ème parallèle et certaines ondulations peuvent atteindre ou dépasser 25° nord. C'est alors la saison des pluies. La bande littorale est en revanche moins arrosée. On parle sur la côte de petite saison sèche.

Au cours des saisons intermédiaires le FIT se déplace entre ces positions extrêmes.

On peut déjà mentionner une pulsation diurne de la position du FIT. Bien que de faible amplitude, cette pulsation est cependant sensible; elle est due au refroidissement nocturne de la masse continentale que représentent les régions sahariennes. A ces fluctuations régulières il faut ajouter des perturbations du FIT atteignant parfois des amplitudes importantes. Ces perturbations sont dues à des dépressions sur l'Afrique du Nord, ou sur la Méditerranée. Au mois de février de l'année 1963 une dépression quasi permanente intéressait tout le bassin méditerranéen. Il en résulta pour l'Europe occidentale une période de froid particulièrement rigoureux. Simultanément, cette zone dépressionnaire provoqua un appel de la mousson. La position du FIT se trouvait beaucoup plus au nord qu'il n'est normal en cette période et nous avons subi au Niger un mois de février très sensiblement plus chaud que la normale.

Il se produit d'autres perturbations du FIT de courte durée, mais d'amplitude beaucoup plus forte, qui sont provoquées par des ruptures du front polaire.

Le 24 janvier 1955, nous voyons un système dépressionnaire sur le Sahara accompagné d'une dépression importante se prolongeant par un thalweg jusqu'à 10°N. Le front polaire est rangé et la masse d'air froid s'écoule jusque dans les régions intertropicales. La position du FIT est haute pour la saison mais il n'est encore l'objet d'aucune ondulation. Il est cependant déjà possible de prévoir comment le phénomène va évoluer dans les jours suivants. Pour la journée du 26 janvier, grâce à quelques radiosondages, j'ai pu tracer le contour du niveau de 700 mb. On y voit une importante dépression centrée par 35°N et 32°E et se prolongeant par un thalweg jusqu'à 10° Nord.

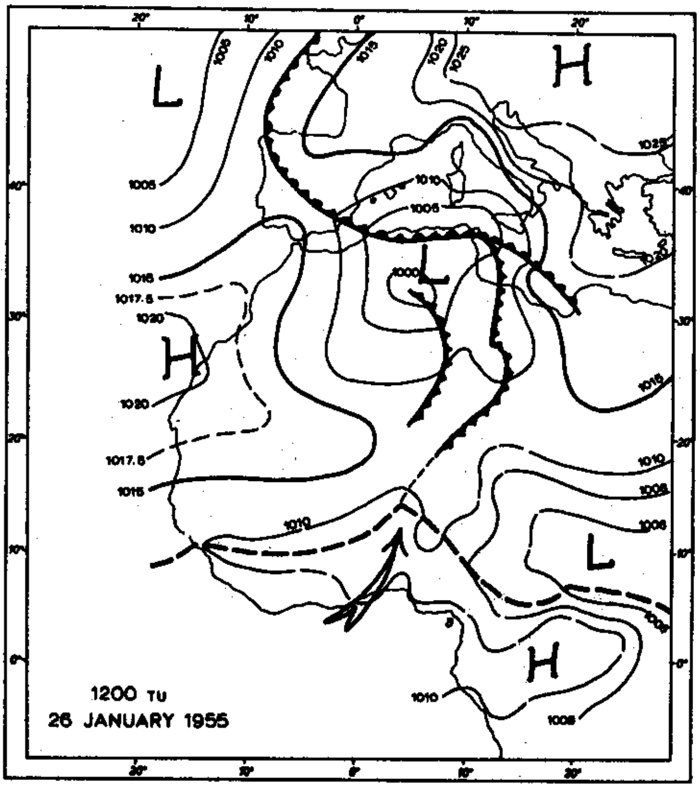
Le calcul de quelques vents thermiques a permis de préciser la forme des lignes isothermes que j'ai dû tracer avec un nombre très réduit de températures. Ces isothermes, tracées de 2° en 2°, indiquent une goutte froide légèrement au nord de la dépression. Cette goutte n'est plus alimentée, ce qui laisse prévoir que la dépression va tendre à se combler et que le phénomène sera de courte durée. Cette goutte froide se prolonge par une adduction froide le long de notre axe de thalweg. Au sol nous voyons une ondulation importante du FIT que nous avons tendance à raccorder au front froid. L'air polaire froid semble être, sur le FIT, en contact avec l'air humide et chaud de la mousson qui a été appelée par le thalweg. Cette ondulation du FIT atteint 14°N. Je ne dispose d'aucune donnée sur la journée du 27, mais le 28 nous pouvons constater que la dépression sur l'Afrique du Nord s'est considérablement comblée. Elle est coupée des régions intertropicales par une dorsale, et nous voyons que le front polaire s'est reconstitué. Si nous traçons la limite entre l'air humide et l'air sec nous voyons qu'il y a une poche d'air humide atteignant 16°N et située plus à l'est de cette ondulation.

Cette limite n'est pas le FIT. En effet, l'étude des vents et même de l'humidité (du nord au sud nous avons les températures de point de rosée suivantes: 16°, 13°, 17°C) nous montre que le FIT s'est reconstitué le long du 10ème parallèle avec une légère ondulation résiduelle qui ne peut que s'atténuer. Notre phénomène, en effet, n'est plus entretenu, ses causes ayant disparu.

A partir du 30, toute humidité au nord du FIT a disparu et le FIT longe le 9ème parallèle. Il n'accuse plus qu'un léger bossellement.

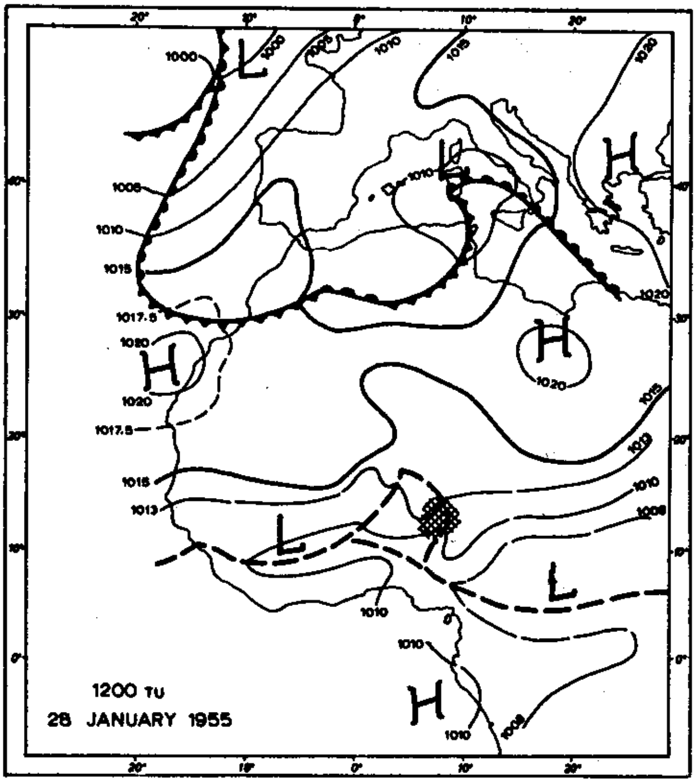
Ces pluies d'hiver sont rares et généralement de très faible intensité. Souvent elles ne consistent qu'en quelques gouttes. Je me souviens cependant d'avoir subi à Niamey, au début de mars 1960, un orage accompagné d'averses violentes qui avaient duré environ 5 heures. Je n'ai pas en tête les quantités d'eau recueillies mais les oueds avaient brusquement gonflé et une rue de la ville avait été rendue impraticable par les dégâts provoqués par les eaux de ruissellement. Il est utile de préciser que les premières pluies tombent en général fin mai, et encore sont-elles négligeables, et que l'on ne peut vraiment parler de saison des pluies que pour la période du 15 juin au 15 septembre.

En hiver les ondulations du FIT ne sont généralement accompagnées que de quelques bandes d'altocumulus pendant 2 ou 3 jours. Très souvent la remontre de mousson, et c'était le cas ici, est orientée suivant un axe Conakry - Onagu - Gao - Tessalit.



1200 TU
26 JANUARY 1955

Figure 1



1200 TU
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Figure 2

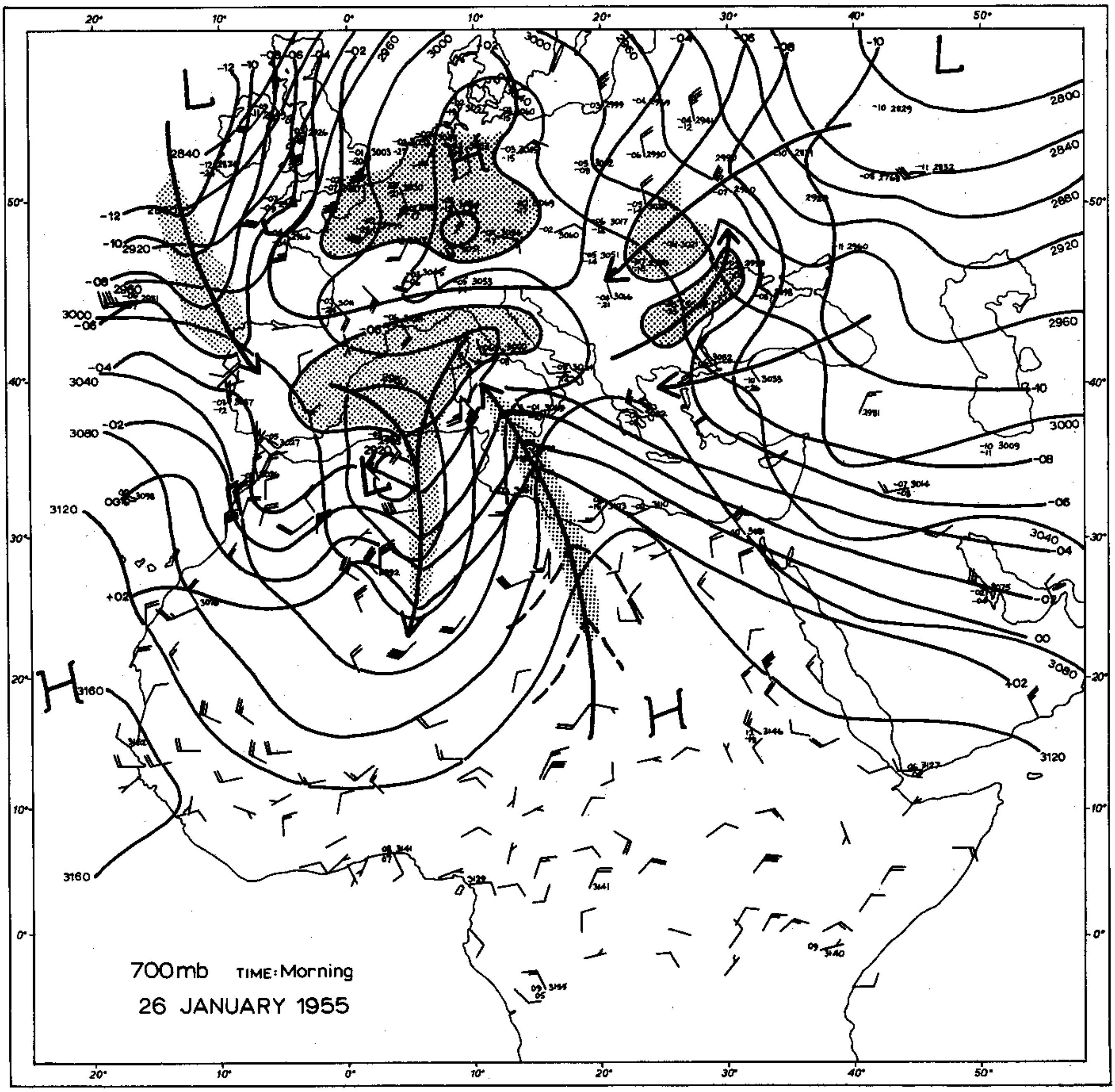
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Figure 3

MESOSCALE OBSERVATIONS OF THE MOVEMENT AND STRUCTURE OF SWARMS IN THE VICINITY OF THE INTER-TROPICAL CONVERGENCE ZONE

by

H.J. Sayer

In eastern Africa, the annual cycle of movement of the Inter-Tropical Convergence Zone (ITCZ) is the main factor influencing the movement of locusts, the arrival of the ITCZ and the associated rains being recognized as the time of the arrival of swarms. For control purposes, rapid movement of the ITCZ and swarms present many logistic difficulties, especially as the accompanying rains impair ground communications. The relatively static solstitial positions of the ITCZ are, therefore, of major importance for swarm control. The southern solstitial position of the front in Eastern Africa is meteorologically very confused, and it is only the northern solstitial which is very clear and easily identifiable. Observations on the ITCZ and its effect on adult locust populations during the months of June to September have clarified what was a confused picture of storms and swarms, and have shown how important this particular part of the locust cycle is from the point of view of control.

By early June, the zone of convergence becomes established along a line roughly parallel to the coast of northern Somalia and stays within about 50 miles of this position for the next three months. There is a daily movement of the front from north to south with a return to the north commencing in the late afternoon. This diurnal oscillation is reflected in the daily swarm displacement. The converging winds will bring all the locusts into the zone from both north and south, so that, eventually, the flying locusts from a great distance around become concentrated in the zone and follow the same daily pattern of movement. Since locusts settle and remain stationary at night, the northerly movement of the front will leave the roosting locusts well to the south of the front by dawn, and this means that, in this area, the settled locusts will be in a strong south-westerly wind. As the temperature rises, the locusts will tend to fly away and,owing to the strong wind, the swarm will become thin and elongated towards the north-east.

At around midday, these low-density and relatively low-flying swarms moving north-eastwards will reach the front which is moving southwards. A striking change immediately takes place in the swarm's appearance. There is a considerable increase in density and the swarm soon towers up into the sky. From either north or south, the swarm appears as a curtain of locusts rising upwards to several thousand feet, marked with dense wavy streaks. From either east or west, the locusts appear as a dense sloping mass with the top towards the south. Traverses by aircraft along the north-south axis have shown (a) every time the swarm is traversed, as indicated by locust impaction, there is an abrupt ascent of the aircraft, which ceases with the locusts, (b) such north-south traverses are rarely more than three miles in extent, and regularly about two miles at low levels, (c) there is a temperature change, the northern air being a few degrees warmer than the southern, (d) there is a change of visibility, the northern air being more hazy than the southern. Traverses along the east-west axis frequently found swarms of considerable length along this axis, up to 40 miles long. Orientated photographs have shown a slope of about 30° upwards towards the south. From many ground and air observations, a typical construction of the front has been made (see Figure 1). Vertical photographs of swarms approaching the front in the south-westerly wind and of swarms in the front have shown locust flying density changes from less than 0.01 to greater than 1.0 locusts per cubic metre.

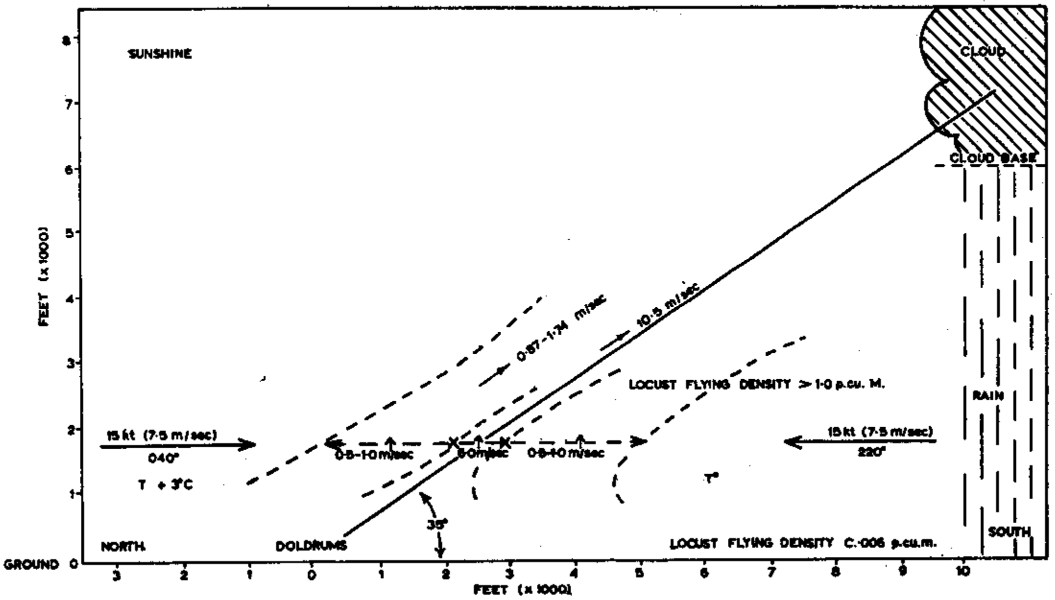

Figure 1 - Typical north-south cross-section of the inter-tropical front as found around Borama, Somali Republic, during June-August, 1960.

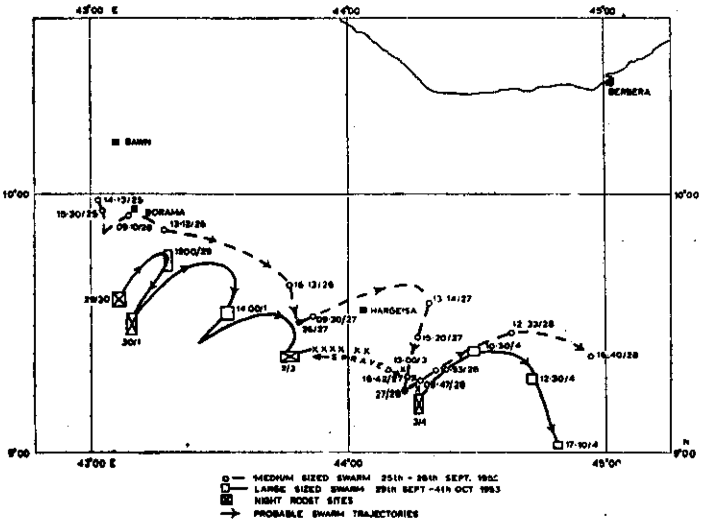

Figure 2 - Plots of trajectories of two large swarms across Somaliland during September 25-October 4, 1953. The front at this time and place is beginning to move southwards and therefore the swarms spend longer in the frontal system, while night-roost sites are located successively farther south.

For the rest of the day until night-roost, the swarm moves with the front, at first southerly and then, for a very short while around sundown, a little northerly. Such daily movements were first recorded in 1953 (see Figure 2), and it is important to note that, although locusts actually cover a long distance each day, the zig-zag track brings them back to a point not very far from where they started.

The flying locusts in the front are clearly being taken upwards by the vertical air currents, and being kept in the updraught by the convergent winds. It would appear that the updraught is very strong and well-marked near the ground, but at higher levels, due perhaps to entrainment, becomes more diffuse and widespread. At these higher levels, due to the decreasing temperature the locusts will tend to cease flapping flight and glide. Since it has been shown that the rate of descent of a gliding locust is about 1 m/sec, the locusts will tend to concentrate at an altitude where the updraught is 1 m/sec, and this may account for the dense wavy masses of locusts at high altitude. Eventually the gliding locusts will fall out of the updraught to descend into the south-westerly wind, over which they have been suspended. The southern side of the swarm will therefore appear to be less clearly defined than the northern side (see Figure 3).

Besides the daily movement of the front there is a several-day surge about the mean position. This further movement often leads to the front becoming, during the southerly surge, less clearly defined and with more widespread bad weather, and swarms become disintegrated and scattered, but are re-concentrated when the front moves north again when the front can be very sharply defined. Under such conditions, individual swarms lose their identity; there is only a locust population which is being constantly redistributed, at one time appearing as a massive huge swarm containing all the locusts in the area, and at another time being a number of smaller swarms with sometimes very low density locusts in between.

Pilot-balloon ascents made through the front have shown that the change of wind direction from south-westerly to northerly is always through north-west, i.e. the wind veers as opposed to backing. This suggests that the wind in the front is not only rising but moving from west to east. This is reflected in the steady displacement of the locusts in this area from west to east. Such a regular easterly movement of locusts eastwards across northern Somalia would eventually bring them over the sea, but it is apparent that locusts do not, in general, get lost over the Indian Ocean, accumulating instead in the north-east corner of the Horn of Africa. This is explained by the fact that in the afternoon, when swarms are most actively flying, a sea-breeze becomes established along the coast and the swarms are thus preserved over the land. The similar establishment of sea-breezes in the afternoon along coastal areas in many locust areas has a conservation effect on swarms, and it is only when such coastal convergence zones are broken down by abnormal weather, e.g. cyclones, that large numbers of locusts are taken out to sea, and perish.

The movement of swarms in northern Somalia along the front from west to east does not necessarily mean that this is the common direction of movement along the front; elsewhere, it has been observed that swarms move in the opposite direction. Such opposing directions of displacement immediately suggest that, along the front, there must be points of accumulation and points of dispersion. A detailed study of the front during the northern solstitial period together with locust swarm data may yield knowledge on this point and may provide very important data from the control point of view.

REFERENCE

Sayer, H.J., 1962 - The Desert Locust and Tropical Convergence. Nature Vol. 194, No. 4826, pp. 330-336.

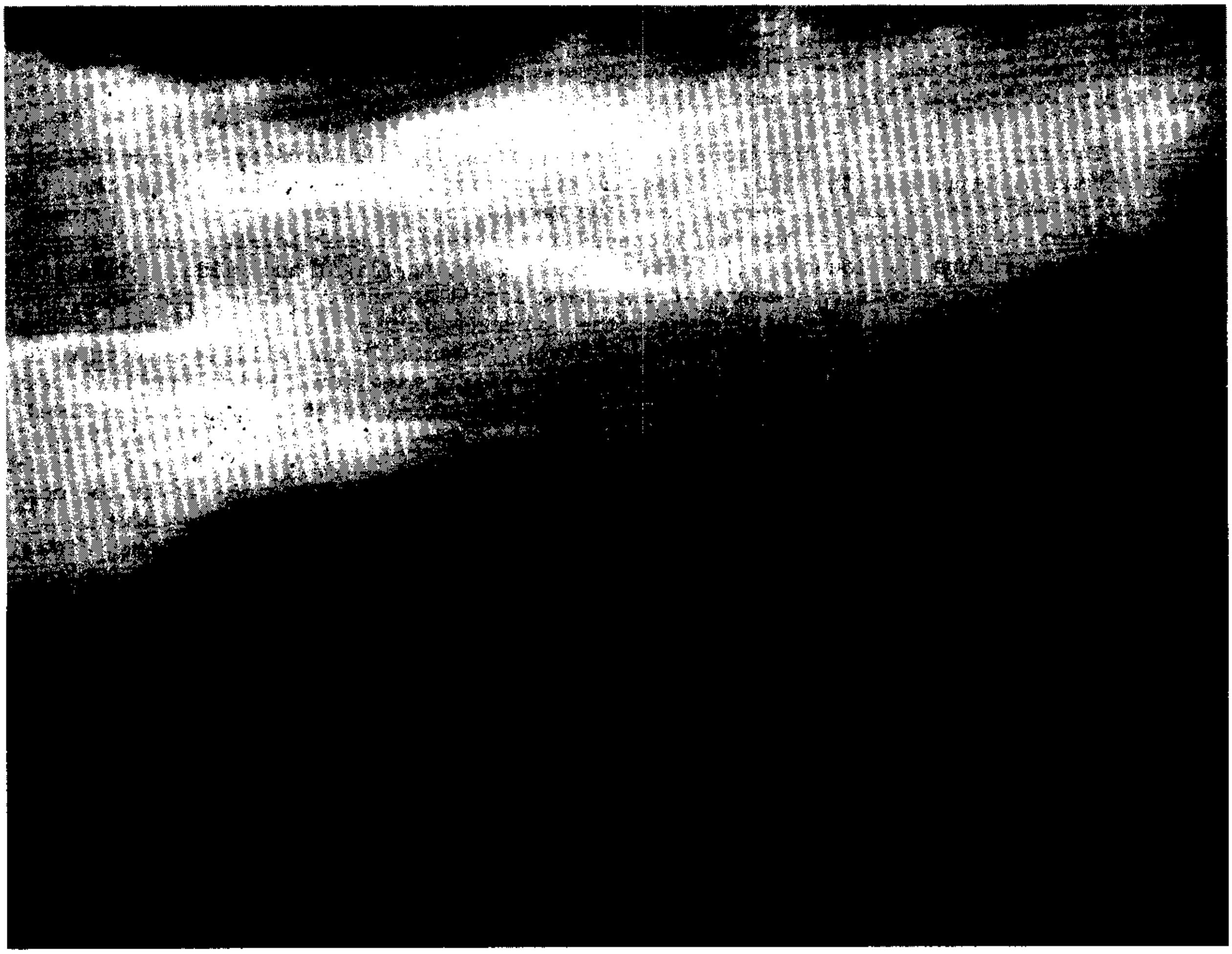

Figure 3 - Large swarm showing typical association with convergence. The camera is pointing approximately towards the north-east from Hargeisa airport (Northern Region, Somali Republic, August 3,1960). The photograph was taken in the late afternoon and the density of the swarm when it passed over the airfield was such as to prevent aircraft taking off. Photograph by A.J. Wood, Desert Locust Survey.

SOME FEATURES OF THE SYNOPTIC METEOROLOGY OF SOUTH-WEST ASIA

by

S. Mazumdar

1. INTRODUCTION

The area covered in this discussion is from the east coast of the Mediterranean and the Red Sea to Assam and East Pakistan, and from the Indian peninsula to the Caspian Sea, Iran, Afghanistan, West Pakistan and Nepal. This is a large area with much diversity and many different synoptic features. Attention will therefore be confined only to some of the major features, especially those which may have a bearing on the movements of Desert Locust swarms.

Two principal factors appear to affect the climate of this vast area like, perhaps, many others : one is the topography, including the land and sea distributions, and the other is the distribution of vegetation.

The topographic features are dominated by the Himalayan range and the Tibetan plateau, which act as a barrier to lower tropospheric air movements between north and south and, besides, appear to play an important part in shaping the monsoon circulation over India and Pakistan. There are a number of other important topographic features, of which mention may be made of the Hindu Kush Range, the Elburz mountains south of the Caspian Sea, the Caucasus mountains in the region between the Caspian Sea and the Black Sea, the Turkish plateau and the mountains around the Gulf of Iskenderon in the north-eastern corner of the Mediterranean, the Kuh-i-Dinar range in south-west Iran, the Jabal-Akhdhar and the Bashagird mountains around the Gulf of Oman, the hills along the east coast of the Red Sea (Hejaz and Asir) and their extension towards the central parts of the Arabian peninsula, the western ghats along the west coast of the Indian peninsula, the ridges along the Arakan coast of Burma, and the Khasi and Jayantia hills of Assam. Other minor but synoptically significant features include the Sinai peninsula located between the Gulf of Suez and the Gulf of Aqaba, and the Dead Sea - an apparent extension of the great Rift Valley of eastern Africa - where the ground descends to a depth of some 360 metres below the sea-level. In the distribution of land and sea, south-west Asia is very different from tropical and equatorial Africa. The resultant differences in the climatic patterns are well known.

There are vast areas in the south-west Asia region which are arid or semi-arid, but even within these areas the nature of the ground varies very considerably. Extensive regions are rocky or sandy with little vegetation except short, thorny shrubs and cacti. Much of the so-called desert areas of western Iraq, Jordan and Syria are really of the steppe variety, with an abundance of short, patchy vegetation and flowers during the spring season. In large tracts, especially those along valleys of the Tigris and Euphrates, the soil surface is predominantly clayey, rather than sandy, and in conditions of desiccation which prevail for the greater part of the year, the surface is covered with exceedingly fine dust. This feature plays an important part in determining the visibility characteristics. Due to intense heating in the summer, the dust particles are lifted up by vertical currents to considerable heights, sometimes reaching as high as four to five kilometres, and the top of the dust layer produces the impression of a dust horizon (1). Similar conditions are encountered at places in the deserts of Sind and Rajasthan. There are two large marshy areas in the region, one along the estuary of the Shatt al Arab (locally called "Hor") and the other in Kutch and the nearby areas of lower Sind. The effect of wind is manifest from the differential erosion visible on the wadis and hill ranges in Iraq, Jordan and Syria. In Iraq the asymmetrical character of most of the anticline results in a steep scarp-like face on the south-west side of many ranges and gentle backslopes on the north-east side (2).

Local climate is determined as much by the general climatic régime as by localized topography, and large variations of rainfall and temperature within comparatively short distances are thus quite common. At Zonguldak (Turkey) on the south-western coast of the Black Sea, the highest rainfall in 24 hours was 431.5 mm, recorded in August 1955, and at Rize on the south-eastern section the annual normal rainfall is 2,441 mm, with 171 rainy days in the year. These values are comparable to many in the monsoon area. At Koçhisar near the Salt Lake in central Anatolia in Turkey the annual rainfall is only 165 mm. The lowest temperature on record is -43.2°C at Karaköse (1,638 metres above sea-level) in eastern Turkey in January 1940. By contrast, summer temperatures of 52°C or more in the shade are known to occur in the western desert areas and the Baluchistan and Sind areas of West Pakistan. One of the best-known cases of orography producing heavy rains is Cherrapunji in India where the monsoon air strikes a range of hills almost at a perpendicular. The intensity of rainfall at this station is very large, the highest recorded rainfall in 24 hours being 1,036.3 mm, and the highest annual rainfall (excluding March) is 22,990.1 mm. Mawsinram, a nearby station, had 18,403.3 mm of rainfall in 1956. These records are of course exceptional, but heavy precipitation is not necessarily confined to hilly areas; a 24-hour rainfall of 974.6 mm was recorded in the monsoon of 1941 at Dharampur (Surat District), a plains station at 20°32'N 73°13'E, about 30 km from the Arabian Sea coast north of Bombay.

2. AIR-MASS CHARACTERISTICS AND FRONTS

The principal air masses in the first two to three kilometres of the atmosphere that participate in the synoptic systems are mentioned below :

(i) Tropical continental air (Tc) is the predominant air mass over vast areas of the Middle East, Pakistan and India in the summer months.

(ii) Polar continental air (Pc) or a modification thereof affects the northern parts of the area in the winter and spring and, to a lesser extent, in the autumn.

(iii) Tropical maritime air (Tm) affects Saudi Arabia, Iraq, Iran, Afghanistan, Pakistan and India in spells almost all the year round, mainly under the influence of moving low pressure areas.

(iv) Mediterranean air affects Lebanon, Israel, Syria, Iraq, Jordan, Turkey and northern parts of Saudi Arabia under the influence of low pressure areas. The Black Sea, Caspian Sea, the Red Sea and the Persian Gulf are also sources of some moisture supply, though to a localized extent.

(v) Equatorial maritime air (Em) prevails over large parts of Pakistan, Nepal and India and also coastal regions of Iran and the Arabian peninsula during the period June to August/September.

The air masses in India (3) are representative of those over a good part of south-west Asia. It is well known that in very few actual cases the air masses conform to their idealized structure. This is because of the incessant modifications that occur during air movements between regions of vastly different climatic régimes. The overrunning (as distinct from replacement) of one type by another is quite a normal feature except possibly in the case of the equational maritime air. The properties that broadly distinguish one air mass combination from another consist of the vertical distribution of temperature and moisture content, and it is usually unprofitable to classify them in terms of the source regions, i.e. continental or maritime, from which, based on the trajectories, they may be considered to have flowed out.

Frontal activity associated with depressions of the comparatively high latitudes conforms in the non-summer months to the known patterns of the middle latitudes. In such cases it is often possible to locate fronts in Iran, Afghanistan, even north India. During summer months the fronts tend to be obliterated due to intense heating, and in regions south of latitude 25°-30°N it is exceptional to locate any systematic temperature contrasts. The only interactions that it may be possible to locate in the lower levels are between comparatively dry and comparatively moist air instead of between warm air and cold air, but the low-level hydrostatic density discontinuities are usually not sufficient to account for the necessary lifting for producing clouds and thunderstorms. The generation of convective clouds is therefore often attributed to the pre-existence of latent instability and the availability of "triggers", notably insolation.

In the search for comprehensive models to explain the occurrence of cloud fields and depressions without resorting to assumptions about fronts and slopes that do not in fact exist within the first two or three kilometres, attention has naturally been turned to hydrodynamical systems, giving only a second place to the thermodynamical consequences. Most of the explanations pertaining to the phenomena of depressions and cloud fields offered during the last fifteen or twenty years subsist one way or the other on low-level convergence, higher-level divergence and consequent large-scale lifting of air to the condensation level and beyond.

A notable contribution to tropical analysis was due to Sen (4, 5) on the analogy of the concept of vortex stress given by von Kármán. Sen was able to combine in one composite model the deformation fields (with their axes of dilatation and compression linking regions of confluence and difference respectively) and the zonal chains of cyclonic and anticyclonic vortices. An idealized diagram suggested by Sen for the 1.0 and 1.5 km levels (called "generative field") is reproduced in Figure 1 (a). Figure 1 (b) shows the pattern of analysis in an individual case. He proposed a similar scheme of vortex streets for levels around 6.0 km (called "directive field") for the steering of tropical storms and depressions, including their recurvature. There are some obvious common features between the vortex street model (developed in 1943) and the more recent isogon-streamline method of kinematic analysis (6), although the two were developed from completely different premises.

The location of the inter-tropical convergence zone (ITCZ) is more difficult over south-west Asia than it is over Africa mainly because of the lack of observations over the sea areas and some of the land areas. However, as the transition in the values of meteorological elements in the north-south direction, including wind and hydrometeors, is sometimes extremely gradual, the width of the ITCZ often covers five to ten degrees of latitude. Lack of observations in the Bay of Bengal usually makes it difficult to track easterly waves which move along or feed into the ITCZ.

One interesting feature of the summer fronts in the area between Iraq and the eastern Mediterranean coast is that they produce fairly widespread duststorms with moderate to severe convective turbulence up to three to four kilometres, without the accompaniment of any low convective clouds (sometimes with only traces of Altocumulus or no visible clouds at all), but with a perceptible drop of surface temperature. These phenomena appear to work upon the interaction between dry, cool air and slightly less dry, warm air, but the available moisture is evidently so small as not to manifest itself in the form of clouds despite the release of energy sufficient for strong convection.

3. LOW PRESSURE SYSTEMS

The low pressure systems that affect the area can be broadly classified into two groups : (a) systems that move through the higher latitudes, the direction of movement having a predominantly west-to-east tendency; and (b) systems that move through the lower latitudes, the direction of movement having a predominantly east-to-west tendency. Over India and Pakistan, the two types of systems are partitioned roughly by the zonal belt between 20° and 25°N. Over the Arabian peninsula westward-moving depressions are rare, but when they do occur, their northern limit does not usually go beyond 15°N.

The former class is associated with Mediterranean or Atlantic depressions or secondaries or tertiaries thereof, and has extra-tropical characteristics. Although some of these characteristics tend to become rather diffuse after long travel towards the east, especially in the case of the derivatives of the primary disturbances, it is rather remarkable that even in the state of marked modification during traverses through regions far away from the region of genesis of the disturbances, the original characteristics are more or less maintained. Thus, if a disturbance is marked by duststorms in an earlier phase, the same characteristics tend to be continued; rainy or snowy or thundery characteristics are often similarly maintained and carried forward. Temperature discontinuities such as would appear at a front tend to be wiped out on account of strong tropical insolation. But in the case of low pressure systems of western origin (these are known in India and Pakistan as "western disturbances"), it is often possible in winter and early spring to recognize some frontal structures associated with them.* The systems get largely occluded as they continue in their long travel. The 850 mb charts usually provide a good guidance for the location of the prevailing discontinuities. The existing position of the basic network in certain areas, however, sometimes hampers the tracking of the disturbances.

The latter class of low pressure systems appears to owe its origin to the storms and depressions in the China Sea or the adjoining regions of the Pacific. The maximum intensity of these disturbances invariably occurs over the sea areas traversed by the intertropical convergence zone. They weaken, through effects of surface friction,on entering land, and continue as depression or even as low pressure waves westwards until they get a chance of regeneration on coming over the sea again. As stated earlier, it is difficult to locate systematic temperature or dew-point discontinuities around these depressions and storms when they traverse the Indian seas.

The movements of depressions present interesting forecasting problems. West to east movements, confined to the higher latitudes, are sometimes modified into south-west to north-east, depending upon the location of anticyclonic cells at 300 and 200 mb levels. Apparent retrograde motions of depressions are sometimes noticed, but in most cases these can be attributed to one system being closely followed by another similar system, so that when the two appear to coalesce, the visible centre (dependent strictly on the availability of observations) seems behind the one located earlier. True retrogression of depressions thus appears to be an extremely unlikely event.

Depressions south of latitude 20°N present difficult problems. Lack of systematic temperature contrasts makes any extension of the Sutcliffe development theory (7) generally inapplicable. For prognosticating movements, neither the Fjörtoft technique nor the extrapolation method is altogether adequate to cover the majority of cases. In the main, therefore, guidance is drawn from climatology for forecasting movements, but even in this approach it is difficult to make a confident prognosis for a period beyond a few hours.

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* The warm front associated with western disturbances can normally be expected to be a region of stable stratification. However, in actual fact, this is not always so. A brief case study is presented as an appendix to this paper to illustrate this point.

The detection of small-scale depressions and cyclones presents a major synoptic problem. Experience of tropical charts shows that broad areas of cyclonic vorticity, which are normally associated with low pressure troughs, have often embedded in them a few distinct foci of accentuated vorticity, but the success or failure in resolving these foci depends upon the availability of data, especially ships' reports, and the suitability of the location of the reporting points is often fortuitous. The result sometimes is that the inference or diagnosis, instead of depending upon the values of the true natural parameters, becomes dependent upon an adequate or inadequate man-made network chosen and set up on the basis of organizational convenience rather than on the inherent nature of macro- and mesoscale synoptic phenomena. In such cases, a single additional observation may lead to a completely different assessment of a situation arrived at with confidence on the basis of routine observations.

Transfer of vorticity may occur from one part of an extended trough to another, giving the impression that one vortex is growing at the expense of a contiguous one. Although this feature has not received adequate attention in works on tropical meteorology,it appears quite possible that two mature cyclonic systems can co-exist while they are fairly close to each other. Conventional analysis sometimes highlights one system and at the same time ignores or down-grades the other to the status of a trough, on the grounds that some of the pressure and wind observations might not be quite reliable. Sometimes it is argued that it is not possible for a powerful system like a fully-developed cyclone to share the energy available in the field with another contiguous system of similar or nearby similar intensity. As evidence contrary to this argument,it may be mentioned that the co-existence of multiple typhoons in the China Sea within a distance of about five degrees of latitude is sometimes clearly observed.

Within a cyclonic system, like an extended trough, vortices occur in a variety of dimensions. The spectrum of the dimension is probably almost a continuous one, ranging from a few hundred kilometres to only a few hundred metres, and possibly further down, in the same scale of gradual transition, to the micro-physical scale. It embraces a range from the large tropical storm or hurricane to the tornado, the Cumulus cloud and the Cumulus shower. Limitations of observational network impose a severe restriction on detection and prognosis when the scale of the phenomena gets gradually narrowed down. However, a small dimension of a tropical cyclonic system by no means ensures that it would not prove, in its physical manifestations, to be a violent one, capable of causing loss of life and property. In the operational sense, therefore, the small-scale systems deserve as much attention as are given to major cyclones and hurricanes.

Orographic features play an important part in the generation, movement and dissipation of the low pressure systems, particularly the derivatives of the primary systems. In consequence, the orographic features also provide many "soft spots" in regard to the occurrence of rain and thunderstorms. The full understanding of the phenomena must necessarily depend on careful mesoscale analysis in addition to normal synoptic analysis, but a few broad features have become familiar on the basis of experience of charts and aircraft reports. For instance, small-scale winter depressions of considerable intensity sometimes generate on waves of cold fronts trailing from lows at higher latitudes, over the Gulf of Oman,which has marked orographic features almost on three sides, and over the Sinai peninsula. The north-east corner of the Mediterranean around Cyprus shows similar features. Movement of marked upper air troughs across the northern parts of West Pakistan and adjoining regions of India leads, under favourable conditions of moisture supply from the Bay of Bengal, to the generation of pronounced depressions in and around the Punjab area which causes extensive precipitation in the plains and snow in the Himalayas. High mountain ranges affect the movement of depressions in almost the same way as a "blocking" high. So far as maritime depressions and storms are concerned, their preference for continuing on water surfaces is well known. On this basis one can explain why such disturbances in the Bay of Bengal tend to choose river estuaries for moving inland. When the time of this movement is close to the time of high tide,much damage is caused by storm bores from the sea flooding the surrounding countryside up to considerable distances.

4. THE SOUTH-WEST MONSOON

The south-west monsoon is one of the major synoptic features of south-west Asia during the period between spring and autumn. Although this phenomenon has been studied by meteorologists for nearly a century, the understanding of its mechanism is still very imperfect. A considerable volume of literature on the subject has grown up (see item (8) in the list of references for a representative bibliography), but no definition which can be regarded as sufficiently comprehensive has so far been evolved in regard to the south-west monsoon. However, the one idea that has been sustained through the years is that the principal cause of the monsoon is differential heating, on account of the particular relationship of land and sea areas, and that all other manifestations arise from this primary cause.

The reason for the gap in our knowledge regarding the monsoon is that the phenomenon is principally a maritime one, and synoptic studies are beset with difficulties due to a perpetual lack of data over the extensive sea areas of the Indian Ocean, Arabian Sea and the Bay of Bengal, except for some mobile surface observations from ships and upper-air data from a very limited number of island stations. As a result of the gaps in the charts, it has often been difficult to trace the movements of the inter-tropical convergence zone in relation to the monsoon. The International Indian Ocean Expedition has made the first systematic attempt at observing the monsoon over the sea areas; their data would no doubt be of great help for a fuller understanding of the phenomena associated with the monsoon.

The genesis of the monsoon current is attributed to the activity of the dominant anticyclonic cells between latitudes 20 and 30 degrees in the southern hemisphere, apart from the effects of differential heating. Coming as it does from the southern winter, the air is cool, and it picks up a large amount of moisture due to the fact that it travels over several thousand miles of oceanic track. The pulsating nature of the stream, emanating from the anticyclonic "source" regions, is observable in the shape of fluctuations in the trans-equatorial transfer of momentum, and this is sometimes attributed to the activities of the cyclonic cells between the chain of anticyclones and the equator. However, the exact nature of the pulsations is as yet far from clear.

In the air-mass classification monsoon air belongs to the equatorial maritime category. The general impression that the monsoon current is a broad, dynamically stable, homogeneous and highly moist stream may, however, well prove to be an over-simplification of the nature of the phenomenon. It cannot be said that the mechanism of the formation of clouds and precipitation within the equatorial maritime air mass of the monsoon is fully understood. Observations from ships, aircraft and weather satellites, besides available synoptic data, show that there can be large differences in the cloud cover at different parts of the monsoon belt, and even in the vicinity of the equator there are occasions when the air is comparatively dry. Radiation measurements carried out with the help of TIROS satellites have provided additional evidence on the discontinuous nature of the cloud cover.* Evidently the stream is not as homogeneous in its thermodynamic structure as would appear from a few isolated observations, and this naturally leads the synoptician to look for evidence of marked subsidence of dry air from aloft over some parts of the stream. The advance of the monsoon current in May/June is found to synchronize with the generation of large amounts of convective clouds. Photographs recorded by TIROS have brought out this feature clearly.

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* The author is indebted to Mr. P. Krishna Rao of the United States Weather Bureau, for directing attention to this important point.

The strengthening of the monsoon is referential by an increase of the wind speed from the surface up to about 1.5 km. Quite often the strengthening of the monsoon appears like some impulsive action in the wind-field, leading to generation of vorticity, and follows the movement of small-scale troughs or waves in the monsoon stream (9). Strong winds appear in rather narrow belts, almost like a jet stream in the low levels, and this characteristic moves down-wind. When the troughs or waves approach the west coast of India, they usually appear as an off-shore vortex or trough, the corresponding coastal winds backing to S or SE from an initial SW or WSW position. Almost simultaneously the pressure gradient along the coast is accentuated and a sharp ridge appears along the west coast hills. Figure 2 illustrates the surface synoptic situation on a day of strengthening monsoon. The off-shore trough is a region of convergence which, accentuated by congestion of air on the windward side of the north-south barrier of the hills, leads to spells of heavy precipitation. By the time one such trough dissipates itself, another may approach from further up-wind, a feature of the oscillatory character of the monsoon rainfall. The troughs or waves can be traced as systematic isobaric ripples (especially if isobars are drawn at 1 mb intervals) in the interior of the peninsula also.* The trough lines thus obtained are usually regions of convective clouds or thunderstorms embedded, as it were, in an extensive field of Altostratus or Nimbostratus clouds.

The monsoon air is known for its capacity of producing extensive and heavy rain, but it is one in which it is not possible, within the lower four to six kilometres, at any rate, to locate fronts of the type one is familiar with in the higher latitudes. It is rather important to take note of this fact, for in the daily analysis in the extra-tropical latitudes nearly all precipitation and convective phenomena are directly or indirectly attributed to fronts. Monsoon thunderstorms also cannot be placed in the "air-mass thunderstorm" category (10), for the diurnal variation of temperature is quite small except during "breaks" in the monsoon. It is therefore of particular interest that even in the single air-mass phenomena in the monsoon, convective clouds often occur in well-defined lines with vivid similarity in appearance to cold frontal clouds. Figures 3 (a) and 3 (b) show radar photographs made at Bombay, in which sections of the linear distribution of convective precipitation cells appear. Aircraft reports also occasionally mention lines of towering Cumulus or Cumulonimbus clouds over the Bay of Bengal and the Arabian Sea in the monsoon season. It appears possible that low-level convergence, associated with shallow troughs in the pulsating monsoon current, contributes to the formation of these pseudo-fronts, especially if suitable upper divergence is concurrently present. Pulsations in the current and the prevailing vertical wind shears would manifest themselves in fluctuations in the transfer of momentum and resultant concentrations of vorticity along "wave fronts" (11). The latter mechanism may comprise medium and mesoscale trough lines. Although quantitative determinations are not feasible due to lack of data, it appears that the convergence over the trough lines offers the required "trigger" for uplifting of the convectively unstable air in order to form cumuliform clouds arranged as in a front.

Other noteworthy features of the monsoon air mass are :

(a) Concentration of low clouds (which are usually more cumuliform than stratiform, contrary to common synoptic notions) over a narrow belt 50 to 100 miles in width along the coast line, while much of the sky over the sea area farther away, pervaded fully by monsoon air, is clear or only partly clouded. Sometimes large parts of the sea area are covered by Cirrostratus clouds only. An interesting feature is the perceptible turbulence in this Cirrostratus, as experienced by aircraft.

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* This technique, comprising 1 mb isobars drawn with due weightage to surface winds for locating trough lines, was developed and successfully used at Safdarjung Airport, New Delhi, by Dr. P. Koteswaram of the Indian Meterorological Service during 1946-1947.

(b) Except after showers, the visibility within monsoon air is rarely very good. This is due to an almost permanent layer of haze which sometimes extends up to five kilometres under a clear or lightly-clouded sky. The top of the haze layer is clearly seen when observation is made from aircraft at a short height above it. The sky aloft is deep blue. The layer of haze often has crests of small Cumulus clouds, like waves, which have no well-defined base but seem to grow by gradual thickening of the haze itself. This feature is clearly seen over the sea.

(c) Lines of large Cumulus or Cumulonimbus clouds often appear to generate at the medium cloud level, i.e. around three to four kilometres. This again is contrary to commonly accepted notions.*

(d) On the sea there is a marked swell which is characteristic of the season. The nature of agitation of the sea surface is governed by the prevailing winds.

(e) The sea surface temperature shows considerable variations, but it has not been possible to establish any systematic correlation between the temperatures and the observed regions of strong and weak monsoon.

(f) Monsoon depressions form generally over regions of low-level convergence topped by upper divergence (13). On the majority of occasions, these depressions do not appear to develop the violence of small-core cyclonic systems encountered in the pre-monsoon and post-monsoon transition months. It should be noted, however, that although the absence of violent winds is observed in the majority of cases, the development of short-lived systems with small cores of violent winds is by no means unknown, but it may not be easy to detect them. Monsoon depressions are the principal agents for producing extensive and locally heavy precipitation over the northern and central parts of India and in Pakistan. The heavy rain is generally confined to the SW quadrant of these depressions.

(g) The appearance of the south-west monsoon synchronizes with that of the easterly jet-stream over the lower half of the Indian peninsula at heights varying between 200 and 100 mb.

Although the lack of data over the Arabian peninsula has somewhat conditioned us to believe that the monsoon probably does not penetrate deep enough into that area, the facts may very well be to the contrary. Figure 4 shows the clouds reported by TIROS satellite during a phase when the seasonal low over the Oman peninsula was well marked. A rather similar feature is visible occasionally over the southern part of the Red Sea and adjoining areas of Ethiopia and the Arabian peninsula when the monsoon air penetrates into these areas under the influence of an activated low pressure area over Somalia and southern Ethiopia. In Yemen and Aden the formation of Stratus is a common feature in the morning, while high cumuliform build-ups and thunderstorm activity occur over the mountains during evening and night.

5. BREAKS IN THE MONSOON

A remarkable feature of the south-west monsoon is the phenomenon of "breaks" when with the shift of the seasonal trough from the Gangetic valley northward to the vicinity of the Himalayan belt, there is an abrupt decrease of rainfall and cloudiness over the peninsula and the greater part of north India except, perhaps, along the Himalayan foothills themselves where sporadic heavy falls sometimes occur. The breaks are associated with active western

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* In an interesting paper, Ramage (12) has discussed the occurrence of a cyclonic circulation at 500 mb level which weakens both upwards and downwards from the middle tropopause, and brought out some features of monsoon rainfall from this model.

disturbances travelling along the Himalayan latitudes. In the initial stages of the break the average moisture content of the air generally remains quite high, although it fails to precipitate. This fact suggests that with the change of the synoptic flow pattern characterizing the break, there is a major modification of the pattern of convergence and vorticity over the peninsula (14).

It has been suggested by Ramaswamy (15) that during breaks in the monsoon, the middle latitude trough in the westerlies increases in amplitude and gets retarded as it moves into the Tibetan plateau. When the Tibetan anticyclone is weakened or broken up at the 500 mb level, the easterlies south of the Himalayan range withdraw fully or partially. The southward movement of the upper trough is a feature of unseasonal western disturbances referred to earlier. The westerly subtropical jet stream, which retreats to the latitudes of Russian Turkestan during the summer monsoon, returns to the south of the Himalayas during breaks in the monsoon. In effect, it is a temporary return to spring or early summer conditions.

6. SOME MICROMETEOROLOGICAL FEATURES

The micrometeorological standpoint is almost as important as any other synoptic approach in locust studies. It would therefore be appropriate to conclude this general survey with a little discussion on some microclimatic features of the tropical region.

The inherent limitations of micrometeorological observations are well known. While observations on the synoptic scale comprise statistical averages of prevailing values of the meteorological elements, which undergo large fluctuations in time and space due to eddies, micrometeorological values of the same elements, beyond certain refinements of scale and degree of sensitivity of measuring instruments, start being dependent upon the measuring techniques or probes employed. This feature introduces a measure of uncertainty in the observations and consequently in our understanding of the nature of the phenomena, and a stage is rapidly reached in a diminishing scale of phenomena when the instrumental devices physically interfere with the phenomena they are employed to measure. Unless one is reconciled to fairly broad limits of instrumental error, it becomes extremely difficult to arrive at reliable data on a reasonably acceptable basis. It is not possible, for example, to analyse an eddy in relation to wind and temperature distribution unless the scale in which the eddy occurs has a certain minimum dimension. This limitation is well known in physical problems (16). The nature of the relationship between small- and synoptic-scale phenomena was aptly described by L.F. Richardson as:"Big whirls have little whirls that feed on their vorticity, and the little whirls have lesser whirls, and so on to viscosity".

Insolation and consequent fluctuations of temperature are the chief factors leading to the formation of turbulent eddies. These, together with the effects of wind and convergence, are known to provide the steps leading to the eventual long-distance migrations of locust swarms. As the effects of insolation commence at the surface, a discussion of behaviour of temperature near this level might be interesting to assess the extent of hydrostatic instability generated there.

Mal, Desai and Sircar (17) made temperature measurements at different heights at Karachi, using ventilated electric-resistance thermometers. They presented their data in terms of yearly percentage frequencies of lapse rates of various magnitudes, and these are reproduced in Table I.

It will be seen that in the layer 1.2 to 17 m (4 - 56 ft) above the ground, extremely strong lapse rates are set up on a substantial number of occasions, and the autoconvection gradient is easily attained and exceeded. In such conditions of hydrostatic instability, the air layer adhering to the ground probably splits up into a cellular structure (as in

Bénard cells) and starts an upward movement. Minor irregularities of the surface and the miniature thermals affect the horizontal streamline flow of the air, giving rise to the phenomena of gusts and lulls and eddies.

Table 1

Yearly percentage frequencies of lapse rates of various magnitudes in Karachi

Lapse rate (deg.C/100m)	31.7	23.9	17.2	11.7	7.2	3.9	1.7	0.6
Layer 4-56 ft (%)	0.1	0.4	2.0	8.5	13.0	13.0	12.0	7.1
Layer 56-156 ft (%)	-	-	-	-	0.6	2.5	24.1	23.7

Lapse rate (deg.C/100m)	-0.6	-1.7	-3.9	-7.2	-11.7	-17.2	-23.9	-31.7
Layer 4-56 ft (%)	6.6	5.3	7.6	6.7	6.2	6.4	3.6	1.1
Layer 56-156 ft (%)	16.7	7.9	7.3	7.2	6.3	2.7	0.7	-

Geiger (18) has quoted Best's results (based on measurements made in England) that between 120 cm and 30 cm above the ground at 12 noon, even in the middle of June, the temperature gradient is 77.2°C/100 m, and 683.3°C/100 m between 30 cm and 2.5 cm. These values are not very meaningful if reckoned in 100 metre units, but they nevertheless indicate a measure of very great temperature contrast, prevailing over short distances over the ground surface, in relation to the dry adiabatic lapse rate of 1°C/100 m and the autoconvection gradient of about 3°C/100 m. Geiger has also given an estimate of the diurnal variation of temperature in the following language : "If a meteorological station located at 2 metres above the ground observes a daytime fluctuation of 10°C, the value at 1 metre increases to about 15°C, at 10 cm to about 20°C and at the ground, to a value of 30°C or even 40°C".

Figures 5 (a) and 5 (b) show the average temperatures recorded by the Agrimet Observatory at Poona (India) above and below the surface at the maximum and minimum temperature epochs. The subsoil temperatures show that the diurnal variation decreases with the increase of depth, and is quite small at a depth of about 15 cm. This property should be valid at other stations as well and it appears to explain why, purely for biological survival and growth, the laying and hatching of locust eggs occur at this depth. It should be observed that the temperature gradients are very much stronger in the shallow subsoil layers than they are above the surface "skin". The reason obviously is that while the gradients of air temperature have a chance of getting moderated through eddy diffusion and small-scale convection, the subsoil temperature contrasts which get established through the process of conduction only, are not easily affected. The conductivity of the soil being poor, the distribution of heat from insolation remains restricted mainly to the upper layers. It will also be noted that between the maximum and minimum temperature epochs, there is a reversal in the direction of the temperature gradient.

The variations of humidity are less clearly defined than the variations of temperature. However, basing again on agrometeorological observations made at Poona, the humidity generally increases with height (up to about 4 m above the surface, for which measurements were systematically made) at the minimum epoch from the end of October to April, and decreases with height from May to the beginning of October. At the maximum epoch the relative humidity decreases with height in all months.

The percentage of soil moisture, another important parameter in locust breeding, fluctuates widely during the year under Indian conditions. Data of Agra, collected during 1962-1963, show that during the non-rainy months the moisture content at a depth of 7.5 cm is about 0.5 to 1.5 gm per 100 gm of dry soil, and at a depth of 15 cm it is between 2 and 4 gm per 100 gm of dry soil. During the height of the monsoon, the moisture content at both these levels rises to 10 to 12 gm per 100 gm, but here again the values can be highly fluctuating not only in relation to the day-to-day rainfall but also to the locations of the observing spots.

However tentative the above data may be, they point to the need for comprehensive micrometeorological observations at suitable locations in the locust belt, e.g. southern Iran, Baluchistan, Sind, Rajasthan, etc.

As suggested earlier, some of the micro-scale variations of the meteorological elements may be both the cause and the effect of small-scale atmospheric eddies. It is of great importance to make systematic observations, to the extent possible, of eddies in their natural state, i.e. with the minimum vitiation by ground-based instruments set up to observe them. From this standpoint, a study of the behaviour of individuals or groups of locusts in a swarm can be fruitful in view of the fact that the evidence up to now generally points to an absence of any flight-planning instinct in locusts.

A technique of multiple-exposure photography developed by Sayer (19) for recording the movements of locusts has brought out most interesting results. It holds out possibilities for the measurement of the dimensions of small-scale eddies by measuring drifts at different parts of a swarm. The effects of turbulence and patterns of airflow on locust behaviour have been studied in considerable detail (20, 21, 22, 23). If similar studies are organized in the locust areas of south-west Asia, much valuable information regarding small-scale eddies and turbulence can no doubt be collected. As there are few direct methods for observing the eddies (unless they take visible form, in the shape of dust-devils for example), synopticians and micrometeorologists may stand to gain much from locust studies.

7. ACKNOWLEDGEMENTS

The author wishes to express his grateful thanks to the Secretary-General of the World Meteorological Organization for providing an opportunity to present this discussion at the WMO/FAO Seminar on Meteorology and the Desert Locust; to the Director General of Observatories for permission to incorporate some charts and data in this paper; to Mr. M. Gangopadhyaya, Director of Agricultural Meteorology, Poona, for providing a large volume of micrometeorological data for reference, and to Mr. H.J. Sayer of the Desert Locust Control Organization for Eastern Africa for offering facilities for familiarization with the organization's work on meteorology and the Desert Locust at Asmara (Ethiopia) and for valuable discussions on the subject. Thanks are also due to Mr. E.C. Chacko of the Bombay Meteorological Office for assisting in the preparation of some of the charts included in this paper.

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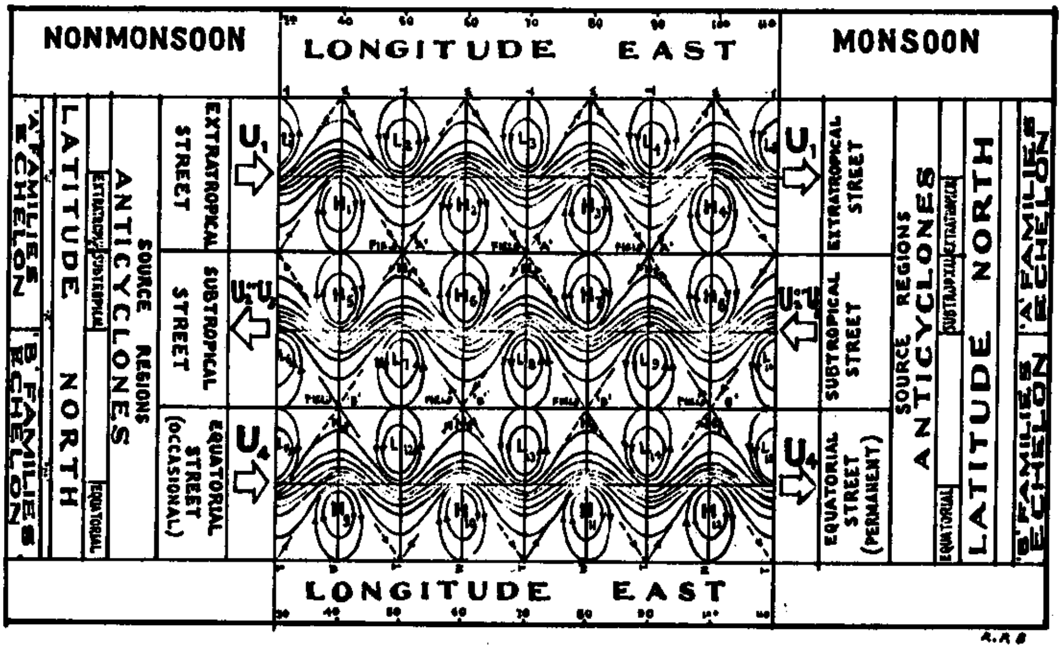

Figure 1 (a) - Atmospheric Vortex Streets (S.N. Sen).

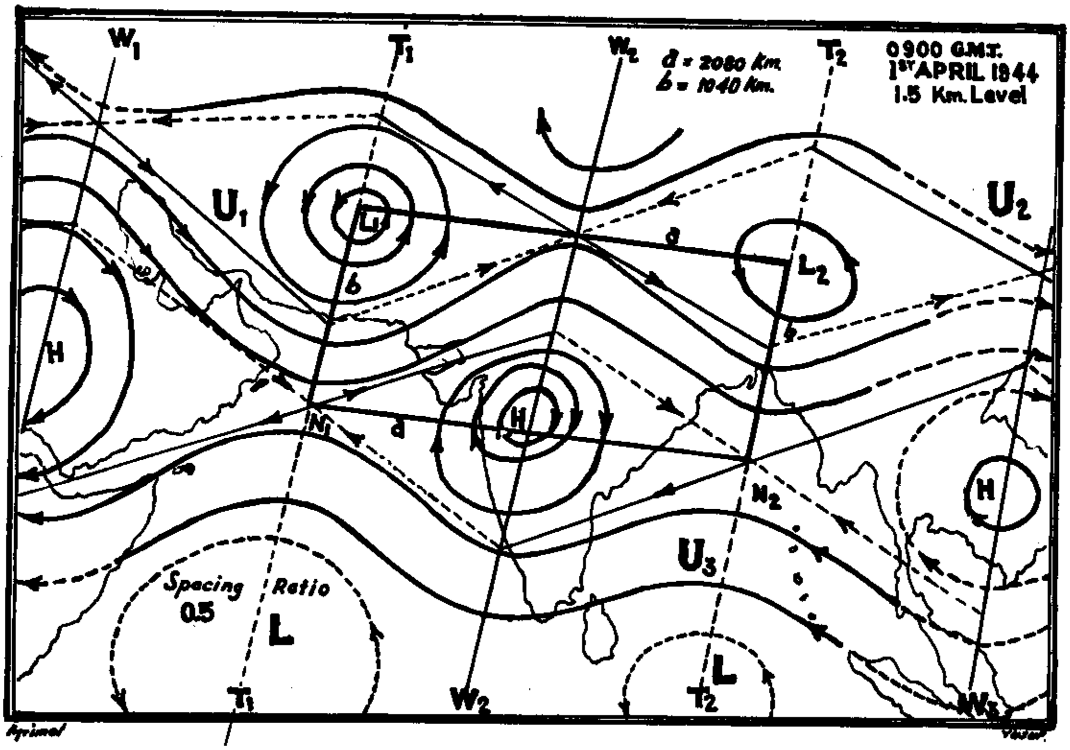

Figure 1 (b) - Vortex Streets drawn on upper air charts with spacing ratio of the streets indicated (S.N. Sen and V. Ganesan).

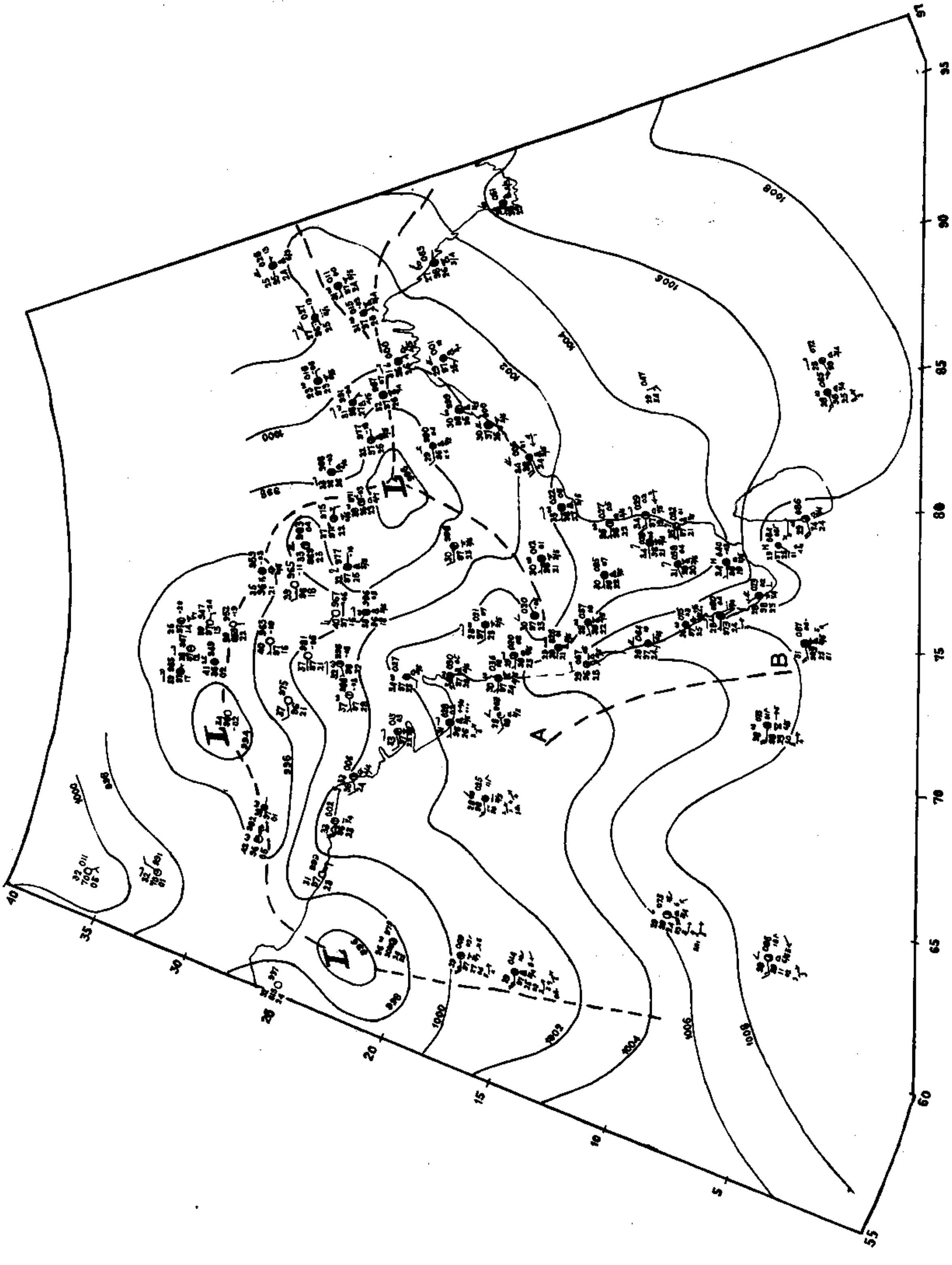

Figure 2 - Synoptic chart of 0600 GMT, 21st June 1964, showing formation of off-shore trough prior to the strengthening of the moonsoon.

Figure 3 (a) - Radar photograph (50 nautical miles range) made at Bombay at 0722 IST (0152 GMT) on 9 August 1963.

Figure 3 (b) - Radar photograph (50 nautical miles range) made at Bombay at 0630 IST (0100 GMT) on 1 September 1963.

Both the photographs show the linear formation of precipitation cells in the monsoon period. The line of echoes retains its shape, sometimes for 1 to 2 hours, and while passing over the station produces heavy showers with or without thunder and accompanied by squally winds.

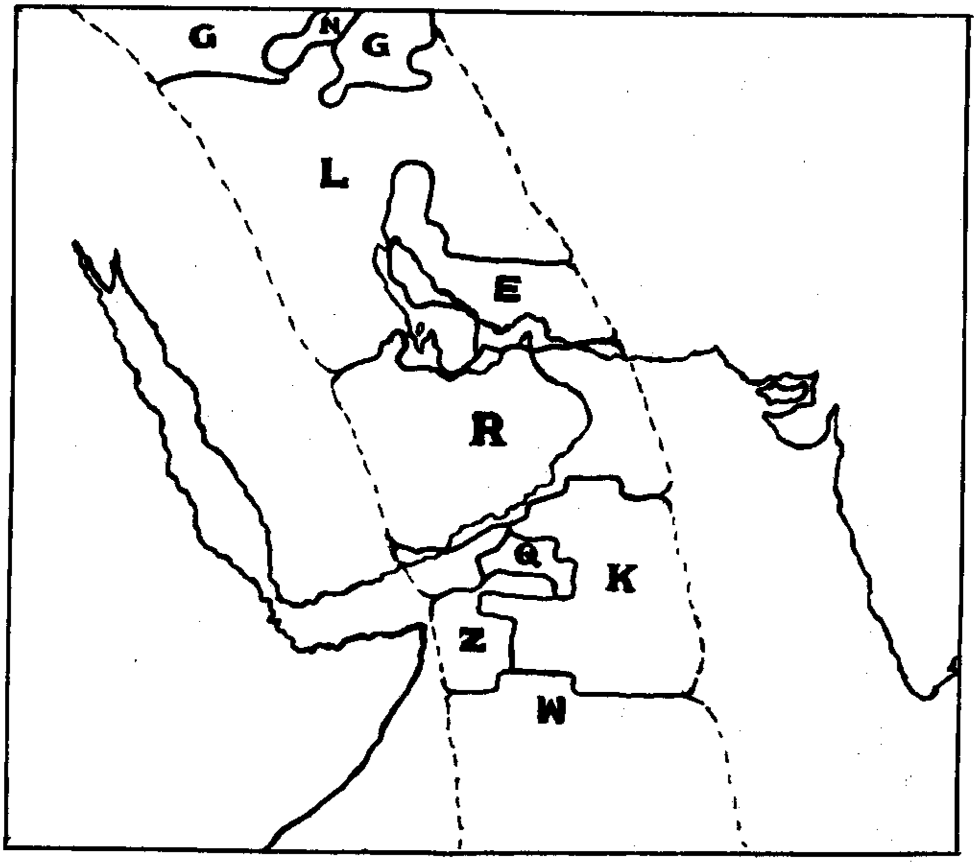

Figure 4 - TIROS VII Nephanalysis, orbit 5545, at 1223 GMT on 28th June 1964, showing cloud formations over Oman Peninsula and the interior of Saudi Arabia.

G - Broken (5-7/8) cumuliform.
N - Broken to overcast Cb (embedded) heavy.
L - Clear to scattered, unknown.
E - Broken (5-7/8) cumuliform and cirriform.
R - Broken (5-7/8) Cb (embedded).
Z and Q - Broken (5-7/8) unknown, thin.
K - Broken to overcast cumuliform and cirriform.
W - Broken (5-7/8) cumuliform and cirriform bands.

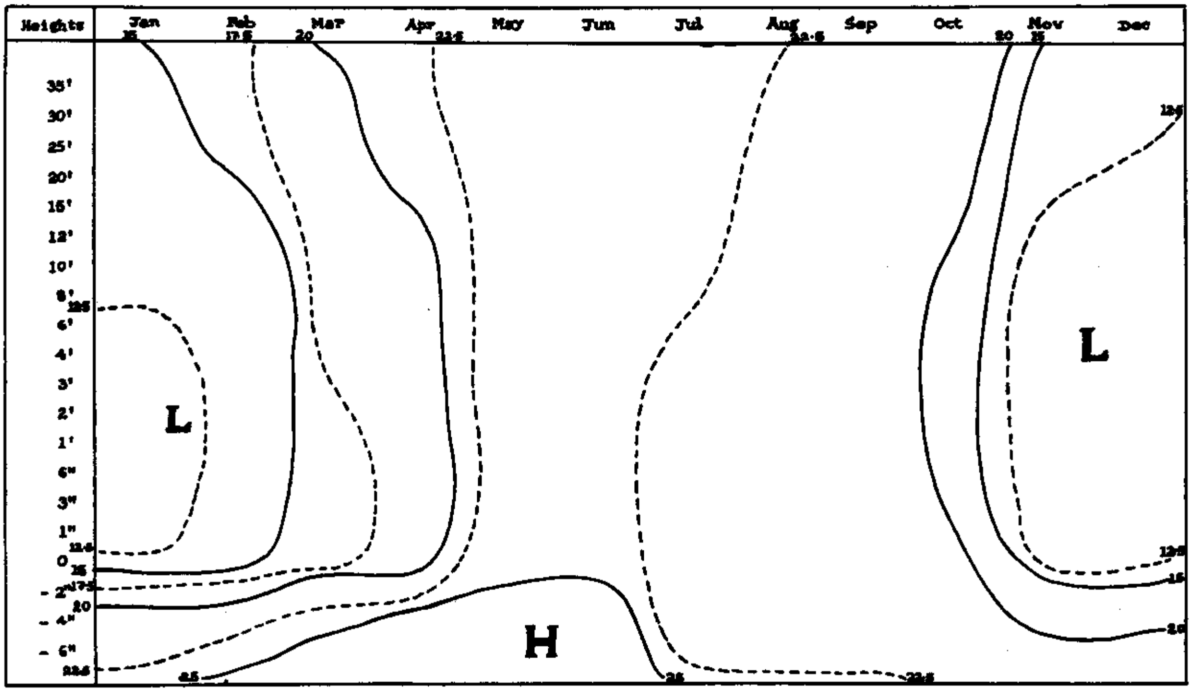

Figure 5 (a) - Poona. Microclimate in the open - Minimum Temperature Epoch. Mean daily temperature in °C (1955).

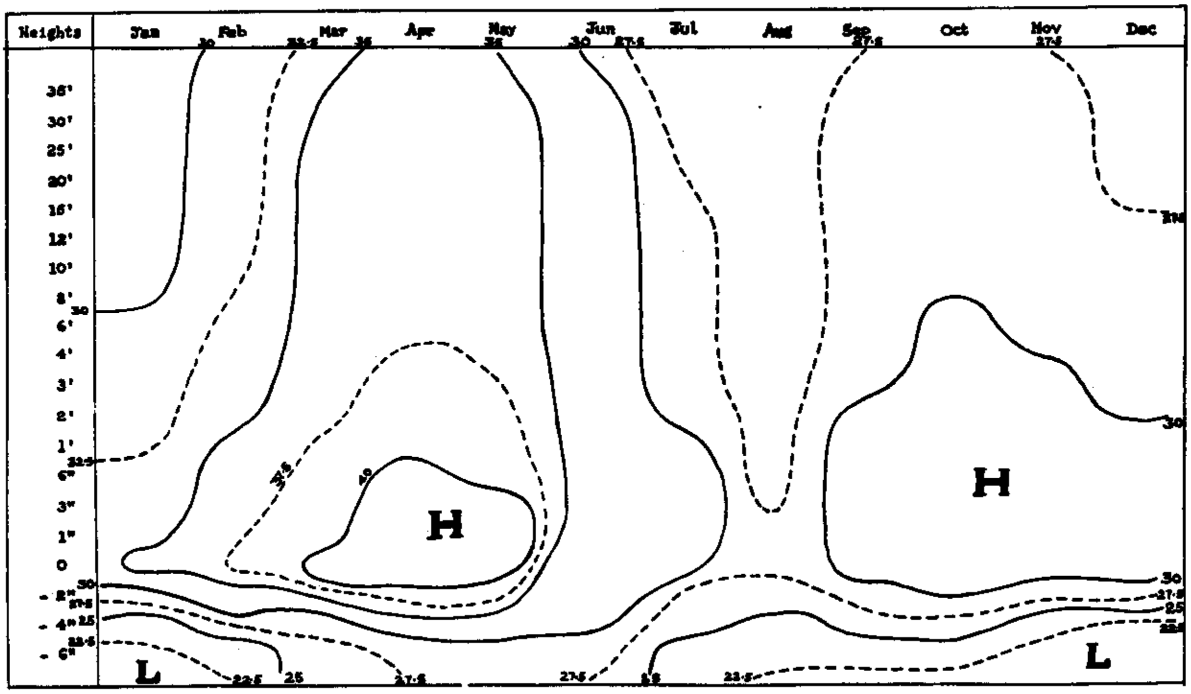

Figure 5 (b) - Poona. Microclimate in the open - Maximum Temperature Epoch. Mean daily temperature in °C (1955).

APPENDIX

Instance of low-level turbulence in clear air in association with a western disturbance

In a moving western disturbance, the region to the east of the disturbance is normally the domain of the warm front, if it has significant extra-tropical characteristics. This region is generally marked by stable, stratified conditions. The absence of strong convective activity in the idealized warm front leads to the expectation that flights through regions due east or south-east of a western disturbance should be reasonably smooth. However, in individual cases, the structure of the discontinuity and the nature of stability can be totally different from idealized conditions, and the actual weather experienced contrary to expectations. The purpose of this appendix is to bring out the circumstances leading to one such case.

The writer had an interesting experience of turbulence in a western disturbance situation. The particulars of the flights are given below. A part of the route was flown at night, but cloud observations were facilitated by some moonlight.

Stages of flight : Bombay-Nagpur-Delhi-Lucknow-Allahabad.
Date : 8-9 March, 1963.

(a) Sector : Bombay-Nagpur (BMB-NGP).
Aircraft : DC 4.
Time of departure : 2215 IST (1645 GMT), 8 March 1963.
Cruising altitude : 10,000 ft.
Weather : Fair, with small amounts of Cirrus towards Nagpur.
Turbulence : Not perceptible.

(b) Sector : Nagpur-Delhi (NGP-DLH).
Aircraft : Viscount.
Time of departure : 0230 IST of 9 March (2100 GMT of 8 March) 1963.
Cruising altitude : 14,000 ft.
Weather : Small amounts of Cirrus to latitude 25°N. Clouds rapidly increased to 8 octa Altocumulus below aircraft, tops about 12,000 ft (as estimated). 5-8 octa Cirrus and Cirrostratus above. No low clouds observed. Delhi overcast with Ac, As, base about 10,000 ft at the time of landing (about 0430 IST of 9 March, 2300 GMT of 8 March).
Turbulence : Slight to moderate turbulence in clear air north of latitude 25°N.

(c) Sector : Delhi-Lucknow-Allahabad (DLH-LKN-ALB).
Aircraft : DC 3.
Time of departure : 0730 IST (0200 GMT) of 9 March 1963.
Cruising altitude : 5,000 ft.
Weather : Mainly overcast with Altostratus and small amounts of Altocumulus, base approximately 10,000 ft. No low clouds at all; there appeared to be a high cloud cover as seen now and then through breaks in the medium clouds. There was extensive haze between Delhi and Lucknow. Visibility improved slightly and the cloud cover decreased to about 6 octa between Lucknow and Allahabad.
Turbulence : Flying became rough within about 10 minutes of take-off. All passengers had to fasten their seat-belts. Turbulence rapidly increased and became violent, and the aircraft pitched and

> rolled almost continuously. A pile of boxes stacked in the rear of the aircraft was tossed on the floor. One or two small articles kept in the overhead racks were thrown out. The hostess had great difficulty in moving about in the cabin to deal with air-sickness. This state lasted for about 90 minutes, until about ten minutes before the landing at Lucknow. The general pattern of the sky did not undergo much change over the Lucknow-Allahabad sector. After a short refuelling halt at Lucknow, the turbulence was surprisingly mild, and seat-belts were soon unfastened.

Discussion

Figure 1 (a) shows the three stages of the flight. Stage (a) of the journey showed nearly normal conditions for March. The latter part of stage (b) and stage (c) can be said to have been under the influence of the western disturbance the position of which is shown in the synoptic chart of 0300 GMT of 9 March (Figure 1). The western disturbance had an associated trough extending from Baluchistan to Rajasthan and a marked upper trough. The pressure gradient was steep over Punjab, north-west Uttar Pradesh and south Rajasthan. Jet stream activity was pronounced over the area of the disturbance at a height of 300 mb. A rather sharp wind discontinuity lay close to the Delhi-Lucknow route up to about 1.5 km (Figures 2 (a) and 2 (b)). The air was characterized by low moisture content in the lower levels and had nearly dry adiabatic lapse rate. These features are by no means uncommon in the spring season in Uttar Pradesh.

The time of sunrise over the Delhi-Allahabad sector was between 0620 and 0640 IST (0050 and 0110 GMT). The third stage of the flight was too early in the day and the sky was too cloudy for strong surface heating and consequent turbulence due to thermals. The violent turbulence occurred in the absence of low-level convective clouds, apparently due to the lack of moisture in the lower levels.

At 0000 GMT on 9 March there was a region of rather strong horizontal convergence to the south-west of the Delhi-Lucknow sector (Figure 3 (a)), while there was a strong gradient of relative horizontal vorticity across the route. These two features are significant in explaining the incidence of severe turbulence in a weak wind-field over an almost perfectly flat terrain.

Clear-air turbulence, which is basically a mesoscale phenomenon, has a close relationship with the vertical wind shear. Based on Sasaki's results (1), a rough guide is available (2) in the following form :

Vertical wind shear	Degree of clear-air turbulence
6 knots/300 m (1000 ft)	Moderate
10 knots/300 m (1000 ft)	Severe

Figures 4 (a) and 4 (b) show the vertical structures of the winds at Delhi, Lucknow, Allahabad, Bereilly and Gwalior, respectively, at 1200 GMT on 8 March and 0000 GMT on 9 March. The winds generally show a veering and strengthening with height. The vertical wind shears are quite pronounced at Delhi, Lucknow and Bereilly, and less so at Allahabad and Gwalior. From the structure of the winds, it appears quite likely that the entire column up to 10,500 or 12,000 m (35,000 or 40,000 ft) over the Delhi-Allahabad route was characterized by varying degrees of turbulence on 8 and 9 March 1963.

The values of Richardson's Number based on the 0000 GMT upper-air observations on 9 March are as follows :

Height	Delhi	Lucknow	Allahabad	Bereilly	Ambala
450 m (1,500 ft)	0.62	19.53	0.38	-	-
750 m (2,500 ft)	0.42	2.05	1.24	-	-
1,200 m (4,000 ft)	0.77	0.48	1.54	0.13	0.25
1,800 m (6,000 ft)	1.12	0.65	1.59	-	-

It is rather interesting that on the Delhi-Lucknow sector the values at 1,200 m (4,000 ft) are substantially lower than at Allahabad. Evidently, the turbulence on the northern side of this route would have been quite intense.

The medium cloud cover and the surface temperature distribution would have perhaps justified the location of a warm front near the Delhi-Lucknow route. The turbulence encountered would, however, make one seriously doubt whether it is at all worth while to consider the analysis in terms of fronts. Evidently, over these latitudes there are large modifications in the structures of the fronts if viewed against their idealized structures.

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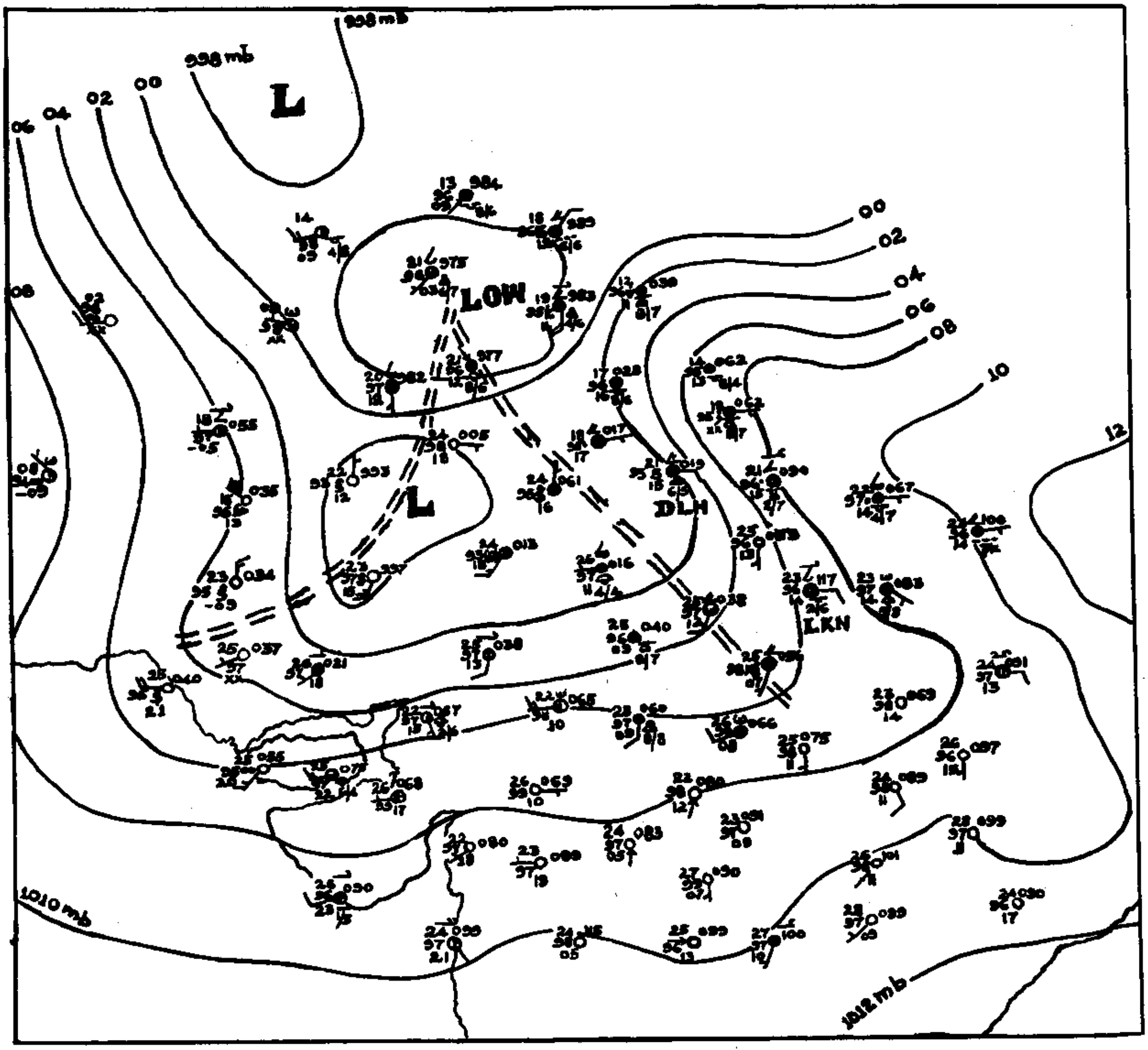

0300 HRS. G.M.T. ON 9-3-1963

Figure 1 - MSL synoptic chart of 0300 GMT, 9 March 1963. The surface wind discontinuities are drawn by dotted lines.

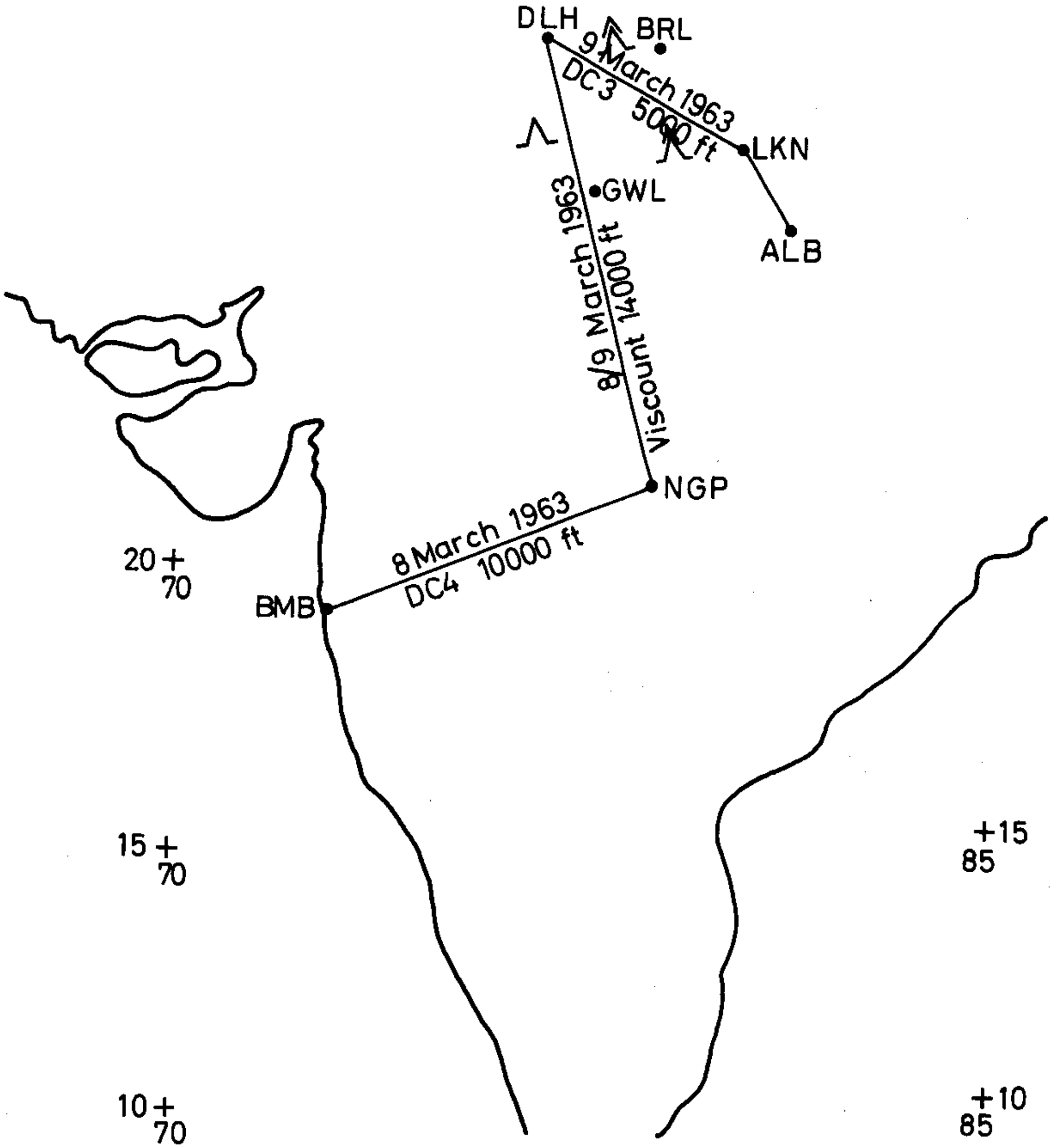

Figure 1 (a) - Map showing routes of flights.

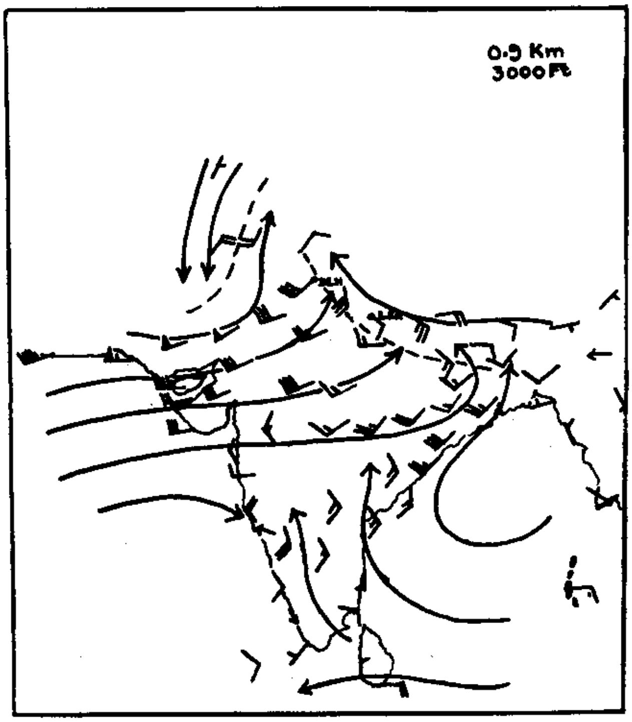

Figure 2 (a) - 0.9 km streamlines at 0000 GMT on 9 March 1963.

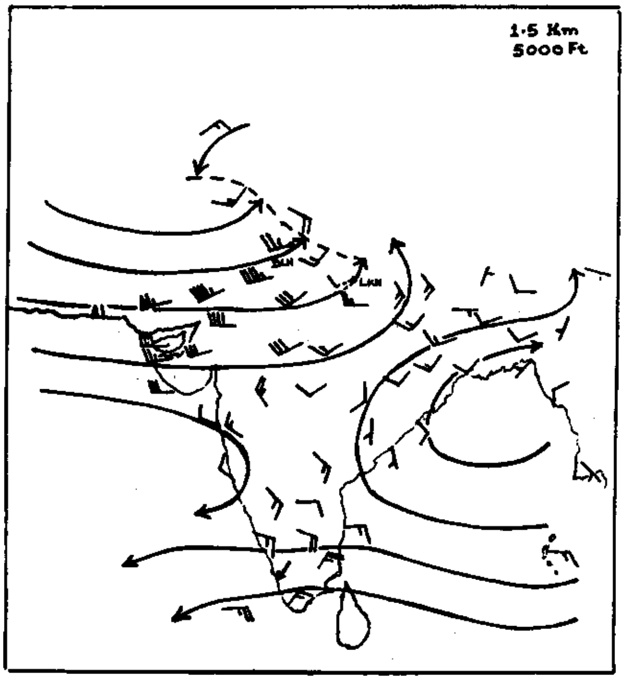

Figure 2 (b) - 1.5 km streamlines at 0000 GMT on 9 March 1963.

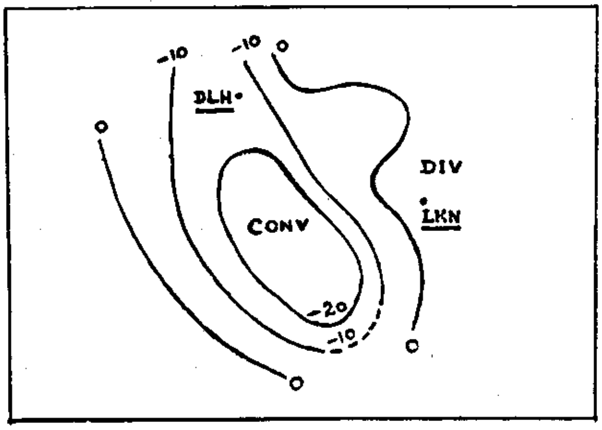

Figure 3 (a) - Pattern of divergence at 1.5 km level at 0000 GMT on 9 March 1963.

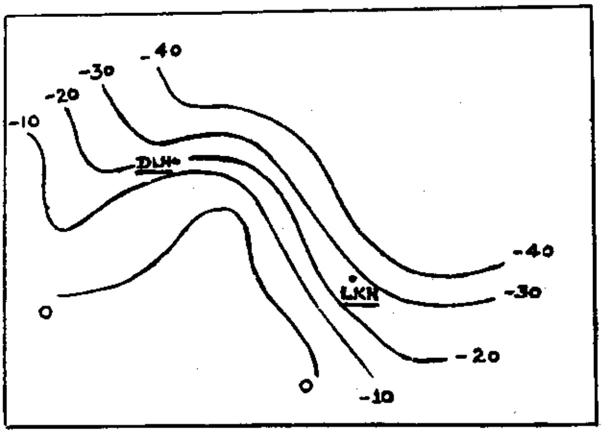

Figure 3 (b) - Pattern of relative vorticity at 1.5 km level at 0000 GMT on 9 March 1963.

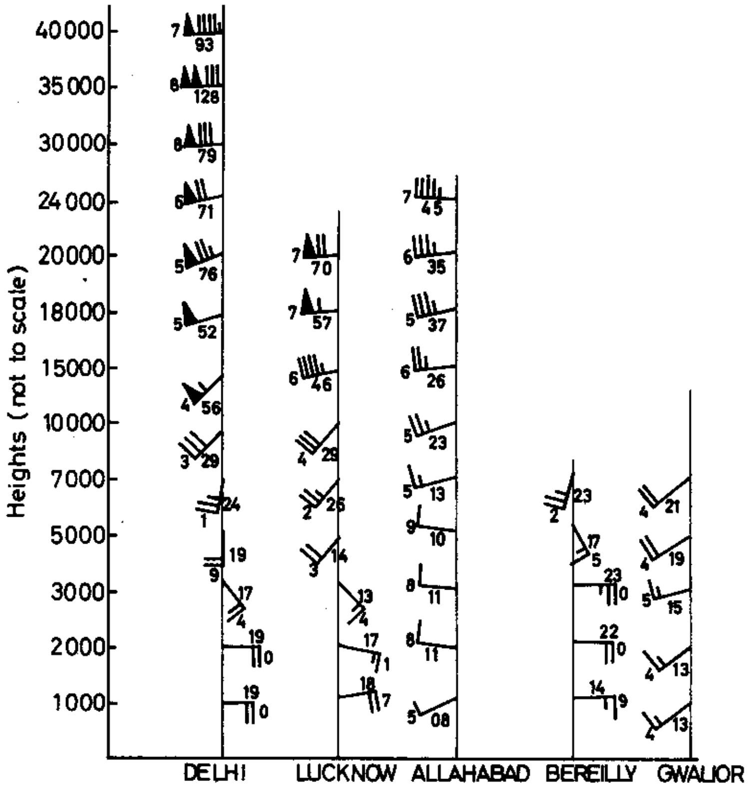

Figure 4 (a) - Upper winds at 1200 GMT, 8th March 1963.

NOTES :

(1) Figures at the middle of the arrows indicate speed in knots.

(2) Figures at the end of the arrows are the key figures for wind direction.

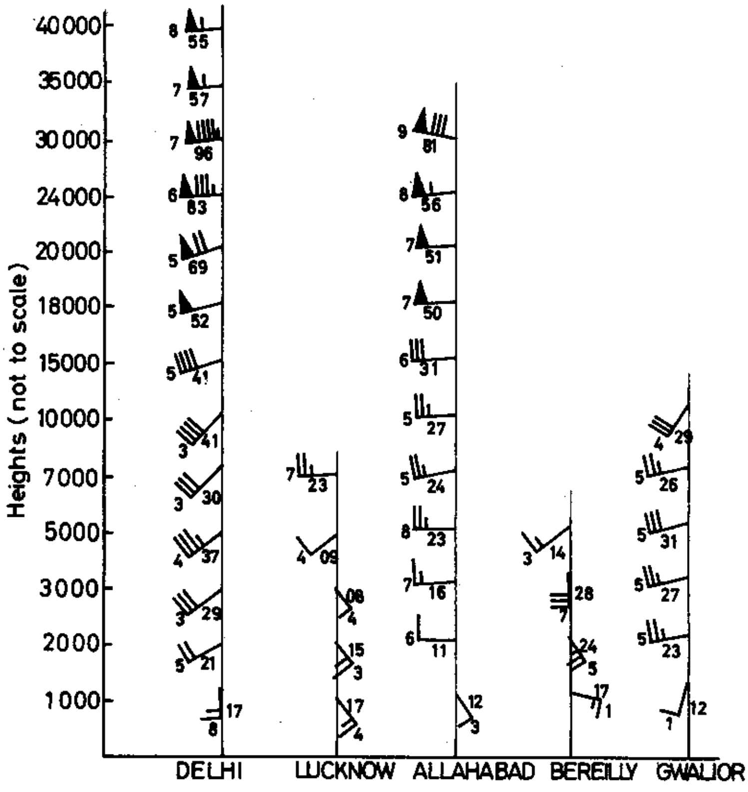

Figure 4 (b) - Upper winds at 0000 GMT, 9th March 1963.

STUDY OF A CYCLONIC SPELL IN THE INDIAN SEAS

by

S. Mazumdar

Abstract

In the second half of May 1963 two severe cyclonic storms of small extent developed almost concurrently in the Arabian Sea and the Bay of Bengal. The Arabian Sea storm was the better documented of the two, for it was probed by aircraft and also photographed by the TIROS VI satellite. It struck the Arabian coast near Salala on 27 May and thereafter weakened and moved away towards WSW. Reconnaissance flights subsequently made over the Arabian peninsula brought information about standing water at many points in the coastal strip and elsewhere, and this has been of some indirect guidance for assessing the nature of precipitation caused under the influence of the storm. An interesting feature brought out by these flights was that, unlike an earlier case, there was apparently no appreciable accumulation of locusts due to the storm. The Bay of Bengal cyclone crossed the coast between Barisal and Chittagong on 29 May. It caused extensive loss of life and property in East Pakistan and the adjoining parts of India. The main synoptic features of the spell are discussed in the paper.

1. SOURCES OF DATA

The analysis of the storms is based mainly on the weather charts and inferences of the India Meteorological Department. Supplementary information used for the study of the Arabian Sea cyclone consists of the following :

(a) TIROS VI nephanalysis from the United States Weather Bureau (USWB), Washington;

(b) TIROS VI photographs and interpretations obtained through the courtesy of the Anti-Locust Research Centre, London;

(c) Reconnaissance flight data of the USWB Research Flight Facility (RFF) aircraft pertaining to the 22 and 24 May, and plotted data made available by the Anti-Locust Research Centre, London;

(d) Hourly observations of Arabian coastal stations and data of reconnaissance flights made by RAF Shackleton aircraft, provided by the Meteorological Office, Aden;

(e) Data of research reconnaissance flights organized by the Desert Locust Control Organization for Eastern Africa and the United Nations Special Fund Desert Locust Project, made available by the Anti-Locust Research Centre, London;

(f) Logs of S.S. Saudi, Jaladhruv, Jaladwega and Mohammedi and a few other ships that operated in the Arabian Sea during the cyclonic spell;

(g) A report from an Air-India flight.

2. MAIN FEATURES OF THE BAY OF BENGAL CYCLONE

There was evidence of a succession of low pressure waves from east to west along the zone between latitudes 3° and 10°N. Most of them moved into the Indian peninsula and beyond in the form of troughs. Lack of data handicaps firm inferences, but the circumstantial evidence indicates that one of these low pressure waves (16 or 17 May) was the starting point of the Arabian Sea cyclone (Figure 1). Between 0000 GMT on 21 May and 0000 GMT on 22 May, a depression appeared to have formed with a small-cored centre near latitude 5°N, longitude 91°E. Aircraft observations over the area of the disturbance were not available, but it appears both from climatology and the subsequent behaviour of the system that the depression had concentrated into a cyclonic storm sometime between 0000 and 1200 GMT on 23 May. The storm took a nearly northward course, recurving NNE-wards as it passed into East Pakistan on the evening of 28 May.

Except over the latter half of the course of the storm, ships' observations were generally few. In keeping with the normal characteristic of pre-monsoon and autumn cyclones in the Indian seas, this storm had a small extent. Although these storms can develop great violence, quite often even close-by ships' observations do not succeed adequately in revealing their intensity or even their existence. A chance ship in the close vicinity of the core may enable the synoptician to spot the storm, but the tracking of the storm in subsequent charts presents a problem, as ships move away for safety from the area affected. These handicaps were evident during the course of the Bay storm. The track shown in Figure 1 is the best estimate that could be made with the available observations.

When the cyclone struck the Chittagong coast, a surface wind of between 90 and 100 mph blew for about half an hour. The highest gust speed recorded at the station was 120 mph. There was no significant tide or storm wave at Chittagong associated with the storm. Although storms rapidly weaken on crossing the coast, the Bay storm apparently proceeded far into the interior with unabated fury.

According to one investigation [3] the estimated lowest surface pressure at Chittagong and Cox's Bazar was of the order of 965 mb. The pressure fell by 20 mb in about an hour and a half, and rose even faster after the transit of the storm core. The amplitude of the microseism recorded at Chittagong reached a maximum of 10.5 microns with a 2.4 sec period, about eight hours before the time of the lowest pressure, i.e. when the storm struck the station.

3. MAIN FEATURES OF THE ARABIAN SEA CYCLONE

The inter-tropical convergence zone (ITCZ) ran roughly along the belt between latitudes 4° and 10°N in the south-east Arabian Sea in the middle of May 1963. As early as 17 May a trough had developed over this area apparently under the influence of a low pressure wave from the Bay of Bengal. A depression of small extent probably formed at 1200 GMT on 18 May with its centre near latitude 8°30'N, longitude 73°30'E (Figure 1). At 0643 GMT on 19 May, TIROS VI saw a vortex with centre at latitude 12°N, longitude 68°E with the diameter of the central overcast area covering 6°.* It seems from subsequent data that the disturbance was growing into a cyclone at this time. At 0527 GMT on 22 May, TIROS VI reported the vortex centre at latitude 12°N, longitude 65°E, with several bands in the north-east quadrant extending about 5° from the main cloud mass. RFF reconnaissance aircraft reported the centre of the severe cyclonic storm or hurricane at 0630 GMT within 15 miles of latitude 11°18'N, longitude 66°06'E, with a maximum surface wind of 60 kt in the east quadrant and the minimum sea-level pressure as 984 mb. It was also reported that

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* As the disturbance was over the ocean area, it is difficult to be altogether precise about the pressure patterns. It appears that at different stages of the storm, the low pressure system had two distinct "eyes".

the "eye" of the storm contained clouds. At 0800 GMT, RFF aircraft reported the centre within 15 miles of latitude 11°30'N, longitude 65°54'E. The maximum wind was 70 kt in the south quadrant. The circular eye, 20 miles in diameter, was poorly defined. It was reported that the maximum temperature in the eye was 25°C, with a 5°C rise in the centre. This is probably one of the rare observations giving a quantitative estimate of the extent of temperature rise due to adiabatic compression of subsiding air in the region of the core. On 24 May, RFF aircraft reported the storm position at 0813 GMT at latitude 14°42'N, longitude 60°06'E. The lowest sea-level pressure measured was 947 mb and the highest wind on the east-west wall was 104 kt. The lowest wind in the centre was 37 kt. Turbulence was reported as moderate to severe in the west wall. According to the U.S. Weather Bureau, TIROS VI saw the position of the vortex at latitude 14°N, longitude 61°E with a central overcast area 10° in diameter. The cyclone continued on its north-westward course on 25 May. On 26 May the U.S. Weather Bureau, basing on TIROS VI observation, reported "a large well-developed tropical storm at 16°N, 55°E with a central overcast area 8° in diameter and extensive banding to 7°N and banding to NE, N and NW of the centre". The cyclone appears to have crossed the Arabian coast near Salala on 27 May and moved west or west-southwest. Precise positioning inland became difficult due to paucity of data.

A noteworthy feature was that the aircraft probes did not show any marked temperature discontinuity in or around the cyclone (except the central rise of temperature mentioned above), such as one would encounter in a frontal structure, but strong linear wind shears were in evidence. The former characteristic is of course well known in regard to cyclonic disturbances in the tropical areas.

Figures 2, 3 and 4 show TIROS VI photographs and nephanalyses on 22, 24 and 26 May. Figures 3(b) and 4(b) show that towards the north-west of the cyclone there was a large area with scanty clouds, possibly indicating that the available moisture supply from the Arabian Sea was largely drawn into the storm, and that the north-western area beyond the storm field was a region of large-scale subsidence. Another noteworthy feature is the predominance of Cumulus and Cumulonimbus clouds in the storm field.

Figures 5 and 6 show some of the observations made by RFF reconnaissance aircraft on 22 and 24 May respectively. On the basis of minute-to-minute observations, Dr. G.C. Asnani of the India Meteorological Department, who accompanied the RFF flight on 22 May, has prepared a streamline diagram of the storm core (Figure 7). The other significant inferences drawn from his observations are :

(a) Light winds at the core which had a temperature of about 25°C, at an altitude of about 450 m (1,500 ft). At one point the wind was almost calm, becoming 41 kt in 4 minutes of flight.

(b) Near the ring of hurricane winds the temperature was about 20°C.

(c) The streamline pattern showed asymmetry towards the west of the storm. However, the "solid rotation" feature appeared to be in evidence.

(d) The "eye" contained clouds.

(e) There were scattered white horses on the sea surface.

(f) A squall line and line of Cumulonimbus clouds were observed at 200 to 300 miles north-east of the storm.

It was reported on 24 May that the lowest wind at the centre was 37 kt, but from this report it is not possible to conclude that a calm centre was necessarily absent. However, the available observations do show that there was an approximately circular belt of very strong winds, on either side of which the wind speed decreased rapidly. It is thus possible to envisage a circulation approximately like a solid rotation (vortex type $\frac{v}{r}$ = constant) embedded inside a vortex of type $\frac{v}{r}$ = constant.

Figure 8 shows the vertical temperature distribution at the storm core as determined by dropsonde observation made by the RFF aircraft on 24 May. The data have been obtained through the courtesy of the International Indian Ocean Expedition. Even allowing for considerable drifts that the dropsonde may have undergone while it descended to the sea, it is seen that between 825 and 700 mb the atmospheric column was almost isothermal, in fact there was a weak inversion between 825 and 775 mb. The average lapse rate between 700 and 500 mb can be estimated to have been about 5.5°C/km. Judging by averages at coastal stations, the temperature at 500 mb was about 5°C above the normal value.

According to the logs of S.S. Mohammedi, the greatest wave height was 26 ft about 200 miles south of the storm centre on 26 May. The wave period varied rather widely, between 8 seconds and 18 seconds. S.S. Saudi, which also came within the storm field, recorded a steady wind of 70 kt for about three hours on 24 May, and on this day she recorded a pressure fall of 18 mb within a period of six hours, the lowest pressure being 988 mb.

An RAF Shackleton aircraft based at Khormaksar, Aden, made a reconnaissance flight on 27 May along the Arabian coast to locate the storm centre. The Aden Meteorological Office was kind enough to make the following flight log available for the study of the cyclone. The details of the report are reproduced below (see Figures 9 and 9 (a)).

The aircraft left Aden at 1130 GMT and cruised at a height of 1,500 m (5,000 ft). Abeam Riyan there was Altostratus at about 5,500 m (18,000 ft) and some castellanus. This became overcast with slight rain. The cloud base lowered to about 4,000 m (14,000 ft), and the temperature fell from 26°C to 15°C (the wet-bulb temperature at Aden was also 15°C). South of Ras Fartak the surface wind was estimated to be 020°/35 kt. Radar showed the vortex centre at 16°00'N, 52°45'E, and the radio altimeter indicated a surface pressure of 945 mb before it became unserviceable. At 45 miles from Salala and 15 miles from the coast a long narrow clearance running parallel to the coast was observed. The surface wind was estimated as 150°/20 kt with the cloud base almost on the surface. The aircraft then climbed to approximately 2,800 m (9,000 ft) to cross the coast, reaching a point ten miles inland where low clouds cleared, revealing the bleak, rocky, rainswept surface with the wadis half-full of water. Medium and upper clouds remained thick but layered, and showers could be seen in all directions. A wall of orographic cloud along coastal hills at Salala made let-down too hazardous. Hence the aircraft proceeded to return. A clearance was seen again just off-shore. On re-entering cloud a rate of descent of 600 m (2,000 ft) per minute was recorded for a few seconds. At 1540 GMT and at 16°05'N, 52°44'E, the aircraft was flying through the southern edge of the eye of the storm. In poor light the walls did not look well defined. Passing out of the eye at about 2,800 m (9,000 ft) the first severe turbulence of the flight was encountered, and in the space of about two minutes the plane reached 2,400 m (8,000 ft) and 3,500 m (11,500 ft). There was slight turbulence over the rest of the flight. Clouds cleared quickly to 5/8 Cirrus near Riyan. The visibility was poor because of dust haze or cloud all the way except for the time spent over land behind Salala, where rain had washed dust out of the air and left it very clean.

The distribution of clouds along the Aden-Salala route as seen and recorded during the reconnaissance flight is shown in Figure 9. The position of the aircraft at different hours is shown in Figure 9 (a). The feature that in some places high Cumulus or Cumulonimbus build-ups had their base at 3,000 m (10,000 ft) or even higher levels is an interesting one. An Air-India Boeing aircraft flying at 11,000 m (36,000 ft) from Bombay to Aden on 26 May reported extensive layers of cloud between longitude 57°E, and Riyan at levels between 6,000 m (20,000 ft) and 12,000 m (40,000 ft), with large vertical build-ups having their base at about 7,500 m (25,000 ft).

Figures 10, 11 and 12 show the vertical time-sections of Masira, Salala and Riyan based on data made available by the Aden Meteorological Office. Even after the storm had moved inland, the surface wind at Salala continued to blow from the south-east. It appears from the charts of 28 May that on this day the centre of the storm was probably close to the coast, suggesting a WSW-ward trend in the movement. It is gathered that the effects of the storm had actually not reached Aden, and it is therefore to be assumed that the storm had either filled up or moved away towards the central parts of Saudi Arabia where no observations are available.

It can be inferred that in its most violent state the cyclone had developed a pressure gradient of the order of 60 mb in a distance of about 150 km, i.e. an average of 1 mb in 2.5 km. Near the core the pressure profile could well have been such that the prevailing gradient was very much more than this average would signify.

The following were the rainfall amounts at Salala when the station was under the influence of the cyclone :

26 May	0600 GMT	0.2 mm
	1800 GMT	3.6 mm
27 May	0600 GMT	134.0 mm
	1800 GMT	40.0 mm
28 May	0600 GMT	20.0 mm
	1800 GMT	32.0 mm

It may be mentioned that the annual normal rainfall at Salala is about 80 mm only. Thus the station received more than twice its normal annual rainfall in 24 hours. A reference is made in a subsequent paragraph to the precipitation along the coastal belt.

The microseisms of Bombay did not indicate the severity of the Arabian Sea cyclone, the amplitude of the oscillations being about half of what could normally be expected. However, the Bombay seismograph did appear to respond to the Bay of Bengal cyclone. The general experience has so far been that storms beyond a distance of about 200 miles from Bombay [2] do not succeed in producing storm-type microseisms at the station.

The sea surface has been considered as a "heat source" from which a substantial part of the storm's energy is derived. Interesting cases have been cited in this respect [1], pertaining to hurricanes in the Gulf of Mexico and the Pacific. In the case of the Arabian Sea cyclone, the distribution of water temperature followed a varied pattern. In the initial stages it appeared that the air was generally warmer than the sea, but as the storm intensified and progressed there were a number of reports in which the sea temperatures were two to four degrees higher than the air temperature, and this was true even when the lower air temperature could not be attributed to rain-cooling within the storm field.

Due to lack of upper air data over the sea area, it is difficult to discuss the synoptic aspects of the steering of the storms. However, the 200 mb winds reported by aircraft give a reasonably close agreement between the trend of steering and the upper winds.

4. AERIAL RECONNAISSANCE IN SAUDI ARABIA

A number of aerial reconnaissances were organized in June and July to assess the locust position over that area, both by the Desert Locust Control Organization for Eastern Africa (DLCOEA) and as a part of the United Nations Special Fund Desert Locust Project. A report on these latter reconnaissances has been published recently [5]. Of particular interest for the present study are the data collected by DLCOEA during the period 16 to 29 June 1963. These were made available by the Anti-Locust Research Centre, London, and are reproduced in Figure 13. Over a large area to the west and south-west of Salala the pilots were able to locate green vegetation, signs of recent rain, water in wadis, running water and large areas of standing water. The flights were mostly carried out at low levels, and the observers thus got a very good opportunity of recording the significant features of the state of the surface. The distribution of accumulated water at different parts of the coastal belt appears to lend force to the view that the cyclone probably moved towards WSW. However, an important aspect of the observations is that over the southern half of the Oman Peninsula there were locations where water accumulation was observed, while over a large stretch to the north and north-east of Salala there was no evidence of water accumulation. The surface water sighted over the Oman area could not possibly have resulted from precipitation associated with the field of the cyclonic storm. As far as the synoptic charts show, no other disturbance had crossed this area. The question may be asked as to whether any small-scale system in the vicinity of the cyclonic storm could have affected the Oman region and remained undetected on account of the general paucity of observations over the area and the smallness of the scale in which depressions and cyclones occur in the month of May. One may consider the isobaric field at 1200 GMT on 26 May 1963 (Figure 14) in which two ships (one near 14°N, 58°E, and the other near 15°N, 59°E) reported the wind as WSW and SE respectively, both with 30 kt wind speed. In the presence of the severe cyclonic storm such winds and the pressures that the ships reported would be clearly untenable, unless these winds and pressures were caused by a secondary vortex which had an identity of its own. If that is the case, the co-existence of two vortices not far from each other could lead to interesting possibilities of steering. According to hydrodynamical principles [4], two such rectilinear vortices should rotate around an intermediate point in the direction of the airflow in each vortex. If the synoptic conjecture mentioned above is valid, the weaker system to the east of the main cyclone should have moved in some northerly direction, possibly causing the Oman rainfall which otherwise remains inadequately explained.

5. CONCLUDING REMARKS

According to Desert Locust Situation Summary No. 62, this exceptional tropical cyclone gave widespread and extremely heavy rain in the southern Arabian peninsula in late May. Records of such cyclones in the past, particularly that of October 1948, have shown that any residual locust population from a very wide area, including most of Arabia and the Persian Gulf, is likely to have been drawn into this area and to have bred on the associated rains. (See also Dr. Rainey's notes on the cyclone affecting Southern Arabia in 1948 on p. 256). The air reconnaissance referred to above did not however reveal the existence of locusts in the Rab al Khali. Saudi Arabia remained clear of locust swarms, although some scattered locusts were found to the east of Taif in early June.

ACKNOWLEDGEMENTS

The author wishes to express his grateful thanks for the assistance by way of charts and data received from Dr. R.C. Rainey of the Anti-Locust Research Centre, London; Mr. A.W. Mathewman, Chief Meteorological Officer, HQ. Middle East Command; Mr. G. Froude, Senior Meteorological Officer, Aden; Dr. G.C. Asnani, Senior Scientific Officer, Institute of Tropical Meteorology, Poona; and Mr. Blackall, forecaster at Khormaksar, Aden, who made the detailed meteorological report on the RAF Shackleton flight through the cyclone on 27 May 1963. The author wishes to thank the Director General of Observatories, India, for permission to include some departmental data and charts in this report. Thanks are also due to Mr. E.C. Chacko for preparing some of the diagrams. Finally, the author would like to thank Miss E. Betts for critically reading the manuscript and for her most useful suggestions.

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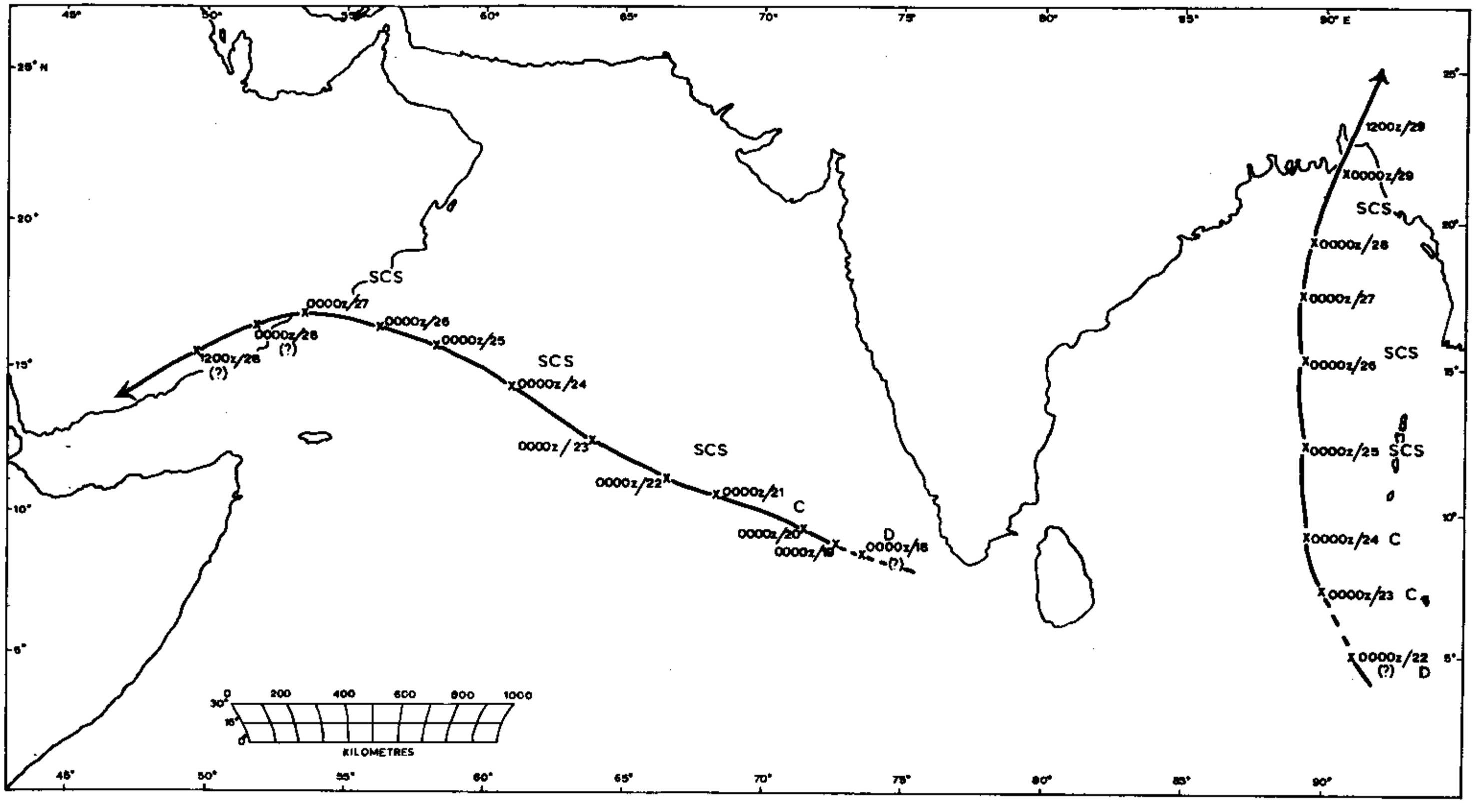


Figure 1 - Estimated tracks of Arabian Sea and Bay of Bengal Cyclones, May 1963.

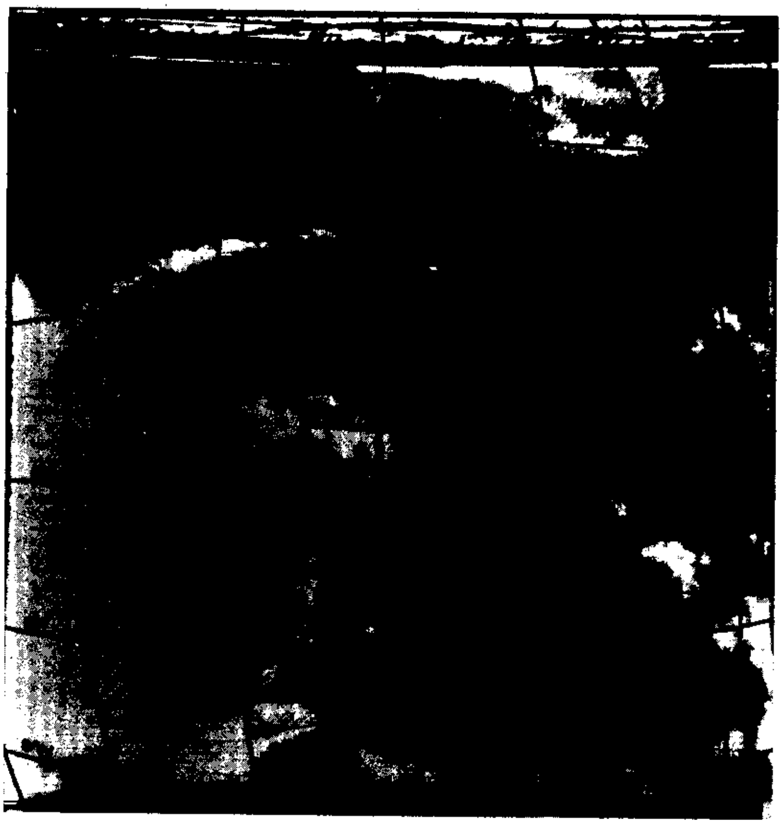


Figure 2(a) - TIROS VI photograph dated 22 May 1963.

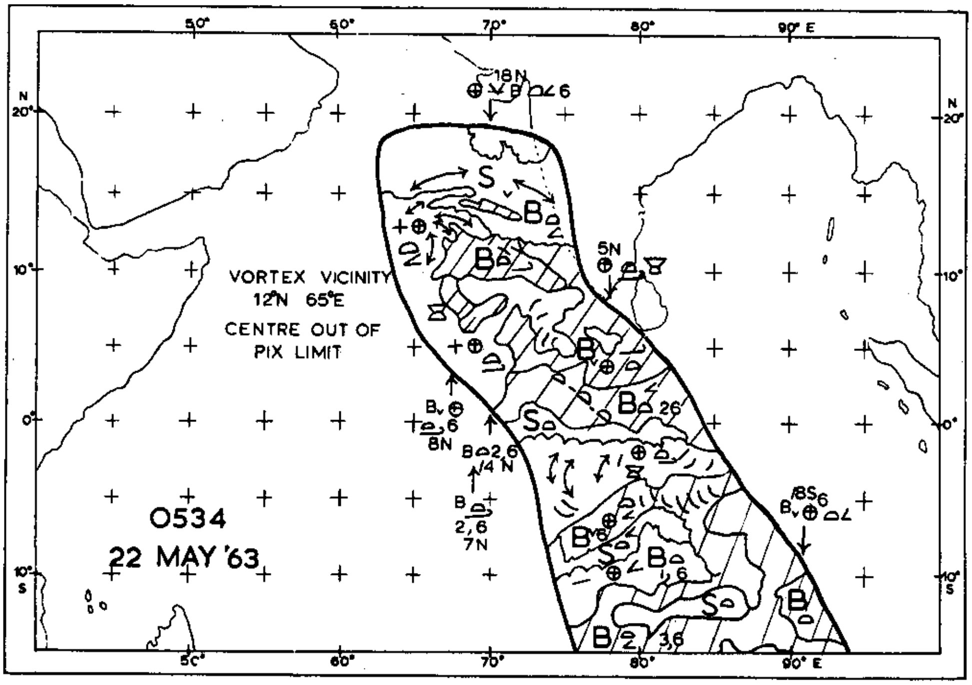


Figure 2(b) - Nephanalysis of TIROS observation dated 22 May 1963.

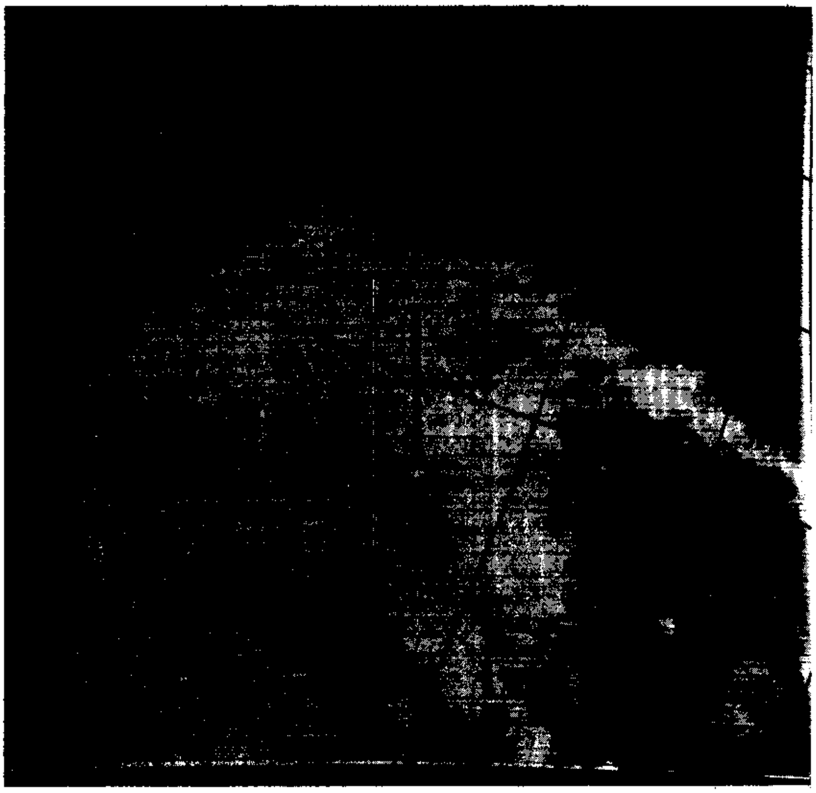


Figure 3(a) - TIROS VI photograph dated 24 May 1963.

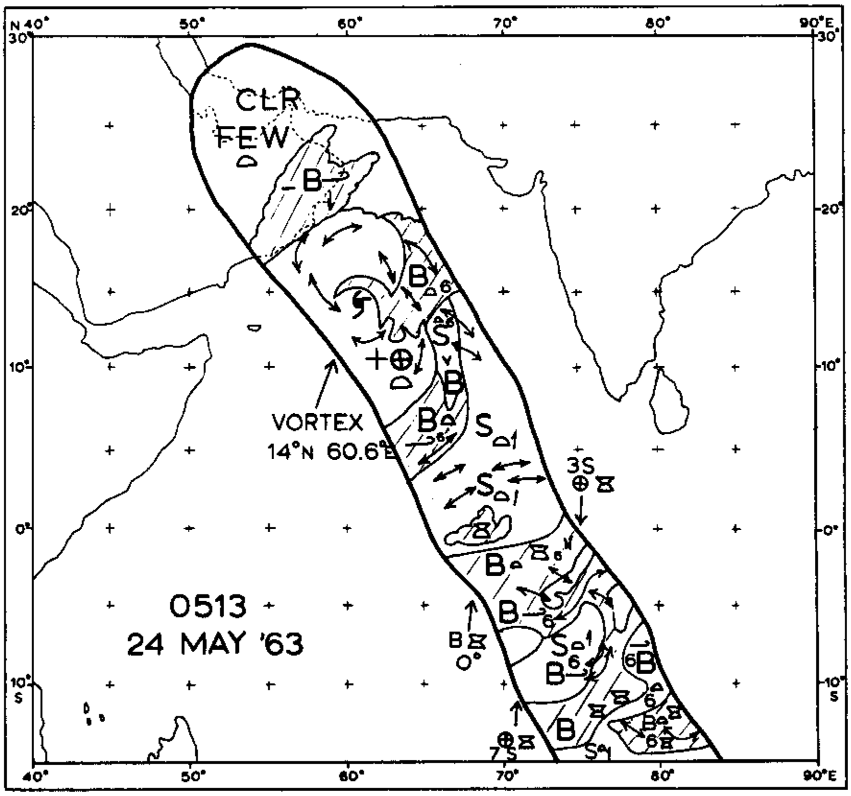


Figure 3(b) - Nephanalysis of TIROS observation dated 24 May 1963.

Figure 4(a) - TIROS VI photograph dated 26 May 1963.

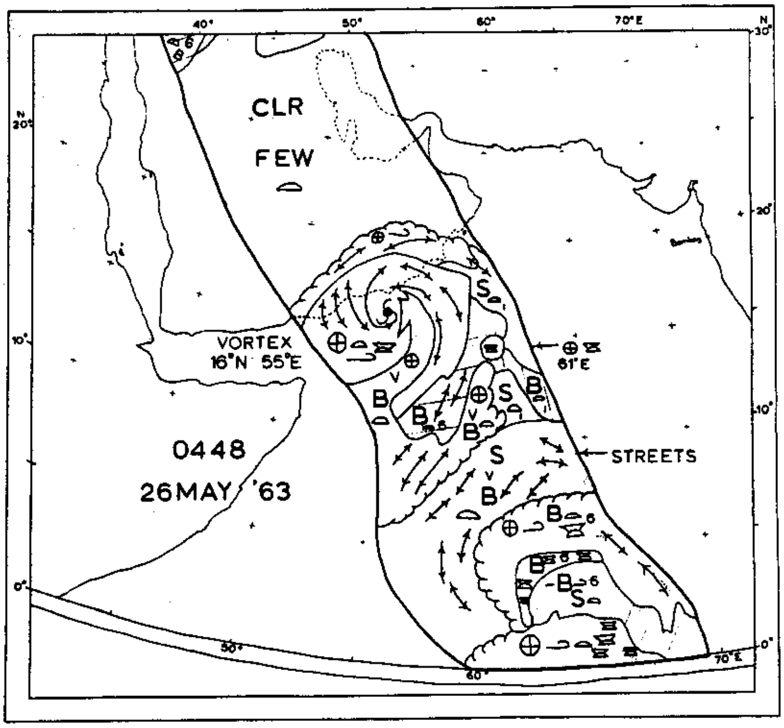
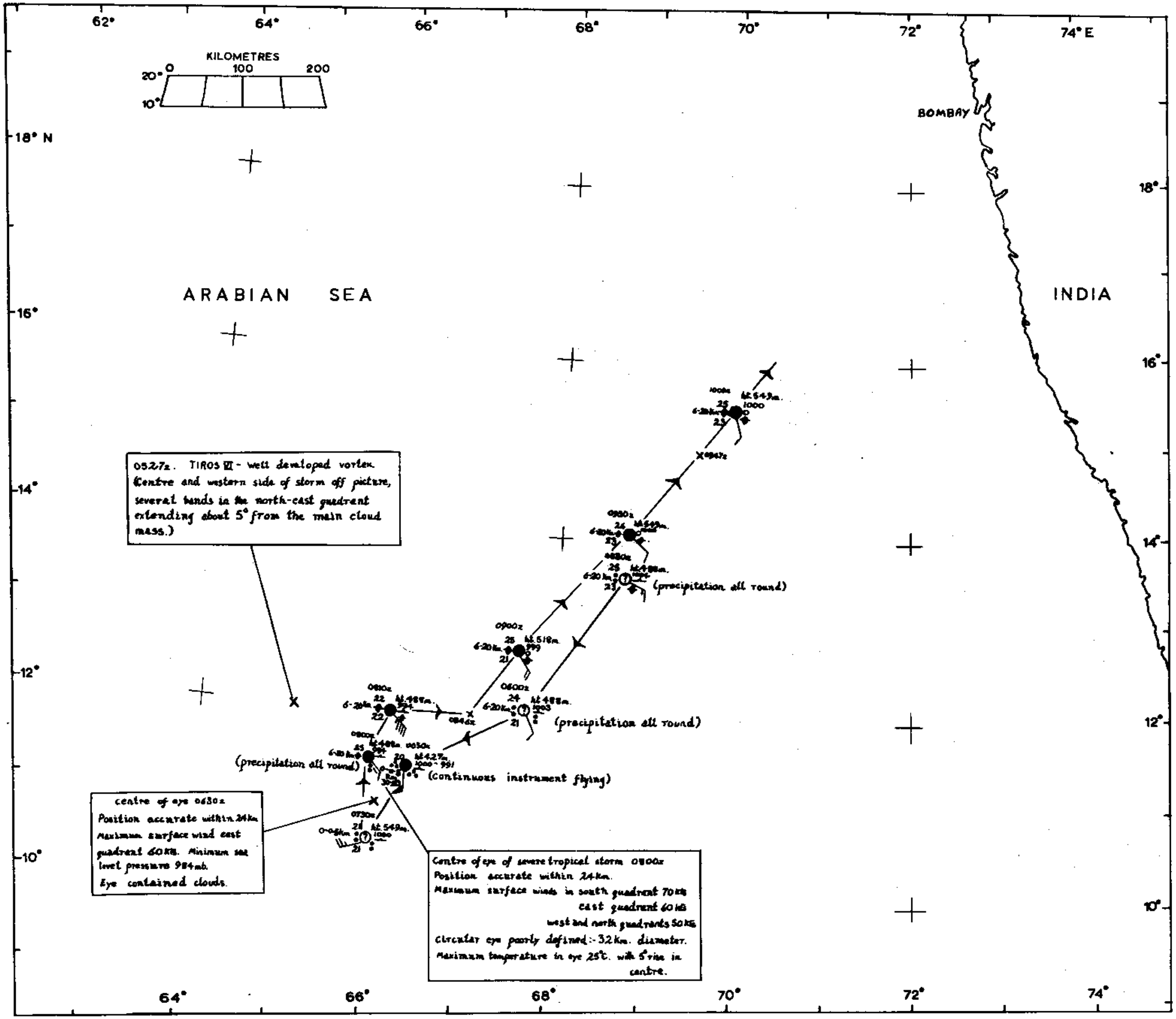


Figure 4(b) - Nephanalysis of TIROS observation dated 26 May 1963.



052.7z. TIROS VI - well developed vortex. (Centre and western side of storm off picture, several bands in the north-east quadrant extending about 5° from the main cloud mass.)

centre of eye 0630z
Position accurate within 24km
Maximum surface wind east quadrant 60KTS. Minimum sea level pressure 984mb.
Eye contained clouds.

Centre of eye of severe tropical storm 0800z
Position accurate within 24km.
Maximum surface winds in south quadrant 70KTS
east quadrant 60KTS
west and north quadrants 50KTS
Circular eye poorly defined:- 32km. diameter.
Maximum temperature in eye 25°C. with 5° rise in centre.

Figure 5 - RFF reconnaissance data of 22 May 1963.

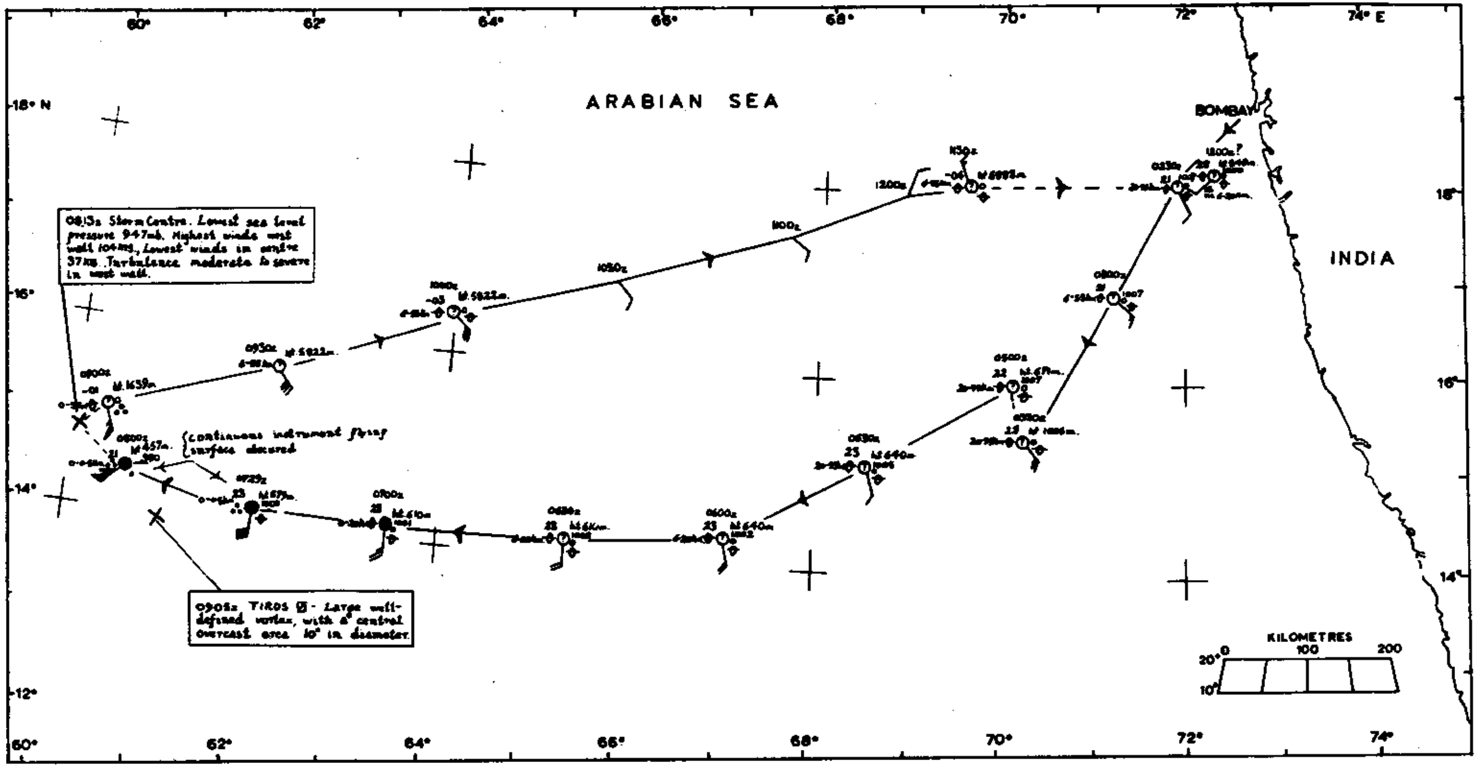


Figure 6 - RFF reconnaissance data of 24 May 1963.

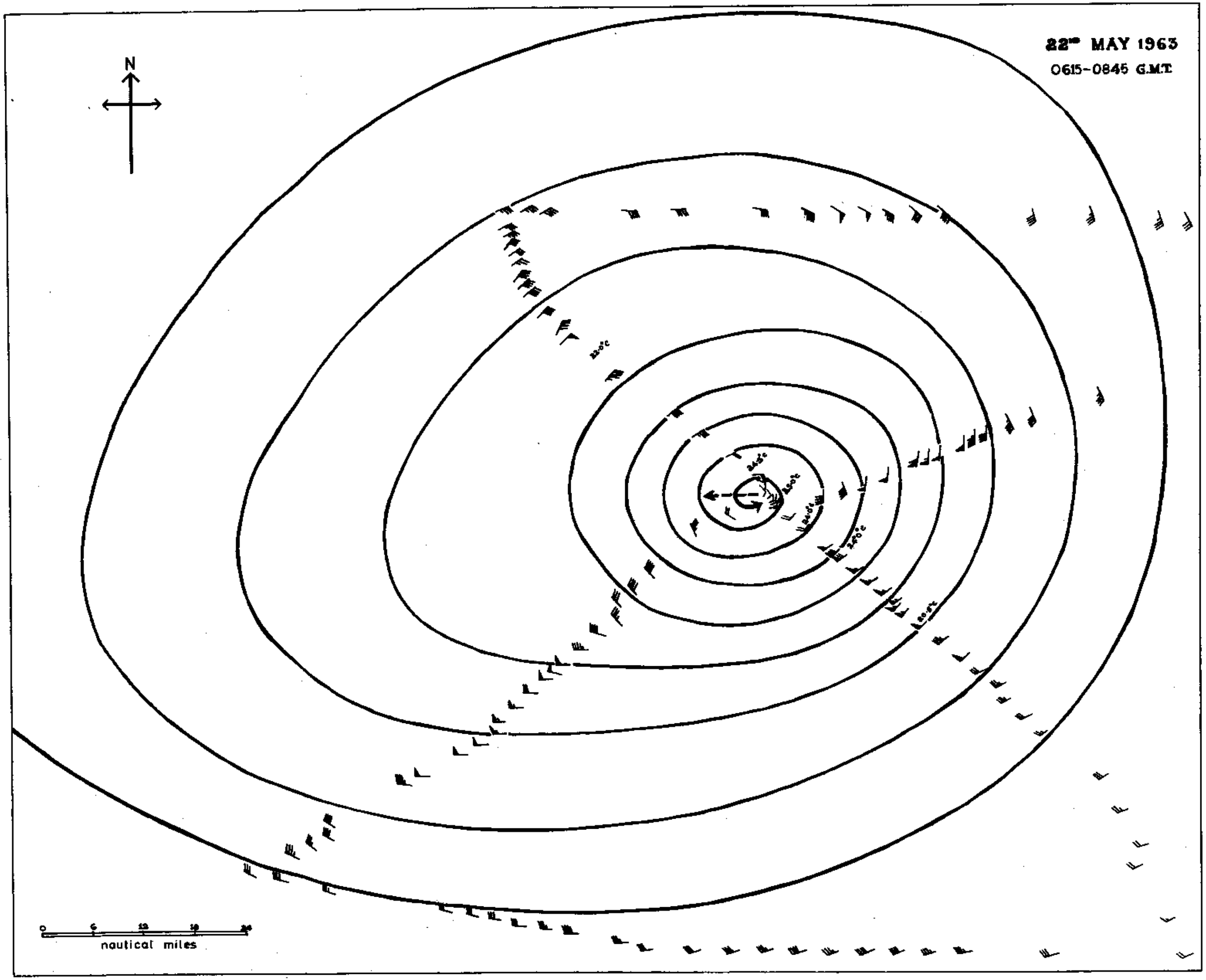


Figure 7 - Streamline diagram of the storm core on 22nd May 1963.
(Reproduced by courtesy of Dr. G.C. Asnani of the Indian Meteorological Department).

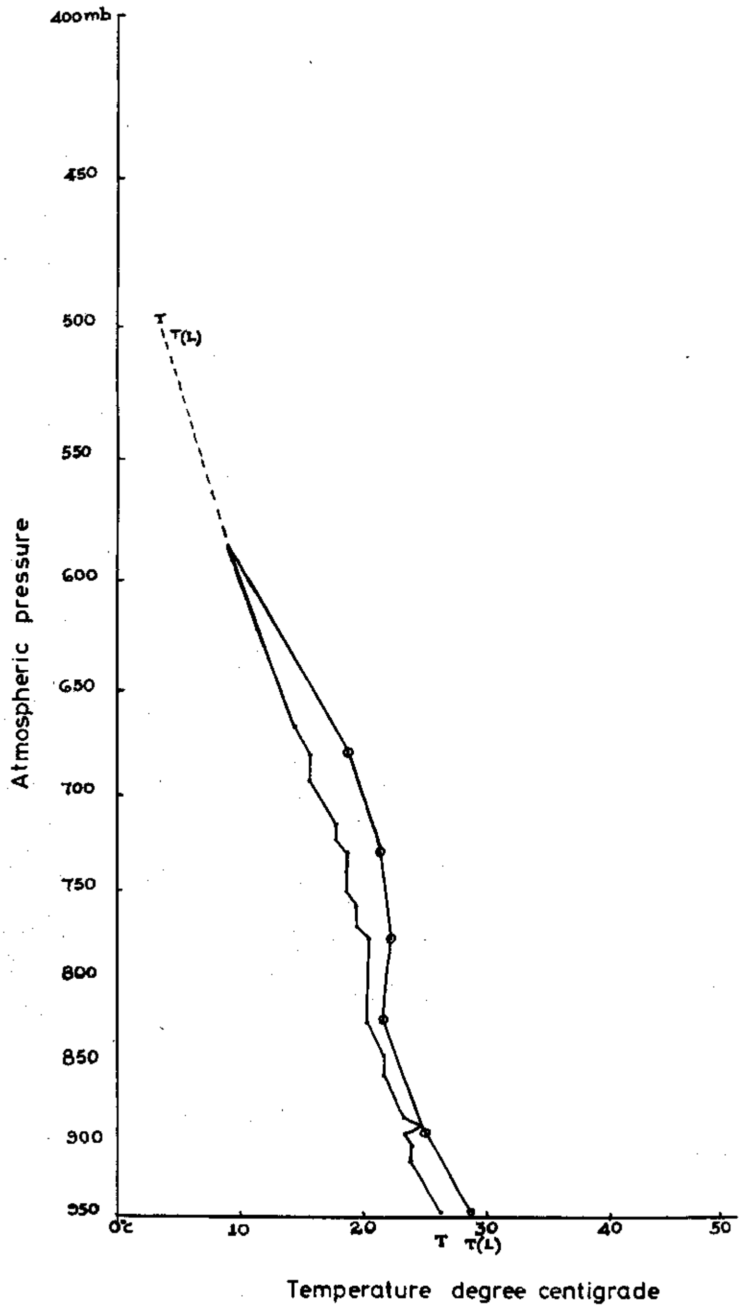


Figure 8 - Drop-sonde observations over storm core on 24th May 1963. Time of releasing drop-sonde was 0852 GMT and the position of the aircraft was 14°53'N, 59°55'E.

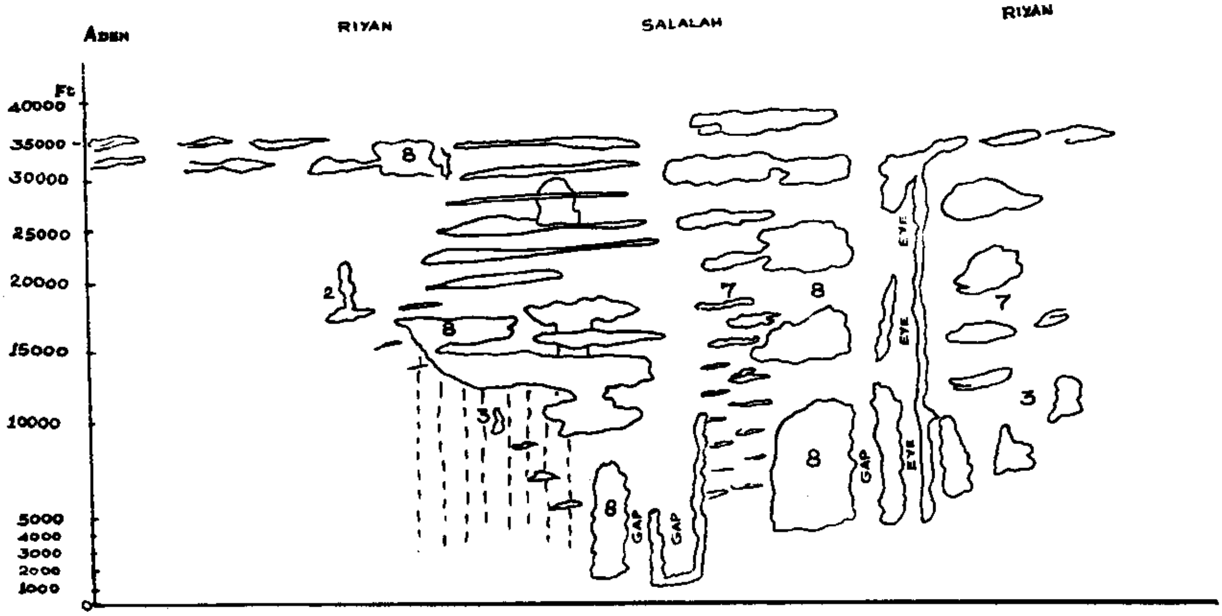


Figure 9 - Cloud formations recorded by RAF Reconnaissance flight along Aden-Salalah route on 27 May 1963.

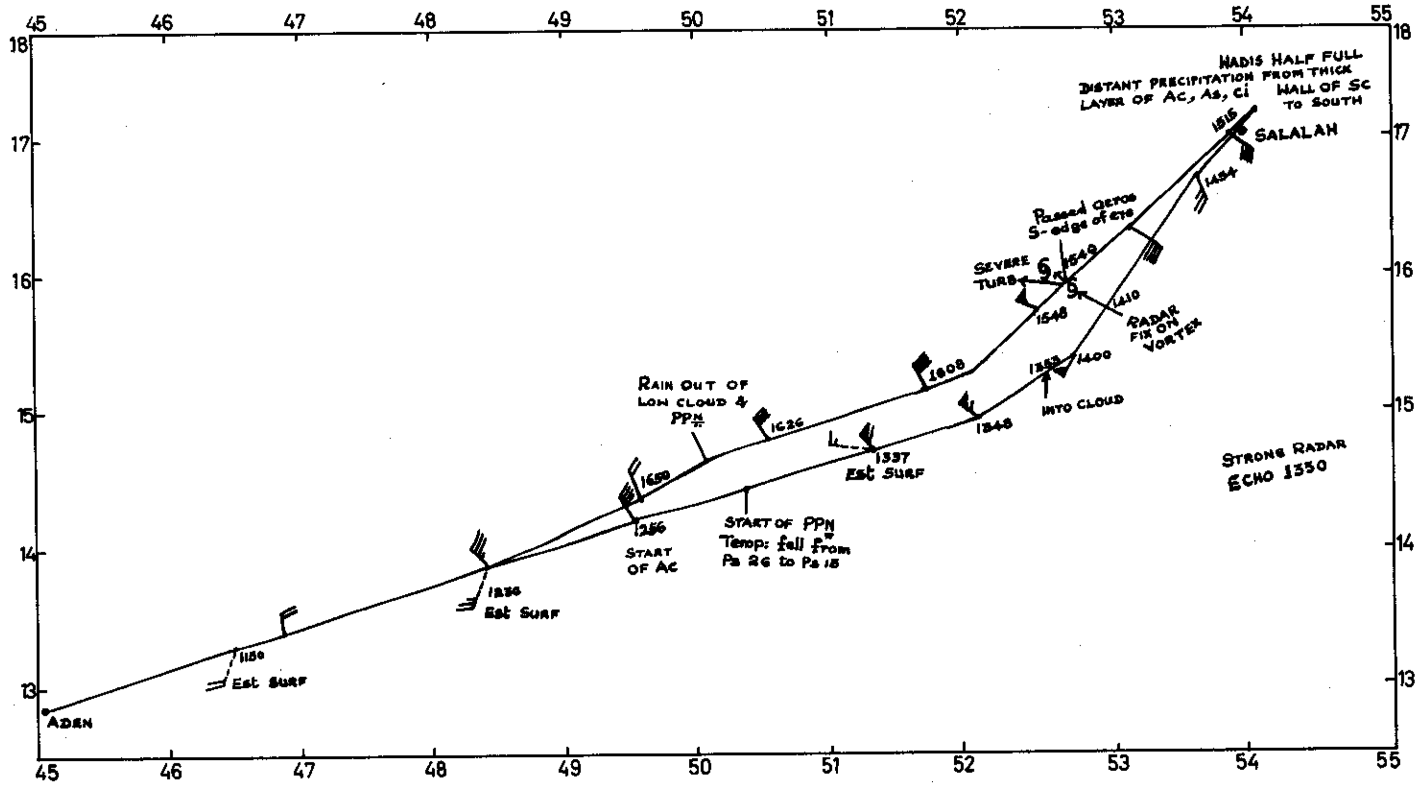


Figure 9 (a) - Positions of the aircraft at different times.

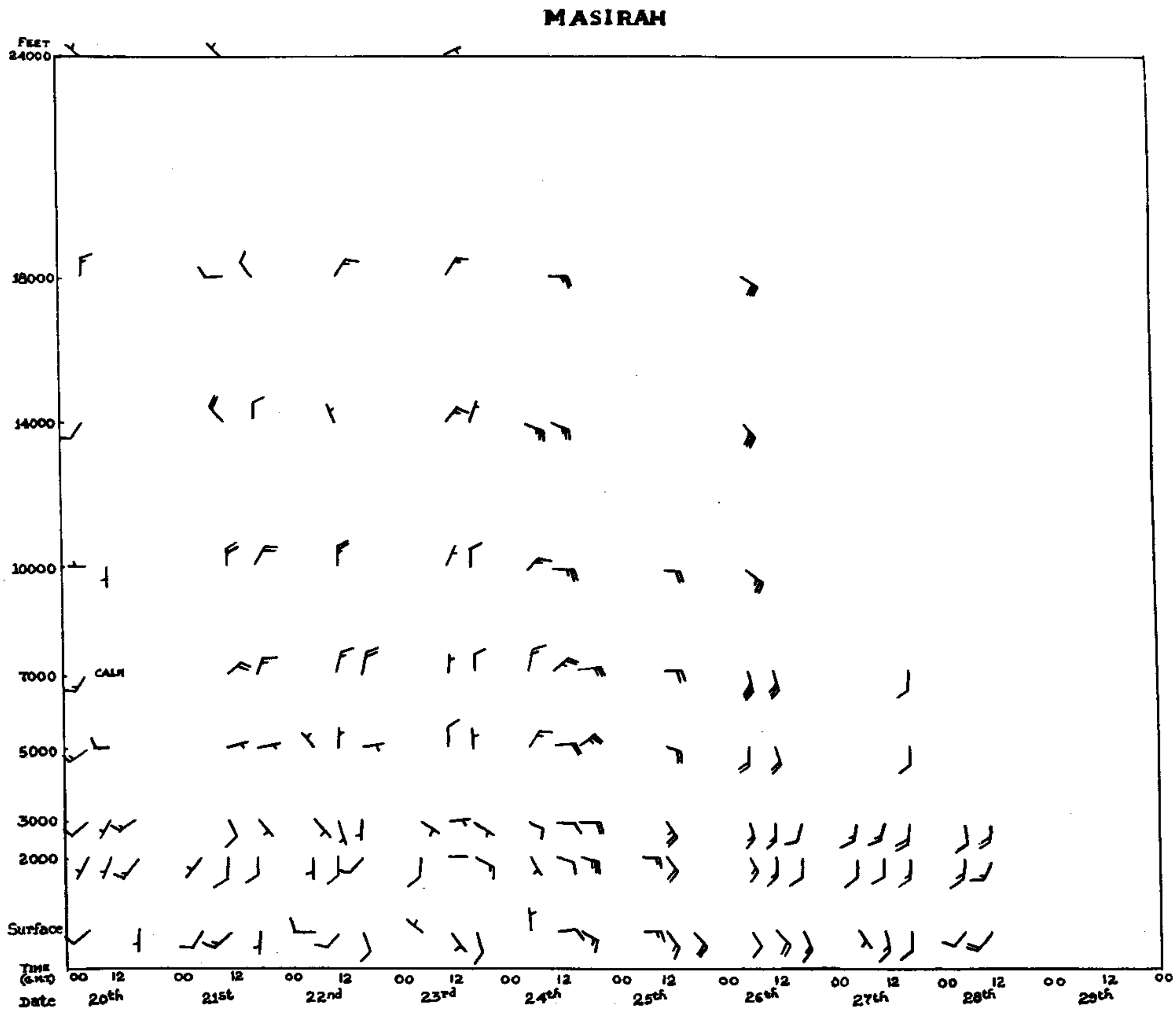


Figure 10 - Vertical time-section of Masirah.

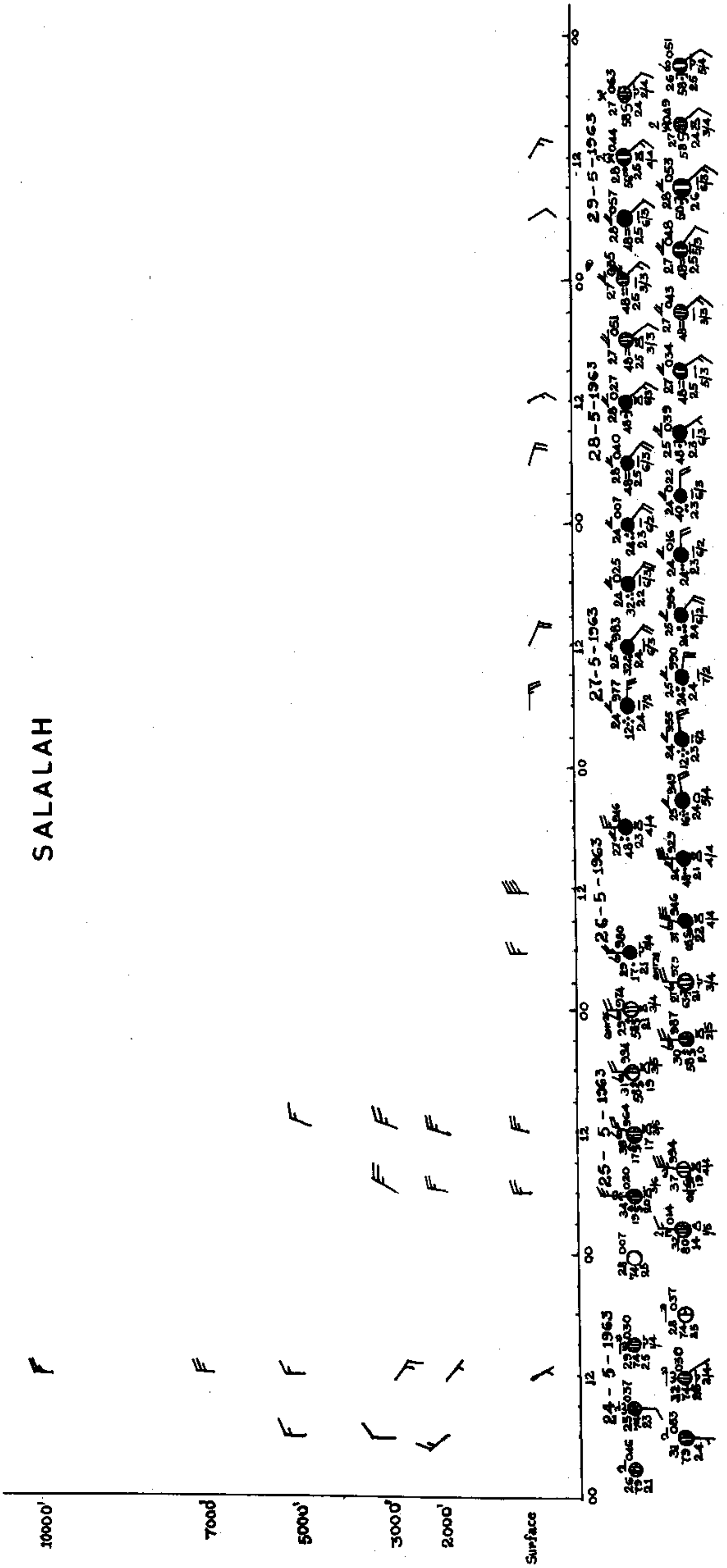


Figure 11 - Vertical time-section of Salalah.

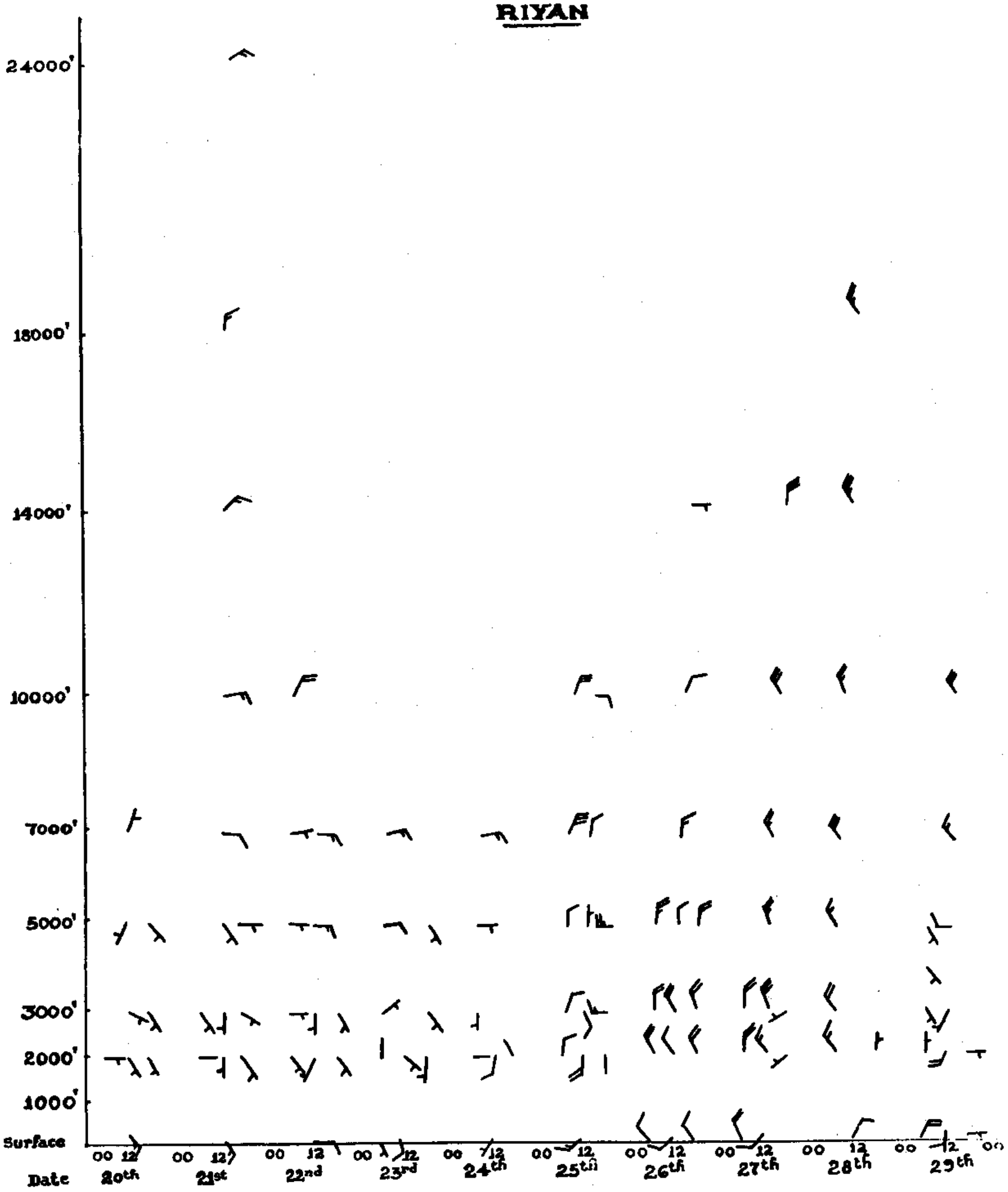


Figure 12 - Vertical time-section of Riyan.

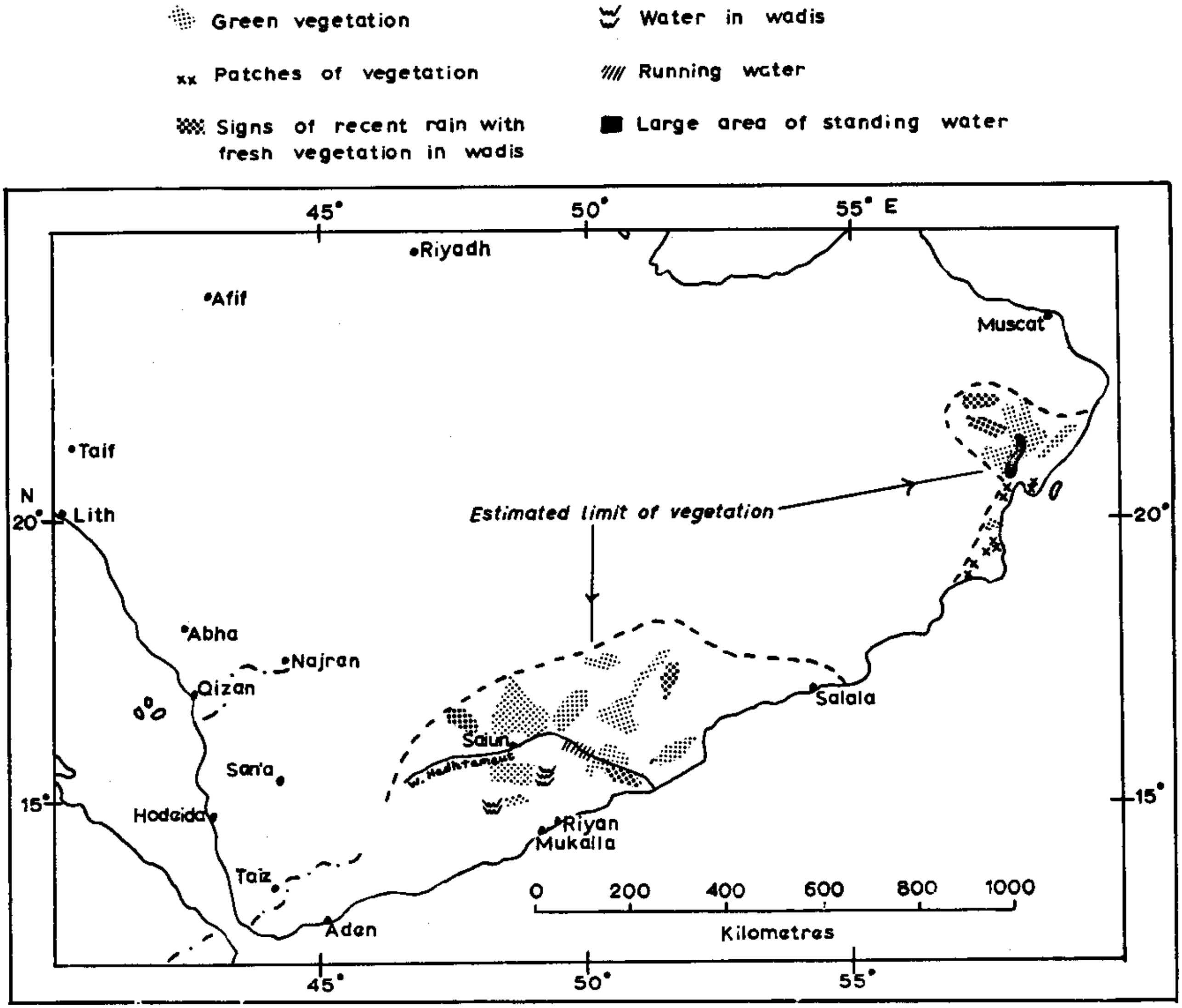


Figure 13 - Observations made by U.N. Special Fund Desert Locust Project Aerial Reconnaissance, 16-29 June 1963.

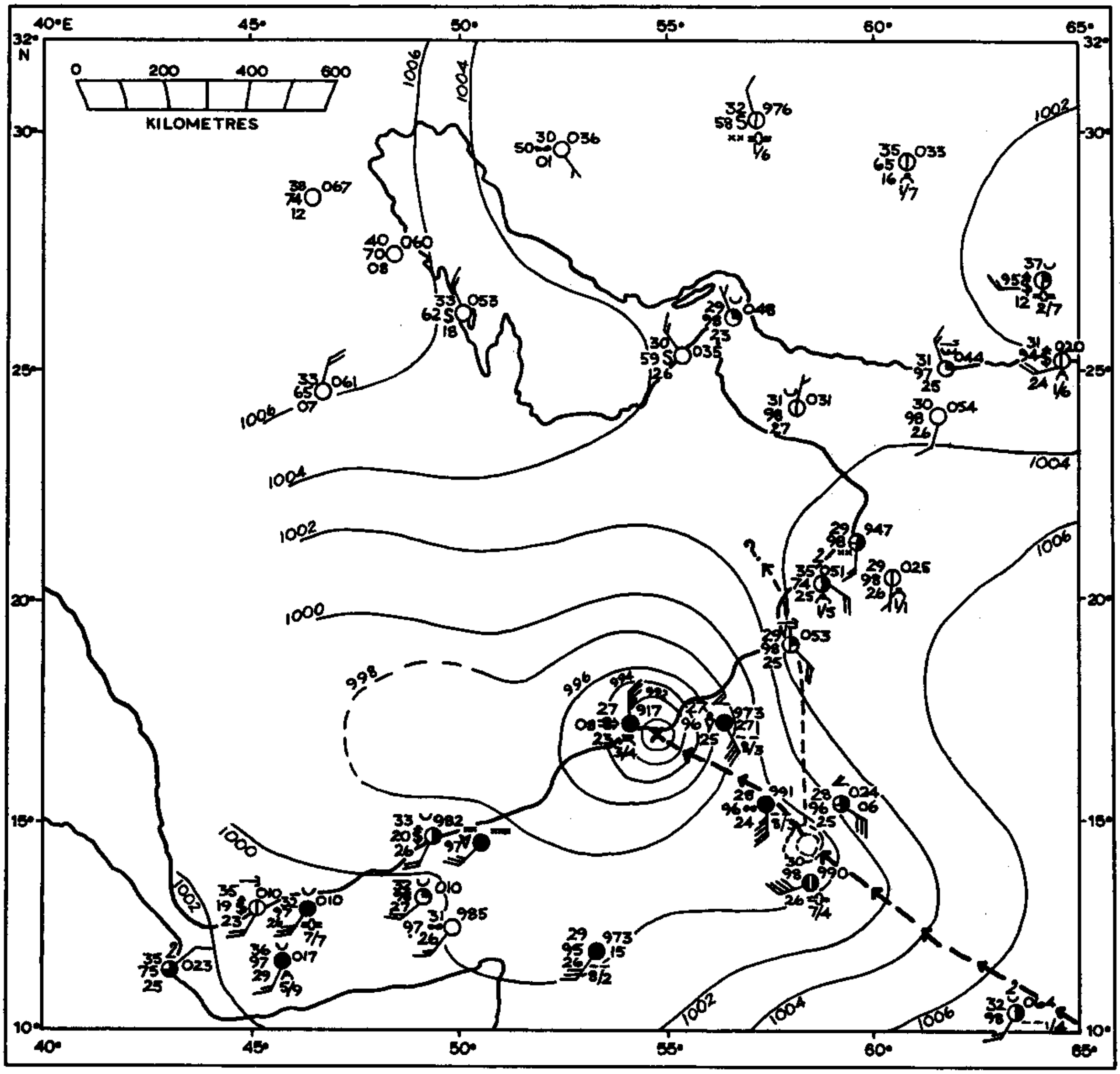


Figure 14 - MSL synoptic chart of 1200 GMT on 26 May 1963.

RADAR AND SYNOPTIC STUDY OF LOCUST SWARMS OVER DELHI

by

S. Mazumdar, N.S. Bhaskara Rao and G.R. Gupta

Abstract

The period from April to September 1962 was characterized by marked locust activity over large parts of West Pakistan and north-western India. Swarms were reported from a number of locations around Delhi in the third week of July. On 26 July large swarms came to Delhi and the infestation continued until 29 July. Radar photographs of the swarms show the following interesting features :

(1) On 26 July the swarm at one time consisted of a series of "waves", one behind another in a roughly linear sense, with the length of each successive pyramid or cone about 5 km, and the length of the combined swarm at one time more than 40 km;

(2) The height up to which locusts in sufficient concentration extended on this day was at least 1.5 km;

(3) The locusts were in flight over the Delhi area for a considerable number of hours; and

(4) Annular-shaped echoes or echoes indicative of sharp curvature are seen in some photographs. These could represent possible mesoscale vortices with locusts trapped in them. The scale of distances between observing stations on the synoptic charts is too coarse for detecting these vortices with confidence, but a further study of such systems is called for.

The associated synoptic charts are discussed. It is seen that certain regions of locust concentration approximately correspond to areas of relative atmospheric convergence.

The results of the investigation suggest that radar is likely to prove to be a very useful tool for the estimation of the horizontal and vertical extents of swarms and for the tracking of swarms, both of which are problems which cannot be adequately solved either by ground-based visual observations or even by aircraft reconnaissance.

1. INTRODUCTION

For any case study of locust swarms, whether in regard to long-distance migrations or short-range movements, one has necessarily to depend upon available locust observations over extended areas. There are certain inherent limitations in the usual methods of collecting information regarding the spatial extent of swarms and their movements. The difficulties are well known, but may be summarized as follows :

(a) The greater part of the geographical belt over which Desert Locusts breed and move is rather thinly populated, and high-speed communication facilities do not exist over large tracts of it.

(b) It is not always possible for a set of ground-based observers to make an accurate estimate, by visual means alone, of the horizontal extent of an individual swarm and of the direction and speed of its overall movement. Errors in estimation may arise particularly if the observer is located in a valley. The problem of observing the direction of movement has been discussed by Waloff (5), Rainey (3) and Sayer. (See p. 168)

(c) Aircraft observations of swarms no doubt very usefully supplement ground-based observations, but the very fact that an aircraft is a non-stationary observing station imposes a limitation on the precision of observations of the overall movements.

(d) As a rule, and with the exception of cases in which locusts are forcibly steered for long periods over extensive sea areas under the influence of depressions or cyclonic storms, swarm movements are punctuated by the settling-down phase often during nightfall, and this introduces further uncertainties in tracking with the help of visual observations.

(e) As in the case of atmospheric vortices, locust movements are also known to take place over a wide and complicated spectrum of displacements. Adequate information on the various small-scale or mesoscale movements of component parts of swarms which eventually produce large-scale resultant movements is as yet not available over many areas.

These rather inherent limitations make it imperative that ground-based observations, which constitute the major part of routine locust intelligence, should be treated with a certain amount of reserve in regard to case studies. Useful as they undoubtedly are, press reports have also to be treated with the same reserve except for the factual information that these reports might contain in regard to a particular station having actually been visited by a swarm on a certain date. The need for the reserve arises from the fact that a ground-based observer has no means of assessing, merely by visual observations, whether the observed movement of groups of locusts overhead or at a distance actually represents the movement of the swarm as a whole and whether the existence of flying locusts over an area for a prolonged period necessarily indicates the movement of a large swarm. These limitations lead to the logical necessity of extending the observer's instantaneous vision over a large area. The solution thus appears to lie in the radar technique.

Rainey (2) discussed some of the theoretical aspects of radar detection of locust swarms and reported an interesting case of radar sighting of a locust swarm on 22 March 1954 in the Persian Gulf about midway between Bushire and Kuwait by H.M.S. Wild Goose. A WMO Technical Note, subsequently published (6), also expressed the view that "the tracking of locust swarms using high-power radar seems a distinct possibility as long as the height of the swarm is sufficient to put it above the radar horizon".

For the case under discussion, a series of radar photographs is available through the courtesy of the Rain and Cloud Physics Research Unit, National Physical Laboratory, New Delhi; a report on these sightings has subsequently been published elsewhere (4). This is a new field and it may require more case studies of this type to appreciate fully the implications of the patterns observed on the radar. However, the material presented here will probably assist in further considerations on the utilization of the radar technique for the detection of swarms and, eventually, in control operations.

2. SUMMARY OF REPORTS ON THE LOCUST SITUATION LEADING TO THE LOCUST INVASION OF DELHI IN JULY 1962

According to Desert Locust Situation Summary No. 52 (pertaining to July and early August 1962) issued from the Anti-Locust Research Centre, London, swarm movements into the inter-tropical convergence zone (ITCZ), which had commenced in the earlier months, continued, with breeding on the associated rains in India and Pakistan. Swarms were recorded in early July at many points in Rajasthan, Punjab, south Himachal Pradesh, Uttar Pradesh and Bihar.

Swarms invaded Delhi on 26 July, the infestation continuing for the three subsequent days. Available press reports on these incidences are summarized below.

25 July : By the middle of July it was estimated that there were some 55 swarms in Rajasthan besides two in Uttar Pradesh.

26 July : Two large swarms invaded Delhi and settled down over an area of about 100 square miles. There was hardly any urban or rural area where the swarms had not penetrated. It appeared that a swarm entered the Najafgarh area of Delhi between 10 and 11 a.m. (i.e. between 0430 and 0530 GMT) and that it had come from the direction of Bahadurgarh in the Punjab.

27 July : Two fresh swarms invaded the capital around 1900 h (1330 GMT). One was reputed to have come from the direction of Gurgaon in Punjab, and another from the direction of Meerut (Uttar Pradesh). Fifty-two villages were reported to have been affected by the Mehrauli Development Block alone. There was heavy egg-laying. Freshly sown crops over 10,000 acres were completely destroyed, involving a loss of about Rs 40,000.

28 July : It was reported that Rohtak district of Punjab had been invaded by a 10-mile long swarm, and that 80 villages in the district had been affected. A swarm was reported to be laying eggs in the Mainpuri District (Uttar Pradesh). A 5-mile long swarm was observed over Karnal in Punjab.

29 July : For the fourth day in succession swarms were reported over Delhi. The swarms on this day were small compared to the previous ones. By this day locusts had settled over 4,000 acres of land in the Meerut District. Locusts were reportedly moving north-eastwards from Jaipur (Rajasthan).

Data regarding the reported infestations in various areas surrounding Delhi have been obtained through the courtesy of the Director of Plant Protection, Quarantine and Storage, Government of India. These data have been plotted on a map which is reproduced as Figure 1. It is seen that the majority of the reported swarms consisted of yellow locusts, but there are several reports of grey and pink locusts. The data pertain to rather widely separated observing points, but nevertheless there is a certain amount of consistency in the estimated directions of displacement, inasmuch as the majority of the Rajasthan reports indicate movements with a distinct west-to-east component.

From the strictly theoretical standpoint, it should be possible to determine the character of the progression of swarms (including their convergence) in an objective manner by drawing isochrones on a chart of "spot" observations. In actual practice, however, this is only very rarely feasible, due to the gaps in space and time between the different reporting points, lack of sufficient information regarding settled swarms and their day-to-day dispositions. As the diagram stands, more than one isochrone singularity can be discovered in it. Many synoptic meteorologists are familiar with similar difficulties in drawing isohyets where the dependability of the patterns is related directly to the closeness of the network of stations reporting rainfall.

3. RADAR OBSERVATIONS OF THE SWARMS

The swarms which came to Delhi were observed on the storm detection radar and the photographs of the echoes were taken by the Rain and Cloud Physics Research Unit, National Physical Laboratory, New Delhi.* A selection of the photographs is presented here.

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* The specifications of the radar are as follows : Model JRC NMB 451A; wavelength : 3.2 cm; antenna height : 12.7 metres above station level; maximum range : 360 km; peak power output: 250 kW; pulse-width : equivalent to 1 microsecond; beam-width : 1 degree.

The series of radar photographs (Figures 2, 4, 6 and 8) gives the plan position indicator (PPI) and range-elevation indicator (REI) displays at different times on different dates. The time of each radar observation can be seen on the clock in the photograph. This time is the Indian Standard Time (i.e. GMT plus 5 hours and 30 minutes). The top of each PPI picture represents north. Figures 3, 5, 7 and 9 show on a simple monochromatic station model the hourly observations and a few half-hourly observations of cloud and surface winds, made at Safdarjung Airport, which is at a radial distance of about 8 km from the site of the radar. These observations as well as the synoptic charts for the same period show that Delhi and its surrounding areas were free from rain until 2100 GMT on 29 July and that the cloud conditions were such that they were unlikely to produce any precipitation echoes on the radar. The REI pictures and other circumstantial evidence give support to this conclusion. Daily records from the 27 state rain-gauge observatories in Rajasthan for the period 26 to 29 July 1962 were all "nil" except for 13.5 mm at Chittorgarh on 28 and a trace at Udaipur on 29 July.

DISCUSSION

Figures 2 (c) to 2 (g) contain prominent echoes in the third (south through west) quadrant. Figure 2 (d) shows several low density bands to the west and west-southwest of the station at distances between 25 and 50 km. These appear to have concentrated into dense bands about an hour and forty minutes later, as can be seen in Figures 2 (e) and 2 (f). The two latter diagrams have been made with radar elevations of two degrees and three degrees respectively, indicating that the swarms had considerable vertical extent. The range-elevation indicator diagram shown in Figure 2 (h) was made in order to scan the vertical extent of the swarm on the azimuth of 252 degrees along which the swarm took a roughly linear configuration, as can be seen from Figure 2 (f). The range-elevation diagram shows that the swarm extended in sufficient density up to a height of at least 1.5 km at several places, and that its length was over 40 km, comprising a series of pyramids or cones each measuring about 5 km along the direction of scanning. It can be presumed that in view of the high density of locusts in the swarms there was a certain amount of attenuation of the radar beam at the remote regions of the field. This, together with the effect of the earth's curvature, leads to the conclusion that the total swarm could have been even larger than appears from the radar photographs.

The effects of ground clutter have to be carefully eliminated by taking into account the nature of the permanent echoes, illustrated in Figures 2 (m, n and o), and by comparing photographs, taken within one or two minutes of each other, with different elevations of the radar antenna. Figures 2 (i), 2 (j) and 2 (k) are examples in this regard. It will also be seen that there was a substantial reduction in the vertical extent of the swarm as between Figures 2 (h) and 2 (l). It has not been possible to verify whether the latter represents a stage prior to settling down. Another interesting feature seen in some of the photographs is the appearance of approximately annular-shaped echoes or echoes showing sharply curved protrusions. For example, Figure 2 (c) shows a ring-shaped echo embedded in a mass of other echoes, on the western sector, the central part of the echo appearing as almost free of locusts. Figure 2 (j) shows one such feature to the south of the station. Figures 6 (a), 6 (b) and 6 (c) show interesting curved patterns to the north-east of the station. That these were not permanent echoes can be seen by comparison with other diagrams with the same elevation angle and the same range. Figure 8 (d) shows another circular pattern to the south of the station. These examples could be multiplied by a close examination of the diagrams, especially over the low-density areas where the echoes have appeared merely as scattered dots. The more prominent features cited above are suggestive of some form of cellular structure, embedded in large masses of locusts. These cells could be areas of relatively high mesoscale convergence, and they could be associated with mesoscale vorticity persisting for one or two hours and drifting or dissipating later. It is felt that this particular feature of the echoes deserves to be closely studied when more radar photographs of locust swarms become available.

Figures 4, 6 and 8 pertain to 27, 28 and 29 July respectively. They differ from the series for the 26th in so far as they indicate a lessening of the concentration on the western sector, and greater activity on the eastern sector.

It will be seen from Figures 3, 5, 7 and 9 that during the period to which the radar photographs pertain, Delhi had varying amounts of cloud, but no Cumulonimbus had been reported until 2200 GMT on 29 July. Non-precipitating Cumulus, Altostratus and Altocumulus did appear now and then, but these could not have been associated with the radar echoes as no precipitation was recorded at Delhi or its vicinity and as the vertical extent of the echoes, as seen in the available RHI diagrams, was of the order of 1.5 km only. Accordingly, there is adequate justification for inferring that the observed radar echoes were caused by locusts and not by any other factor or atmospheric condition.

A discussion of the relevant synoptic features is given in the following paragraph. The scale on which the variations of the swarm positions and configurations took place was such that with the available meteorological data it would be almost impossible to correlate their short-period variations with meteorological parameters as observed on the charts. However, it is proposed to undertake a more detailed study of several aspects of these radar observations.

4. SYNOPTIC FEATURES

As 26 July was the date on which the major swarm movements took place, the synoptic features of this date are discussed in a more detailed manner. The mean sea-level synoptic chart of 0300 GMT is reproduced in Figure 10, while Figure 11 shows the 600 m streamlines at 0000 GMT on 26 July. Delhi tephigrams of 0000 and 1200 GMT of the same day are reproduced in Figures 12 and 13.

The synoptic chart shows the monsoon discontinuity as a double dotted line connecting the seasonal low over the central parts of West Pakistan and the trough over West Bengal and the adjoining parts of Bihar. The streamline chart (Figure 11) shows that northern India and West Pakistan were pervaded by westerlies; this implies that the monsoon discontinuity was extremely shallow. In this respect it can be said that the prevailing conditions over north-west India were akin to the so-called "break" monsoon conditions, associated with dry or nearly dry spells in the monsoon season. It will be seen that the stations in the vicinity of Delhi had clear or lightly clouded skies. The streamline chart shows winds from the western sector, of speeds varying between 15 and 25 kts. This feature could be associated with a flow of swarms from Rajasthan into the areas surrounding Delhi.* The tephigrams (Figures 12 and 13) show the dry- and wet-bulb curves and the winds. They indicate the existence of the usual moist adiabatic lapse rate and a marked diurnal variation of temperature in the lower levels. It will be seen that the winds close to the surface changed from westerly at 0000 GMT to a weak south-southeasterly at 1200 GMT. Although it is difficult to draw any definitive conclusion due to lack of sufficient data, it is not unlikely that this wind shift was associated with a possible mesoscale vortex over Delhi and the nearby areas to the west of the station. If so, it could be a factor conducive to the convergence of swarms into the Delhi area. Figure 14 shows the oscillations of the axis of the monsoon trough along the longitude of Delhi during the period 21 to 30 July, at 600 metres above sea-level. Between the 22nd and 24th, the axis was to the south of Delhi, and thereafter it moved northwards. It again moved south of Delhi on 30 July. It was close to the station on the 25th and again on the 29th. It may be mentioned that Delhi had a thunderstorm on the night of 29/30 July.

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* Aspliden and Rainey (1) have discussed the relationship between the wind and movements of swarms.

Figure 15 gives the vertical time section of Delhi over the period 20 to 30 July, the dates having been written from right to left in the diagram. The 24-hour changes of contour height are drawn at intervals of 20 metres, and the rises and falls are as usual indicated by R and F. The surface observations at 0000, 0600, 1200 and 1800 GMT are plotted at the appropriate places below the base line of the diagram. Generally no significant changes are noted in the upper-air temperatures. Low-level pressures fell on the 24th, followed by a rise on 28 to 29 July. The interesting feature about the upper-air winds is that easterlies generally prevailed up to 22 to 23 July, and the easterlies were then abruptly replaced by westerlies which prevailed until 29 July.

Figure 16 depicts the pattern of divergence at 600 metres based on the 0000 GMT upper-air charts from 22 to 29 July, prepared according to Bellamy's technique. Isopleths of positive and negative divergence have been drawn at unit intervals, the unit being $k = 2.3 \times 10^{-5}$ sec^{-1}. It is realized that the available network of pilot-balloon observations is rather open and does not lend itself to meso-analysis which is probably the only adequate mode for synoptic studies of locust situations. However, even as the diagrams are, it is possible to draw a few interesting conclusions from them. The convergence area was close to Delhi or included Delhi between 22 and 25 July when the axis of the monsoon trough at the same level was to the south of the station. Divergence areas became prominent during the subsequent three days, and on 29 July when the trough line commenced its movement southwards, Delhi came within an area of significant convergence. On 26 July an axis of convergence could be drawn, oriented approximately from north-west to south-west, while on the following day a small area of convergence appeared to the south of the station. The Rajasthan area was dominated by a region of divergence almost during the entire period considered. The exact extent to which the concentration and dispersal of locusts is governed by atmospheric convergence and divergence in a non-depressional field is not known. Analysis is beset by perpetual difficulties arising out of insufficiency of data, for the displacements occur over a wide spectrum of distances. The radar photographs discussed earlier show that on 26 July there were extensions of swarms in the south-western quadrant, while on the three subsequent days the extensions were seen to the east and south of the station. The convergence areas on the east and south of Delhi on 27, 28 and 29 July should lead to the expectation of locust activity on the southern and eastern areas, and the radar photographs bear this out. It has however not been possible to establish the validity of the statement (mentioned under summary of press reports in paragraph 2 above) that one swarm came from the direction of Meerut, i.e. against the prevailing wind.

The circumstances which can lead to the accumulation and temporary immobilization of swarms has been discussed by Rainey (3).

5. CONCLUDING REMARKS

Despite obvious limitations of data, an attempt has been made in this preliminary study to point out the possibilities provided by the radar technique for the detection and control of locust swarms. Questions relating to the complete interpretation of radar locust echoes will no doubt become clearer when further studies of this kind are undertaken in India and other countries in the locust belt. For supplementing radar studies it is necessary to undertake carefully planned mesoscale analyses over areas commonly affected by swarms.

Any worth-while investigation of the locust problem has necessarily to depend upon reliable machinery for collecting locust intelligence. A great deal of assistance can be rendered by extending facilities for systematic aircraft reconnaissance and photography to those areas where these facilities do not exist at present. A case also exists for setting up a system of high-speed communications, including mobile radio communications (as established, for instance, by the Desert Locust Control Organisation for Eastern Africa based at Asmara in Ethiopia), for linking up field stations with the respective national or regional headquarters for locust control.

ACKNOWLEDGEMENTS

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The authors are grateful to Dr. R.C. Rainey for his kind interest in this investigation and his valuable suggestions, and to Dr. Sardar Singh, Director of Plant Protection, Government of India, for supplying detailed observations pertaining to the spell.

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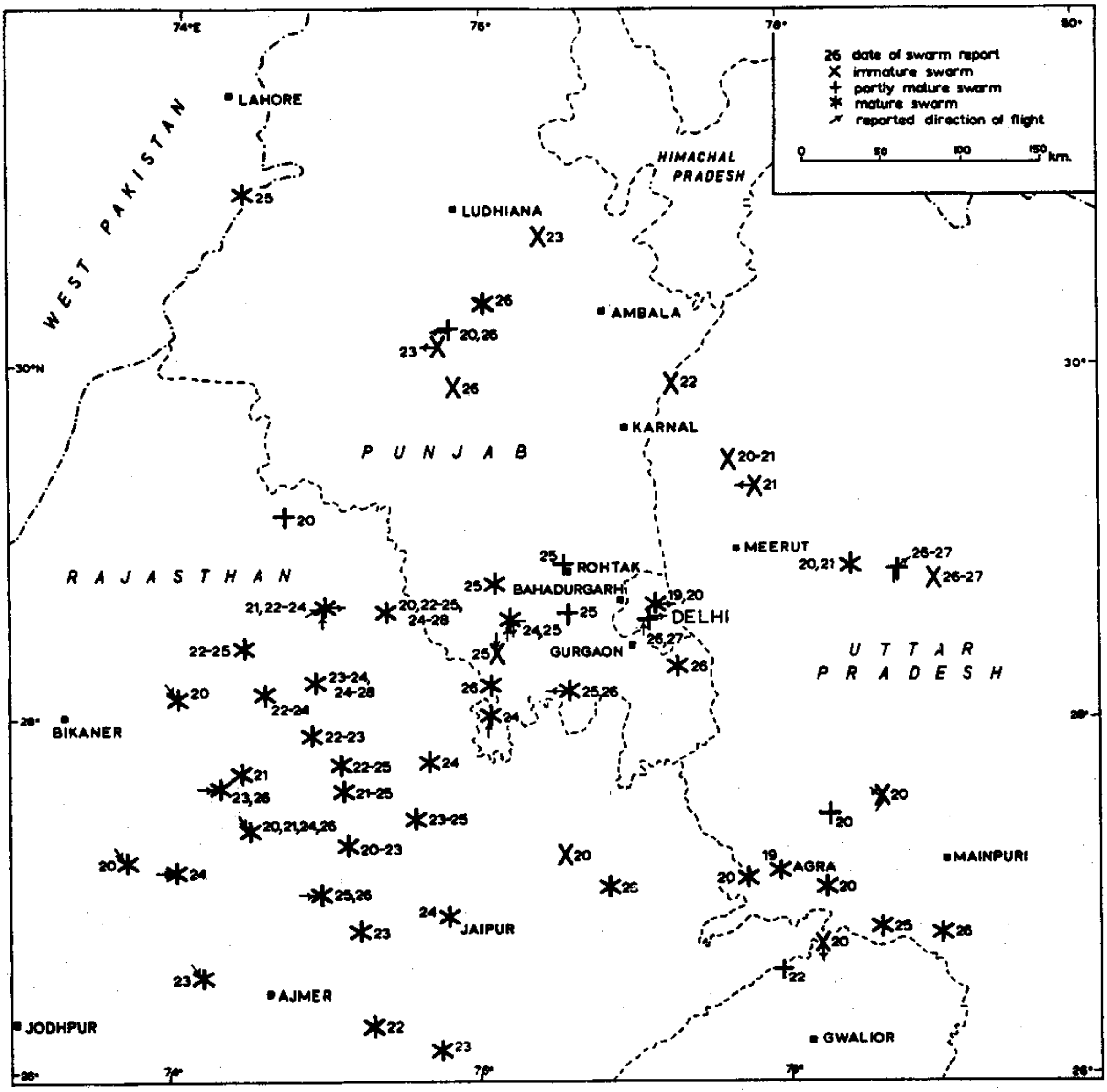
26 date of swarm report
X immature swarm
+ partly mature swarm
✱ mature swarm
reported direction of flight
0 50 100 150 km.
74°E
76°
78°
80°
30°N
30°
28°
26°
LAHORE
WEST PAKISTAN
LUDHIANA
AMBALA
HIMACHAL PRADESH
KARNAL
PUNJAB
RAJASTHAN
ROHTAK
BAHADURGARH
DELHI
GURGAON
MEERUT
UTTAR PRADESH
BIKANER
AGRA
MAINPURI
JAIPUR
AJMER
JODHPUR
GWALIOR

Figure 1

Figure 2 - Radar photographs on 26 July 1962.

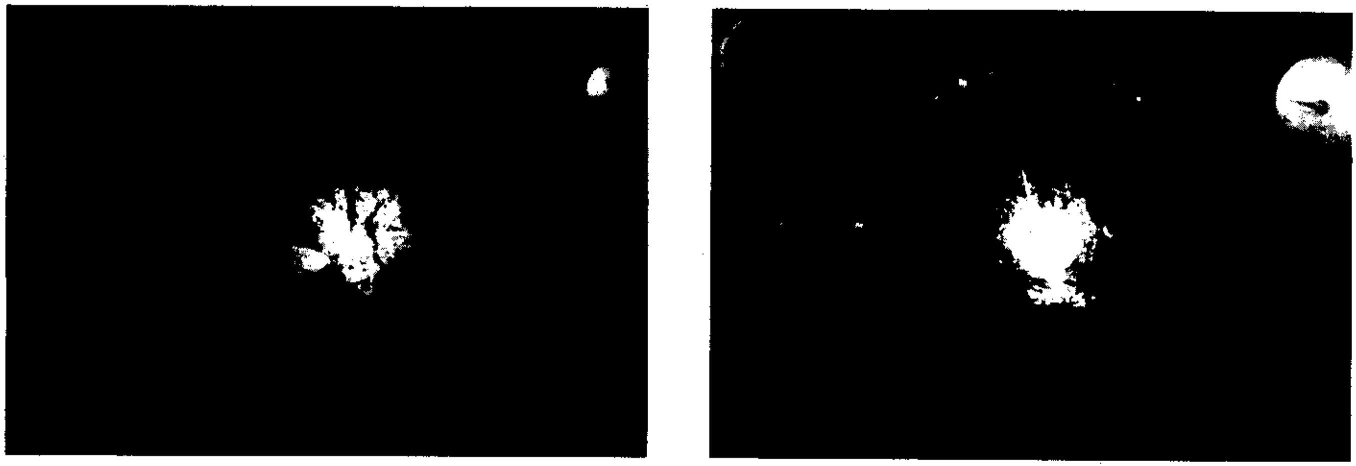

Figure 2 (a) -
Indication - PPI
Time - 1030 IST (0500 GMT)
Elevation - 1 degree
Range - 50 km

Figure 2 (b) -
Indication - PPI
Time - 1052.5 IST (0522.5 GMT)
Elevation - 2 degrees
Range - 50 km

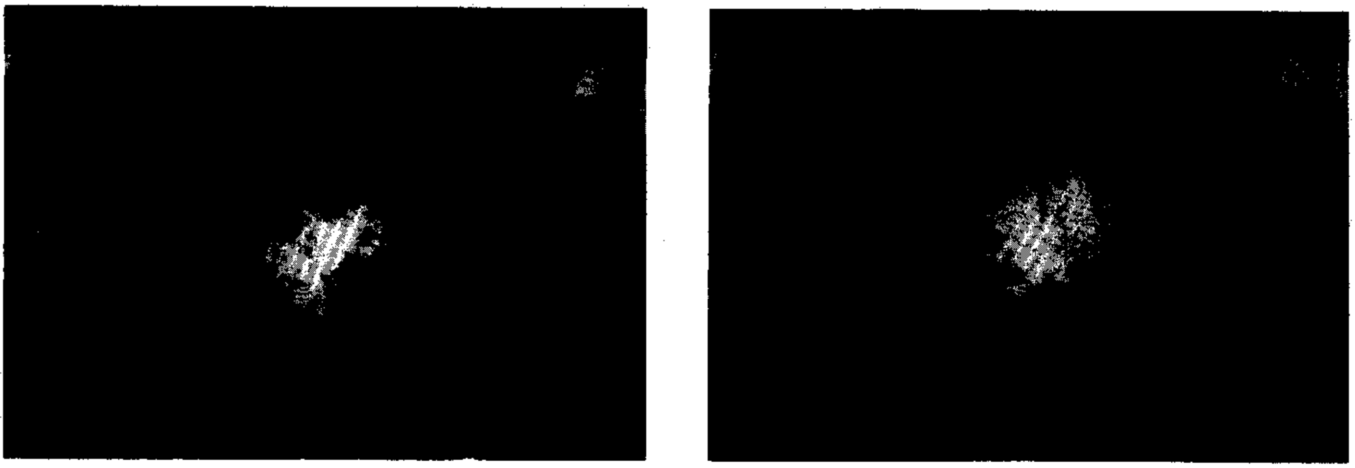

Figure 2 (c) -
Indication - PPI
Time - 1155 IST (0625 GMT)
Elevation - 2 degrees
Range - 20 km

Figure 2 (d) -
Indication - PPI
Time - 1334 IST (0804 GMT)
Elevation - 1 degree
Range - 50 km

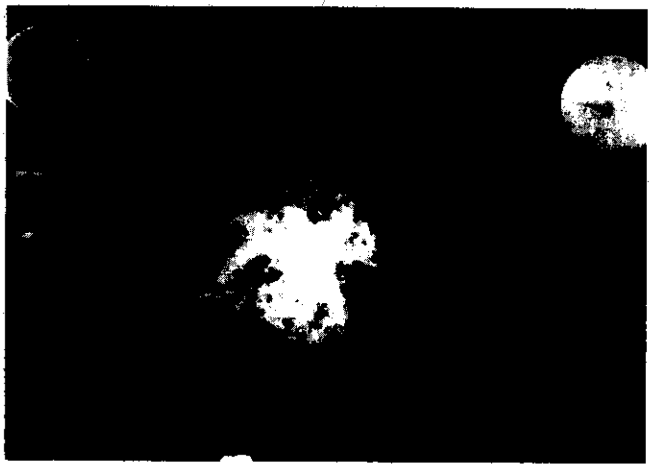

Figure 2 (e) -
Indication - PPI
Time - 1335.5 IST (0805.5 GMT)
Elevation - 2 degrees
Range - 20 km

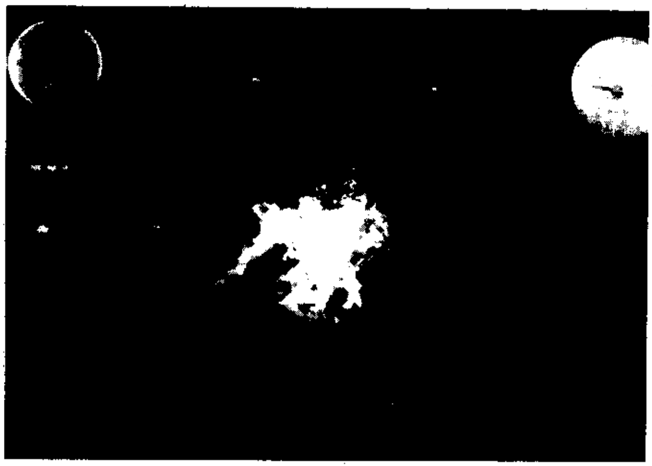

Figure 2 (f) -
Indication - PPI
Time - 1336 IST (0806 GMT)
Elevation - 3 degrees
Range - 20 km

Figure 2 (g) -
Indication - PPI (Off-centre)
Time - 1337 IST (0807 GMT)
Elevation - 1.5 degrees
Range - 20 km

Figure 2 (h) -
Indication - REI
Time - 1339 IST (0809 GMT)
Azimuth - 252 degrees
Range-markers 5 km apart

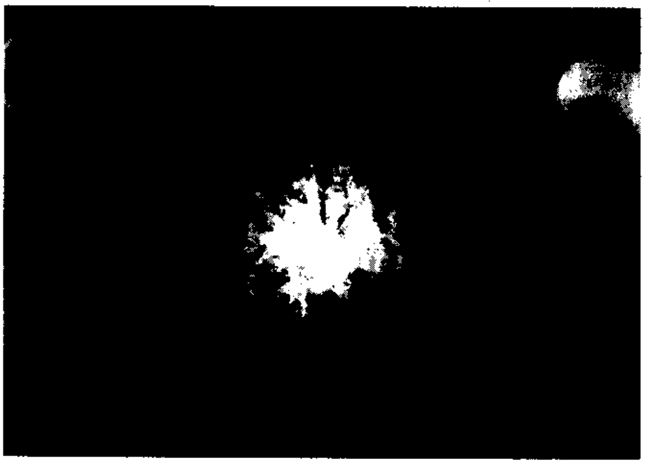

Figure 2 (i) -
Indication - PPI
Time - 1414 IST (0844 GMT)
Elevation - 1 degree
Range - 50 km

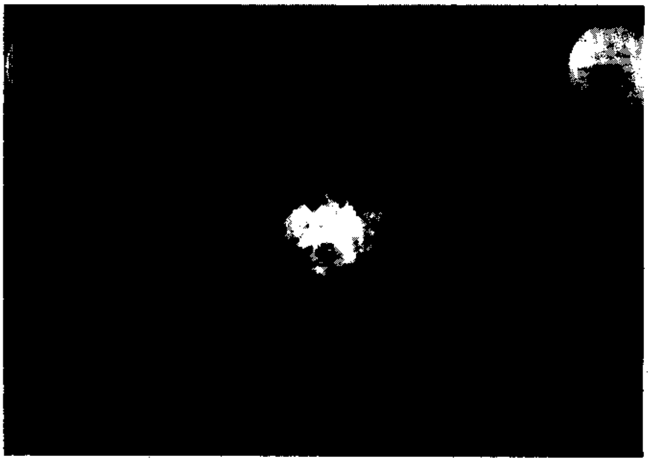

Figure 2 (j) -
Indication - PPI
Time - 1414.5 IST (0.844.5 GMT)
Elevation - 2 degrees
Range - 50 km

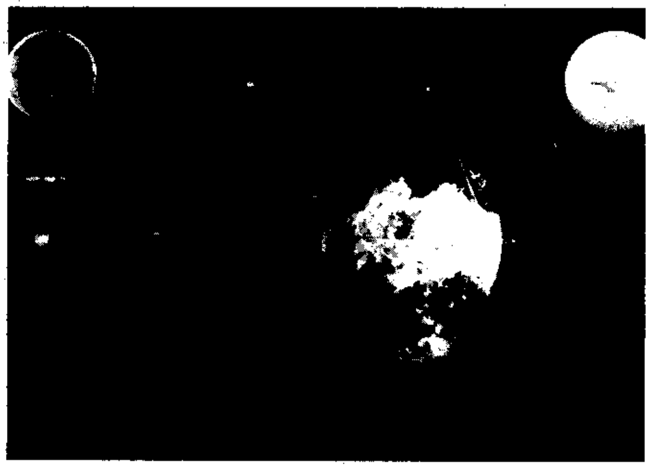

Figure 2 (k) -
Indication - PPI (Off-centre)
Time - 1415 IST (0845 GMT)
Elevation - 1.5 degrees
Range - 20 km

Figure 2 (l) -
Indication - REI
Time - 1658 IST (1128 GMT)
Azimuth - 286 degrees
Range-markers 5 km apart

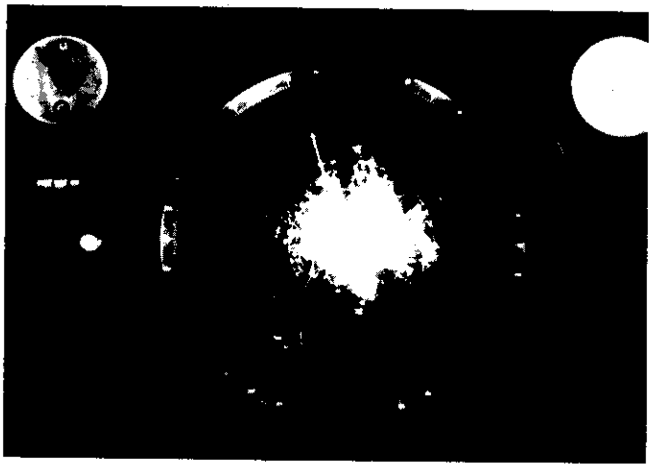

Figure 2 (m) -
Indication - PPI
Time - 1054 IST
Elevation - 1 degree
Range - 50 km

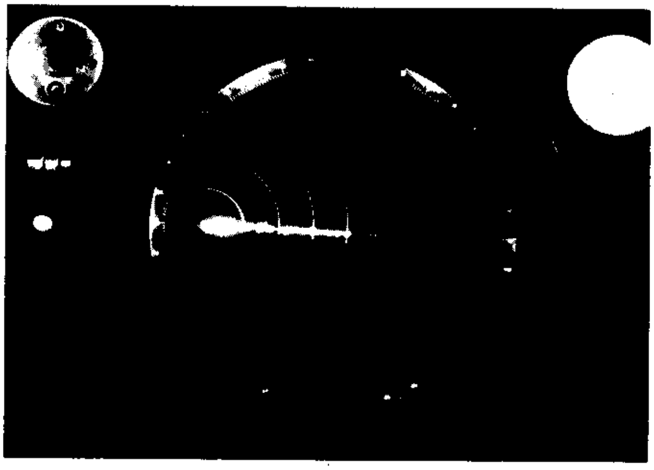

Figure 2 (n) -
Indication - REI
Time - 1105 IST
Azimuth - 252 degrees
Range - 20 km

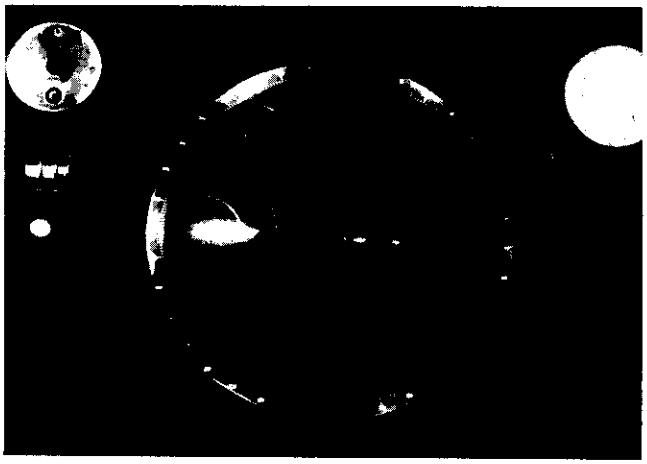

Figure 2 (o) -
Indication - REI
Time - 1110 IST
Azimuth - 32 degrees
Range - 20 km

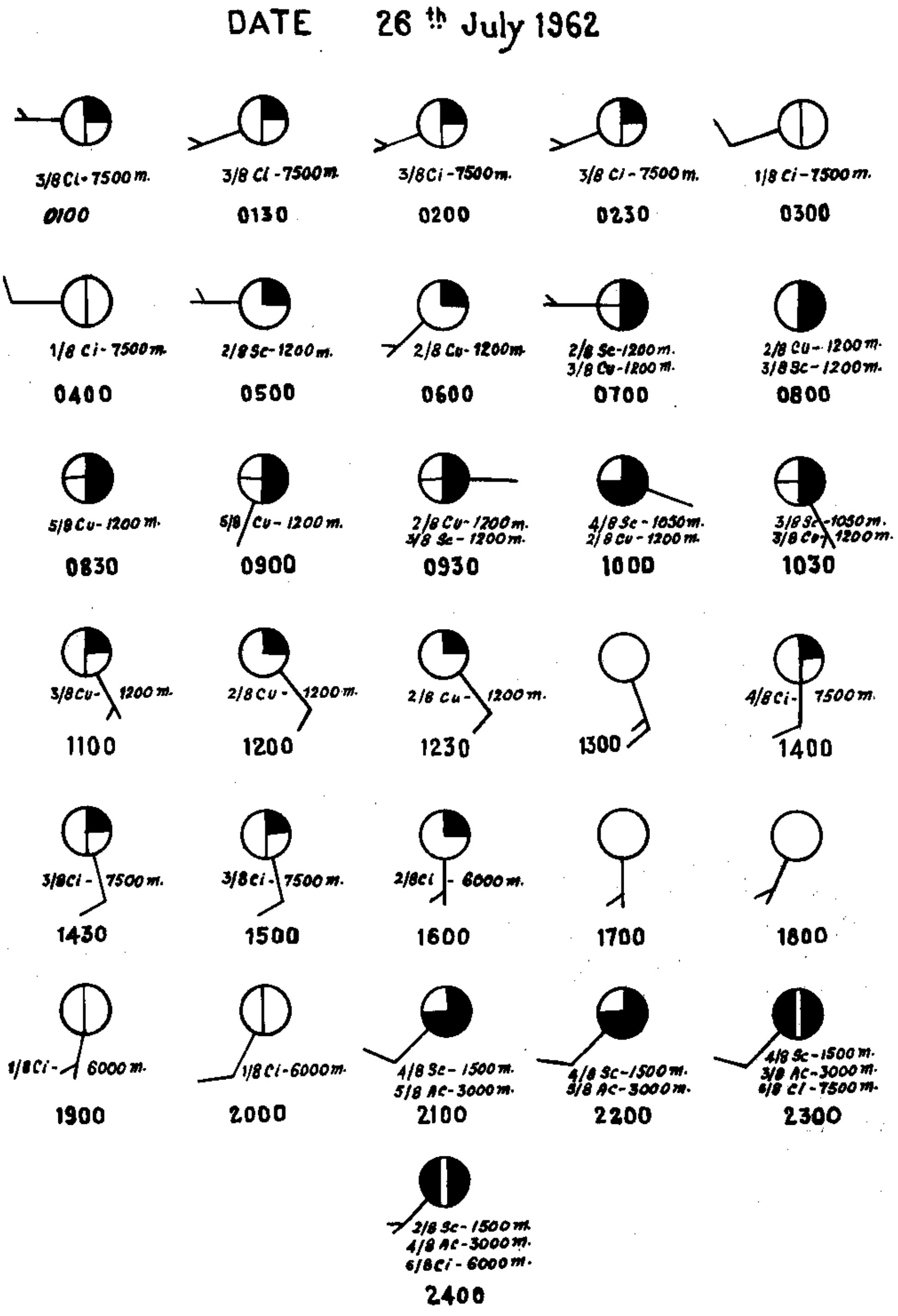
DATE 26 th July 1962
3/8 Ci-7500 m.
0100
3/8 Ci -7500 m.
0130
3/8 Ci -7500 m.
0200
3/8 Ci - 7500 m.
0230
1/8 Ci -7500 m.
0300
1/8 Ci- 7500 m.
0400
2/8 Sc-1200 m.
0500
2/8 Cu-1200 m.
0600
2/8 Sc-1200 m.
3/8 Cu-1200 m.
0700
2/8 Cu-1200 m.
3/8 Sc-1200 m.
0800
5/8 Cu-1200 m.
0830
5/8 Cu- 1200 m.
0900
2/8 Cu-1200 m.
3/8 Sc-1200 m.
0930
4/8 Sc-1050 m.
2/8 Cu-1200 m.
1000
3/8 Sc-1050 m.
3/8 Cu-1200 m.
1030
3/8 Cu- 1200 m.
1100
2/8 Cu - 1200 m.
1200
2/8 Cu - 1200 m.
1230
1300
4/8 Ci- 7500 m.
1400
3/8 Ci - 7500 m.
1430
3/8 Ci - 7500 m.
1500
2/8 Ci - 6000 m.
1600
1700
1800
1/8 Ci - 6000 m.
1900
1/8 Ci-6000 m.
2000
4/8 Sc- 1500 m.
5/8 Ac-3000 m.
2100
4/8 Sc-1500 m.
3/8 Ac-3000 m.
2200
4/8 Sc-1500 m.
3/8 Ac-3000 m.
6/8 Ci-7500 m.
2300
2/8 Sc-1500 m.
4/8 Ac-3000 m.
6/8 Ci-6000 m.
2400

Figure 3

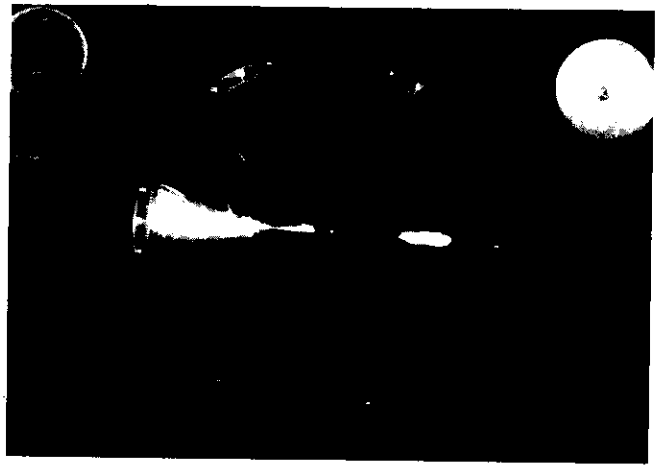

Figure 4 (a) -
Indication - REI
Time - 1118 IST (0548 GMT)
Azimuth - 32 degrees
Range-markers at intervals of 2.5 km

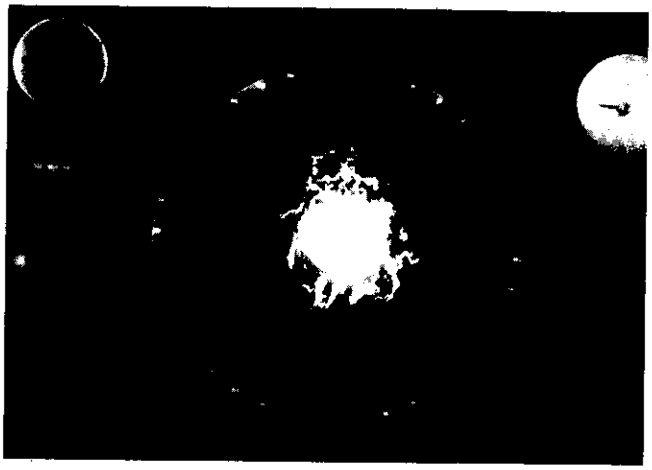

Figure 4 (b) -
Indication - PPI
Time 1505.5 IST (0935.5 GMT)
Elevation - 1 degree
Range - 100 km

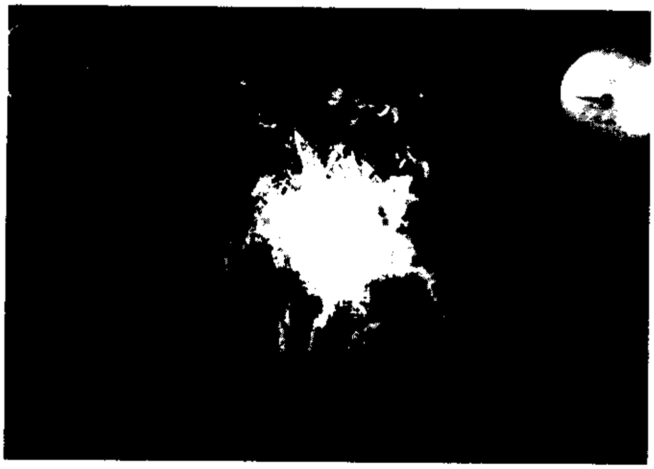

Figure 4 (c) -
Indication - PPI
Time - 1506 IST (0936 GMT)
Elevation - 1 degree
Range - 50 km

Figure 4 (d) -
Indication - PPI
Time - 1506.5 IST (0936.5 GMT)
Elevation - 1.5 degrees
Range - 50 km

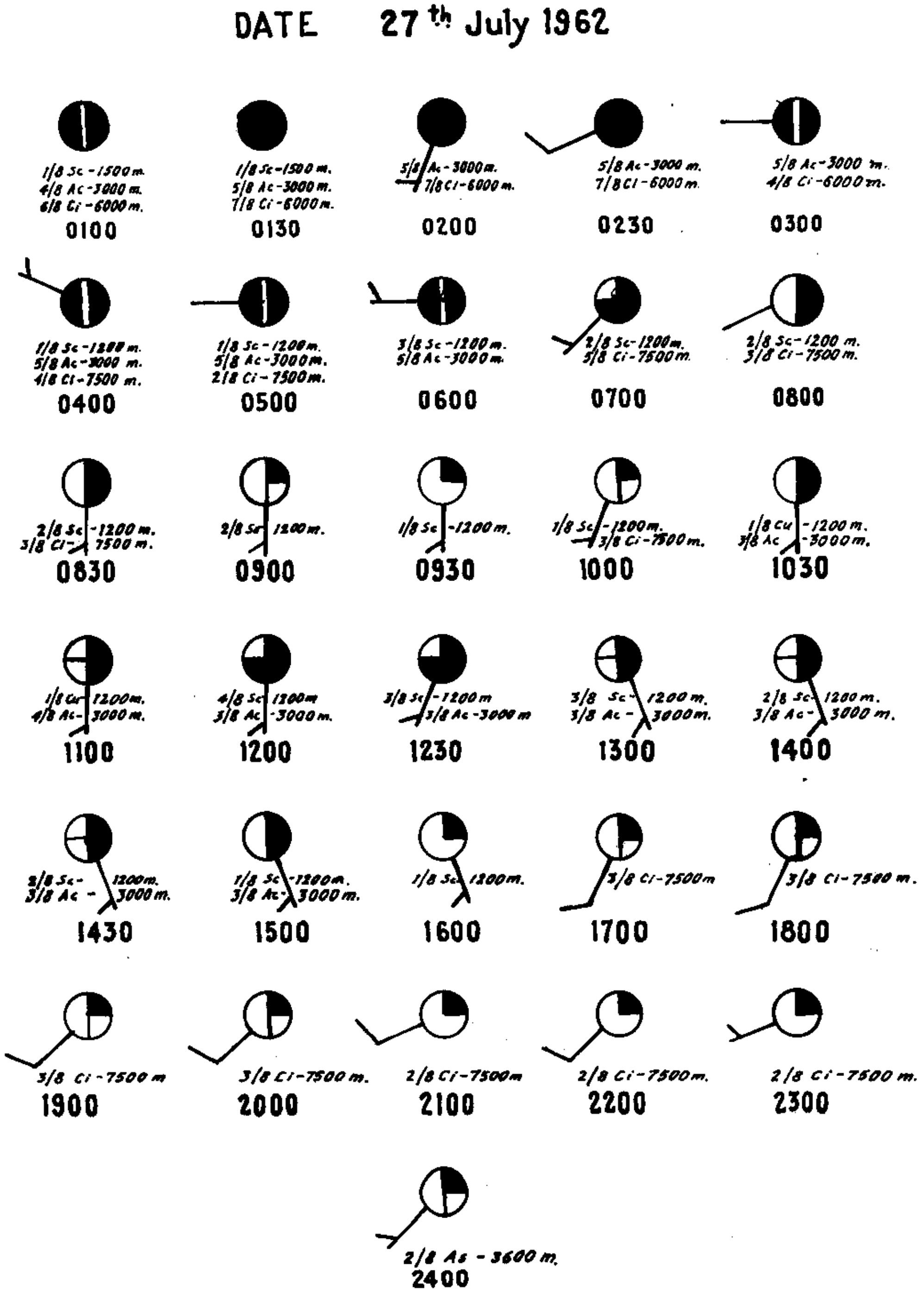
DATE 27th July 1962
1/8 Sc - 1500 m.
4/8 Ac - 3000 m.
6/8 Ci - 6000 m.
0100
1/8 Sc - 1500 m.
5/8 Ac - 3000 m.
7/8 Ci - 6000 m.
0130
5/8 Ac - 3000 m.
7/8 Ci - 6000 m.
0200
5/8 Ac - 3000 m.
7/8 Ci - 6000 m.
0230
5/8 Ac - 3000 m.
4/8 Ci - 6000 m.
0300
1/8 Sc - 1200 m.
5/8 Ac - 3000 m.
4/8 Ci - 7500 m.
0400
1/8 Sc - 1200 m.
5/8 Ac - 3000 m.
2/8 Ci - 7500 m.
0500
3/8 Sc - 1200 m.
5/8 Ac - 3000 m.
0600
2/8 Sc - 1200 m.
5/8 Ci - 7500 m.
0700
2/8 Sc - 1200 m.
3/8 Ci - 7500 m.
0800
2/8 Sc - 1200 m.
3/8 Ci - 7500 m.
0830
2/8 Sc 1200 m.
0900
1/8 Sc - 1200 m.
0930
1/8 Sc - 1200 m.
3/8 Ci - 7500 m.
1000
1/8 Cu - 1200 m.
3/8 Ac - 3000 m.
1030
1/8 Cu 1200 m.
4/8 Ac - 3000 m.
1100
4/8 Sc 1200 m
3/8 Ac - 3000 m.
1200
3/8 Sc - 1200 m
3/8 Ac - 3000 m
1230
3/8 Sc - 1200 m.
3/8 Ac - 3000 m.
1300
2/8 Sc - 1200 m.
3/8 Ac - 3000 m.
1400
2/8 Sc - 1200 m.
3/8 Ac - 3000 m.
1430
1/8 Sc - 1200 m.
3/8 Ac - 3000 m.
1500
1/8 Sc 1200 m.
1600
3/8 Ci - 7500 m
1700
3/8 Ci - 7500 m.
1800
3/8 Ci - 7500 m
1900
3/8 Ci - 7500 m.
2000
2/8 Ci - 7500 m
2100
2/8 Ci - 7500 m.
2200
2/8 Ci - 7500 m.
2300
2/8 As - 3600 m.
2400

Figure 5

Figure 6 (a) -
Indication - PPI
Time - 1051 IST (0521 GMT)
Elevation - 1 degree
Range - 50 km

Figure 6 (b) -
Indication - PPI
Time - 1052 IST (0522 GMT)
Elevation - 1.5 degrees
Range - 50 km

Figure 6 (c) -
Indication - PPI
Time - 1146.5 IST (0616.5 GMT)
Elevation - 1 degree
Range - 50 km

Figure 6 (d) -
Indication - PPI
Time - 1147 IST (0617 GMT)
Elevation - 1.5 degrees
Range - 50 km

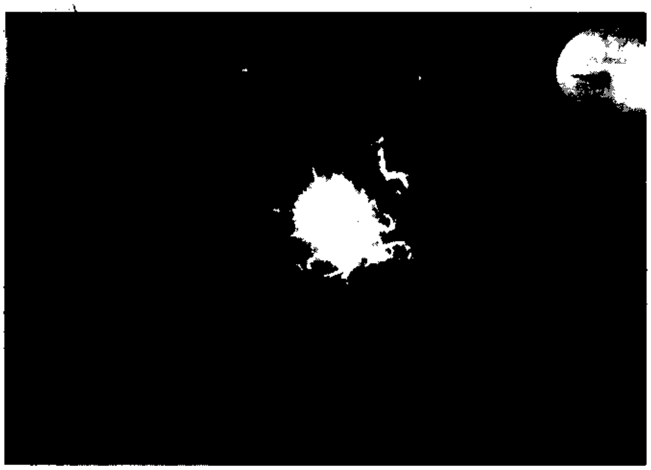

Figure 6 (e) -
Indication - PPI
Time - 1420.5 IST (0850.5 GMT)
Elevation - 1 degree
Range - 100 km

Figure 6 (f) -
Indication - PPI
Time - 1421 IST (0851 GMT)
Elevation - 1 degree
Range - 50 km

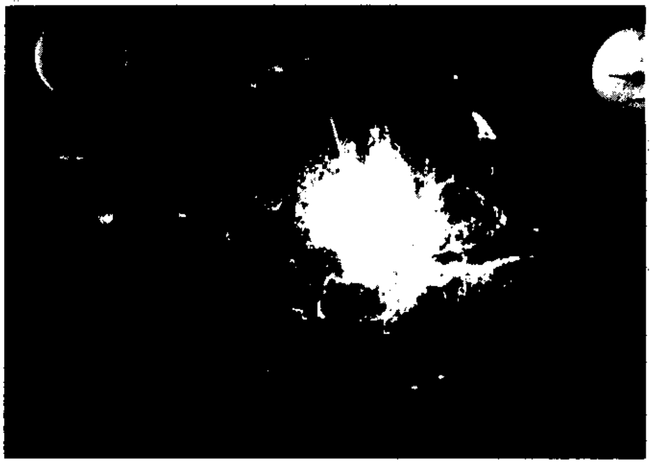

Figure 6 (g) -
Indication - PPI
Time - 1505.5 IST (0935.5 GMT)
Elevation - 1 degree
Range - 50 km

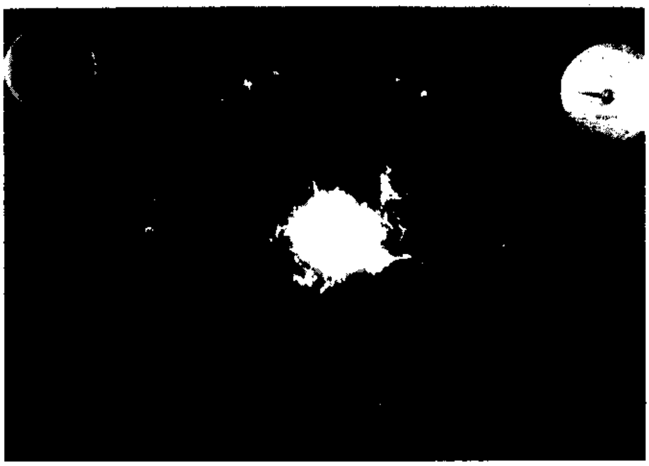

Figure 6 (h) -
Indication - PPI
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Elevation - 1 degree
Range - 100 km

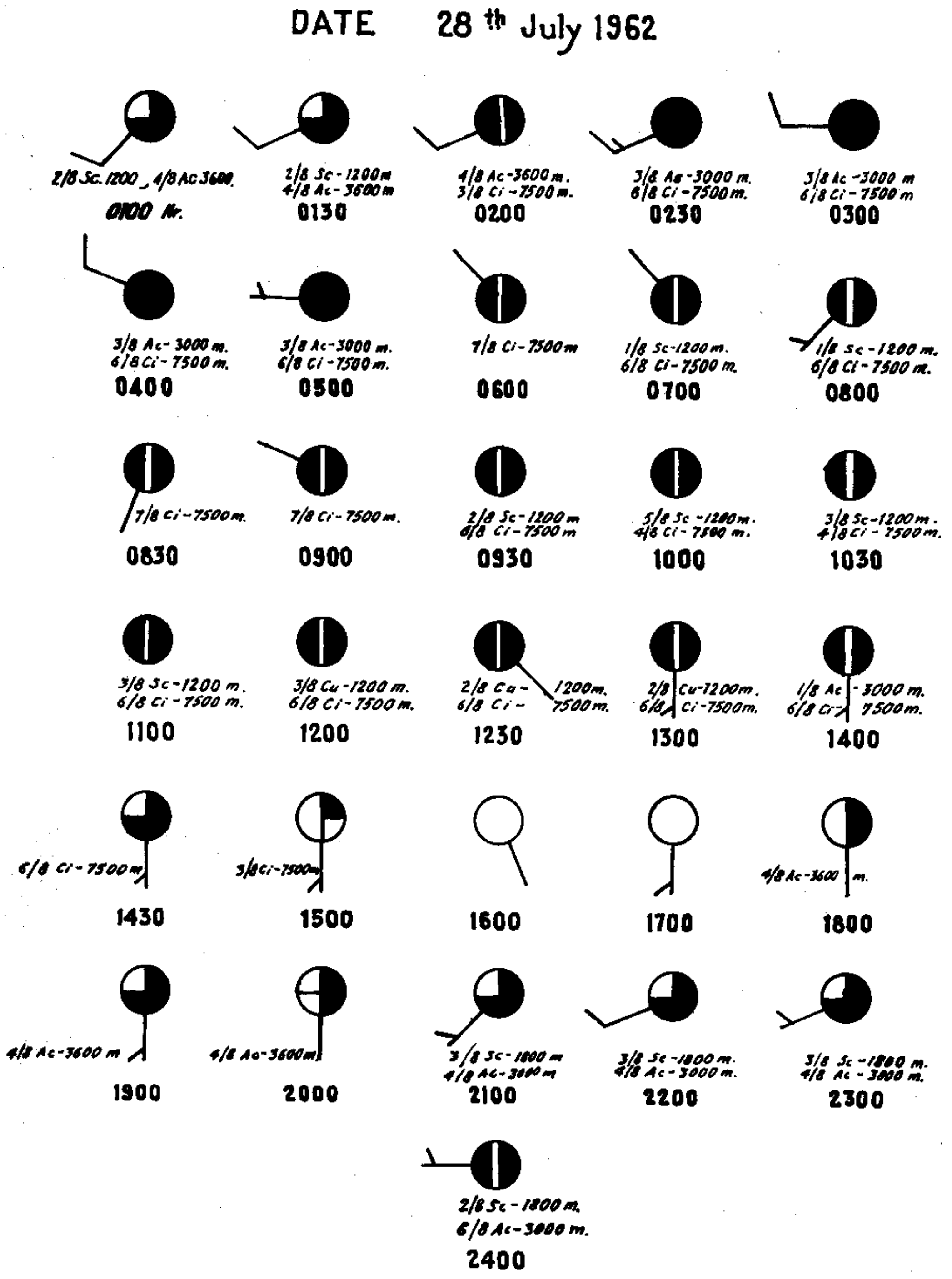

DATE 28th July 1962
2/8 Sc. 1200 _ 4/8 Ac 3600.
0100 Hr.
2/8 Sc - 1200 m
4/8 Ac - 3600 m
0130
4/8 Ac - 3600 m.
3/8 Ci - 7500 m.
0200
3/8 Ac - 3000 m.
6/8 Ci - 7500 m.
0230
3/8 Ac - 3000 m
6/8 Ci - 7500 m
0300
3/8 Ac - 3000 m.
6/8 Ci - 7500 m.
0400
3/8 Ac - 3000 m.
6/8 Ci - 7500 m.
0500
7/8 Ci - 7500 m
0600
1/8 Sc - 1200 m.
6/8 Ci - 7500 m.
0700
1/8 Sc - 1200 m.
6/8 Ci - 7500 m.
0800
7/8 Ci - 7500 m.
0830
7/8 Ci - 7500 m.
0900
2/8 Sc - 1200 m
6/8 Ci - 7500 m
0930
5/8 Sc - 1200 m.
4/8 Ci - 7500 m.
1000
3/8 Sc - 1200 m.
4/8 Ci - 7500 m.
1030
3/8 Sc - 1200 m.
6/8 Ci - 7500 m.
1100
3/8 Cu - 1200 m.
6/8 Ci - 7500 m.
1200
2/8 Cu - 1200 m.
6/8 Ci - 7500 m.
1230
2/8 Cu - 1200 m.
6/8 Ci - 7500 m.
1300
1/8 Ac - 3000 m.
6/8 Ci - 7500 m.
1400
6/8 Ci - 7500 m
1430
3/8 Ci - 7500 m
1500
1600
1700
4/8 Ac - 3600 m.
1800
4/8 Ac - 3600 m
1900
4/8 Ac - 3600 m
2000
3/8 Sc - 1800 m
4/8 Ac - 3000 m
2100
3/8 Sc - 1800 m.
4/8 Ac - 3000 m.
2200
3/8 Sc - 1800 m.
4/8 Ac - 3000 m.
2300
2/8 Sc - 1800 m.
6/8 Ac - 3000 m.
2400

Figure 7

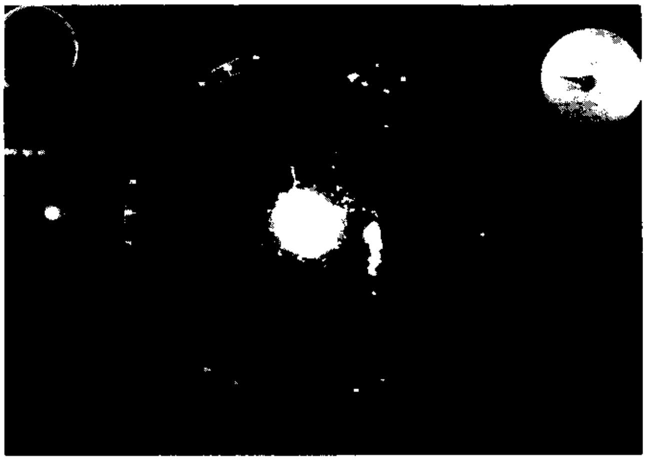


Figure 8 (a) -
Indication - PPI
Time - 1033.5 IST (0503.5 GMT)
Elevation - 2.5 degrees
Range - 50 km

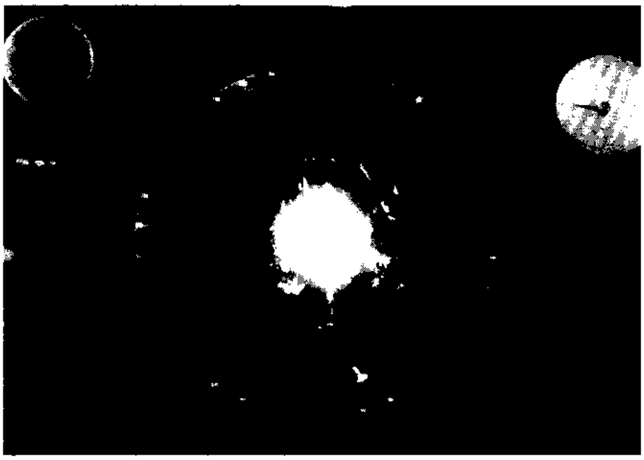


Figure 8 (b) -
Indication - PPI
Time - 1130 IST (0600 GMT)
Elevation - 1 degree
Range - 100 km

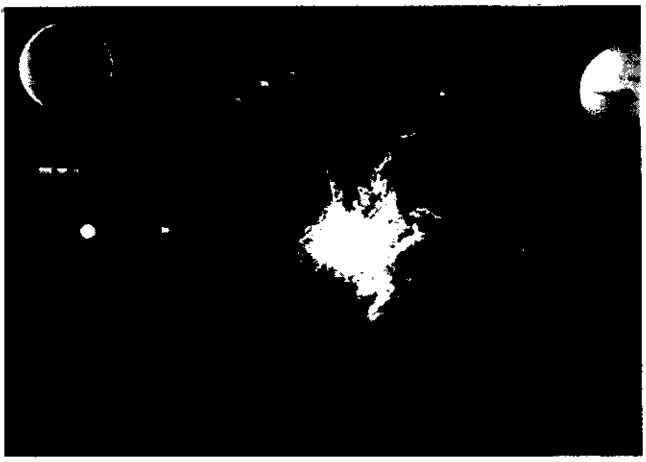


Figure 8 (c) -
Indication - PPI
Time - 1401.5 IST (0831.5 GMT)
Elevation - 1.5 degrees
Range - 50 km

Figure 8 (d) -
Indication - PPI
Time - 1502 IST (0932 GMT)
Elevation - 1 degree
Range - 100 km

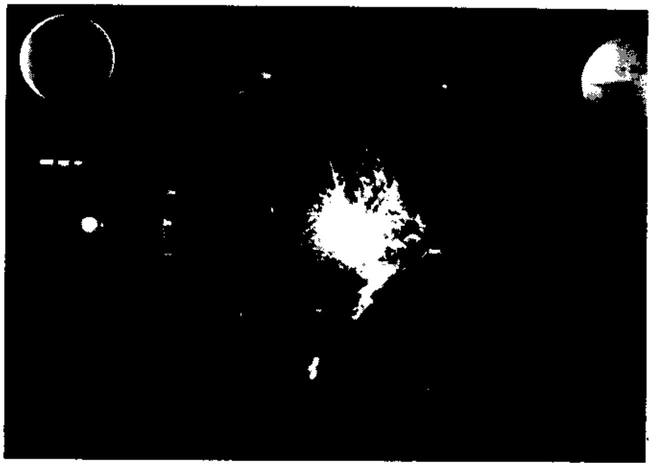


Figure 8 (e) -
Indication - PPI
Time - 1504.5 IST (0934.5 GMT)
Elevation - 1.5 degrees
Range - 50 km

Figure 8 (f) -
Indication - PPI
Time - 1556 IST (1026 GMT)
Elevation - 1 degree
Range - 100 km

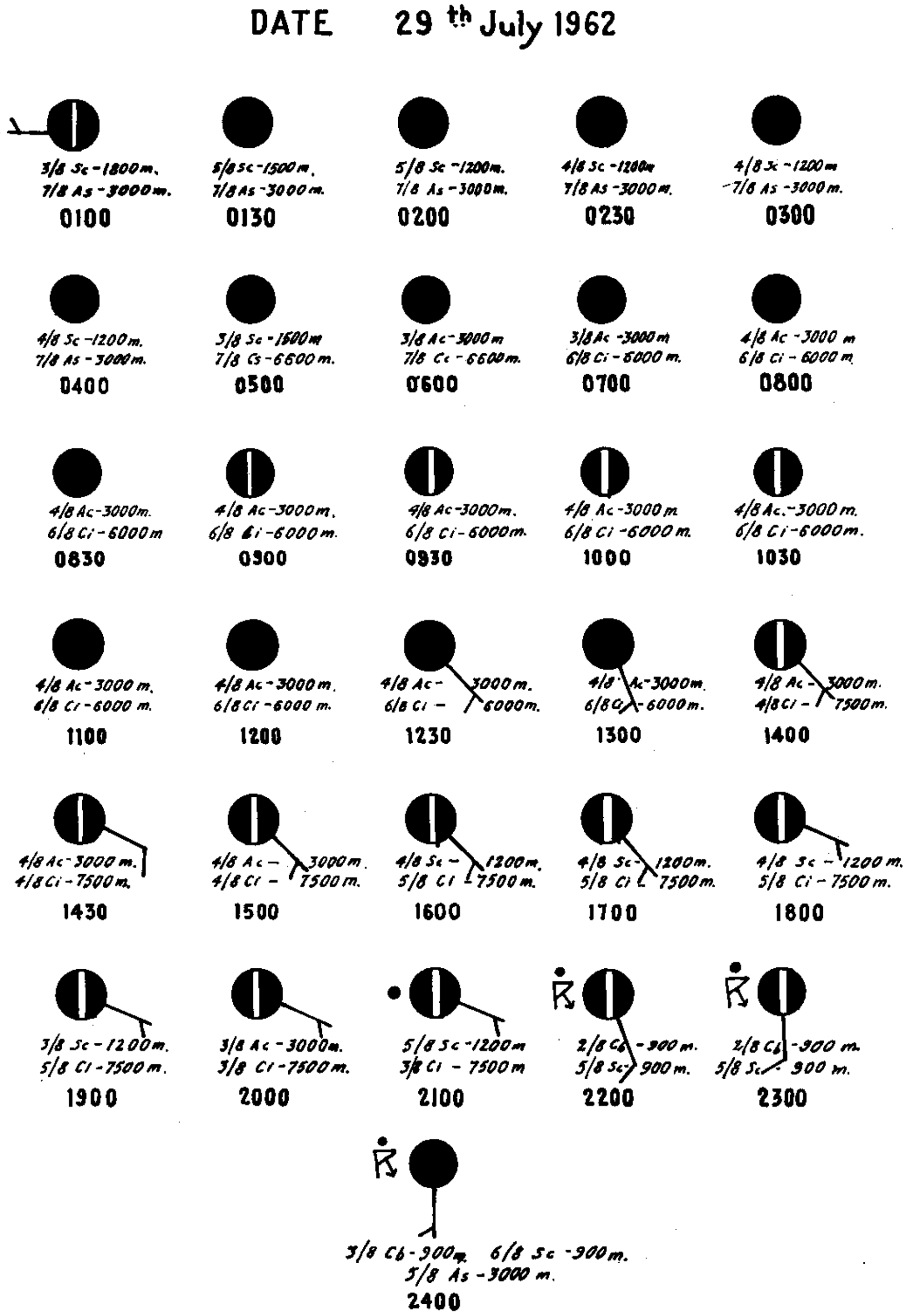

DATE 29th July 1962
3/8 Sc - 1800 m.
7/8 As - 3000 m.
0100
5/8 Sc - 1500 m.
7/8 As - 3000 m.
0130
5/8 Sc - 1200 m.
7/8 As - 3000 m.
0200
4/8 Sc - 1200 m
7/8 As - 3000 m.
0230
4/8 Sc - 1200 m
7/8 As - 3000 m.
0300
4/8 Sc - 1200 m.
7/8 As - 3000 m.
0400
3/8 Sc - 1600 m
7/8 Cs - 6600 m.
0500
3/8 Ac - 3000 m
7/8 Cs - 6600 m.
0600
3/8 Ac - 3000 m
6/8 Ci - 6000 m.
0700
4/8 Ac - 3000 m
6/8 Ci - 6000 m
0800
4/8 Ac - 3000 m.
6/8 Ci - 6000 m
0830
4/8 Ac - 3000 m.
6/8 Ci - 6000 m.
0900
4/8 Ac - 3000 m.
6/8 Ci - 6000 m.
0930
4/8 Ac - 3000 m
6/8 Ci - 6000 m.
1000
4/8 Ac. - 3000 m.
6/8 Ci - 6000 m.
1030
4/8 Ac - 3000 m.
6/8 Ci - 6000 m.
1100
4/8 Ac - 3000 m.
6/8 Ci - 6000 m.
1200
4/8 Ac - 3000 m.
6/8 Ci - 6000 m.
1230
4/8 Ac - 3000 m.
6/8 Ci - 6000 m.
1300
4/8 Ac - 3000 m.
4/8 Ci - 7500 m.
1400
4/8 Ac - 3000 m.
4/8 Ci - 7500 m.
1430
4/8 Ac - 3000 m.
4/8 Ci - 7500 m.
1500
4/8 Sc - 1200 m.
5/8 Ci - 7500 m.
1600
4/8 Sc - 1200 m.
5/8 Ci - 7500 m.
1700
4/8 Sc - 1200 m.
5/8 Ci - 7500 m.
1800
3/8 Sc - 1200 m.
5/8 Ci - 7500 m.
1900
3/8 Ac - 3000 m.
3/8 Ci - 7500 m.
2000
5/8 Sc - 1200 m
3/8 Ci - 7500 m
2100
2/8 Cb - 900 m.
5/8 Sc - 900 m.
2200
2/8 Cb - 900 m.
5/8 Sc - 900 m.
2300
3/8 Cb - 900 m. 6/8 Sc - 900 m.
5/8 As - 3000 m.
2400

Figure 9

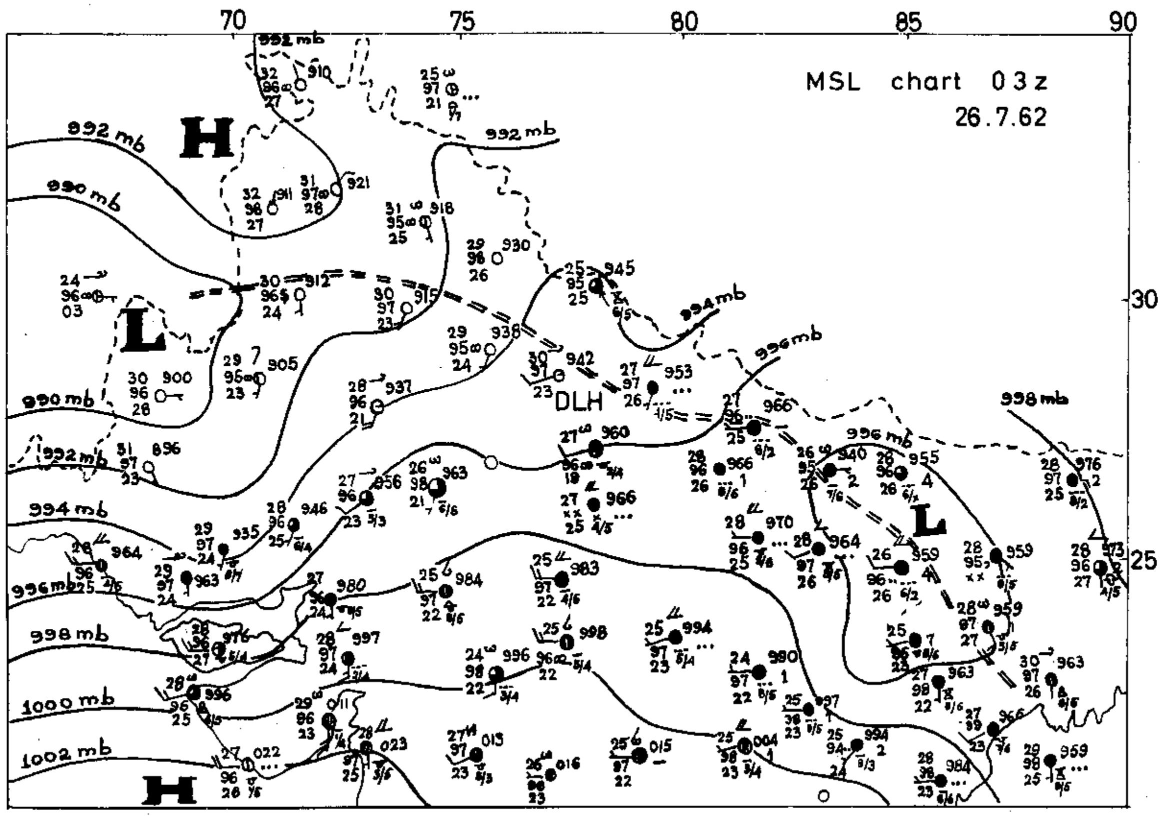


Figure 10

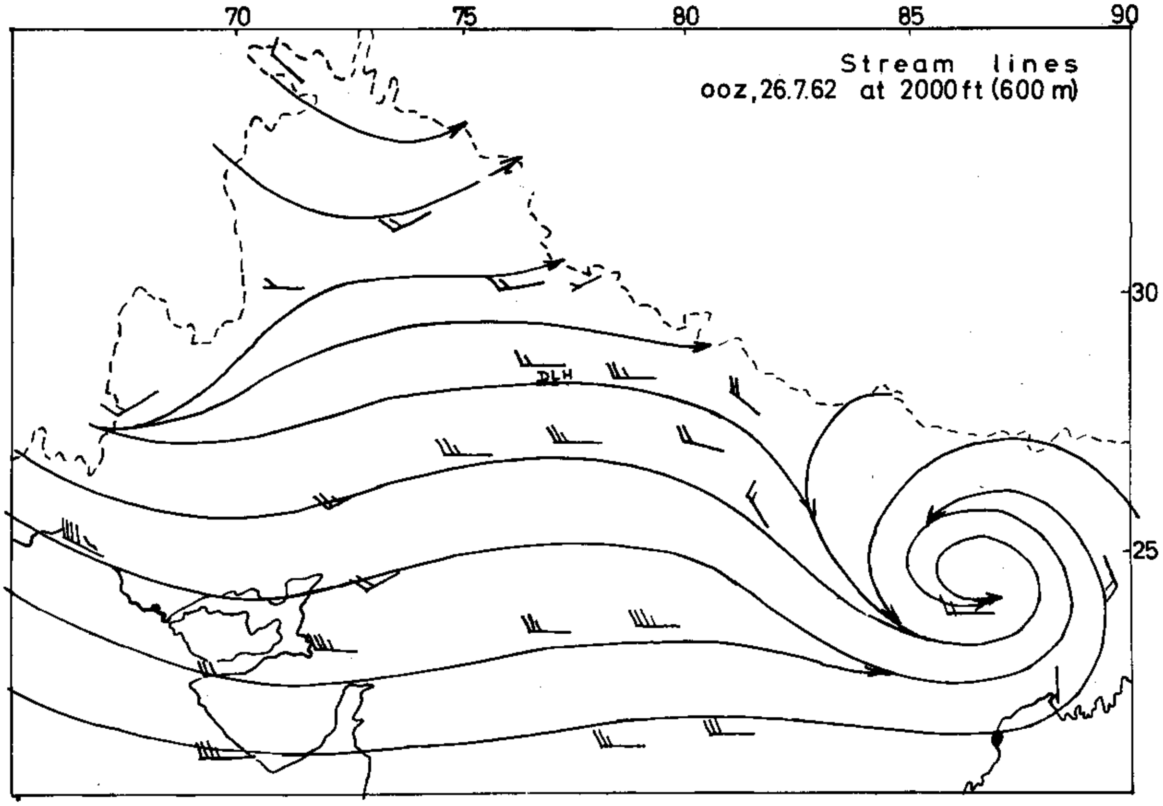


Figure 11

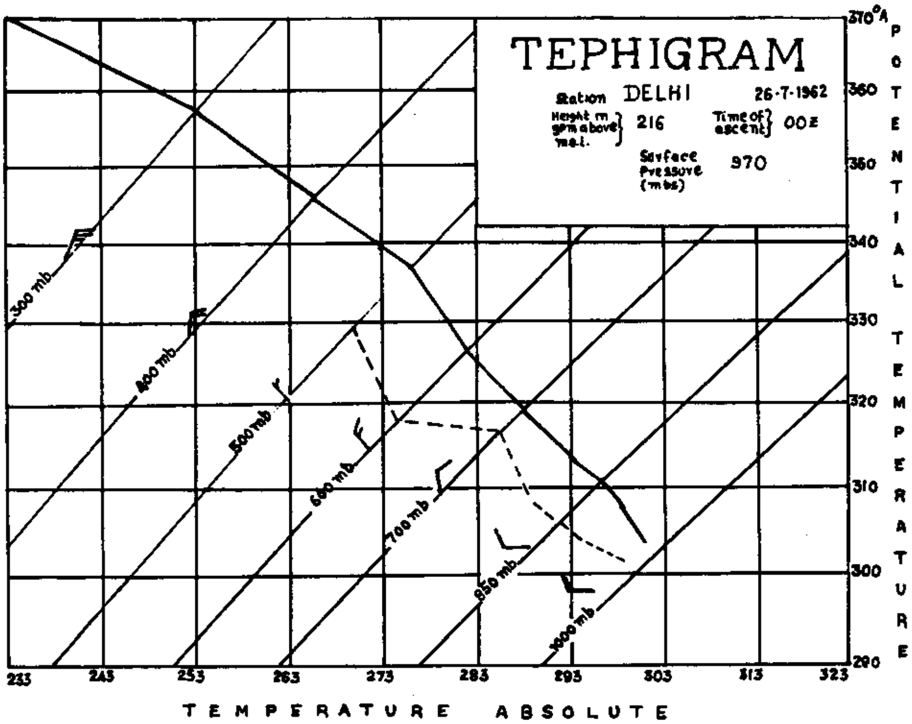


Figure 12

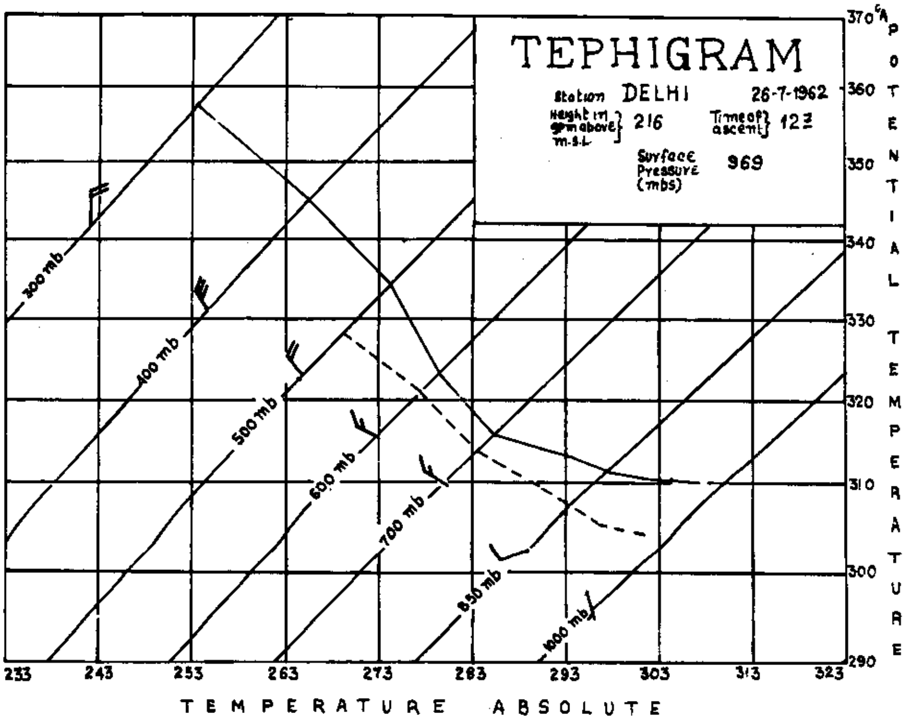


Figure 13

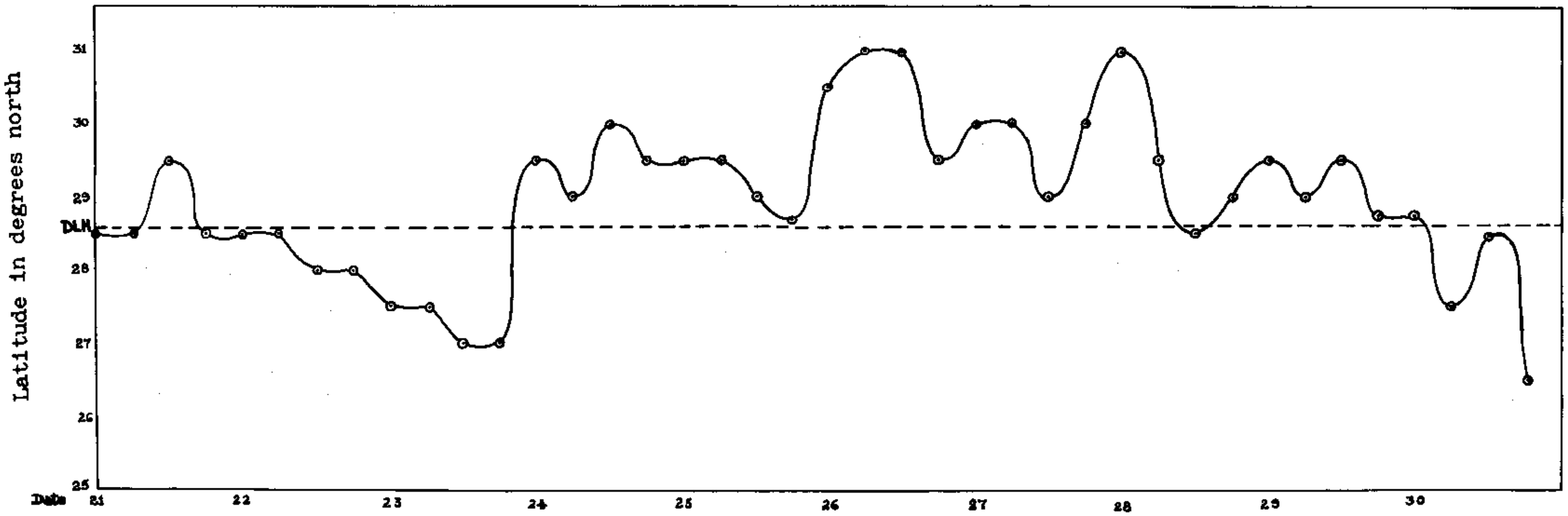
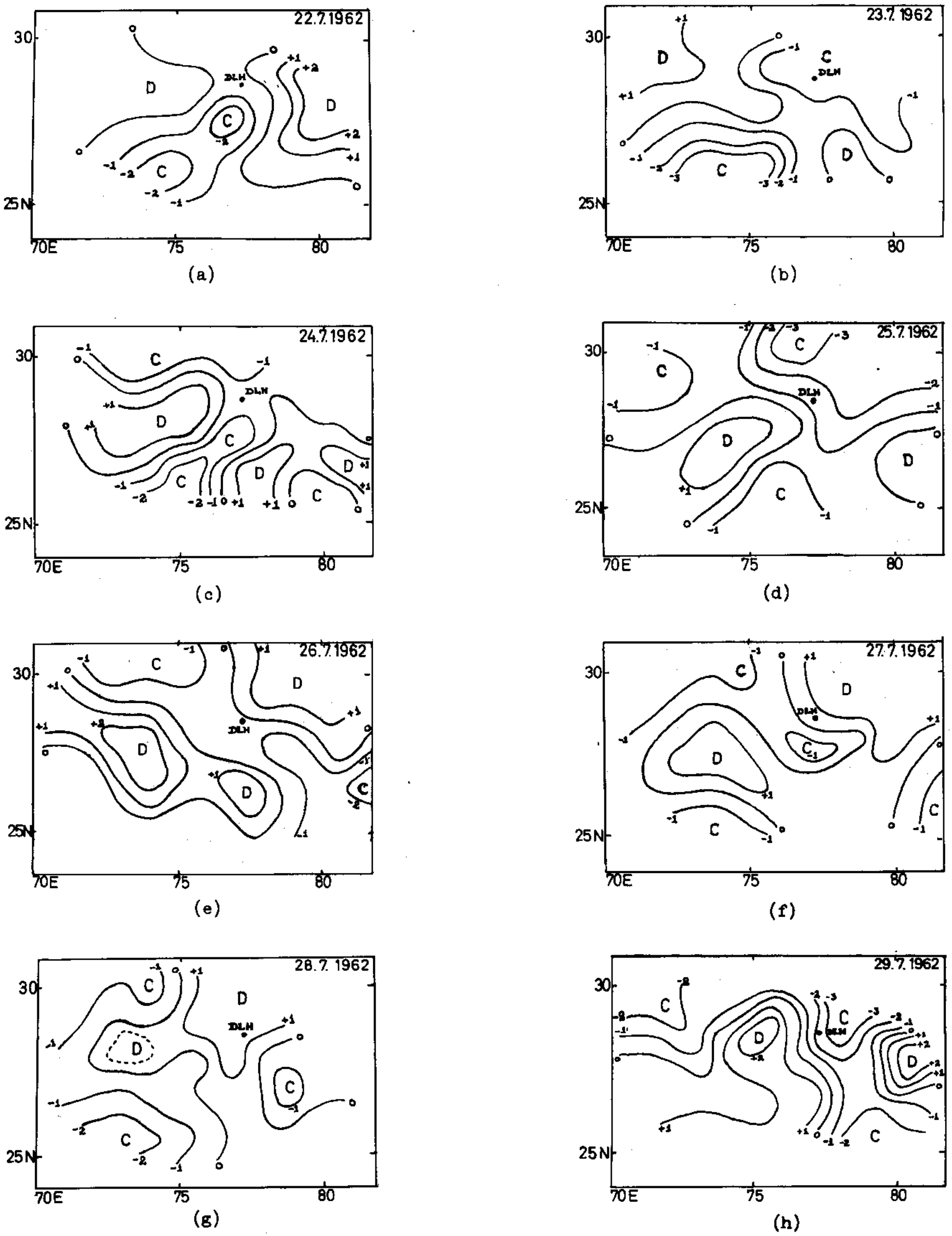
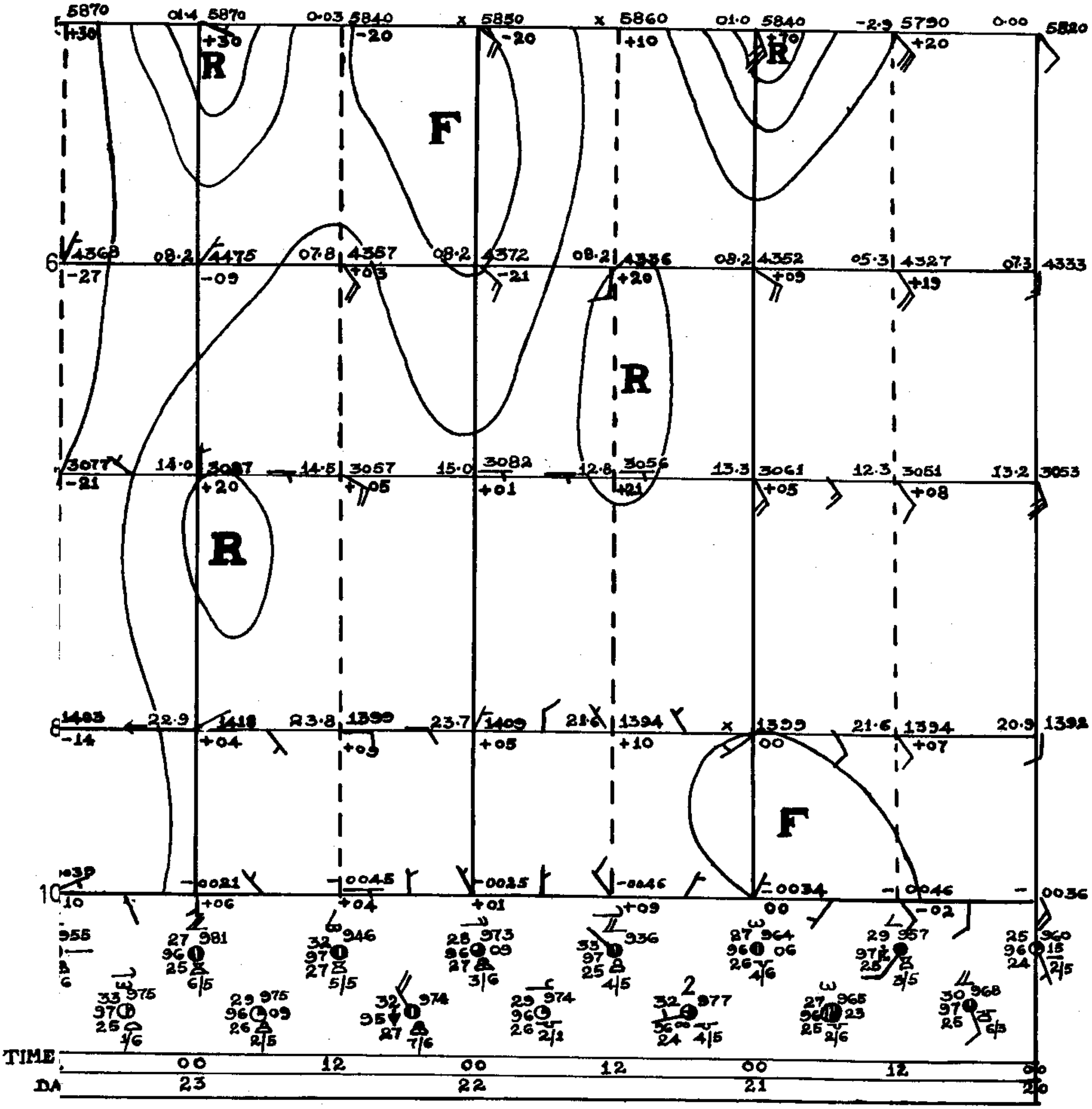


Figure 14 - Position of the axis of the monsoon trough along the longitude of Delhi at 2000 ft (600 m) 21st - 30th July 1962.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 16 - Divergence charts at 600 m at 00Z 22nd to 29th July 1962.


5870 +30
01·4 5870 +30
0·03 5840 -20
x 5850 -20
x 5860 +10
01·0 5840 +70
-2·9 5790 +20
0·00 5820
R
F
R
6 4368 -27
08·2 4475 -09
07·8 4357 +03
08·2 4372 -21
08·2 4356 +20
08·2 4352 +05
05·3 4327 +13
07·3 4333
R
3077 -21
14·0 3087 +20
14·5 3057 +05
15·0 3082 +01
12·8 3056 +21
13·3 3061 +05
12·3 3051 +08
13·2 3053
R
8 1405 -14
22·9 1418 +04
23·8 1399 +03
23·7 1409 +05
21·6 1394 +10
x 1399 00
21·6 1394 +07
20·9 1392
F
10 1039 10
-0021 +06
-0045 +04
-0025 +01
-0046 +09
-0034 00
-0046 -02
-0036
TIME
00
12
00
12
00
12
00
DA
23
22
21
20

INFLUENCE OF METEOROLOGICAL FACTORS ON THE BEHAVIOUR OF THE DESERT LOCUST

by

K.U.Siddiqi

Sufficient evidence has been accumulated to show that the behaviour of the Desert Locust is directly influenced by meteorological parameters, such as winds at 600 m, convergence, rainfall, temperature, position of storms and depressions and the fluctuations in the position of the Inter-Tropical Convergence Zone (ITCZ).

The description of the synoptic situation during the later part of June 1961 and its influence on locust behaviour over the Indo-Pakistan subcontinent is presented in this paper.

According to the information published in the bulletin of the Anti-Locust Research Centre, London, egg-laying and hatching were observed in some parts of Iraq in early May 1961. Successive breeding, however, continued later. Hoppers were found in Iran during the first fortnight of June 1961 and mature and immature swarms in southern Iran some time later. Pakistan remained free of swarms and hoppers until the middle of June but on 23 June 1961 a swarm was detected at Panjgur in Pakistan and over Kutch in India two days later.

The impact of the synoptic meteorological phenomena on the above-mentioned behaviour of locusts is discussed in the following paragraphs.

Figure 1 shows the track of a cyclonic storm in the Arabian Sea. The dotted line shows the position of the disturbance at 0300 and 1200 GMT, both before its intensification into a cyclonic storm and after it had weakened. The positions of the centre of the low are subjective due to paucity of data and are intended only to portray the area of low pressure. The significant aspect of this disturbance was its rather slow movement; normally similar depressions rapidly weaken and move away inland rather quickly.

As a result of the presence of this disturbance, the boundary between the monsoon air and the dry continental air fluctuated during the period. The position of this boundary on successive days is shown in Figure 2. Again, the position, particularly over the sea, is subjective due to paucity of data.

Figure 3 represents the airflow at 2,000 feet above sea-level on four successive days. From these patterns a qualitative idea of the regions of convergence is not difficult.

Synoptic charts have shown that the airflow at 600 m over south-east Iraq and southern Iran was mainly north-westerly to west-north-westerly during May and June 1961 prior to the movement of the depression in the north Arabian Sea.

It therefore appears logical to assume that the swarm detected at Panjgur on 23 June 1961 was the one in which hatching took place in Iraq in early May and which migrated to south Iran in the middle of June. It could not proceed further east as the flow pattern at 600 m had changed due to the presence of the depression. Due to relatively strong northerly or north-north-westerly winds, it had no alternative but to fly downwind over the sea and settle down over the first available land area. Due to marshy land extending a few miles inland from the west coast of India, the swarm settled down at Kutch at the end of the marshy region where it was detected on 25 June 1961.

The above discussion shows that the movement of the swarm was controlled at first by the wind flow at 600 m and later by the flow around the disturbance. The successive fluctuations in the movement of the boundary between moist and dry air appear to be significant in the behaviour of this swarm.

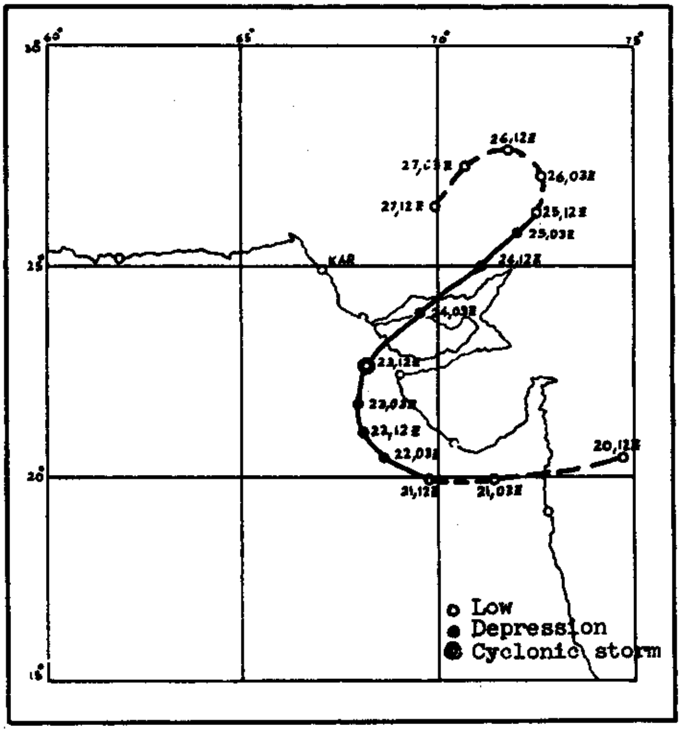


Figure 1 - Track of depression/storm.

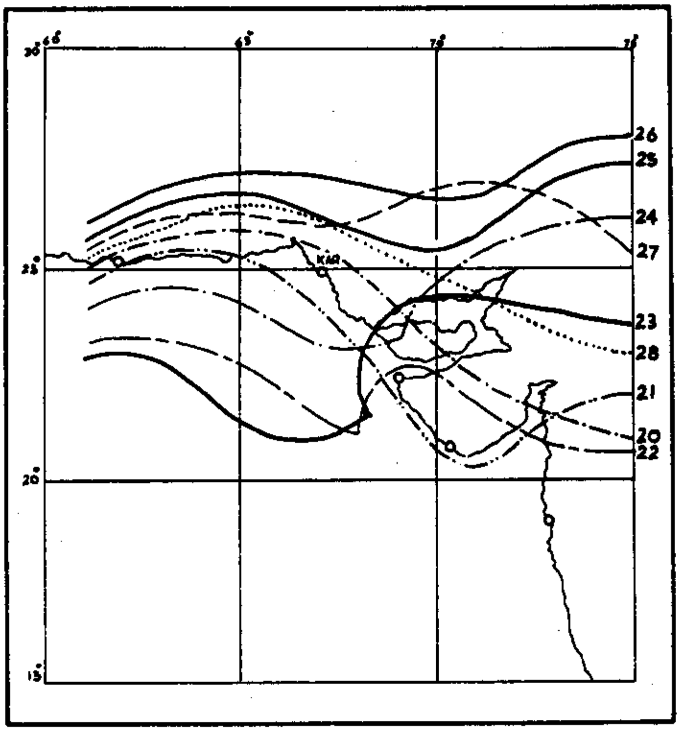


Figure 2 - Position of Inter-Tropical Convergence Zone from June 20 to 28, 1961.

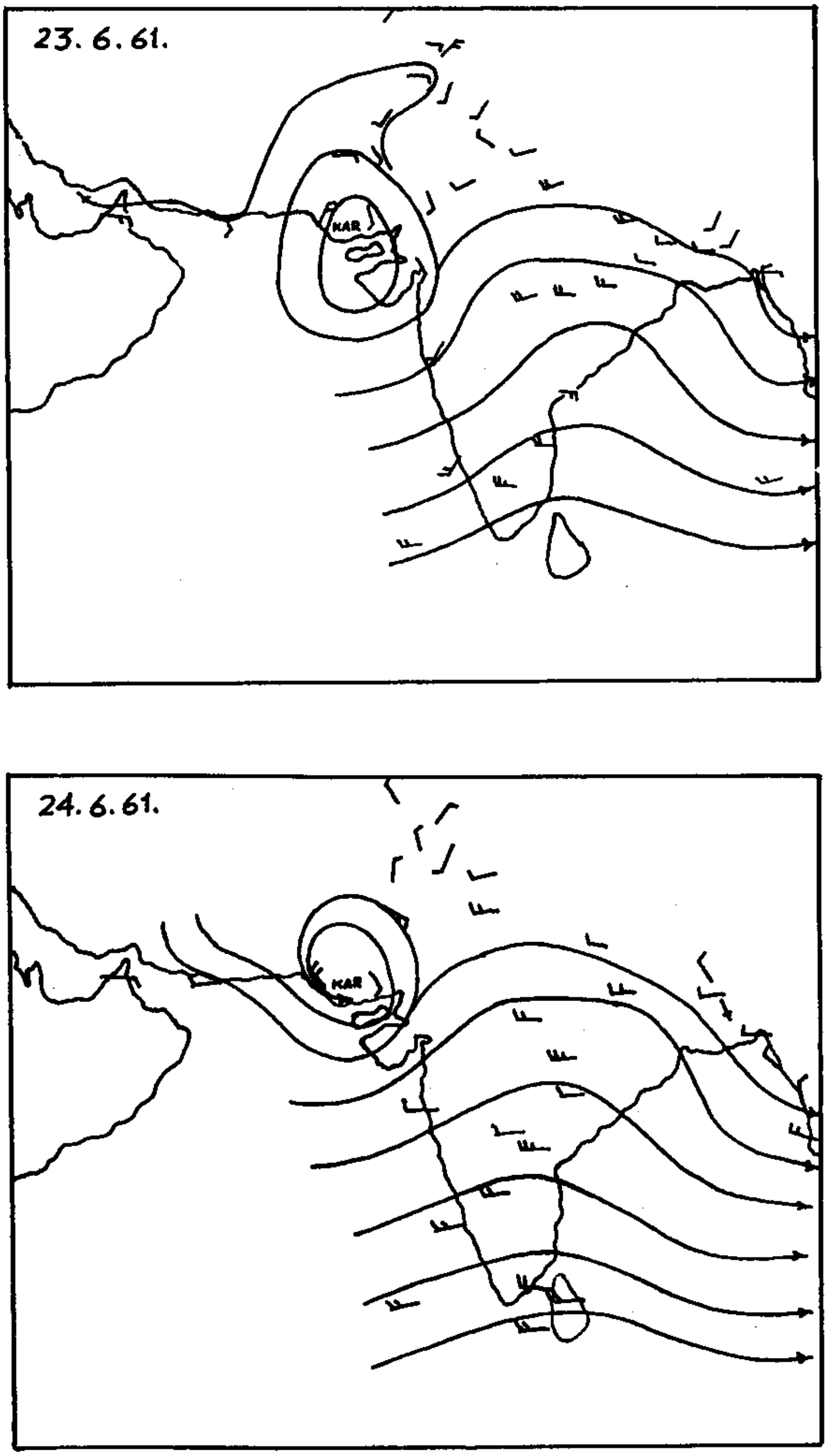


Figure 3 - Wind flow at 2000 ft. above sea-level at 0000 GMT.

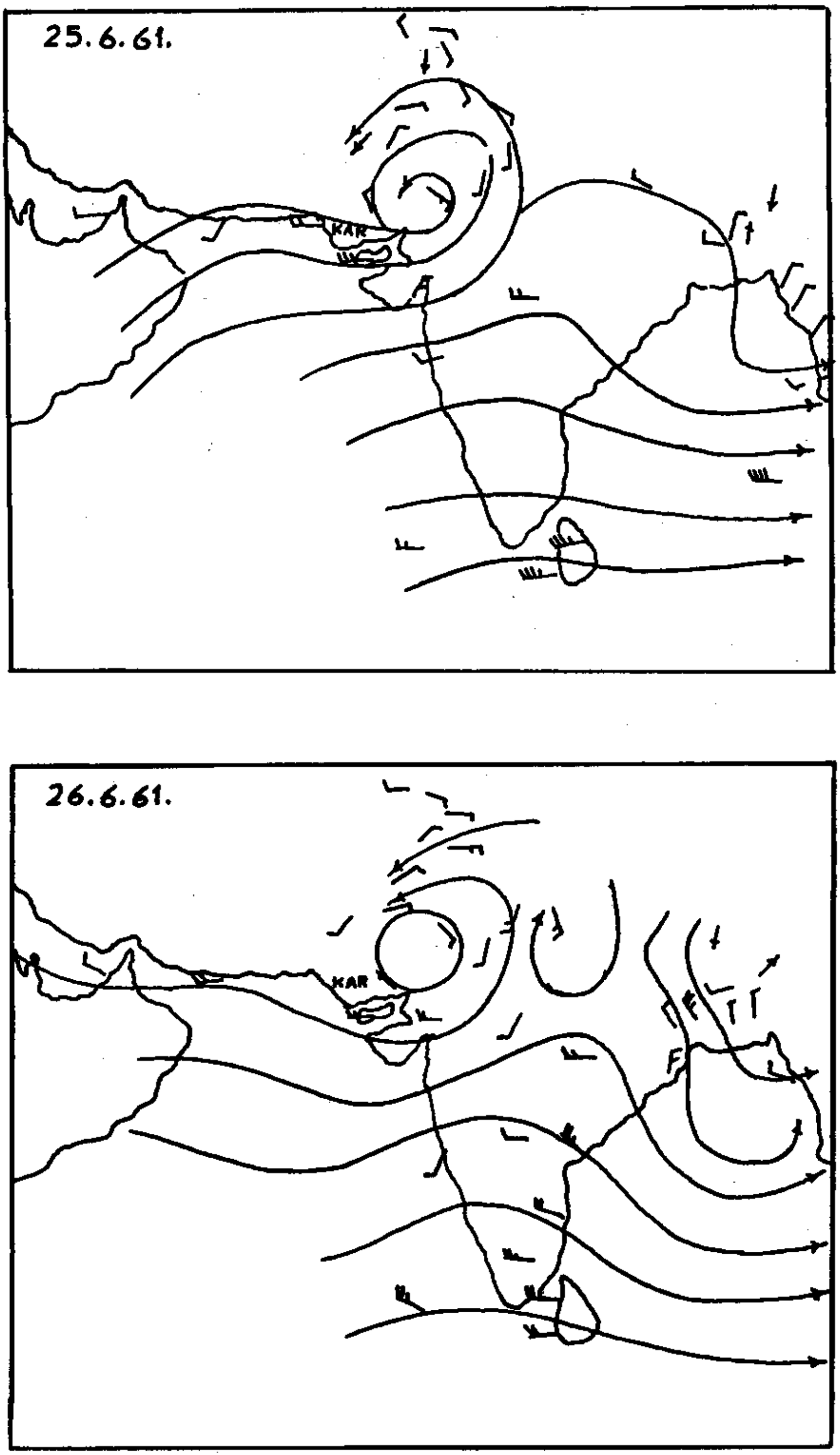


Figure 3 - Wind flow at 2000 ft. above sea-level at 0000 GMT.

DEPRESSIONS AND ASSOCIATED DESERT LOCUST SWARM MOVEMENTS IN THE MIDDLE EAST

(An outline with particular reference to the spring of 1961 and 1962)

by

Berenice Shaw

An association between locust movements and passing westerly depressions has been recognized in these latitudes for many years, with evidence of the swarm movements taking place, in a generally northerly direction, in the temporary spell of warm southerly winds ahead of the cold fronts. This type of movement occurs right across the northern part of the Desert Locust invasion area, from north-west Africa to West Pakistan and northern India.

By the end of the spring period in particular, swarms migrating in this way bring about a quite new geographical distribution, for up until the time of these movements the locusts were located in areas further south (Figures 1 and 2). By March, in both 1961 and 1962, swarms had begun to leave for new areas, i.e. to move on to areas in which spring breeding commonly occurs. Previous evidence suggested that the depressions passing through had brought firstly the winds which made the move possible (the locusts thus moving downwind in the southerly winds of the warm sector), and secondly the rain necessary for making conditions suitable for breeding. Figures 1 and 2 show the scale of movement which took place. In 1962 swarms extended considerably further north-eastward than in the comparable period of 1961, reaching southern Turkey, north-east Iran, and into Turkmenian S.S.R.; this was the first time Desert Locust swarms had reached the Soviet Union for more than thirty years.

The Desert Locust Information Service of the Anti-Locust Research Centre has been able since March 1961 to make use of current meteorological observations to follow these swarm movements, working from synoptic observations for 1200 GMT which have been plotted daily for a large part of Africa, the Mediterranean Basin, the Middle East and south-western Asia, together with an elementary analysis at the 850 mb level. In addition, use has been made of various other meteorological information, e.g. aircraft reports, atmospherics reports, TIROS weather satellite observations, data received with locust reports. Reference has also been made throughout to the published material in relevant daily weather reports of a number of national Meteorological Services.

In the two spring periods of 1961 and 1962 it was found that at least thirteen depressions passing through the Middle East were associated with major swarm movements (Table 1), with some new swarms observed at distances of more than 300 km away from any earlier recorded positions. For example, during the passage of one such depression in early March 1962, swarms were reported appearing well to the north of their earlier recorded limits; in northern Saudi Arabia on 7 and 8 March, Jordan and Israel on the 8th and 10th, western Iran on the 10th, and north-eastern Iran on the 11th. It may appear at times that the actual dates of the first swarm reports would suggest their having moved in a direction against the corresponding wind reported at the same time, but anomalies and delays of locust reporting, especially in uninhabited areas, must be borne in mind.

This kind of movement, during the passage of successive depressions, appeared to account for the larger part of all the major displacement of swarms northward at this time of year. Thus it is obviously of particular advantage to be able to forewarn countries likely to suffer from the effects of what we can term the "dangerous" depressions, so that they can prepare counter-measures in time. Some of these depressions were thought at the time to be potentially suitable for transporting the locusts northward, and the Desert Locust Information Service has been able to send out a number of due warnings to the countries imminently affected. For this to be done effectively we need to know which, of all the depressions and kindred disturbances appearing in this part of the world, are the ones which move locusts - and which are the ones that do not - provided of course that there is a suitable source of swarms to be moved in the first place; what are the characteristics of the significant depressions, and how soon and how easily they can be recognized.

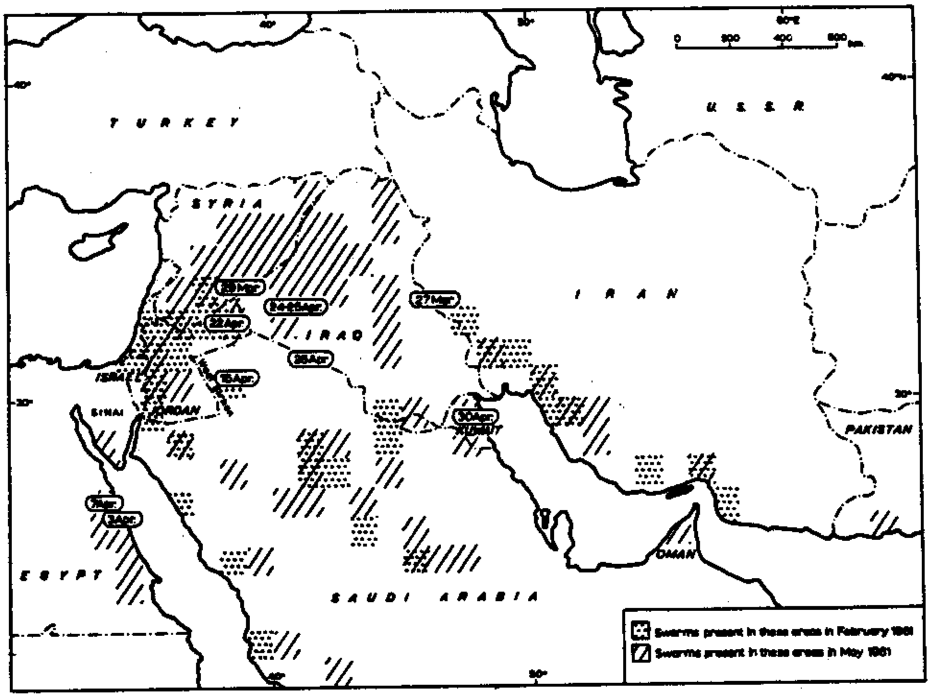
Finally, it is not proposed, or indeed possible, at this point to provide all the answers to these questions. However, some facts have clearly emerged from the 1961 and 1962 studies about the kind of depressions which so far have affected locusts. Firstly, they were generally the most intense ones which passed through the Middle East region. Quite frequently they could be distinguished as closed lows on upper-air charts, at least up to the 700 mb or 500 mb level. Secondly, they introduced a surge of warm southerly air, ahead of the cold front, sufficiently vigorous to transport the locusts northward for a lengthy distance. In this respect not only the intensity but also the track followed by the depression is significant; this was observed particularly in the case of some of the Saharan or Khamsin depressions. Thirdly, the surge of warm air from the south was complemented by a marked cold pool of air moving in the rear of either the same or a closely associated depression.

Table 1

SUMMARY OF WESTERLY DISTURBANCES AND LOCUST MOVEMENTS IN THE MIDDLE EAST : SPRING 1961 AND 1962

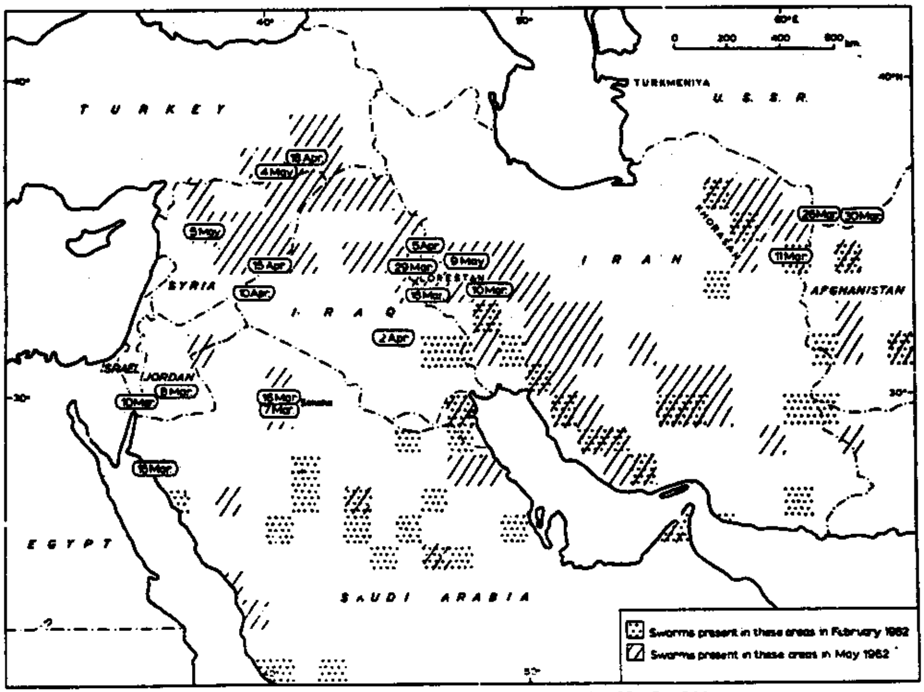
Period	Lowest M.S.L. pressure	Surface temperature in N. Arabia ahead of cold front	History and characteristics	Effect on major locust movements: northerly displacement of swarms
1	2	3	4	5
14 - 16 March 1961	1006 mb.16th.Iraq			
27 - 30 March 1961	990 mb.27th.W. Egypt 998 mb.28th.Cyprus	mid 20°C	Khamsin depression across N. Africa to Levant followed by a cold front from the north across Turkey	Swarms reached Iraq/Iran border on 27th and others extended northward in Syria 26th - 29th
3 - 5 April 1961	999 mb. 5th. W. Saudi Arabia	Upper 20°C	Shallow Saharan depression deepening as it reached Sinai and Saudi Arabia	Swarms extended northward in SE desert of Egypt 3rd - 7th
12 - 15 April 1961	993 mb.8th.Tunisia 1003 mb.13th-14th Turkey/Iraq border	c.30°C	Khamsin depression formed as a cold pool cut off from an Atlantic low traceable back at least to Newfoundland on 1st - Merged in eastern Mediterranean with a cold front from the north on 12th	Swarm reached Wadi Sirhan (NW Saudi Arabia) on 15th
20 - 25 April 1961	1004 mb.22nd.Syria	low 30°C	Depression with a very active cold front from the north, coinciding with the arrival of a Khamsin	Swarms appeared in Jordan on 22nd and W.Iraq on 24th
26 April - 2 May 1961	1004 mb.28th.Turkey	mid 30°C	Two depressions following closely across southern Europe	Swarms arrived on Iraq/Saudi border on 26th and in Kuwait on 30th

1	2	3	4	5
6 - 12 March 1962	1003 mb.7th.Egypt 996 mb. 8th.Cyprus	mid 20°C	Khamsin joining a depression from across southern Europe and preceded by other disturbances across Arabia	Swarms reached Sakaka (N. Saudi Arabia) on 7th, Jordan on 8th, Israel and Lorestan (Iran) 10th, and Khorasan 11th
14 - 17 March 1962	977 mb.15th.Sicily	25-30°C	Complex low pressure area in central Mediterranean, joined by a Saharan depression to give an exceptionally deep system for this area at this time of year	On 16th swarms arrived in Sakaka, the Red Sea coast of NW Saudi Arabia, and western Iran
22 - 23 March 1962	998 mb.21st.Egypt	c.30°C	Khamsin depression	–
26 - 28 March 1962	992 mb.27th.Iraq/ Turkey border	low 30°C	Khamsin depression followed by a succession of depressions moving southward from Europe	Swarms in eastern Iraq on 29th, Turkmenian S.S.R. on 26th and 30th
29 March - 2 April 1962	1003 mb.1st western Saudi Arabia	c.30°C	Trough of low pressure and cold front across Sudan and Arabia with waves developing along the front	Swarms invaded southern Iraq 2 April
6 - 9 April 1962	1003 mb.7th. W. Turkey	mid 30°C	Khamsin joining depression across southern Europe	Swarms in W. Iran 5th - 9th, first swarm appearing western Iraq on 10th
14 - 16 April 1962	1002 mb.14th. Turkey	low 30°C	Depression from NW, deepening on arrival in eastern Mediterranean, with shallow Khamsin developing along southern part of cold front. Low pressure cell persisting over N. Arabia 16th - 22nd	First swarms reached Syria on 15th, Turkey 18th
4 - 5 May 1962	997 mb.4th.Syria	34 - 39°C	Active Khamsin depression	Swarms extended northward in Syria on 5th, SE Turkey 4th - 5th
7 - 10 May 1962	1001 mb.8th. N. Iraq	mid 30°C	Depression from NW, deepening and becoming more active in the Cyprus area	Swarms moved north-westward in W. Iran 7th - 9th



REDISTRIBUTION OF DESERT LOCUST SWARMS DURING SPRING 1961
with some reported dates of appearance of swarms in new areas
during passage of depressions March-May

Figure 1



REDISTRIBUTION OF DESERT LOCUST SWARMS DURING SPRING 1962
with some reported dates of appearance of swarms in new areas
during passage of depressions March-May

Figure 2

MEDITERRANEAN SYNOPTIC WEATHER AND THE ASSOCIATED 1000-500 MB THICKNESS PATTERN

by

J.C. Gordon

Before discussing the weather of the Mediterranean it is first necessary to describe the topography of the area. The Mediterranean Sea is almost entirely surrounded by mountains except for the North African coasts of Libya and Egypt. In parts these mountains exceed 3000 m and as a whole form a formidable barrier to surface and low-level air. The only gaps in the mountainous belt are at the Straits of Gibraltar, the Carcassonne Gap in Southern France and the Sea of Marmara leading to the Black Sea.

The main effect of topography on Mediterranean weather is virtually to preclude the passage of surface depressions from outside the area of the Mediterranean basin. Less than 10 per cent of depressions affecting the Mediterranean originate outside the area.

Orographic depressions form mainly in the Gulf of Genoa, the Sahara and in the area of Cyprus. These depressions are generally slow moving but those of the Sahara in particular may move rapidly in the thickness pattern. As pointed out by Mr. S. Mazumdar, mountain ranges at right-angles to each other tend to produce orographic depressions. Such an area is created by the Alps and the Apennines and a similar configuration occurs in the Cyprus area.

Frontal belts do enter the Mediterranean basin from outside the area but considerable modification takes place when they do so. Because of the general stability ahead of warm fronts the air associated with them tends to be deflected round the mountain barriers and not over them. Also, because of intense heating at the surface at certain times of the year, warm frontal belts become less marked. As a result warm fronts are not very active in the Mediterranean although they may be well marked thermally but with dry air masses.

Cold fronts too are modified during their passage over the mountains but because of the frequent instability behind cold fronts the low-level air may pass over the obstacles. In doing so, considerable drying may take place and normal post-cold-frontal weather may not reappear for some distance beyond the mountain range.

Most weather in the Mediterranean tends to be associated with cold fronts or depressions. And in turn these tend to be associated with cold upper troughs or cold pools. At the Main Meteorological Office at Nicosia in Cyprus more reliance is placed upon the weather related to thermal troughs and cold pools than that associated with frontal belts. It has been found that cloud and precipitation are mainly located on the forward side of mobile cold pools and thermal troughs.

Some work has been done in investigating the frequency, distribution and movement of cold pools in the Mediterranean area during the period 1953 to 1956. The charts used in this work were the 1000-500 mb thickness maps prepared twice daily at the Meteorological Office at Luqa, Malta. A cold pool may be defined as being represented by at least one closed thickness line in a fairly deep layer of air. In effect it is a mass of relatively cold air surrounded by relatively warm air.

Cold pools may enter the Mediterranean basin from outside the area but more frequently they are formed inside the area. This may occur when cold air from the north-west or north enters the area ahead of an anticyclone over the North Atlantic or (when cold air) from the north-east on the eastern side of a Central European anticyclone. As the anticyclone gives way to more mobile westerly systems, warm air moves to the north of the cold plunge and this cuts off the cold air and so a cold pool is formed.

The main concentration of cold pools in the Mediterranean basin considered on a yearly basis is in the western half of the Mediterranean. This is also true for all seasons of the year except summer when the main concentration moves east and north to Italy and the Adriatic. The concentration of cold pools in the Eastern Mediterranean is much less than elsewhere in the Mediterranean basin. This is probably due to the strong heating over North Africa and Asia Minor.

The life of a cold pool in the Mediterranean varied from a single appearance on a 1000-500 mb thickness chart to one instance of 22 consecutive appearances. The average duration is of the order of 2½ days (but it may, of course, have moved out of the area which was considered). Those cold pools with a duration of greater than 4½ days were investigated on a seasonal basis. There were two maxima - the greater in spring and the other in autumn. The reason for the greater longevity in spring is probably due to the less rapid heating of the sea than the land, but that in autumn is much less obvious. It may be due to more mobile westerly systems recurring further north but this would normally be an explanation of an increased number and not necessarily an increased persistence.

These double maxima may be an explanation of the double maxima of rainfall over Alexandria in Egypt which Professor Flohn pointed out.

The movement of long waves in the upper air, if successfully forecast, may act as a basis for more detailed forecasting in particular areas of the Mediterranean basin.

As stated earlier, orographic and heat depressions tend to form south of the Atlas Mountains. These depressions are often slow moving. If, however, penetration of cold air takes place to the west, they may deepen considerably. Their subsequent behaviour will generally be one of two types. They may remain slow moving but with secondaries moving north-east along the thermal gradient on the forward side of the upper trough or they may move bodily north-east or east-north-east. In the former case the long-wave pattern is almost stationary while in the latter the long-wave pattern is mobile.

The Gulf of Genoa is also a frequent source of orographic depressions. If upper cold air penetrates to the west of the surface lows they may deepen considerably and move south-eastwards.

Both the above types of depression can become very intense and form a circulation covering most of the central Mediterranean. Their associated cold surface fronts may be preceded by very strong southerly winds. Also, the southerly winds generally tend to be very warm. Under such conditions it is quite probable that locusts may be carried a considerable distance northwards.

Many different types of Mediterranean weather were illustrated by that of March 1962.

The month started with the situation as shown in Figure 1. The 1000-500 mb thermal pattern shows a cold pool over south-east France with a weak trough to the west of Italy and a generally westerly thermal flow over much of the Mediterranean.

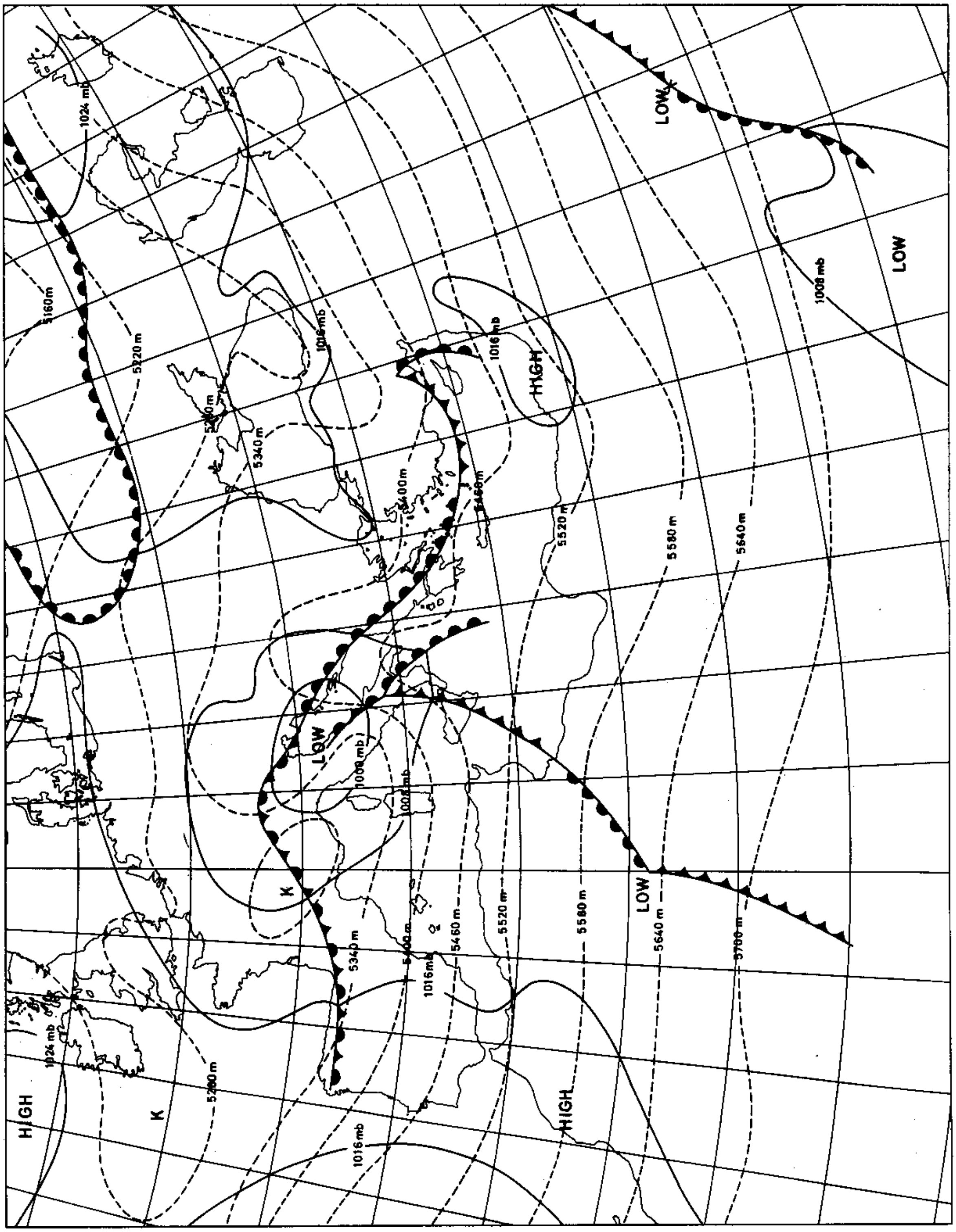
Subsequently the surface ridge over the British Isles retreated as cold air was advected southwards for the first two or three days of the month, the effect of this being to increase the amplitude of the upper long-wave pattern on what had been, until then, a fairly mobile small amplitude long-wave system. The surface depression shown over northern Italy in Figure 1 subsequently moved east-north-east.

By 6 March the surface synoptic chart and the associated 1000-500 mb thickness pattern were as shown in Figure 2. The amplitude of the upper long waves was now quite considerable and associated with the upper trough was a complex surface low-pressure area over much of the central Mediterranean and Eastern Europe. The whole system moved bodily eastwards during the following few days, illustrating a mobile large amplitude upper flow.

Subsequent to this a further burst south-eastwards of cold air took place over Western Europe on 12 and 13 March and the effect of this was to deepen the Saharan surface low south of the Atlas Mountains. This depression moved east-north-east as cold air continued to penetrate southwards to the west of the surface centre. The situation on 14 March was as shown in Figure 3. As can be seen the circulation covered much of the Mediterranean basin. Also the very strong gradient both to the east and west of the surface cold fronts should be noted. In such a strong southerly flow rapid advection northwards of locusts could easily take place.

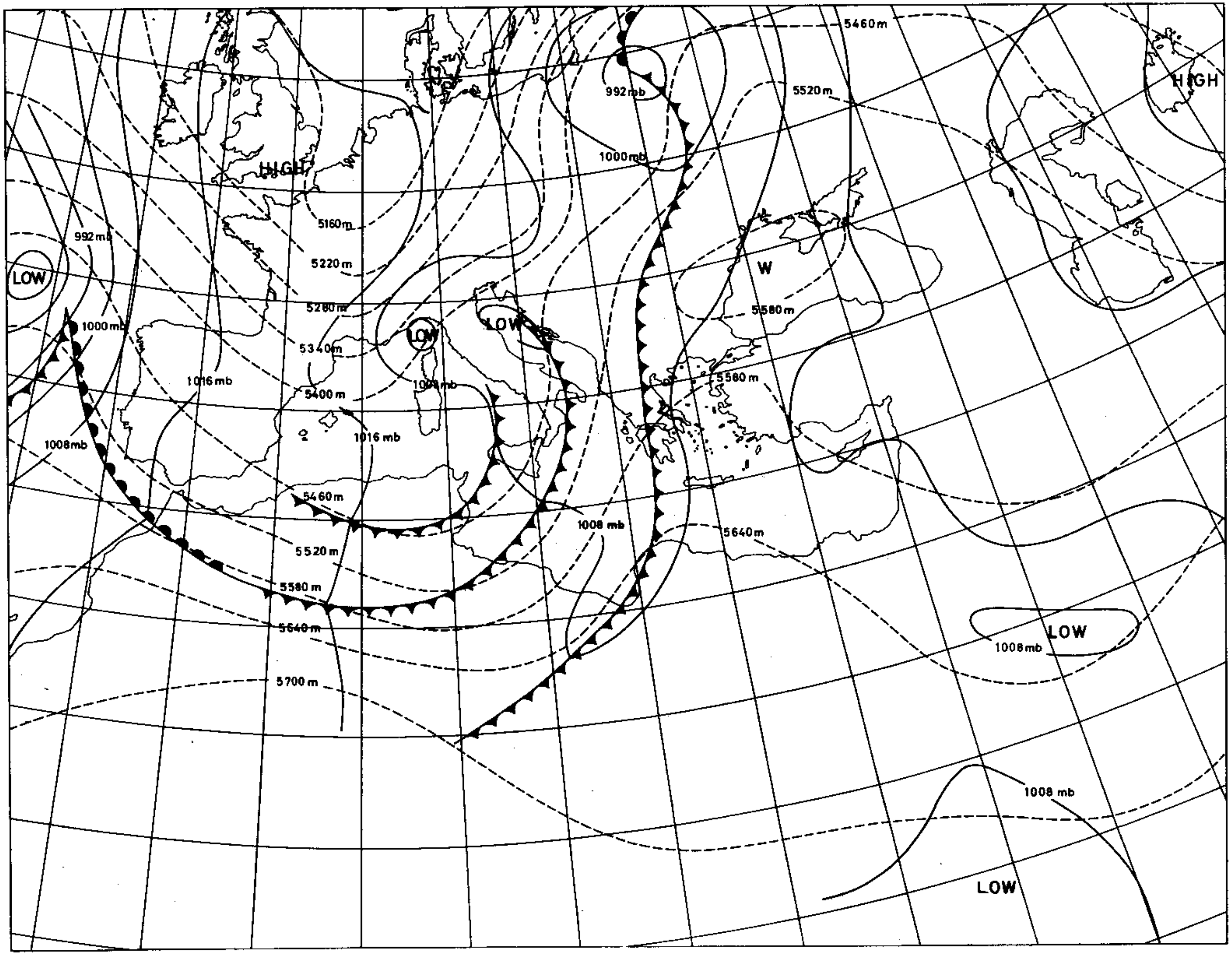
As the cold air over the Western Mediterranean continued to be advected south and south-east, the whole system moved east-north-east under the influence, to a great extent, of the strong thickness gradient over south-east Europe. The upper thermal trough relaxed somewhat during the next day or two but it continued to move eastwards and crossed Arabia on 16 and 17 March in association with surface depressions.

The upper long-wave system was fairly mobile for much of the remainder of the month and the systems associated with it tended to be fast moving.



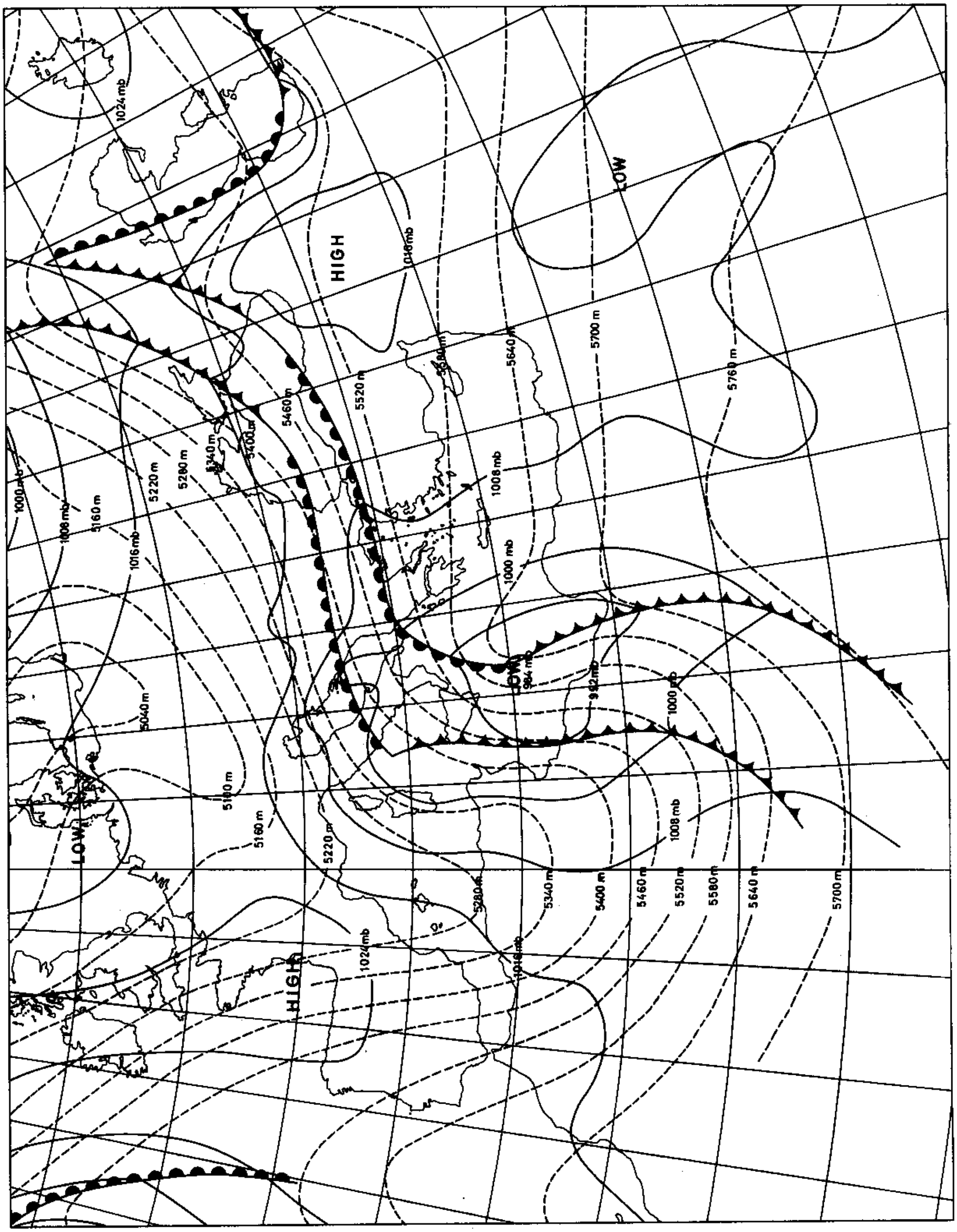
0001 GMT 1st March 1962. Pecked lines 1000-500 mb thickness lines in metres. Full thin lines isobars at 8 mbs interval.

Figure 1



1200 GMT 6th March 1962. Pecked lines 1000-500 mbs thickness lines in inches. Full thin lines isobars at 8 mbs interval.

Figure 2



1200 GMT 14th March 1962. Pecked lines 1000-500 mb thickness lines in metres. Full thin lines.

Figure 3

A STUDY OF TWO SYNOPTIC METEOROLOGICAL SITUATIONS ASSOCIATED WITH LOCUST INCIDENCE IN SPRING AND SUMMER IN THE UNITED ARAB REPUBLIC (U.A.R.)

by

M.H. Omar

1. INTRODUCTION

Dr. R.C. Rainey had suggested the study of the two synoptic meteorological situations associated with locust incidence in the United Arab Republic (U.A.R.) on 3 - 7 April 1961 and 28 June - 3 July 1959. The locust situations were as follows :

(i) 3 - 7 April 1961

Young swarms, originating from locust breeding which extended along the Red Sea coast of the Sudan and south-eastern Egypt as far north as latitude 24.15°N, were recorded in the breeding area by 25 March, and apparently moved northwards to 27°N by 3 - 7 April.

(ii) 28 June - 3 July 1959

Breeding in Israel and Sinai produced fledglings in the latter part of June. Young swarms spread southwards to Qena district by 29 June and reached Aswan in early July; scattered locusts were also recorded in the northern Red Sea on 3 July.

The main features of the 1200 GMT mean sea-level charts, upper air charts for 700 and 850 mb, together with the 600 m streamline charts during the periods 1 - 7 April 1961 and 26 June - 3 July 1959 were studied. Streamline charts at 600 m altitude have proved to be important for studies related to locust invasion /1/. As for mean sea-level charts and 700 mb charts, reference is made to the Daily Weather Report of the Meteorological Department, Cairo /2/ for the above-mentioned periods. Streamline charts for the 6-day period of 2 - 7 April 1961, together with 850 mb charts on 3 and 5 April 1961, are given in Figure 1. Streamline charts for the period 28 June - 3 July 1959, together with 850 mb charts on 28 June and 3 July 1959, are given in Figure 2.

2. STUDY OF THE FIRST CASE (1 - 7 APRIL 1961)

2.1 General

This situation is that of a Khamsin depression. The word Khamsin is locally used in the U.A.R. to denote a hot, dry and dust-laden wind blowing in spring. Usually this wind is associated with desert depressions that move almost parallel to the Mediterranean coast. The depression under study appeared to the west of the Libyan desert on 1 April. There were closed upper cold lows at 700 and 500 mb over north-west Africa associated with the appearance of the depression. During its motion, rainfall drops were observed at Siwa on 2, Damietta on 3, Quseir on 5, Abu Sueir on 7 April. Local rising dust was observed at Asyout on 3, Cairo on 4 and 5, and Quseir on 6 April.

There were some low and medium clouds, the low type being mainly at and after the cold front. The depression gave rise to a moderate heat wave with peaks on 3 April for the north-western regions, and on 4 April for other areas.

Details concerning Khamsin depressions, their formation and classification, can be found in references /3, 4, 5/.

2.2 Mean sea-level charts

On 1 April there was a weak high pressure covering the Western Desert, Eastern Mediterranean, Asia Minor and Greece. On 2 April the depression proceeded eastwards through Cyrenaica. On 3 April it had traversed the Western Desert of Egypt. A weak high pressure covered the Central Mediterranean area and a local anticyclone, centering over the Caspian Sea, extended towards Iraq. On 4 April the depression covered the Sinai peninsula and northern districts of the Red Sea and amalgamated with the Sudan low. A weak high pressure covered Greece, Italy, West and Central Mediterranean. On 5 April the low pressure over Sinai had moved north and the low pressure area extended from North Sudan to East Mediterranean and the Libyan Desert. On 6 April a depression covered North Arabia, with a trough extending to East Mediterranean and Asia Minor. On 7 April the depression over North Arabia persisted with a trough extending to Asia Minor. High pressure extended from the Caspian Sea to Italy and Central Mediterranean. A high pressure cell occupied the Libyan Desert.

2.3 700 mb level charts

On 2 April the centre of the closed low was to the west of Cyrenaica. On 3 April the closed low had moved towards the north-east over Western Asia Minor with a trough over Western Libya. On 4 April the trough was over Egypt. On 5 April there was a centre of low over Syria with a trough over Arabia; this centre moved slightly towards the south-west on 6 and 7 April.

2.4 850 mb level charts

On 1 April there was a closed cold low over the western Libyan Desert and a high cell occupied the Western Desert of Egypt. On 2 April the low had moved eastwards over Cyrenaica. On 3 April it had moved north-eastward and was centred between Crete and Cyprus with a trough over the Libyan Desert. On 4 April the low centre had moved towards the south-east and was situated a little to the north-east of the Delta; the trough moved eastward over the Western Desert of Egypt. On 5 April the centre had moved to the south and was over the Delta, while the trough had passed the Nile valley and was over the northern part of the Red Sea. On 6 April the low had moved towards the north-east. There was a ridge of high over the Caspian Sea,Black Sea, Greece, Italy, Libya and Cyrenaica. On 7 April a high cell extended over Southern Cyrenaica and the eastern part of the Western Desert of Egypt.

2.5 Streamline charts at 600 m altitude

In the locust area the wind was northerly on 1 April. Due to the cyclonic circulation associated with the trough of the Sudan low, south-easterly winds appeared in the southern part of the area on 2 April. On 3 April the wind in the area was south-easterly and strengthened as a result of the deepening of shallow lows in the area associated with the extension of the Sudan low. On 4, 5 and 6 April there were south-easterly winds in the area. On 7 April the wind was north-northwest.

It is noteworthy that locusts first appeared at 27°N on 3 April, when the south-easterly wind strengthened.

3. STUDY OF THE SECOND CASE (26 JUNE - 3 JULY 1959)

3.1 General

On 26 June occurred the characteristic summer type situation with the complex monsoon Middle East low over Iraq, Arabia and Sudan and the high pressure west of the U.A.R. The deepening of the low on 27 June was associated with advection of cold air at 500 and 700 mb levels over Asia Minor. The rapid deepening and north-west displacement on 2 July were also associated with a cold upper trough to the west of Asia Minor, at 500 and 700 mb levels. During the period under study an intensive warm spell occurred in the northern parts of the Red Sea on 30 June; the maximum air temperature at screen height reached 6°C above normal at Quseir.

An excessive short heat wave occurred in upper Egypt during the period 1 - 3 July with maximum air temperature of 44°C at Aswan on the three days.

3.2 Mean sea-level charts

On 26 June there was a low over north Italy and a high pressure over the Black Sea. On 27 June the low over the Middle East had deepened and moved towards the East Mediterranean and the southern part of the Black Sea. The low north of Italy had deepened and moved south-west. The high over the Black Sea was filling. On 28 June the Middle East low was still deepening and a closed centre appeared over Iraq. The trough extended to the north-west over Greece where a closed low appeared. On 29 June the Middle East low still persisted, though the low over Iraq disappeared. A trough appeared over Middle Egypt. There was a closed low over Italy and a ridge of high pressure over the Caspian Sea. On 30 June the depression over Western Italy had deepened and shifted to north-west. The Middle East system was filling and shallow lows appeared over north-west Iraq. The trough over Middle Egypt had disappeared. On 1 July the low, over Western Italy the previous day, was now over Central Europe. A centre of low pressure appeared to the north-west of Asia Minor. This amalgamated on 2 July with the Middle East low which had deepened remarkably and extended towards the north-west. The low over Central Europe had moved northward and a ridge of high pressure occupied Central and Eastern Europe. On 3 July the Middle East low had deepened more and extended towards the north-west. The low over Asia Minor had moved northward and deepened.

3.3 700 mb level charts

On 26 June there was a closed cold low over south-east Asia Minor and a trough over the Delta and Middle Egypt. A high cell appeared over Western Arabia and the central Red Sea. On 27 June there were two troughs over the Black Sea and Iraq. On 28 June a closed low was centred over the south-western coast of the Black Sea; a trough over the Delta of Egypt was associated with cold air advection. On 29 June the low had moved eastward and its centre was over the southern coast of the Black Sea. The trough over the Delta had moved eastward and flattened; and there was a tongue of cold air over the Nile valley and the northern Red Sea. On 30 June the trough had moved eastward up to about 40°E longitude. On 1 July there was a low over Northern Iraq and a trough over Eastern Italy. Two cells of high pressure appeared : one to the west of the Libyan Desert, the other over south-east Arabia. On 2 July the trough over Italy had moved eastward and was over Greece. There was a trough over Cyrenaica and another over the Nile valley of Egypt. A low appeared over Iraq and the south Caspian Sea. On 3 July there was a closed cold low over west Asia Minor and a trough over Libya.

3.4 850 mb level charts

On 26 June closed lows appeared over Northern Iraq, Southern Arabia and south of the Black Sea. A ridge of high pressure to the south of Cyrenaica bulged towards the south-east.

On 27 June there was a low over Northern Italy and low heights extended over Arabia with a trough elongation towards the north-west. On 28 June there was a closed low over Iraq. On 29 June there were two low systems : one was centred over Eastern Arabia and the other over Eastern Asia Minor. On 30 June the low over Asia Minor disappeared and a high system was centred over southern Cyrenaica. On 1 July the low over Arabia extended to the north-west and the high to the west of Egypt retreated. On 2 July there was a closed low over the south-eastern Black Sea and high heights extended again eastward. On 3 July the low over the Black Sea had moved southward over Asia Minor with a trough over the Northern Libyan Desert.

3.5 Streamline charts at 600 m altitude

The strengthening of the NNW winds in the locust area during the period 28 - 30 June is explained by the extension towards the north-west and the deepening of the Middle East monsoon low. It is to be noted that locusts were observed at Qena by 29 June. On 30 June the wind at Aswan had veered to NNE and strengthened. It is noteworthy that locusts passed Aswan on 1 July as indicated by locust data at Cairo.

The winds at Hurgada strengthened gradually in the period of 1 - 3 July following the deepening of the Middle East low and its displacement towards the north-west. It was on 3 July that scattered locusts were observed in the Northern Red Sea.

4. CONCLUSION

4.1 The close association between locust movement and wind direction and speed is apparent in both cases studied and is in general agreement with Rainey's findings in connexion with the down-wind movement of locust.

4.2 It would seem that the Khamsin depressions in spring and the displacement of the Middle East low towards north-west in summer are important synoptic features which affect locust incidence in the U.A.R.

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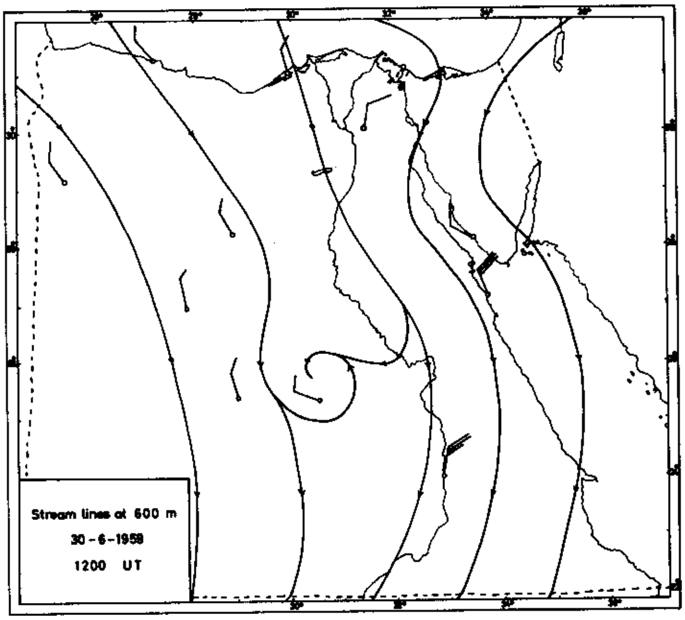
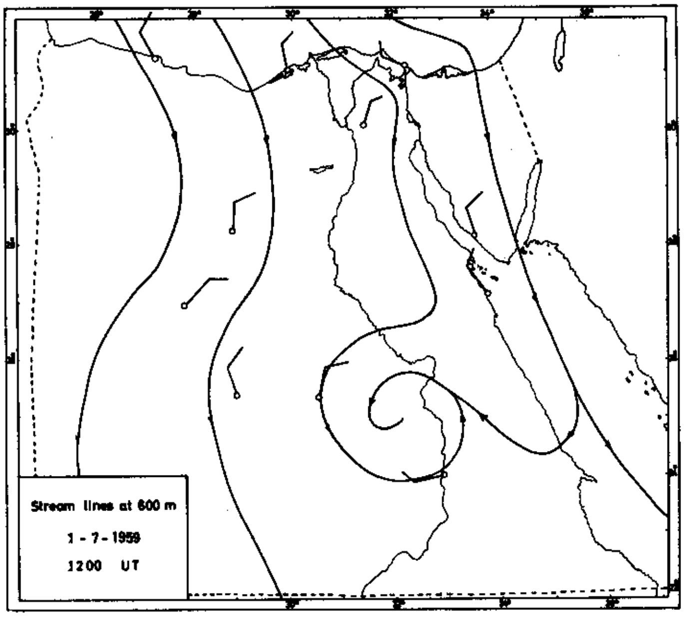


Figure 1



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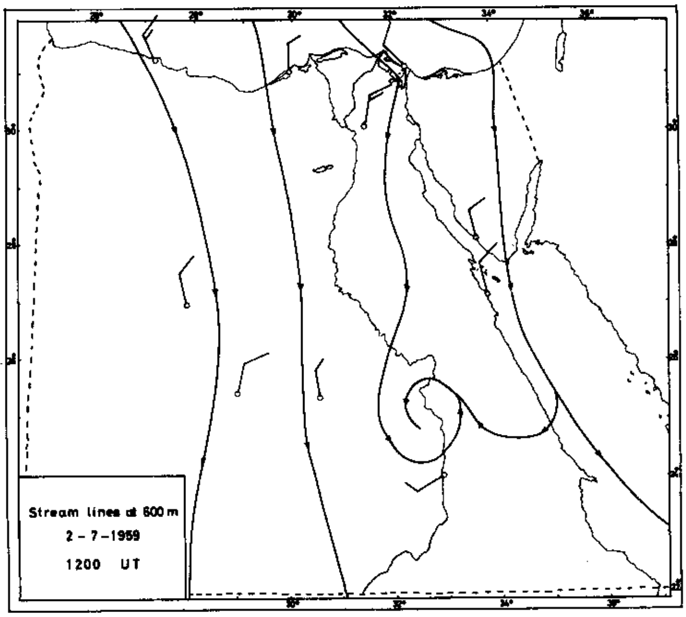
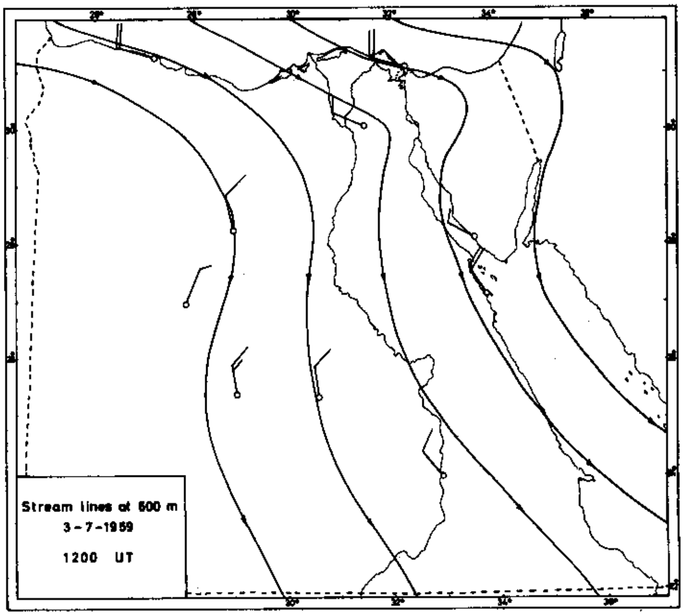


Figure 3



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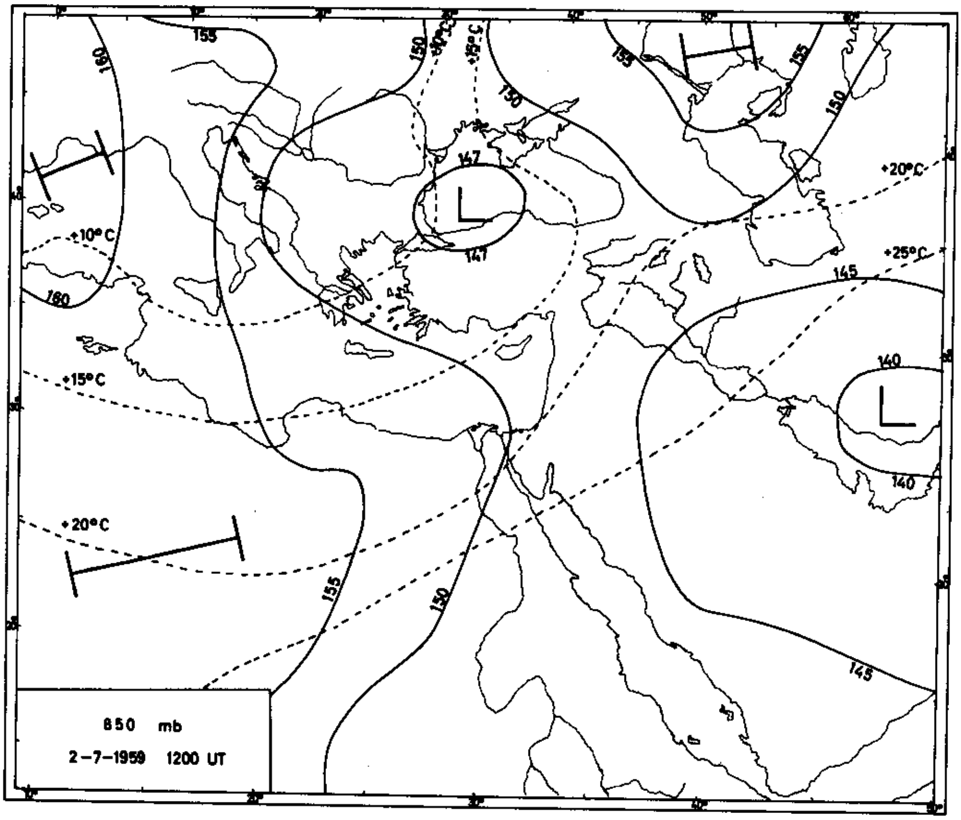

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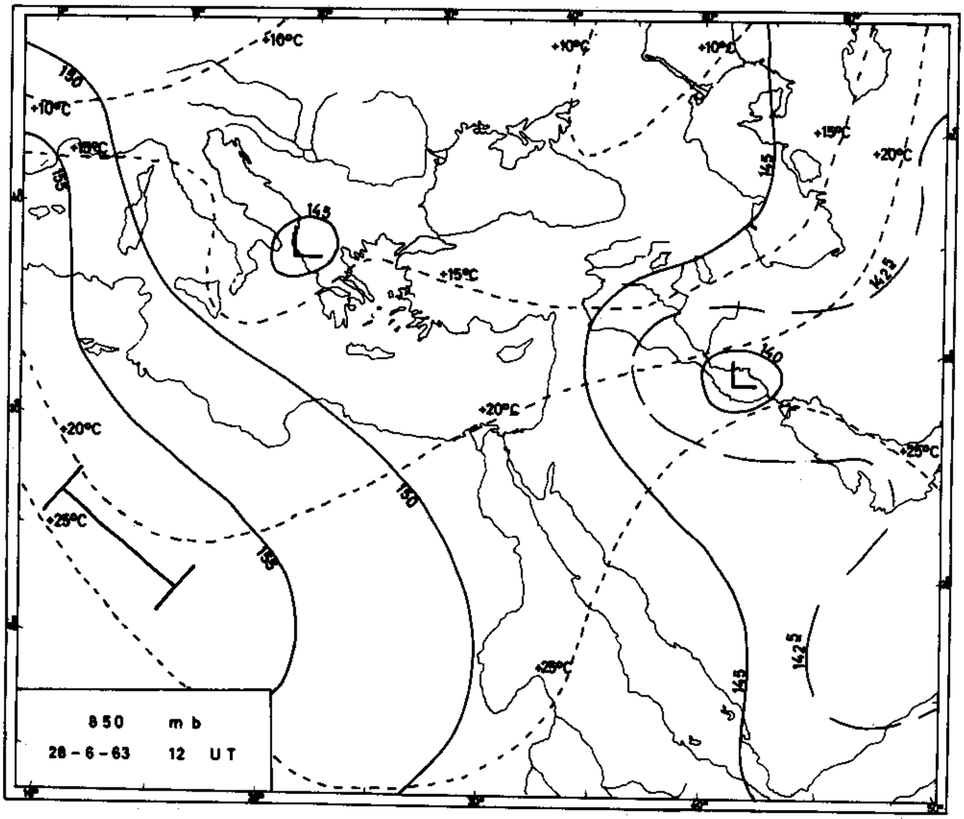

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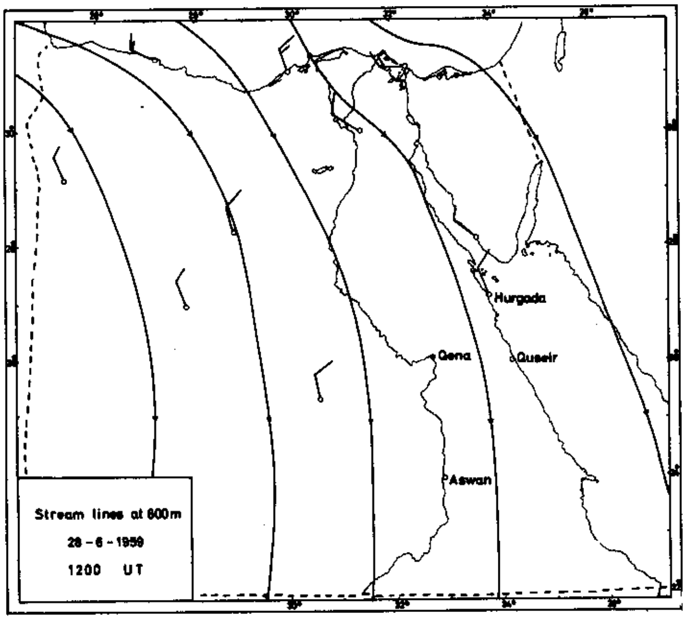

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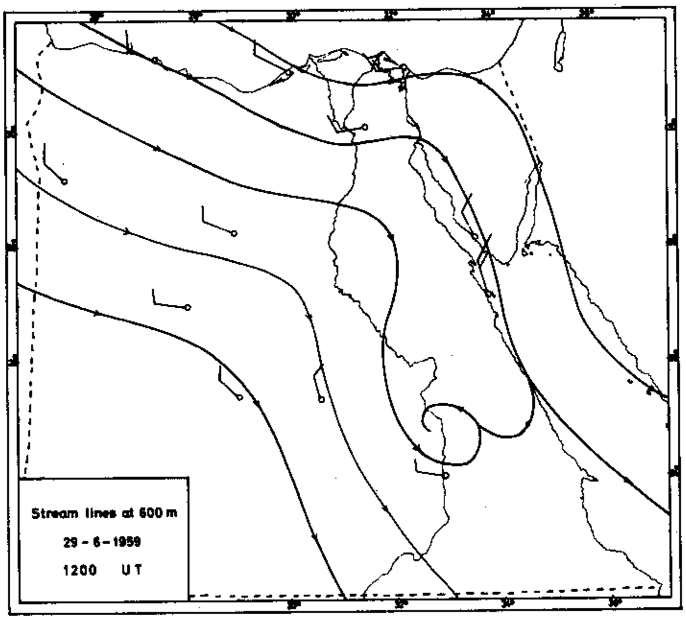

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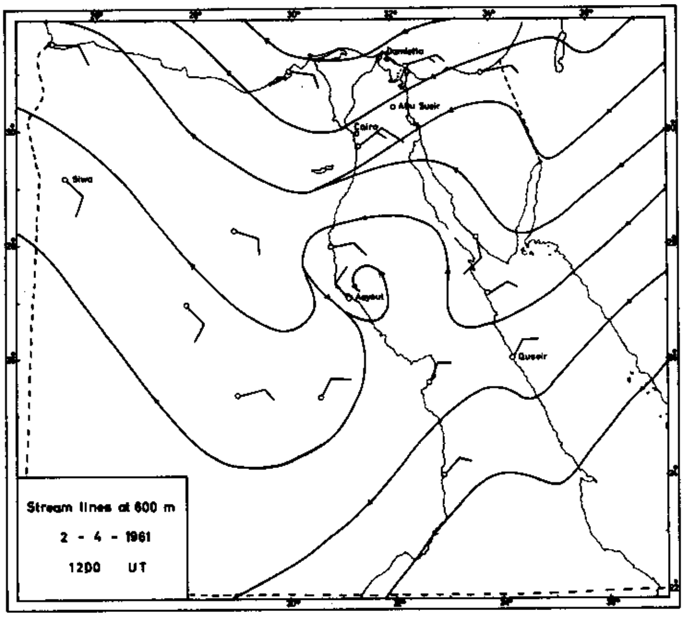

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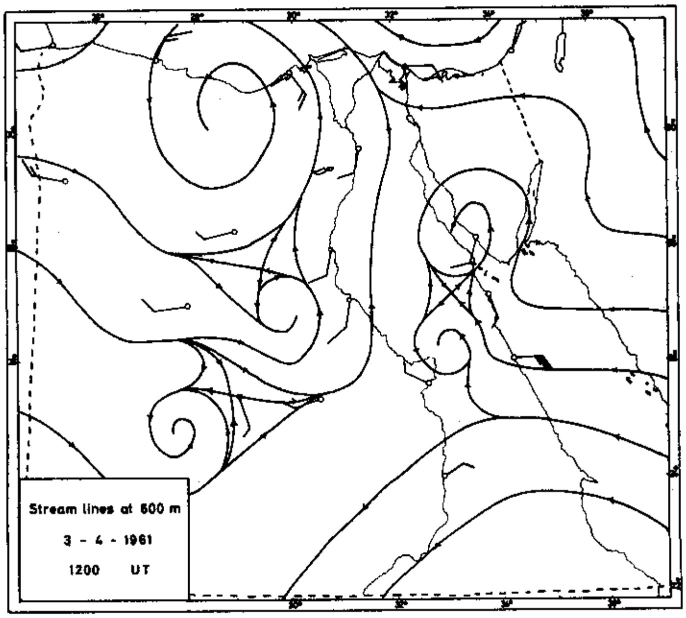

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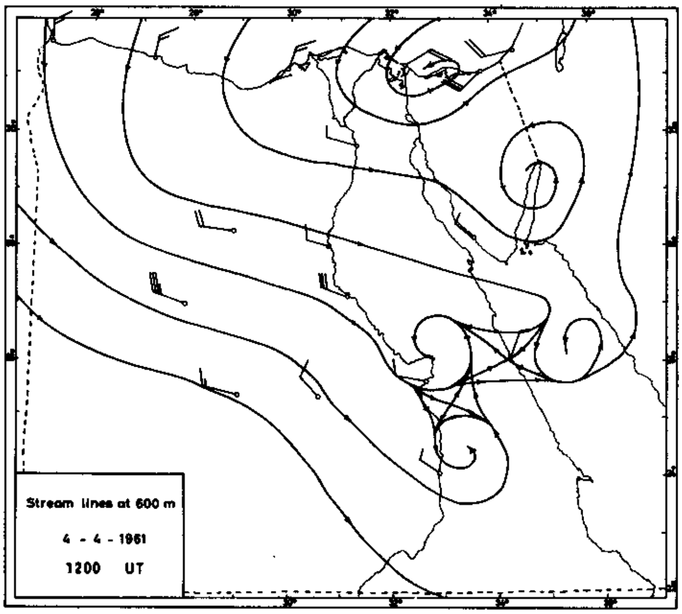

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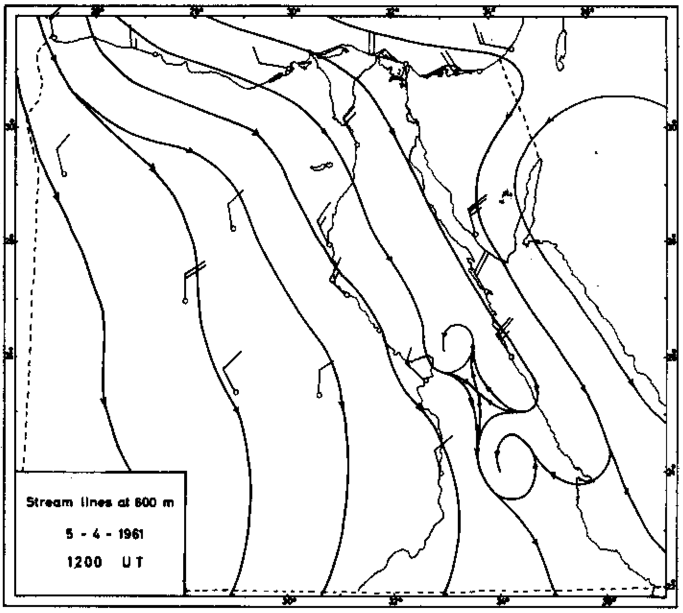

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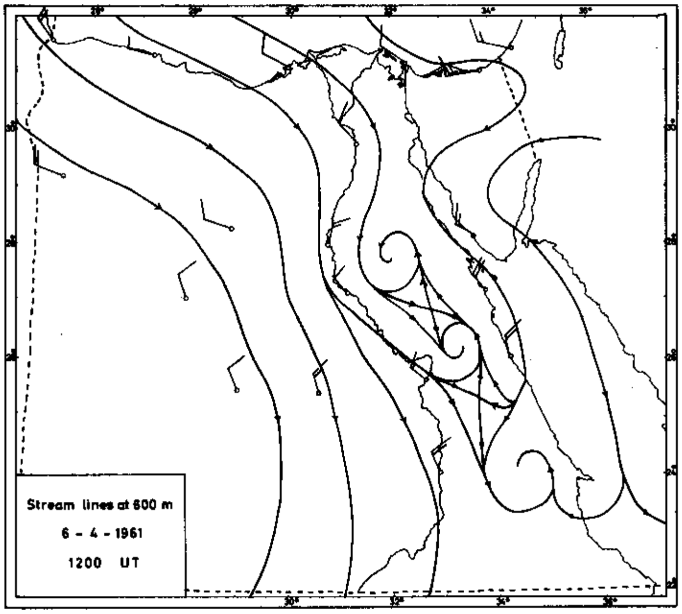

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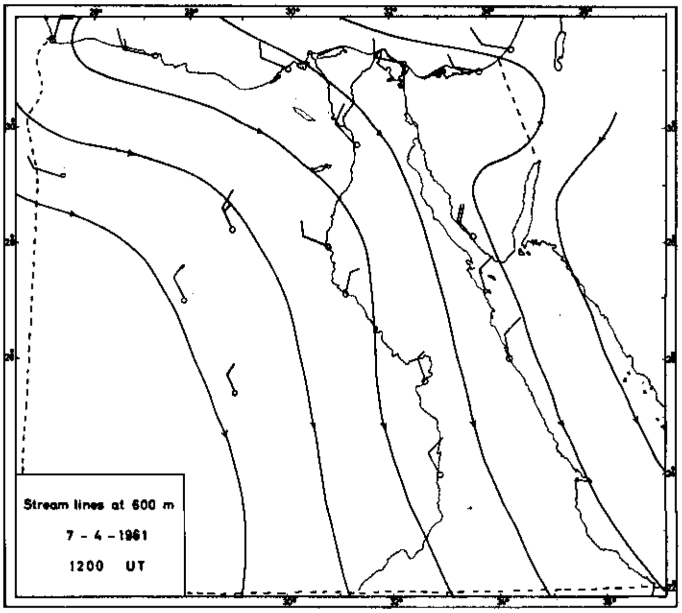


Figure 14

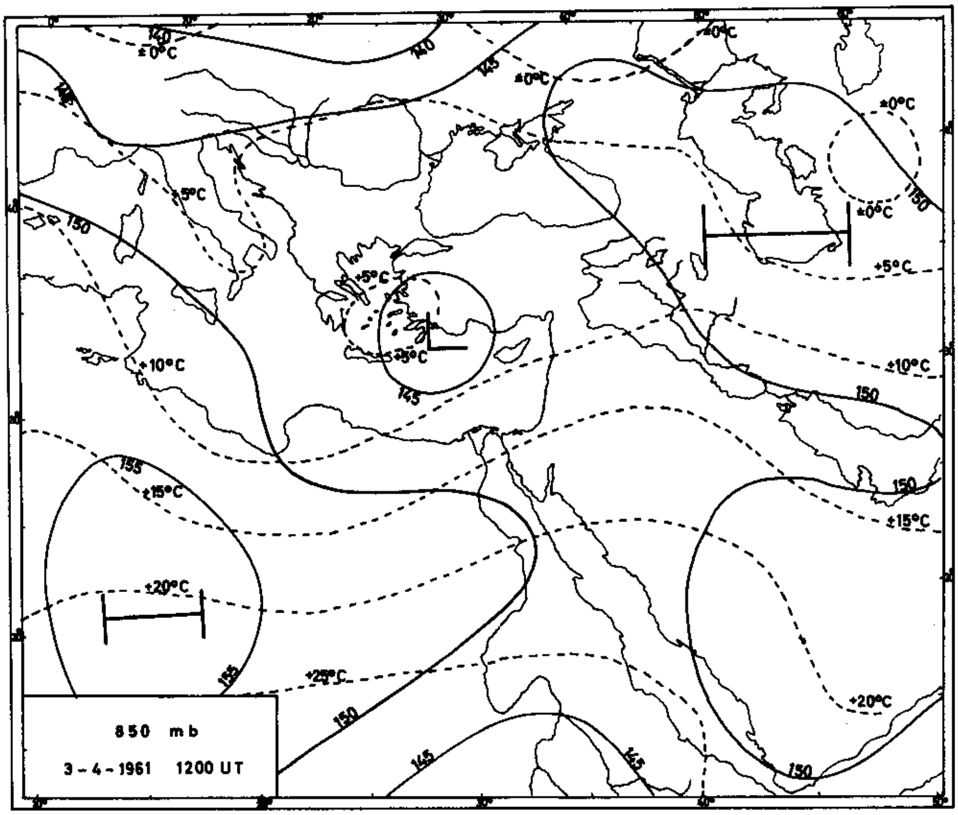


Figure 15

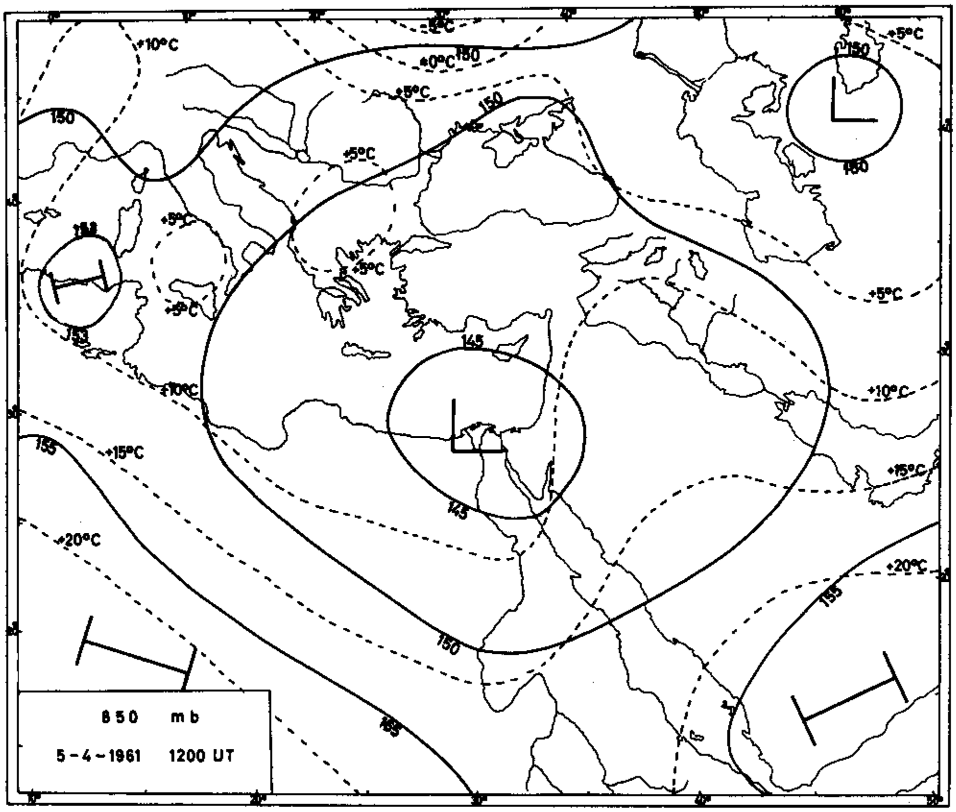


Figure 16

THE DESERT LOCUST INVASION INTO ISRAEL IN MARCH 1962

by

J. Feige

Desert Locusts drifting north along the Red Sea coast in the first part of 1962 reached Trans-Jordan during the month of March and penetrated on two occasions into Israel. They were seen at Yotvata and near Elat on 10 and 13 March.

The synoptic conditions during the first part of March showed a quasi-stationary low-pressure trough from the Sudan and along the Red Sea that caused a south-easterly air-flow over Arabia in the low levels of the atmosphere. At the same time low-pressure cells moved towards Cyprus at times causing westerly winds and unstable weather over the eastern Mediterranean and the Levant (see Figures 1 to 4).

According to eyewitness reports, the locusts were moving along their usual track down the wadis of Trans-Jordan into the valley of Arabia and towards the Negev desert (an area where locusts were often found breeding). As far back as the days of the Bible, it has been known by the farmers that locust invasions can be expected with the hot easterly desert winds, whereas westerly winds cause the locusts to "disappear". On the above-mentioned dates it appeared that the locust movement was against the prevailing wind. A more thorough inspection of the pilot-balloon observations showed that this impression was due to the fact that although surface winds were north-westerly, winds at an altitude of 200 to 300 metres had already a marked easterly component and the locusts only landed into the wind.

A further study of the climatic conditions indicated that the weather was most unfavourable to locust breeding in the area at the time, as temperatures (including soil temperatures) were most of the time below 20°C, and no rain was reported for the previous 25 days in the affected area. The westerly winds drove the swarms off even before they could be sprayed effectively by the plant protection division of the Ministry of Agriculture.

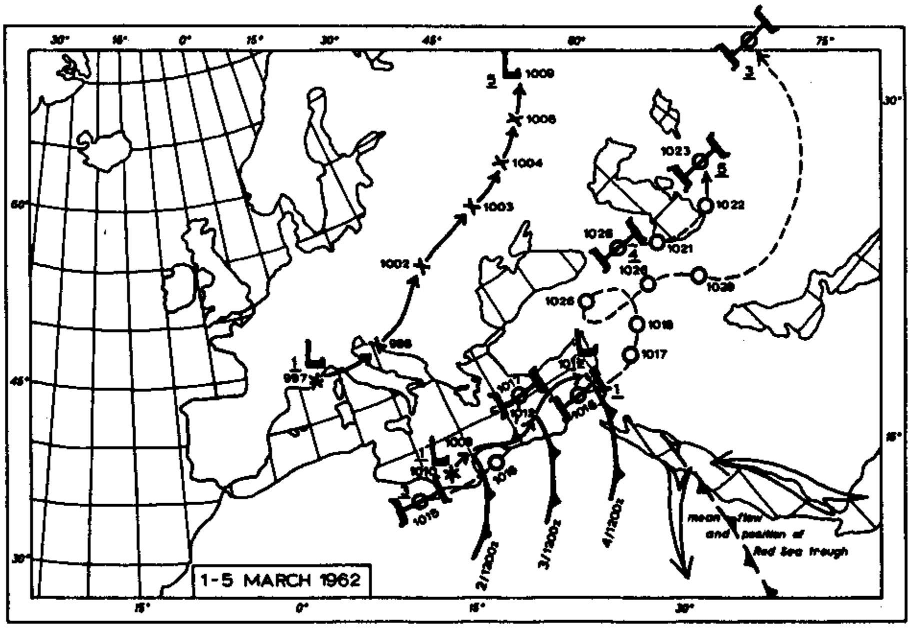


Figure 1

✱ X position of low pressure centres

O position of high pressure cells

various frontal systems

convergence line or trough line

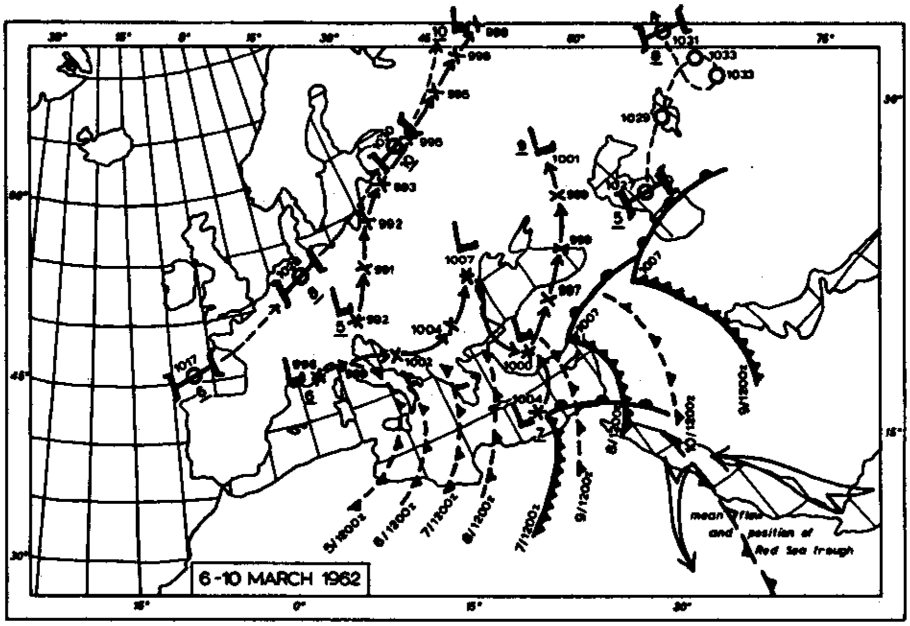


Figure 2

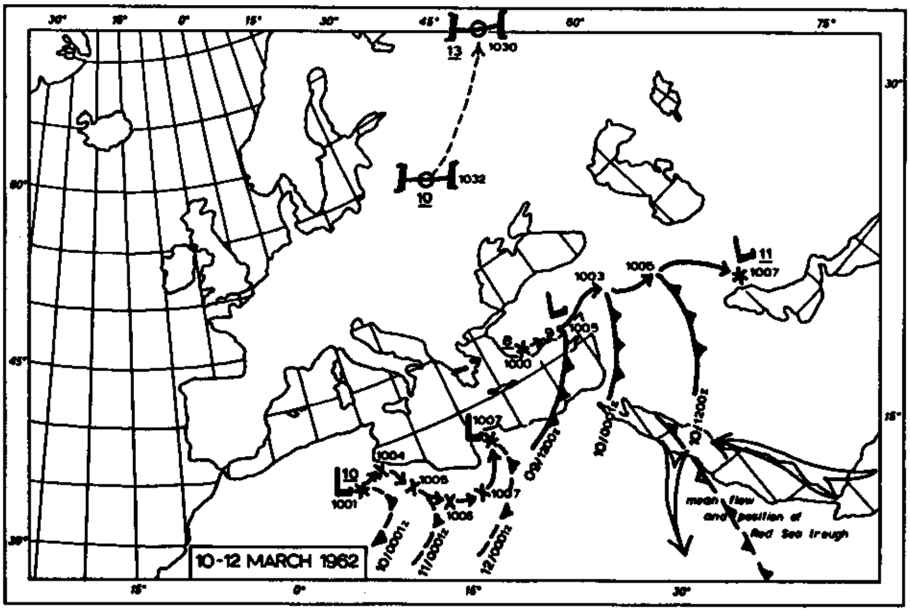


Figure 3

✱ X position of low pressure centres
○ position of high pressure cells
various frontal systems
convergence line or trough line

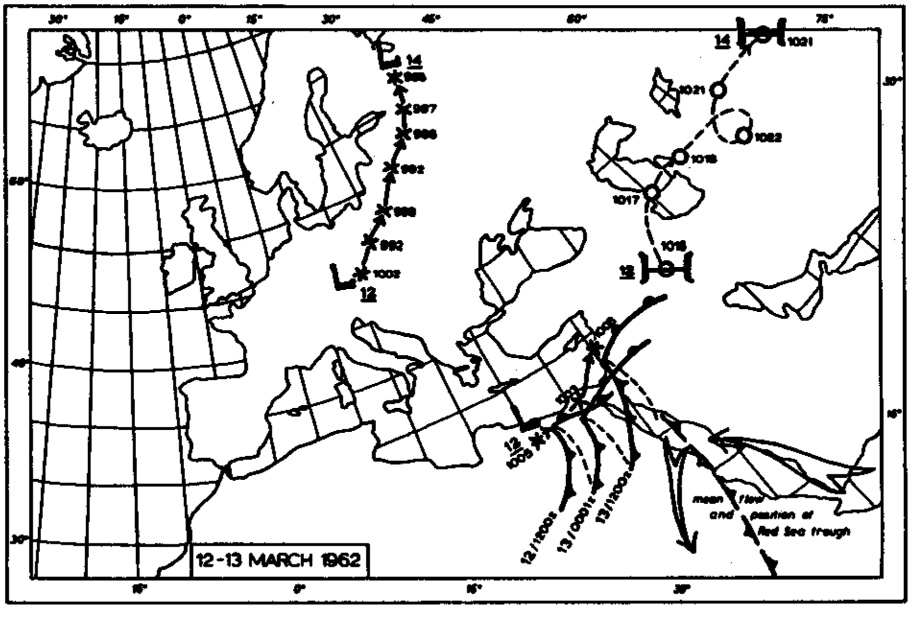


Figure 4

SYNOPTIC SITUATIONS ASSOCIATED WITH SWARM MOVEMENTS ACROSS SYRIA

by

R. Deeb

1. Synoptic situations

1.1 Periods of 1-6 and 10-13 May 1961

On 1 May 1961, there was a complex frontal depression, with two centres, one over the Black Sea and the other over northern Egypt, while Syria was under the influence of a ridge of high pressure. The wind was generally SE, 5 kt, and the temperature was relatively high.

On 2 May, the pressure fell rapidly and the Sudan trough extended to the north, and Syria was in the warm sector of the depression which was centred over Turkey, with its cold front crossing the Mediterranean parallel with our coast. The wind became S, 15 kt, and there was a notable increase in temperature. Some rising sand was reported inside Syria.

On 3 May, the pressure was still falling in the interior, while the cold front was crossing the coastal region. The wind was still S to SW, 15 kt, over the western part of Syria while it was SE, 10-15 kt over its eastern part.

On 4 May, at 0001 GMT, a small depression formed in north-eastern Syria on the cold front which was parallel to 41°E longitude. The wind became S, 5 kt, over the southern region and N, 5 kt, over the northern region, and there was a good decrease in temperature.

At 1200 GMT there was a family of frontal depressions extending from the north of the Caspian Sea across the east of Turkey, Syria and central Arabia, leaving behind it a region of rising sand inside Syria. The wind was SW, 20-25 kt, between the lines 33°-35°N and 35°-38°E, and the temperature was about 26°C.

On 5 May, instability developed, and some precipitation and thunderstorms occurred over the western part of Syria with sandstorms over its eastern part. The wind was still SW, 10-15 kt.

On 6 May, precipitation and thunderstorms were widespread all over Syria behind the frontal depression which was centred over Iraq. The wind was W, 20-25 kt, and the temperature was about 20°C.

On 10 and 11 May, Syria was under the influence of the Sudan trough which extended towards the north. The wind was generally E to SW, 3-5 kt, increasing to 15-20 kt at noon.

On 12 May, the Sudan trough and the Arabian Gulf trough amalgamated and affected Syria; a cold front crossed the Syrian coast parallel with it. The pressure fell rapidly and the temperature difference was 5°C between the cold and warm sectors. The wind was SW, 5 kt behind it.

On 13 May, the Arabian Gulf trough extended towards the east and the Sudan trough retreated, giving the usual summer situation of high temperature, dry air, and variable light wind.

1.2 Period of 1-5 May 1962

On 1 May 1962, the extension of the Sudan low was covering Syria with a thermal depression centred over the south-east corner of the Mediterranean; there was a notable fall in pressure during these days especially over the eastern and northern parts of Syria and Iraq where rising dust was reported. The wind was E to SE, 15-20 kt, and the temperature was relatively high (31°C at 1200 GMT).

On 2 May, the Sudan trough was still affecting the country, and the thermal depression associated with it moved eastwards, with its centre over east Jordan. The wind was N over the western district and E to SE, 15-20 kt, over the eastern and northern district. Rising dust and sand covered the whole area during this day.

On 3 May, the cold front associated with a depression over the Black Sea was approaching the Syrian coast; a frontal thermal depression was centred over northern Egypt. This wind was still SW, 10 kt, over the eastern and northern districts of Syria.

On 4 May, at 0000 GMT, Syria was in the warm sector of the frontal depression which was centred over the coast, where thunderstorms and showers were reported. The pressure was falling over the eastern parts of Syria where the wind was E, 5-10 kt. At 1200 GMT the depression was over central Syria, with rising sand around its centre over the cold and warm fronts. The wind veered to the SE, 20 kt, in the warm sector of the depression over the eastern and northern districts of Syria; the temperature was about 36°C.

On 5 May, the depression moved towards north-east Syria; the Sudan trough was still covering the area. The wind was SE, 10 kt, over Iraq and the north-eastern districts of Syria.

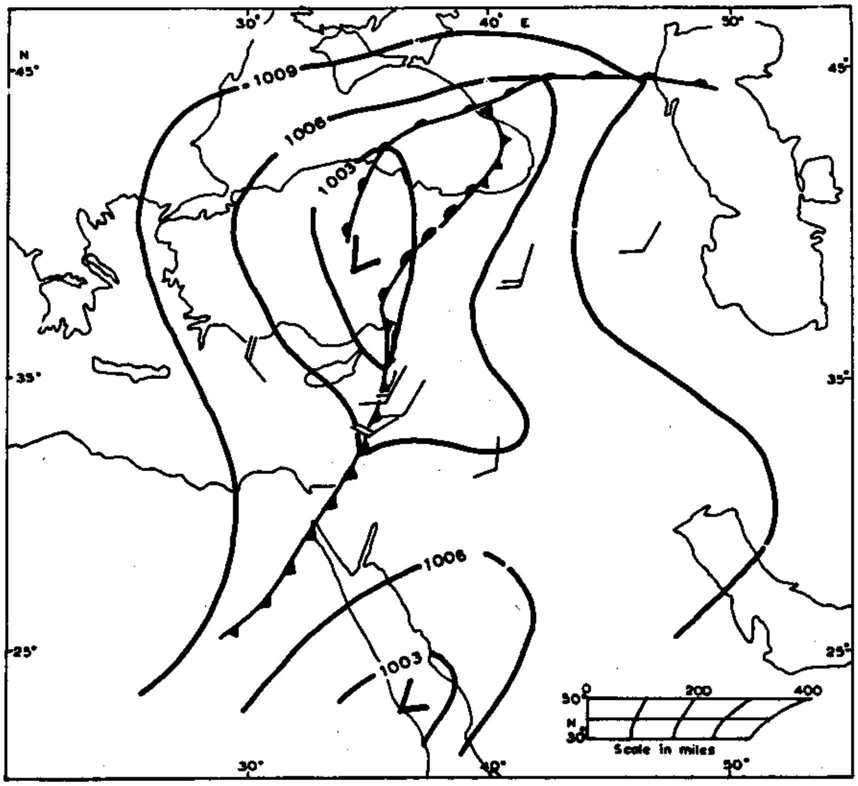
2. Swarm movements

2.1 Periods of 1-6 and 10-13 May 1961

Swarms reached Israel and Jordan in December 1960, and spread into southern Syria in February 1961. Up to the end of April, however, the invasion was confined to south of 34°N. During the period 3-6 May, swarms moved north to 35°N and on 10-13 May to 36°N.

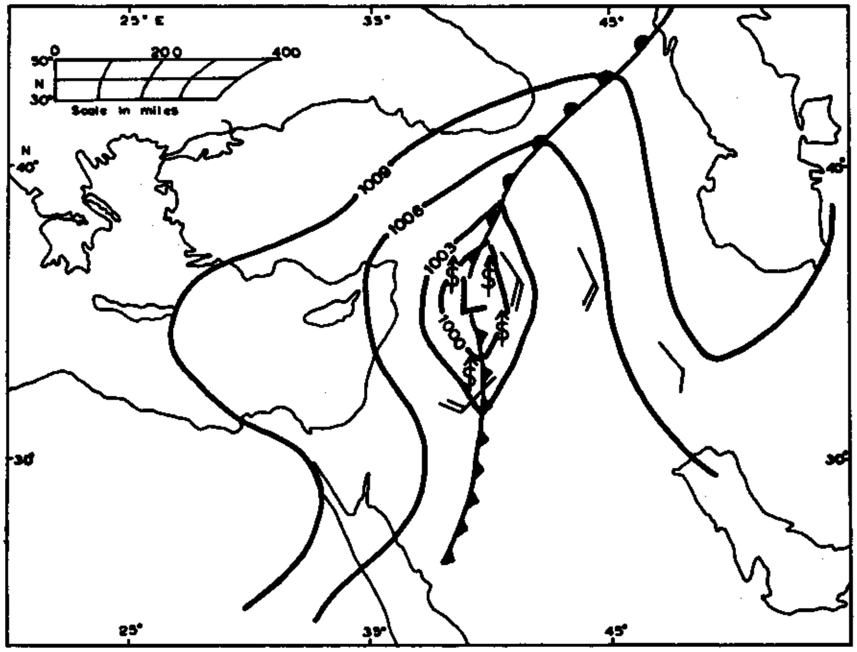
2.2 Period of 2-5 May 1962

Mature swarms spread across Iraq from late March 1962 onwards; some appeared in the south-eastern part of the Euphrates Valley in Syria from mid-April, with one reaching south-eastern Turkey, but the invasion was limited in extent. During the period 2-5 May, however, there were clear indications of more laying swarms moving across eastern and northern Syria, and spreading into Urfa and Mardin provinces of south-eastern Turkey from 4 May.



3 May, 1961. 0001 z. Surface.

Figure 1



4 May, 1962. 1200 z. Surface

Figure 2

SYNOPTIC STUDIES OF LOCUST SWARMS IN TURKEY DURING 1960

by

A. Kurun and N. Yesilovali

For a long period the south-eastern part of Turkey has been subject to invasions of locust swarms; the intervals between each infestation seem to decrease. Up to 1945 infestation had occurred at intervals of ten to fifteen years, then the area was clear for eight years until 1953 and for a further five years until 1958. Infestation occurred again in 1959 and 1960, and once more in 1962.

Meteorological situation

A careful study of the 850 mb constant pressure charts for 7 April 1960 revealed a centre of low pressure in an area covering south-western Turkey and south-eastern Greece, and on the surface chart for 0600 GMT for the same day, the existence of a stationary front extending in a west to east direction was also clearly distinguished. This synoptic situation accounted for the southerly winds blowing from Syria to the south-eastern part of Turkey.

The synoptic situation on 8 April showed a very deep low at all levels, moving in a south-westerly to north-easterly direction and extending its influence over most parts of the area. Rainfall occurred the same night, with the arrival of cooler air. Control measures against the locusts were made difficult by the intermittent rain showers. A point which may be usefully considered here is that the microclimatic characteristics of the area appear to be such that invading swarms of Desert Locusts become deflected in different directions. Although the terrain is mainly flat, the existence of large or small hills causes winds of eddy character and intermittent showers.

For the few days following 24 April 1960 the synoptic situation remained largely unchanged. The migration of swarms from Syria was made easier by the south-easterly to south-westerly winds blowing over the area at a speed of 5 to 15 kt; the corresponding low-pressure systems were shown on both the constant pressure charts and surface charts (Figures 1 to 9).

The course of progress of infestation in the south-eastern region of Turkey in 1960 has been summarized by Mr. Suleyman Balamir, Expert of Entomology, Plant Protection Institute, Ankara.

On 7 April 1960 the first swarm of Desert Locusts crossed the Syrian border into Turkey at 12.30 p.m. at the Karatepe frontier-guard position about 14 kilometres east of Akçakale in the Urfa district. Akçakale was immediately informed by the Karatepe frontier-guard of the passage of the swarm, and the necessary steps were taken by the duty teams. The swarm was found in an area covering 1400 decametres in Dibat and Gentari, two villages to the north-east of Akçakale. It was flying at an altitude of about 50 metres from the ground, and had a density of 180 to 200 locusts per square metre. The locusts were yellow in colour, but not sexually mature.

NOTE : Details of the meteorological aspects of earlier locust invasions of Turkey were made available at the seminar in "Desert Locust protection in Turkey in the years 1959-1960 and meteorological situation" by N. Yesilovali and A. Kurun, T.R. Department of Agriculture, State Meteorological Organization, Ankara, 1963.

The second swarm of Desert Locusts, on 8 April 1960, invaded Turkey in the vicinity of the State Reproduction Farm of Ceylanpinar and flew in a random manner towards nightfall in winds blowing from different directions. The swarm was sited at dusk in Suvat, Mesrefe and Zenzele, all villages in the Akçakale area. No control was carried out that night owing to heavy rain showers, strong wind, and the muddiness of the ground; neither were any measures taken on 9 April, due to the mud. As the weather became warmer, the locusts started to move; they were followed by the duty team. Because of the variable winds the locusts kept changing their direction. Finally at 3.15 p.m. the swarm had begun to fly towards the south, but a little later it was turned back by a cross-wind and then landed in five groups. Each group was three to five kilometres apart, and settled temporarily at different places in Seyhan, Mesrefe-Satavi, Umitveren, Kize and Hizan villages. This swarm had been flying at an altitude of 30 to 150 metres, and was yellow in colour but sexually immature.

Another swarm appeared on 24 April 1960, at 2.20 p.m., after taking 20 minutes to pass the Turkish border through Karatepe and Ebubekir frontier-guard posts of Akçakale. It then flew over Hizan village, north-east of Akçakale, turned toward the east and after flying by way of Birseyhan valley settled in the Tektek mountains. The swarm, followed by jeeps, turned towards the north-east and settled in the wheat-fields of the hills to the west of Karataş village and also the wheat-fields to the north-east of the same village. The locusts took about half an hour to settle in these places.

CLIMATOLOGICAL SUMMARY

	Name of station	Temperature (°C)			Wind direction and velocity (m/sec)						Precipitation (mm) (daily)
		07^{00}	14^{00}	21^{00}L	07^{00}		14^{00}		21^{00} L		
7 April 1960	URFA	11.8	22.7	18.4	WSW	2	E	4	E	4	.
	MARDIN	12.7	17.5	16.7	S	3	SE	4	SSE	6	.
	VIRANSEHIR	.	.	.	SE	2	SE	4	SE	4	.
	KIZILTEPE	13.0	.	.	N	7	SW	2	E	2	.
	CEYLANPINAR	11.4	25.8	21.6	NE	2	SE	4	NE	1	.
	NUSAYBIN	.	.	.	C	-	C	-	C	-	.
	AKÇAKALE	.	.	.	E	7	E	4	SE	4	.
	SURUG	.	.	.	W	16	W	16	W	2	.
	CIZRE	14.5	.	.	C	-	NE	1	NE	1	0.0
8 April 1960	URFA	15.4	21.7	10.4	C	-	SW	4	E	1	0.0
	MARDIN	16.5	19.7	8.8	SW	11	S	5	SE	7	.
	VIRANSEHIR	.	.	.	NE	4	NE	4	NE	4	.
	KIZILTEPE	12.0	.	.	E	9	N	4	E	9	.
	CEYLANPINAR	18.0	20.4	10.7	E	4	E	4	C	-	.
	NUSAYBIN	.	.	.	E	-	E	-	NE	-	.
	AKÇAKALE	.	.	.	SW	4	W	7	W	2	0.0
	SURUG	.	.	.	C	-	W	2	C	-	.
	CIZRE	13.4	.	.	SE	1	SE	1	SE	1	.
24 April 1960	URFA	16.7	27.3	20.4	W	3	SW	3	WSW	10	0.0
	MARDIN	17.4	20.0	18.0	NW	8	NNW	11	E	5	.
	VIRANSEHIR	.	.	.	C	-	C	-	C	-	.
	KIZILTEPE	14.0	.	.	E	9	E	9	E	9	.
	CEYLANPINAR	20.3	30.7	22.0	SE	9	SE	1	SE	1	.
	NUSAYBIN	.	.	.	E	-	E	-	E	-	.
	AKÇAKALE	.	.	.	NW	4	W	4	W	2	.
	SURUG	.	.	.	C	-	W	7	W	2	.
	CIZRE	12.3	.	.	NE	12	NE	2	NE	2	.

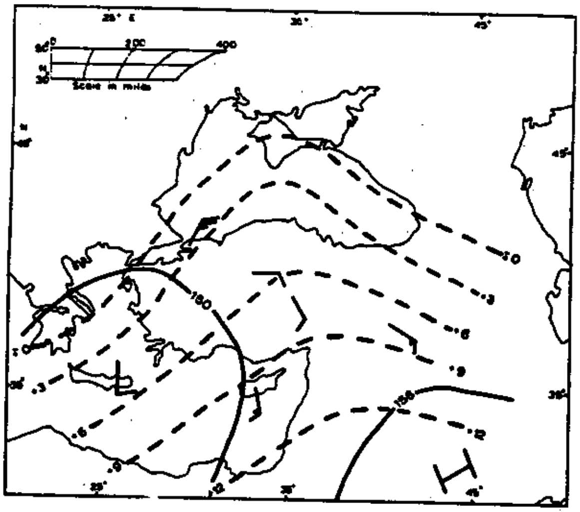


Figure 1 - 7 April, 1960. 0000z. 850 mb.

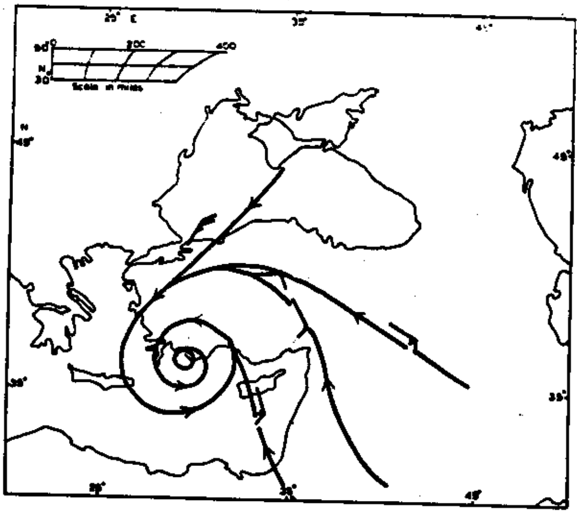


Figure 2 - 7 April, 1960. 0000z. 850 mb. Streamlines.

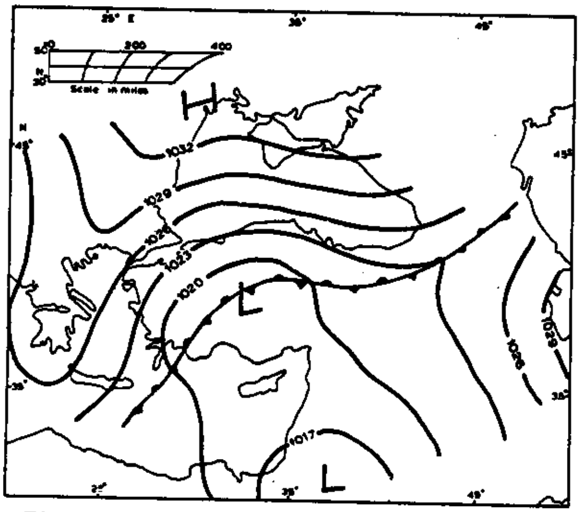


Figure 3 - 7 April, 1960. 0600z. Surface.

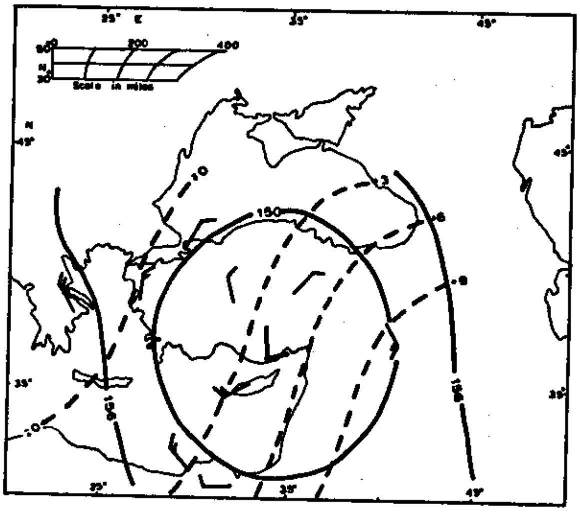


Figure 4 - 8 April, 1960. 0000z. 850 mb.

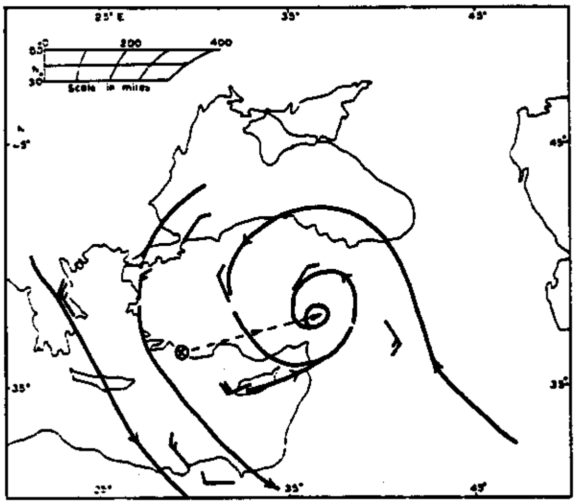


Figure 5 - 8 April, 1960. 0000z. 850 mb. Streamlines.

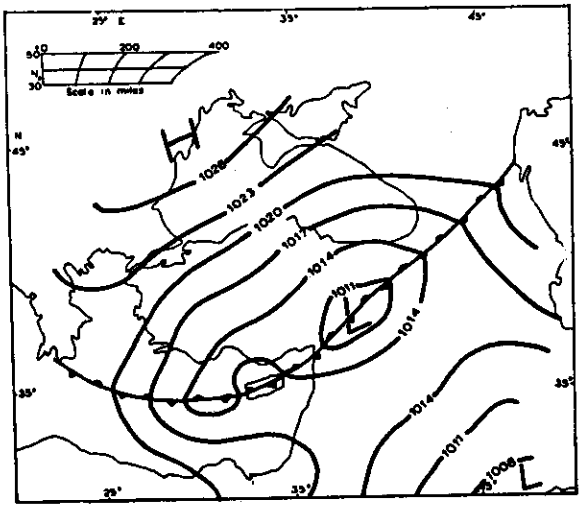


Figure 6 - 8 April, 1960. 0600z. Surface.

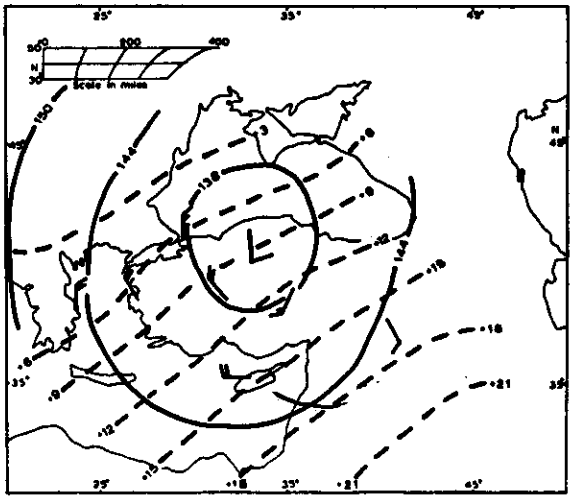


Figure 7 - 24 April, 1960. 1200z. 850 mb.

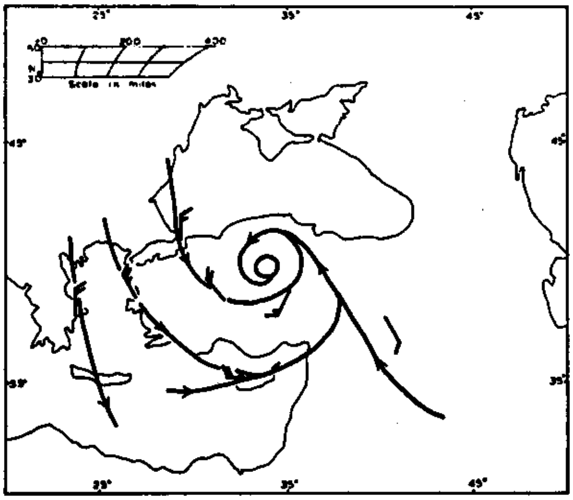


Figure 8 - 24 April, 1960. 1200z. 850 mb. Streamlines.

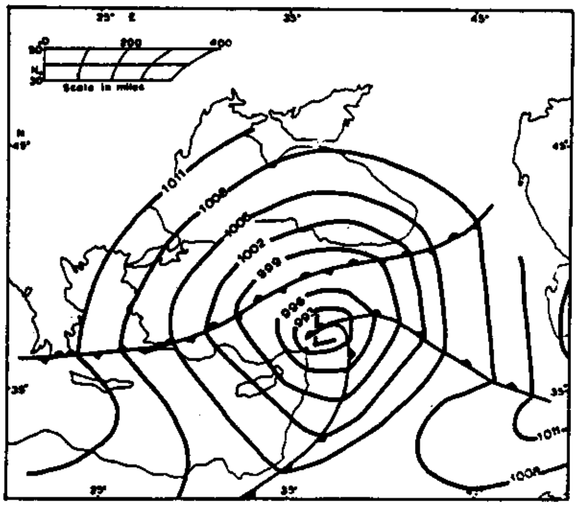


Figure 9 - 24 April, 1960. 1200z. Surface.

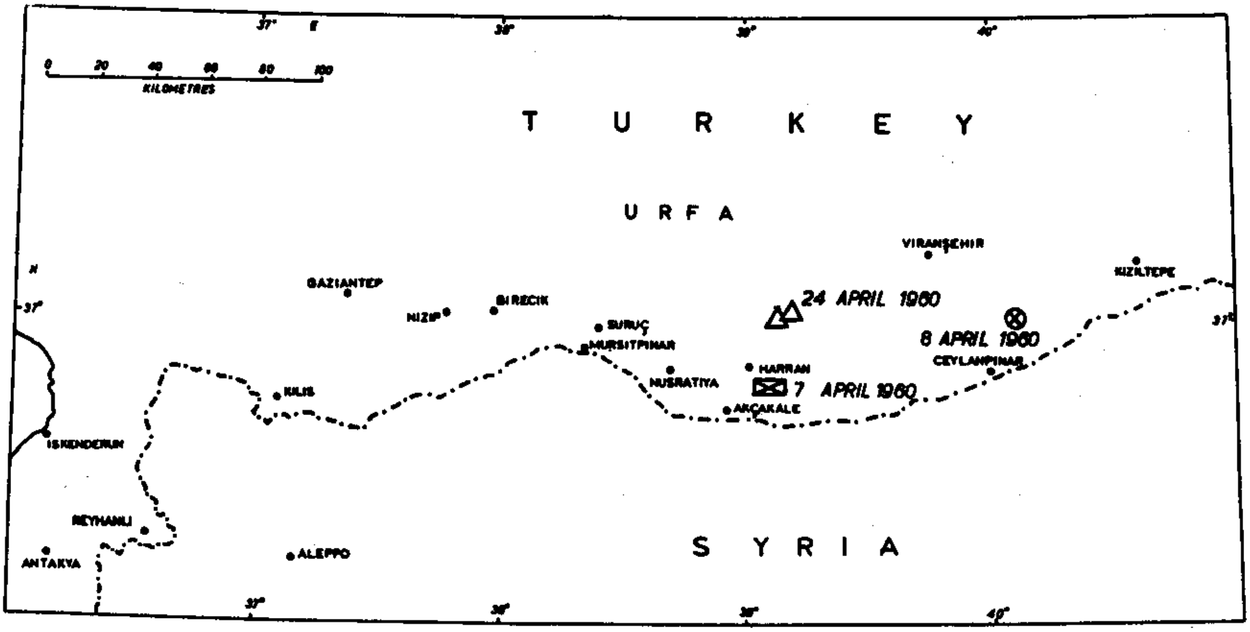


Figure 10

SYNOPTIC SITUATIONS ON 9-12 MARCH 1962 FOR IRAN AND NEIGHBOURING COUNTRIES

by

H. Ardekani

1. GENERAL SITUATION

The period 9-12 March 1962 is one which was recommended by Dr. R.C. Rainey for further study in relation to the movement of locusts in the region. Accordingly, an analysis was undertaken at the Forecasting Office at Mehrabad Airport, Tehran, of surface and upper-air charts for the four days for an area extending from 25°N to 45°N and from 20°E to 60°E. The selected time of observation was the 1200 GMT chart in each case. The charts included those for the surface, 850 and 700 mb. Streamline charts were also drawn for the two higher levels in addition to contours.

The routine charts which had been analysed at the Forecast Office were re-plotted and re-analysed in this study. Supplementary data were obtained as follows :

(1) From the U.S. Weather Bureau Publication of Daily Surface and Upper-Air Synoptic Observations;

(2) From the Climatology Branch of the Iran Meteorological Department;

(3) From copies of synoptic charts supplied by Dharran Airport, Saudi Arabia;

(4) From copies of charts supplied by the United Kingdom Meteorological Offices at Aden and the Persian Gulf.

The opening chart of the sequence for 9 March is marked by a pronounced frontal trough extending southwards from the north-west Caspian coast through eastern Turkey and central Iraq to central Arabia. This trough links with a trough of equatorial origin extending northwards into the southern Red Sea from Ethiopia. A well-marked secondary cold front emanating from a small secondary low centre of 1002 mb over central Turkey extends south-westwards across the eastern Mediterranean. Other features on the chart include a quasi-meso anticyclone of 1012 mb centred over Ahwaz and a non-frontal decaying low of 998 mb located east of Kerman.

At 1200 GMT, 10 March (Figure 1) the broad-scale situation has undergone considerable development. The trough which was over the northern Caspian has merged with the secondary low over Turkey to form a dynamic low pressure centre of 996 mb over Rezaiyeh with an associated trough extending south-eastwards. The secondary cold front previously mentioned has been sucked into the system drawing upon the supply of very cold polar continental air in its wake. The front now lies from the main low centre southwards through Iraq and north-western Saudi Arabia. The original main trough has meanwhile drifted slowly south-eastwards into south central Arabia. The quasi-meso high and the old frontal low have been destroyed by the energetic main low pressure system.

Twenty-four hours later the main low pressure system has moved to east central Iran. The main cold air supply is bounded by the secondary cold front which lies along the Elburz range and feeds back into the Russian high pressure system. The original frontal link joins troughs stretching from Turkestan across southern Arabia to northern Ethiopia.

In the final chart for 12 March separate anticyclonic cells have formed over the southern Caspian and over Iraq and north-eastern Saudi Arabia behind the main trough in which the previous secondary cold front has now become the main frontal system. The low centre of 1000 mb is now centred over eastern Iran and the situation is somewhat simplified. A further occlusion linking troughs over south-east Europe and North Africa is approaching from the west.

Turning now to the upper levels the 850 mb chart is recognized as providing a useful level for much of the Middle-East region which occupies plateau topography. On 9 March this level indicates a sharp trough extending from the central Black Sea across central Turkey to the eastern Mediterranean. This feature can be identified with the surface secondary cold front already mentioned. A small trough extended from north central Arabia to northern Ethiopia and a further trough lay to the east over eastern Iran from Kerman to the Gulf of Oman. The 1200 GMT chart for 10 March reflects at 850 mb the vigorous surface disturbance and its associated trough. This system moves south-eastwards across the 850 mb map but the elongated trough has tended to be cut off and left behind the main system. On 11 March a small high is centred over the eastern Mediterranean at 850 mb whereas a subtropical high cell over the Indian Ocean is feeding warm air up across Arabia into the Persian Gulf. The final 850 mb chart for 12 March contains a well-developed high cell over Arabia largely superimposed on the surface anticyclone, with its associated ridge extending northwards over eastern Turkey. The main trough has now moved eastwards to the 55th meridian and cold air is feeding into the trough from the north-west. The 850 mb streamline charts give a reasonably good indication of the wind flow at this level for the four-day period.

The sequence of four 700 mb contour and streamline charts show a well-developed westerly trough ridge type circulation across the region. On 9 March a 700 mb centre is located over central Turkey with a somewhat weak trough extending southwards at about 37°E. A weak ridge at 50°E separates the first trough from another trough further east. On 10 March (Figure 2) the trough extending from the 700 mb low, which has now moved to eastern Turkey, has intensified considerably. There is a sharp wind discontinuity at the trough line, reaching down across northern Arabia to the Sudan. On 11 March the trough has split. The northern half has moved eastwards while the southern half has been held back by the subtropical upper warm anticyclonic cell over the Indian Ocean. A well-developed ridge follows behind the trough. On 12 March the remnants of the cut-off trough lie over the northern Red Sea while a new trough approaches from the west. The northern half of the trough lies down the central Caspian and general westerly flow covers the region. The streamline pattern for 700 mb illustrates the features of the wind flow at this level for the four-day period. In particular the chart for 9 March exhibits strong convergence over western Turkey with a broad westerly current emanating from the marked diffluence of the wind over the south-eastern Mediterranean. Subsequent charts indicate a general broad westerly flow dominated by the trough already discussed. The pronounced southerly flow over the Red Sea to the east of the Sudan neutral point is noted on the chart for 12 March.

Dr. R.C. Rainey, in his report on his recent mission, includes a section on weather and swarm movements in eastern Ethiopia and neighbouring countries in mid-March 1962, in which he summarizes the situation discussed in this paper in relation to locust movements. On 10 March he reports first indications of a northward movement out of eastern Ethiopia. Swarms, dominated by the major synoptic situation, extended as far north as Jordan and Israel, the latter countries reached by swarms from the south on 9 and 10 March. In Iran important northward movements of egg-laying swarms were recorded in Lorestan and Khorasan on 10 and 11 March. Observations at 3 km and higher levels, states Dr. Rainey, provide evidence of a flow of warm air, moving from the south and south-west from the vicinity of eastern Ethiopia and across Arabia and Iran, ahead of a trough of low pressure extending from a depression of which the centre was moving eastwards across the Black Sea and Caspian areas. These conclusions are broadly in accordance with the situation as described and analysed in our own charts.

The analyses undertaken in connexion with this investigation are not only of interest in relation to the movement of locust swarms in the region. They also serve as a good example of active synoptic development in the region and show that if care is taken to supplement data deficiencies analyses for subtropical areas may be drawn that can match those in detail and accuracy which appear on the synoptic charts of the temperate regions.

2. DETAILED SITUATION IN IRAN

2.1 Pressure

The sequence was dominated by the movement of the main low pressure system across the country. The first chart of the series indicated the approach of this system towards the north-west corner of the country. An elongated trough of 1008 mb stretched from Rezaiyeh to the Caspian. Pressure fell continuously and the trough extended into the country in a general south-easterly direction. The greatest development occurred between 10 March, 1500 GMT and 11 March, 0300 GMT (Figures 3, 4). The latter chart showed a well-developed low centre at about 998 mb centred 100 kilometres south-east of Tehran. This centre moved east-south-eastwards and 36 hours later was centred over south-eastern Iran. The north-west to south-east track followed by this system is the normal track of depressions which branch to the right on approaching Iran.

The frontal analysis is a little obscure but there appeared to be a frontal zone on 9 and 10 March running north-west to south-east separating general north-easterly surface winds of higher temperature and dew point blowing from the Caspian Sea and Elburz mountains from drier and cooler south-westerlies. This frontal zone appeared to be the focus of development of the low system which by 11 March, 0300 GMT, had formed a large warm sector encompassing the whole eastern half of the country south of 35°N latitude. The frontal system moved away slowly to the east as cooler air spread in from the west and north-west.

2.2 Streamlines

The isobaric surfaces are a little unreliable in these regions of plateau topography and it is therefore of interest to turn to the streamline charts for the period.

The first indication in the flow pattern of the approach of the major depression system is given at 9 March, 1500 GMT. Cyclonic flow occurs in the north-west of Iran bounded by a neutral point along the Elburz range. There is indication of anticyclonic ridge flow in the southern half of Iran but the flow is generally south-west along the whole of the western border. By 10 March, 0300 GMT (Figure 5), two cyclonic vortices appear along the meridian of 54°, but the major system does not appear until 10 March, 1500 GMT, when a strong cyclonic vortex is found to the west of the north-west border. Twelve hours later (Figure 6) cyclonic vortices appear over central Iran associated with the main depression located on the surface synoptic chart at this time. The vortices move eastwards and at 11 March, 1500 GMT, the main centre is south-east of Meshed. The flow over west central Iran is strongly confluent into this vortex. There is a chain of vortices across northern Iran at 12 March, 0300 GMT, but by 12 March, 1500 GMT, the flow has simplified to some extent into a broad quasi-westerly current.

2.3 Rainfall

Rainfall on 9 March was confined to the west of Iran. Maximum amount was 5 mm. On 10 March (Figure 7), the rain had spread eastwards to Gorgan and south-east to Kerman. Maximum amounts in these two areas were 10 mm while rain continued in the west reaching 20 mm north-west of Hamadan. By the 11th the main rain area was along the Caspian coast and eastwards to Meshed. Only scattered light amounts fell elsewhere. Finally on 12 March the rain area was concentrated in the extreme north-east with 25 mm just west of Meshed. The remainder of the country was dry except for small amounts along the Caspian coast. The whole pattern of rainfall during the four-day period moved east and north-east as the main depression crossed the country.

2.4 Temperature

The temperature pattern is complex and largely governed by altitude. There was a retraction of the 30°C maximum temperature isopleth from the Abadan area south-eastwards during the four-day period. This was accompanied by substantial cooling in the north and west. At the same time, the temperature rose in central Iran on 10 and 11 and fell again on 12 March. Such changes were associated with the occurrence of southerly winds ahead of the low and their subsequent replacement by northerlies.

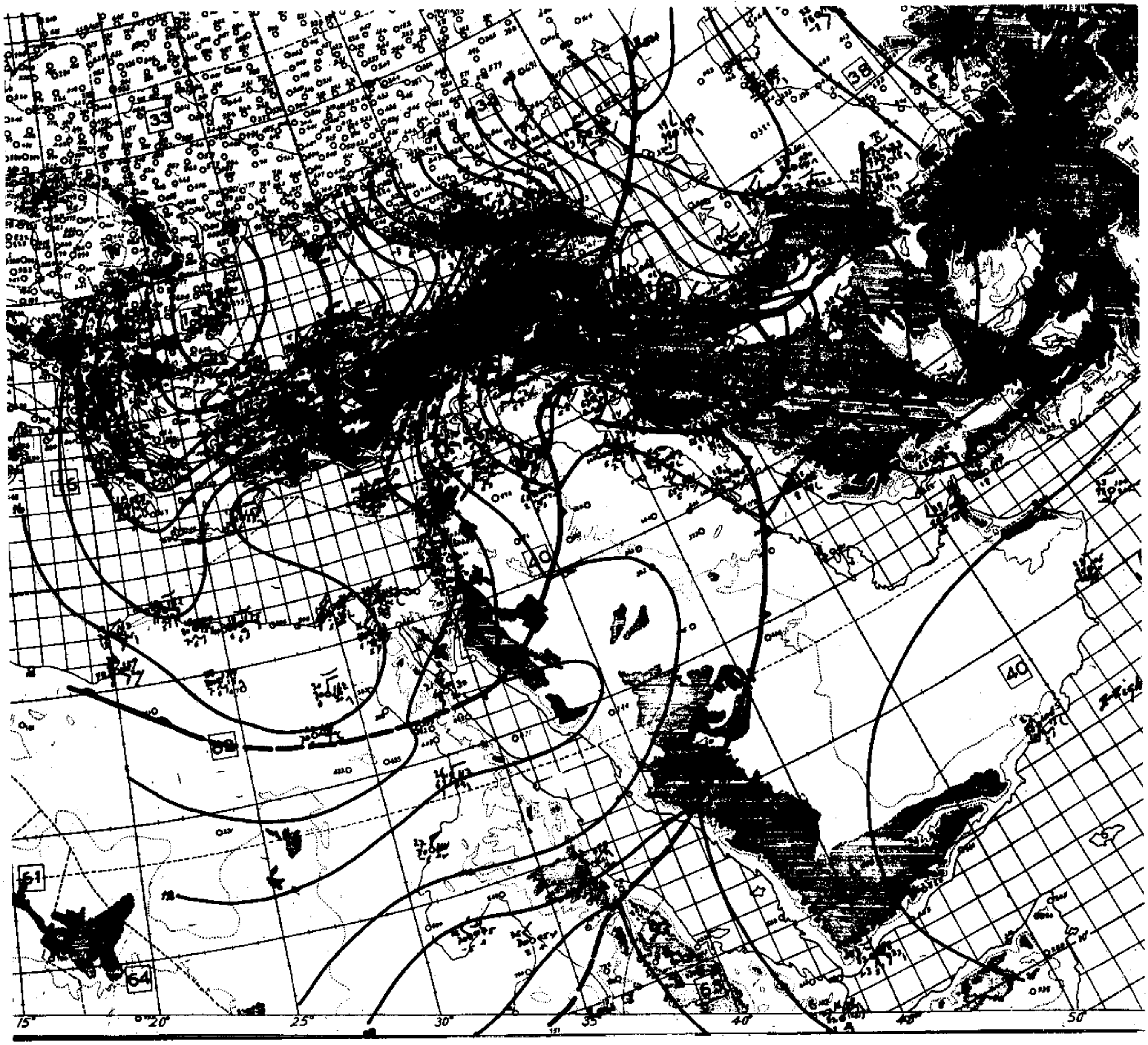


Figure 1 - Surface chart 1200z, 10 March 1962.

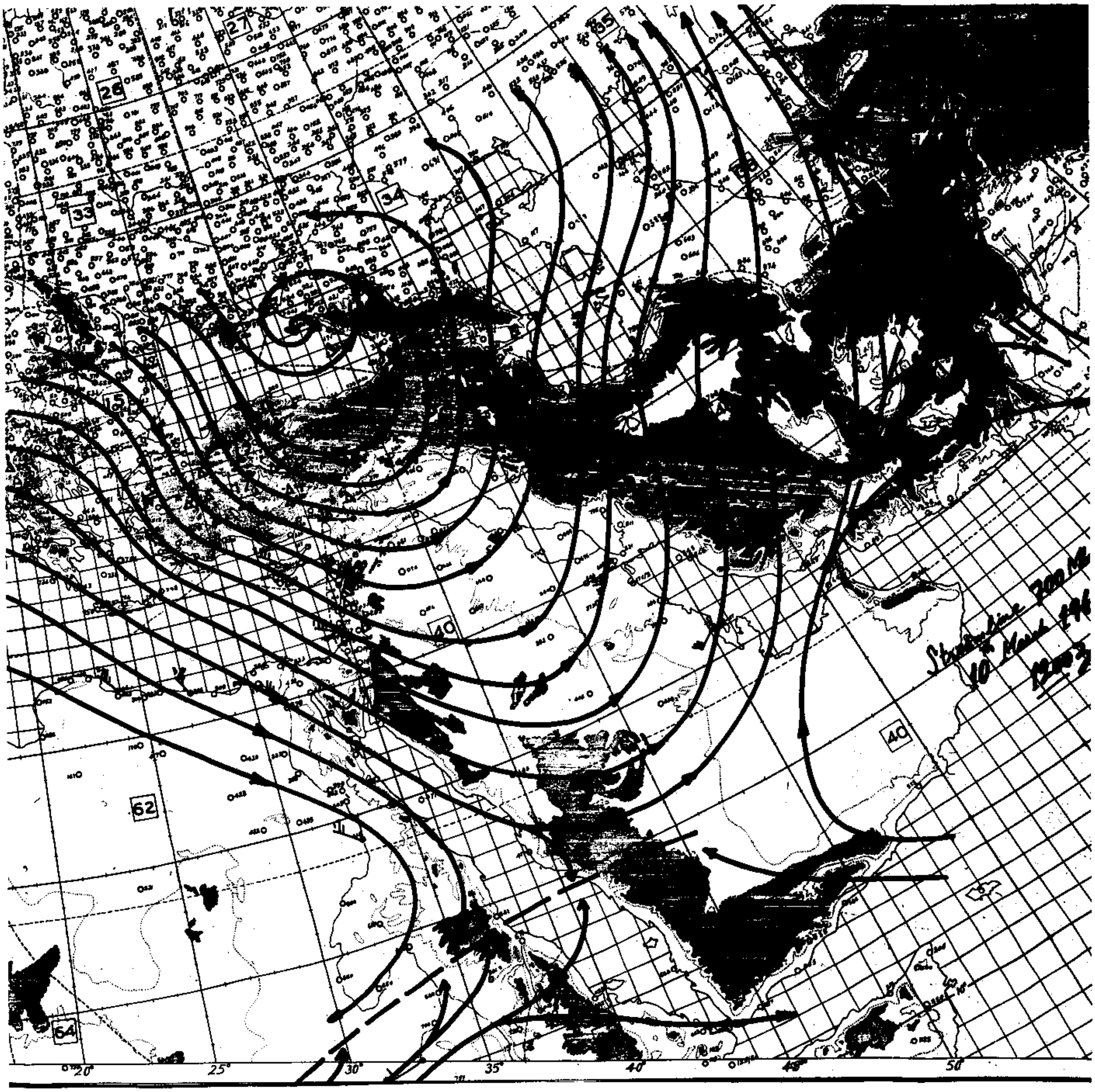


Figure 2 - Streamline 700 mb, 10 March 1962, 1200z.

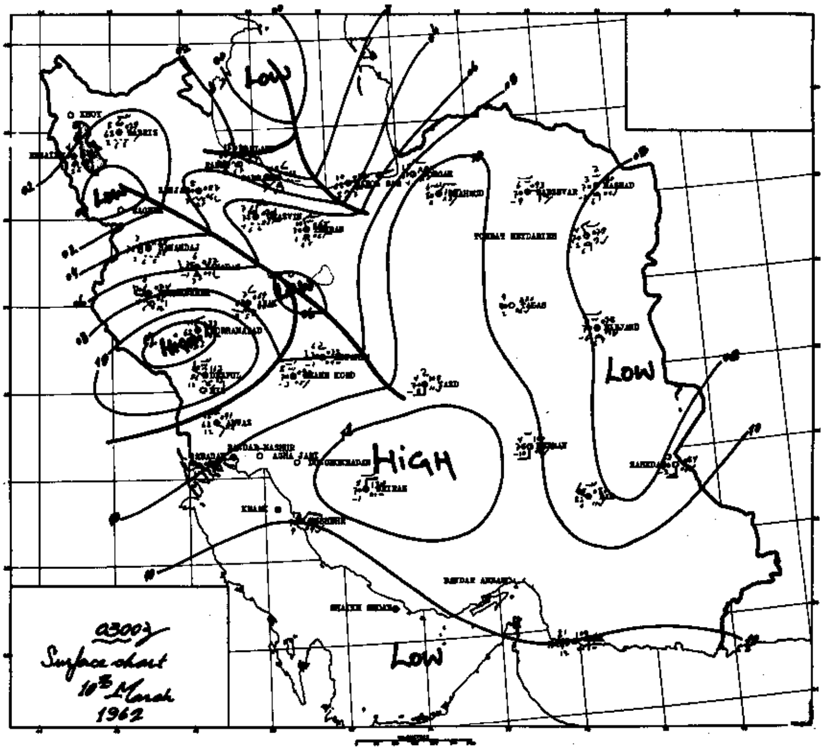


Figure 3

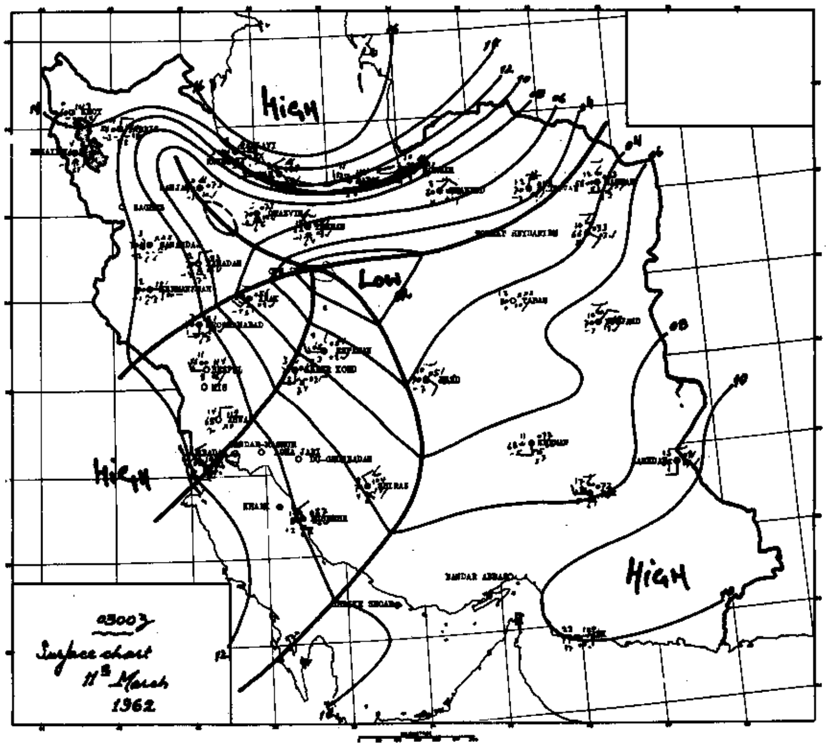


Figure 4

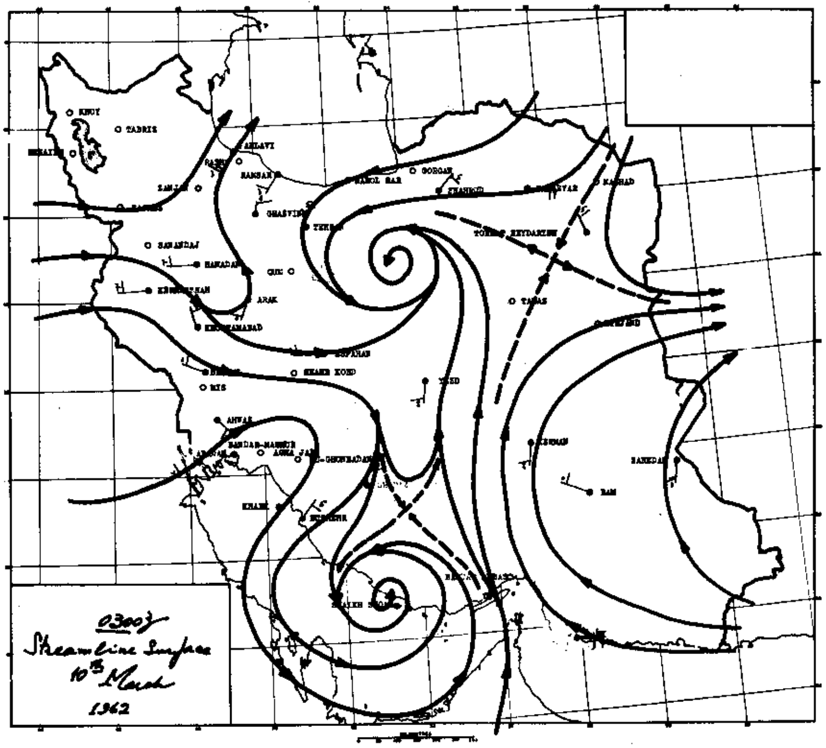


Figure 5

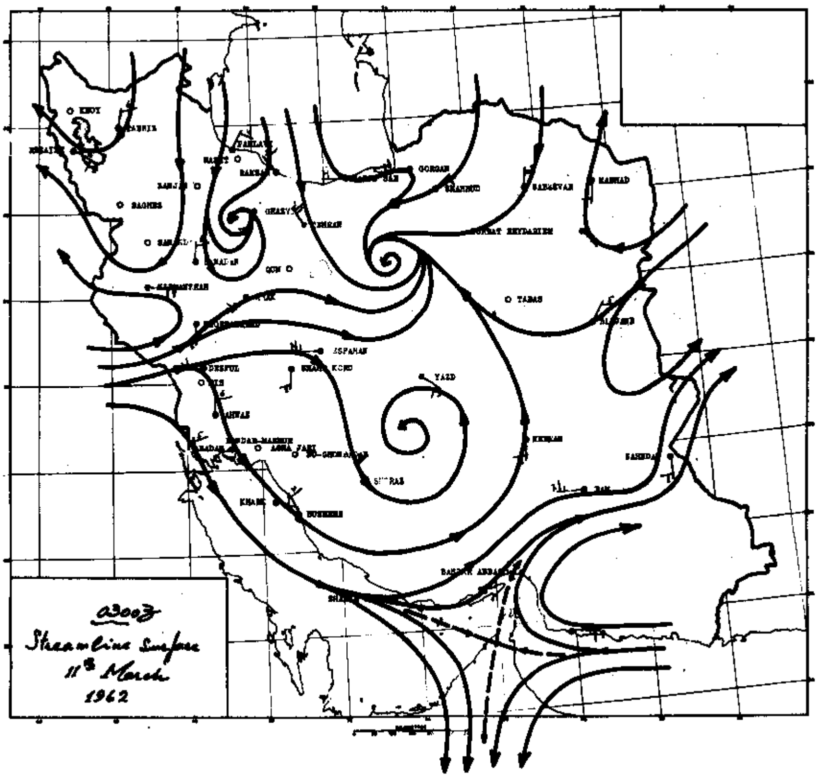


Figure 6

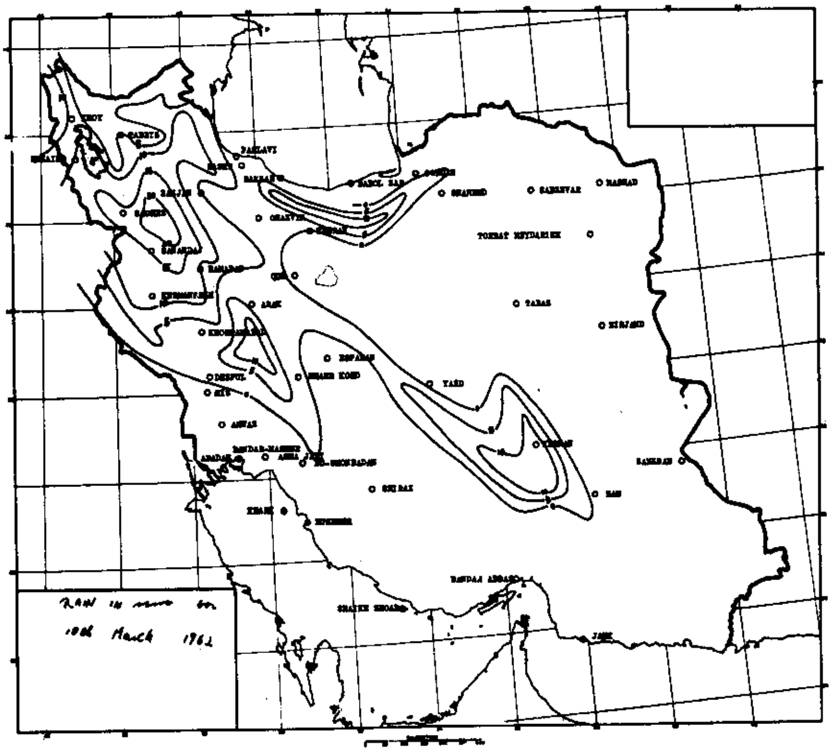

PAHLAVI
BABOL SAR
SABZEVAR
MASHAD
TORBAT HEYDARIEH
TABAS
BIRJAND
ARAK
DESFUL
AHWAZ
BANDAR-MASHHUR
ABADAN
SHAHR KORD
YAZD
SHIRAZ
ZAHEDAN
BAM
BANDAR ABBAS
SHAIKH SHOAIB
JASK
RAIN in mms for
10th March 1962

Figure 7

SYNOPTIC SITUATIONS DURING LOCUST SWARM PENETRATIONS INTO THE U.S.S.R. IN 1962*

by

S.P. Starostin

Locust swarm penetrations into the U.S.S.R. occurred in 1928 and 1929 in Turkmenia, in 1928 and 1930 in Azerbaijan and in 1962 again in Turkmenia. Locust swarms began moving into southern Turkmenia in 1929 in the first days of May, and during the whole of that month the swarms moved northwards.

In 1962, penetration into Turkmenia took place on 28-30 March, i.e. more than a month earlier. This unexpected appearance showed the extent to which periods of penetration can vary according to weather conditions.

It has now been definitely established by workers in England (Dr. Rainey), and in the Soviet Union (Professor Scherbinovsky), that locust flights are linked with synoptic conditions : swarms congregate in the neighbourhood of atmospheric fronts separating warm and cold air masses. The movement of these front lines is usually accompanied by heavy rains, while the winds blow in the direction of the fronts. This, precisely, is connected with the concentration of swarms near the fronts, since swarms always move down-wind.

In winter and spring months, a polar front makes its appearance over Iran and the southern areas of central Asia separating tropical and temperate air masses. Depressions move along this front in a west to east direction.

Locust swarm flights into the U.S.S.R. are determined by the specific location of this polar front over Iran during March and April.

The situation of the polar front in December and January represents the northernmost flight limit of the wintering swarms. Later, from March to May, tracks of depressions become more northerly. According to the general synoptic situation, the depressions move either to the south of the Elburz and Turkmeno-Khorasan range, bringing rains to northern Iran, or to the north of these hills, to the Caspian Sea area and southern Turkmenia. In this latter case the front passes along the southern regions of the U.S.S.R., providing favourable conditions for the movement of swarms into the U.S.S.R.

It can be seen from synoptic charts for the last few days of March 1962 that from the 27-30 there was a mass of very warm air over eastern Iran and Afghanistan with daytime temperatures of over 25° at 850 mb over the Kerman, Seistan, Birjand areas and western Afghanistan. At the same period air temperatures over the southern regions of Turkmenia were between 20° and 25°.

On 27 March, a polar front at the surface was moving along the southern shore of the Caspian towards Sabzevar and Meshad, crossing southern Turkmenia to the north of Kushka and moving on towards Alma Ata.

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* Additional information on this locust invasion has been recorded by P.A. Levishko, in "The Desert Locust in Turkmeniyan S.S.R.", 1962, and by M.V. Stoljarov, in Russian Entomological Journal, Vol. XLIII, 1964.

On 28 March, there was little change in the position of the front, except perhaps in the Nukus area where there was a slight movement northwards.

The situation remained unchanged throughout 29 March, but on the next day there was a sharp change. By noon the front had made a substantial move to the south, forming a line approximately over Birjand, Herat, Kabul and Alma Ata. A depression was moving eastwards along the front. On 27 March, it was between the Black and Caspian Seas; on the morning of the 28th it was already east of the Caspian and south of the Aral Sea, and by 29 March it had moved on beyond Turkmenia.

This passing movement of the depression was accompanied by south and south-westerly winds blowing over southern Turkmenia and north-western Afghanistan. These winds were directly responsible for the movement of swarms into the Kushka area.

The position of the front on 28 and 29 March over southern Turkmenia was such as to permit locust penetration only into the southernmost parts of Turkmenia.

By 30 March, the front had shifted, moving towards central Iran and Afghanistan; northerly winds had begun to blow over southern Turkmenia and penetrations of locust swarms from Afghanistan came to an end.

On 16-18 April, there were a few minor penetrations from Afghanistan, but these appeared to be of a strictly local nature. Information on synoptic conditions accompanying these latter flights is not available.

CONTRIBUTIONS TO A SYNOPTIC CLIMATOLOGY OF NORTH-EAST AFRICA

by

H. Flohn

In this paper, north-east Africa is understood to be that part of the African continent which is north of the equator and east of longitude 33°E. It consists mainly of Ethiopia, Somalia, northern Kenya and of the depression of the Red Sea. For comparison, we have to consider also the western slopes and escarpments of the Arabian peninsula.

While in the summer rain belt of the Sudan - from the western coast of Africa to the Nile Basin - orographic features are only of secondary climatic importance, the climate of north-east Africa is largely controlled by mountains, high plateaux and deeply entrenched rifts and valleys. Extending from about latitudes 6°N to 17°N, the highlands of Ethiopia and Eritrea form a nearly closed escarpment looking west and mounting from 2,400 to 3,000 m, with a few isolated peaks rising from 4,200 to 4,600 metres. Its eastern extension can be followed, on the eastern side of the Ethiopian rift, right across the Somali peninsula to the vicinity of Cape Guardafui, with a steep escarpment facing north. The immense deep depression of the Red Sea extends from latitude 28° to 12°N and diverging from its southern part a system of rift valleys dissects the Ethiopian highlands from NNE to SSW, and extends far beyond the equator into the Central and East African rifts. In addition to this, narrow and winding valleys are carved in the Ethiopian highlands, the most impressive being those of the Blue Nile and Takazze rivers.

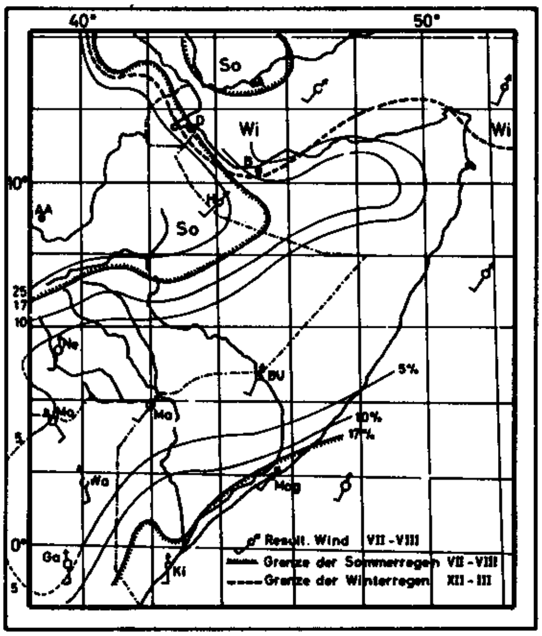


Figure 1 - Resultant noon winds and percentage of rainfall during northern summer (July-August), after [9].

These orographic features control, to a very large extent, the processes of weather and climate. In tropical and subtropical areas with low average cloudiness, the horizontal variations of radiation balance produce diurnal circulations between high plateaux and low plains, between land and sea, which may extend, with remarkable regularity, over distances of more than 200 and even up to 300 km. Only in such cases, when the large-scale flow exceeds a threshold value of (about) 10 m/s or the cloudiness is very high, can the diurnal circulation be suppressed. These diurnal circulations - sea and land breezes, valley and mountain breezes - reverse, nearly every day, between 8-10 h local time in the morning and between 18 and 20 h in the evening. During the day-time, strong winds blow from sea to land, from lower to higher elevations, converging along the escarpments and mountain crests. Here their ascending branches may be visible as stratified Stratocumulus clouds (under stable conditions) or more frequently, in a conditionally unstable atmosphere, in the form of towering Cumuli. Along both sides of broad valleys or rifts we observe these ascending branches of diurnal local wind systems, while in the centre of the rifts low-level divergence leads to subsidence.

During night-time, most local circulations are definitely weaker, but by no means less regular; they produce in the convergence zone at the bottom of broad valleys ascending components which may - in some cases - lead to local cloud systems. But in general the climatic effects of the nocturnal circulations are much less pronounced than those of the day-time systems, since above the continents the vertical lapse rate tends to be stable during night, but most unstable during the day, at least between 10 h and 16 h local time. The night-time stability limits the vertical extension of clouds and, therefore, the triggering of rain in areas of convergence; in dry air it prevents cloud formation over the ascending branches of the circulation.

It is not sufficiently known among meteorologists that in these circumstances the vegetation pattern may reflect such regular day-time circulations; along the slopes of deep valleys are horizontal belts of different vegetation types changing from desert or steppe at the bottom to lush green forests at higher altitudes. This phenomenon has been extensively described by C. Troll [24] for tropical South America, as well as by U. Schweinfurth [21] for the Himalayas. The large importance of the vegetation pattern in describing local and regional rainfall patterns has been recently stressed by Griffiths and Hemming [11] who have given a fairly detailed map of the average annual rainfall for the area under consideration using the scale 1:3 million.

Where the diurnal wind-systems interact with large-scale ("planetary") atmospheric currents, extended zones of convergence or divergence may develop. In such cases these zones shift between day and night, even on a regional scale, shown by H.W. Sansom [19] for the area between Lake Victoria and the Kenya highlands. Here the night-time convergence zone is situated at Lake Victoria, and by noon is displaced together with the accompanying cloud systems to the highlands. Obviously many hitherto unexplained local or regional climatic patterns are due to this interaction between large-scale currents and diurnal wind systems.

These diurnal circulations are also responsible for the diurnal variation of rainfall and rain frequency; while in most mountain areas afternoon showers prevail, some localities are mostly affected by night rains, produced or at least increased by converging nocturnal wind systems acting together with radiation processes at the cloud tops. Thus the diurnal cycle of rainfall amount or (better) frequency is highly significant in synoptic climatology.

During summer (June - September), when the broad westerly current [8] sweeps right across the African continent with a layer of moist air in the lowest 2 to 3 km (partly originating from the Atlantic, partly from the rain forests of the Congo Basin), the western escarpment of the Ethiopian highlands acts as an orographic barrier to the winds. The westerlies are deflected to SW or even SSW along the Nile plain and forced to descend the mountain gap at latitude 18° to 19°N which leads to Port Sudan. South of about 6°N, a much weaker branch is diverted into the broad gap of Lake Rudolph between the highlands of Ethiopia and those of northern Uganda and Kenya. Due to orographic lifting and the rapid decrease of moisture content with height, most of the water vapour is precipitated along the western fringe of the Ethiopian highlands, and the air after crossing the highlands descends at its eastern fringes desiccated by Föhn effects.

But the role of the Ethiopian highlands (including those of Eritrea and Somalia) is not restricted to this barrier effect. Although there exists no direct observational evidence, it seems reasonable to assume that the radiation budget on the high plateaux, at altitudes of 2,400 to 3,200 m, does not differ substantially from that at sea-level at the same latitude (cf. observations from the Pamir mountains, p. 248). The flux of sensible heat from the elevated surface to the air is then responsible for a weak but fairly constant horizontal temperature gradient between the heated plateau and the cooler surroundings at the same altitude. During the rainy season the large amount of orographic rain may act as a second heat source, now of latent heat released within the cloud layer mostly between 700 and 500 mb. Since the horizontal transport of heat is slow, we may assume, as a working hypothesis, that above the Ethiopian highlands a weak heat-low system is superimposed on the large-scale circulation, with low-level convergence and anticyclonic curvature in the middle troposphere. L. Weickmann Jr. has recently [25] published maps of the average sea-level pressure for January, April, July and October. Each of these maps shows a low over Ethiopia or, during July, a pressure trough across southern and eastern Ethiopia.

Due to the sparsity of reliable and regular upper-air data - Aden, Khartoum and Nairobi are much too distant - an exact numerical verification of this working hypothesis cannot be expected in the near future; for this purpose we would need an evaluation of all representative flow components averaged with respect to latitude, longitude, height and season. This hypothesis is supported by the remarkable aridity during the whole northern summer of all northern, eastern and southern flanks of the highlands, from the Red Sea lowlands and the Danakil desert to Somalia, Ogaden and northern Kenya to the area of Lake Rudolph, which strongly indicates divergent low-level flow. On the highlands, we observe during this season widespread convective rains, mainly produced by afternoon showers and concentrated along the mountain crests and escarpments. However, there is sufficient evidence [2] [15] of widespread rains during night and early morning together with rainless spells of several days apparently to indicate the occurrence of synoptic scale systems as in other parts of the tropical summer rain belt.

Along the bottom of the Ethiopian rift - as well as in other broad and deep valleys - convective rains are also rare and relatively weak. Here the rainfall map of Griffiths and Hemming [11] - as well as S.P. Jackson's Climatic Atlas of Africa [13] - show a semi-arid zone with less than 750 mm, compared with more than 1,000 or even 1,500 mm in the adjacent highlands. A typical example is given by the long record of Adamitullo on Lake Zwai with an annual average of not more than 574 mm [11, 30]. It would be of great interest to investigate - by careful mapping of the natural vegetation pattern - the occurrence of arid or semi-arid bottom sections within the gorges of the Blue Nile and other rivers as well as in the rifts running parallel in southern and south-western Ethiopia.

Of special interest is the aridity of the Lake Rudolph area (latitude 2° to 5°N). Here one would expect, during a large portion of the year, some convergence between a branch of the equatorial westerlies and the more or less meridional large-scale flow patterns in lower Kenya. During most of the year, the wind statistics of Lokitaung (4°12'S, 35°48'E) and Marsabit (2°18'S, 38°00'E) in northern Kenya [26] reveal the occurrence of up to 30 to 35 per cent westerly winds (SW-NW) during day-time, while easterly winds predominate. In contrast to this apparent convergence, the area is extremely arid (Lodwar 152 mm/year, 82 mm between March and May), with few rains during spring and fall. If we assume, parallel to the above-mentioned heat-low system of the Ethiopian highlands, a similar system over the highlands of north-east Uganda and north-west Kenya, one of the consequences would be a divergence zone (during day-time) in a zonal belt with a diameter of approximately 300 km on both sides of Lake Rudolph. This is the right order of magnitude for a double system of diurnal circulations.

During northern summer (i.e. from mid-June to early September) only one area of the latitudinal belt 0-12°N remains arid: the triangular section extending from about longitude 40°E and about 2°N to the Arabian Sea near 15°N, 65°E. This exceptional aridity of north-east Africa has been ascribed, mostly without further explanation, to the large-scale parallelism between the SW monsoon and the eastern coastline and to the well-known occurrence of up-welling cool water along this coast. Since the arid region extends much further [11, 13, 31] we have to consider [9] a combination of all possible divergence effects :

(a) Directional divergence ("diffluence") between winds from S and SSE at the southern south-eastern edge of the highlands and the large-scale SW flow above Somalia and north-eastern Kenya, as produced by the above-mentioned heat-low circulation (Figure 1). This effect is responsible for the aridity of the southern fringes of the highlands. As a consequence of this effect, we have to expect confluence (and, in fact, convergence) at the south-western fringe of the Ethiopian highlands, where all available stations [11] obtain annually more than 2,000 mm.

(b) Speed divergence within the SW monsoon, where the winds on the average increase from Beaufort 2 near the equator to Beaufort 6 near latitude 15°N, reflecting the increase of pressure gradient with latitude. This effect is responsible for the aridity of Ogaden, western Somalia and also the triangular section of the Arabian Sea;

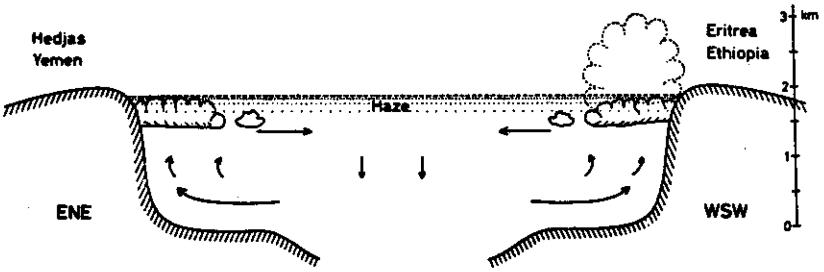
(c) Frictional stress divergence between land and sea in the area of the steady SW monsoon along the coast;

(d) Anticyclonic (off-shore) deflection of the wind-driven ocean currents with up-welling cool water.

Within the arid region of northern Somalia, the vegetation distribution [11] indicates a zone of somewhat higher summer precipitation - occurring as frequent afternoon showers and even thunderstorms - along and also south of the escarpment, approximately at latitude 9°30' to 10°N. This convergence zone has been described by H.J. Sayer [20] as part of the Inter-Tropical Convergence Zone (ITCZ). However, this interpretation is hardly consistent with the pressure and wind-field over the adjacent parts of the Indian Ocean [25]. During a personal discussion with Mr. Sayer it was concluded that this convergence zone develops between late morning and noon and apparently dissipates during the night. Here the strong steady SW monsoon converges with the regular diurnal sea-breeze from the Gulf of Aden [1] which obviously crosses the lower parts of the asymmetric escarpment and extends farther south. If this hypothesis can be supported by further evidence - especially by night or early morning wind observations in that area - we shall have to consider a phenomenon similar to the well-known Maloja wind of the Swiss Alps, where a powerful day-time local wind ascends from the Bergell, crosses the asymmetric watershed and descends slowly some 20 to 30 km down into the upper Inn valley [14]. A similar pattern has been described at Poona, where the sea-breeze from the Arabian Sea extends far beyond the Western Ghats [17].

Of special interest are the areas where two orographically strengthened sea-breezes converge, as occurs over the north-eastern tip of Somalia [15, 20], and which should also occur over the mountains of southern Yemen. Such convergences are well known and very effective over mountainous islands, like those of Indonesia. However, the effect of such local or subregional convergences on cloud formation and rainfall depends to a large extent on air-mass stability and moisture content.

In this dry belt south and east of Ethiopia - as well as in the adjacent triangular section of the Arabian Sea - *spring* and *fall rains* predominate. This is by no means unusual; the beginning and end of the summer rain period occur at the same latitudes in other parts of north Africa during the same season, i.e. in accordance with the seasonal meridional displacement of the Inter-Tropical Convergence Zone. For the same reason, Fántoli [5, 6] has ascribed the spring and fall rains of Somalia to the seasonal shift of the ITCZ; the same may be true for the spring rains of northern Kenya, although during fall only weak rains are observed here. The aridity is restricted to the summer season, as explained above.



Cross-Section of the Red Sea Trench (13-18°N)
Local Circulation (Winter)

Figure 2 - Day-time circulation at the Red Sea trench, during winter.

North of latitude 12°N we observe - over a fairly large portion of northern Ethiopia and Eritrea [2, 30] as well as over Yemen [18], Asir and Hadramaut [32] and apparently independent of the ITCZ rains of Somalia - more or less regular spring rains in March and April, which are separated from the summer rain period by a dry period in late May and June. They are known as the "*small rains*", and all available evidence [2, 12] seems to indicate that they are produced by an interaction between travelling upper troughs in the westerlies, which penetrate, during spring, not infrequently farther equatorwards than in winter, and shallow tropical disturbances steered towards the north. Such shallow low-level cyclones are frequently found during this season over the Sudan; their behaviour in connexion with upper troughs has been described by El Fandy [3]. It should be added that the rare precipitation in the centre of the Sahara belt is mainly due to such travelling upper troughs in the transitional seasons; the same is true for the few spring rains in northern Arabia. In the western Sahara south of the Atlas, cyclonic depressions develop not infrequently during spring and subsequently move towards the Mediterranean [29]. Between late August and October, similar interactions between tropical disturbances and upper troughs have been described for the southern part of Egypt [28]; in rare cases (e.g., 28 August 1944) they may even produce heavy rains (up to 40 mm) on the Nile delta.

One of the strangest climatic features are the surprisingly frequent winter rains along the slopes of the Red Sea depression between latitude 19°N and 12°N. At the coastal stations along both sides of the Red Sea we observe, during the whole winter season from October to March or April, between 9 and 25 days with rains, while in the northern belt between latitude 22°N and 28°N not more than one to three rainy days are observed. On the dissected slopes between the Ethiopian plateau and the low-level plains along the Red Sea the seasonal rainfall frequency amounts to 90 days and more (15 to 22 rainy days per month), and rainfall averages reach 1,000 mm and more and produce lush green forests [4, 7, 23]. The most conspicuous feature is the short horizontal distance between the area of heavy winter rains and the sparse summer rains of the Eritrean plateau. While at Asmara more than 90 per cent of the annual rainfall is restricted to a summer period of hardly more than 2½ months, only 20 km to the east, winter rains yield about 90 per cent of the annual amount [23]. There exists hardly any other spot, on the whole globe, where such different rainfall régimes are observed in such a short distance. It should be added that similar régimes are observed on the Sudan escarpment, near latitude 18° to 19°N [22], as well as along the eastern side of the Red Sea depression and on the "Tihama" of Yemen and Asir, where spring and summer rains on the highlands extend close to the winter rains of the slopes along the escarpment and also produce a dense vegetation [18]. These winter rains extend from about 13°N to 21° or 22°N.

The analysis of the data reveals a rather complex pattern :

(a) Tropical summer rains on the highlands of Eritrea/ Ethiopia and of Asir/Yemen are largely of convective origin within the unstable low-level westerlies, which extend during summer up to nearly 3,000 m. They are therefore largely, though not wholly, restricted to the escarpments, crests and plateaux. This is especially true on the Eritrean plateau, where the equatorial westerlies converge with the diurnal sea-breeze from the Red Sea, which is difficult to separate - with a limited number of observations - from the overlying easterly flow. Over the plateau, night-time rains connected with some synoptic-scale features, probably comparable to easterly waves [15, 2] are occasionally observed. On the bottom of the Red Sea depression the divergence of these local wind systems prevents substantial rain, with rare exceptions.

(b) Spring rains are, as mentioned above, produced in the eastern (advance) section or in the core of upper troughs of the westerly subtropical jet, frequently in interaction with low-level tropical disturbances in the Sudan. As before, these rains are to a large extent controlled by local circulations, and are therefore of comparatively minor effect at the bottom of the depression. They are relatively infrequent (one to five days a month). During winter and spring, the well-known elongated Cirro- and Altostratus streets of the subtropical jet are frequently observed above the Red Sea area. Such cloud streets also appear on some of the most impressive satellite pictures [10].

(c) Winter rains along the slopes have been suggested by C. Troll [22, 24] and others as being produced by local day-time circulations alone. In fact, observers from Asmara have confirmed the frequent occurrence of day-time Stratocumulus clouds at heights between 1,000 and 1,800 m (i.e. under an inversion situated below the height of the plateau) and frequent (and quite heavy) drizzle from these stable "warm" clouds, which are constantly driven towards the escarpment (Figure 2). In the rare case of an unstable stratification a few towering Cumuli may rise, and a few drops of rain may fall even near the airport. During night and early morning, observers at Massawa and Assab, at the bottom of the depression, not infrequently report dense low-level cloudiness with some rain, indicating the reversed nocturnal circulation. But this explanation alone is certainly incomplete, since north of 20°N winter rains are rare, and north of 22°N they are practically absent, in spite of a quite similar topography.

An investigation of the surface wind distribution along the shipping route /27/ shows that the orographical features of the Red Sea depression are responsible for the strong predominance of winds from NNW and SSE, i.e. parallel to the escarpments along both sides of the depression. From mid-September to mid-May, winds from NNW prevail in the northern section and converge somewhere with prevailing SSE winds in the southern section. While the NNW winds are deflected from the Mediterranean westerlies, the SSE winds are diverted from the low-level ENE monsoon or trade of the Arabian Sea and the Gulf of Aden. Instead of the usual subtropical divergence axis between extra-tropical westerlies and tropical easterlies, we observe here - as a consequence of orographically forced anticyclonic deflection and of a two-side channel effect - a fairly regular regional low-level convergence zone /16, 27, 33/ which is situated, on the average (Figure 3), near 19°N from October to January, and near 17°N from February to April.

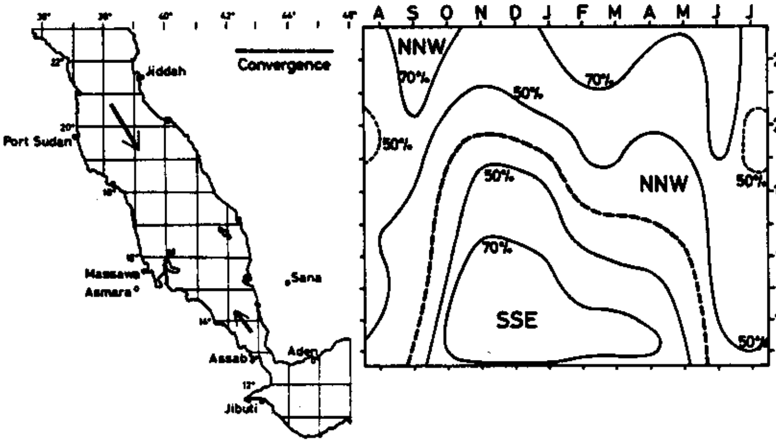

Red Sea, Prevailing Surface Winds

Figure 3 - Frequency of winds from NNW and SSE above the Red Sea; data from /27/.

In their central part, both wind systems are very steady and prevail, producing 70 to 80 per cent of all winds. Undoubtedly the position of the Red Sea convergence varies according to the synoptic situation and to the intensity (and inertia) of both wind systems. While such a regional convergence zone controls the latitude of maximum cloudiness and rain distribution, the powerful local wind systems perpendicular to these regional winds are responsible for the diurnal shift from the weak convergence at the bottom in night-time to the much stronger day-time pattern, with rainfall and clouds along the slopes. Outside of this regional convergence zone the diurnal circulations exert but a weak influence on local weather.

During summer, the low-level NNW winds are quasi-geostrophic in the northern part of the Red Sea - due to the high zonal pressure gradient between the Azores anticyclone and the Punjab heat low - and are much stronger than in winter. Driven partly by their own inertia, they extend to the Gulf of Aden. Here it is not possible to define the ITCZ which on both sides of the trench is situated near latitude 18 to 20°N, as a low-level convergence zone over the Red Sea depression. The ITCZ is interrupted by this channelled low-level system and the diurnal circulations along both escarpments, but is found again on the Arabian peninsula, where prevailing SW winds are reported from the area south of about 20°N [32], i.e. at nearly the same latitude as over north-eastern Sudan.

According to all available meteorological experience at all mountainous or coastal areas of the tropics, the role of diurnal circulations can hardly be underestimated. Due to the large diurnal radiation changes and the relatively weak large-scale atmospheric currents, they are, in tropical areas, more frequent and much more powerful than in middle latitudes. Their convergence and divergence with the large-scale wind systems control, to a large extent, the climatological patterns of precipitation and, as a consequence, the distribution of natural vegetation and agricultural land use. Many impressive observations of locust movements [16] confirm this point of view.

These preliminary and certainly incomplete contributions are based on some scattered hints in the literature, on a few impressive observations during a flight from Nairobi- Addis Ababa - Asmara - Port Sudan, but mainly on frequent discussions with a great number of meteorologists having local and regional synoptic experience. Only a few can be named here :

R.N. Coles (Addis Ababa, now Bangkok)
A. Fántoli (Rome)
J.F. Griffiths (Nairobi, now Austin, Texas)
E. Hanel (formerly Asmara)
E.R. Krueger (formerly Khartoum)
H.J. Sayer (Asmara)

Their valuable help is highly appreciated.

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COMMENTS ON A SYNOPTIC CLIMATOLOGY OF SOUTHERN ASIA

by

H. Flohn

Southern Asia consists mainly of the Indo-Pakistan subcontinent, from Peshawar and Assam to Ceylon. In order to understand its synoptic climatology, we have to include some neighbouring areas, especially the highlands of Central Asia - from Afghanistan across Tibet to Szechwan and Upper Burma - as well as Baluchistan, eastern Arabia and the northern Indian Ocean. In this review we should like to outline the principal synoptic features responsible for the weather and climate of this vast area. This is partly based on extensive, but unpublished, investigations of my collaborators since 1952, restricted to the period from May to August [6, 7], and partly on numerous reports of experienced meteorologists from India and Pakistan, which unfortunately cannot all be cited here in detail [1, 9, 12-16].

During winter - especially from mid-December to February - upper westerlies prevail at the maximum wind level near 200 mb above the whole area north of latitude 15°N and in all layers above the Punjab and Peshawar basin. But they may also even reach the southern tip of the peninsula. Below the westerlies, the well-known north-east monsoon - which may also correctly be defined as the north-east trade - is quite shallow (1 - 1.5 km) in the latitudinal belt between 22° and 30°N; its vertical depth increases towards the south above the peninsula. Due to the Föhn effect of the surrounding high mountains, this north-east monsoon consists of dry continental air, diverging and subsiding as in most trade wind areas.

Within the upper westerlies, the subtropical jet is observed nearly every day between latitude 25° and 30°N, with frequent troughs and ridges (Rossby waves), moving fairly rapidly in an easterly direction from North Africa to southern China [10, 13]. In the advance section of the troughs, where vertical stretching prevails together with upper divergence and lower convergence [14], we observe not infrequently strong convective activity, indicated at first by ac cast or ac floc, then by large towering Cumulonimbus (with strong shear in the forerunning anvil). Due to the extremely dry air, with Cumulus bases frequently situated at 4 or 5 km, a large part of the falling rain evaporates before reaching the ground but heavy gusts, thunder and lightning and, in arid regions, dust or sand storms, are no rare events. On the southern warm side of the subtropical jet, precipitation connected with these systems is in most cases only weak. In the north-west of the subcontinent, especially in northern Punjab and Baluchistan, and in the Himalayas and their foothills, these "Christmas rains" (equivalent to the Mediterranean winter rains) form a definite rainy season varying in intensity largely from year to year. They are also responsible for the high snow cover of the Hindu Kush, of the Karakorum and of the north-western Himalayas. These high precipitations are by no means reflected in the measurements of valley stations like Leh or Gilgit; here the regular occurrence of daytime upslope breezes diverging from the valley bottom prevents substantial precipitation [18]. Only on rare occasions do these winter rains extend into the peninsula, but then they may reach as far as 15°N.

The weak orographic curvature of the Himalayas seems to be responsible for the frequent occurrence of troughs near 90°E (Gulf of Bengal), where the average wind direction shifts from 280-290° in the west to about 260-270° in the east. In the northern Punjab - as well as in adjacent Afghanistan and Baluchistan - the winter rains increase in intensity (and sometimes also in frequency : six to ten days a month) during March and April, but decrease during May. In the interior mountain areas they constitute the main rainy season in spring.

During spring, the distribution of the upper westerlies is nearly the same as during winter, including the existence of the quasi-permanent Bengal trough. But the increasing solar radiation leads to the development of shallow, but persistent heat lows above the southern part of the peninsula, which gradually move to the north and eventually reach (in early June) the Punjab. On their southern side, shallow and weak westerlies - which during the last century were falsely called "sea-breezes" - with little or no effect on weather. Over the Bay of Bengal and across its northern coast, weak southerly (SW-SE) winds with moist maritime air gradually replace the dry north-east monsoon. Now the divergence aloft in front of a travelling upper trough of the subtropical jet may coincide, above north-east India, (Bengal, Assam, East Pakistan and perhaps also Upper Burma) with a shallow layer of unstable moist air, a situation which typically produces severe storms. Therefore from mid-March to May the squalls of the "Bengal Nor'-westers" increase strongly in frequency, intensity and rainfall. With this synoptic mechanism the rainy season of north-eastern India starts during spring, much earlier than the marked reversal in the upper winds.

Over the Indian Ocean, some tropical cyclones are observed, most of which can be followed from the South China Sea or the Gulf of Thailand, as they progress to the coast. Occasionally they develop into full-size tropical hurricanes with warm core and with anticyclonic flow above 200 mb. They are then steered toward the north-west or even north in the advance section of a westerly trough, and are accompanied by torrential rains and floods. Despite their rareness, they may even re-occur after a week or so and are sometimes accompanied by disastrous flood effects in the densely populated low-level area in the delta of the Ganges and Brahmaputra.

During May and the first ten days of June the seasonal warming of the air above northern India and the Himalayas weakens and finally reverses the meridional gradient of temperature and pressure in the latitudinal belt between 15° and 30°N. This results - almost simultaneously with the northward displacement of the low-level heat low - in a complete reversal of the upper winds (between about 450 and 100 mb) from west to east, in a rapid increase of the vertical depth of the equatorial westerlies, now known as the south-west monsoon, to 6-7 km and in their intrusion into the low-pressure area extending from the Pubjab to Assam and further to the east-south-east. This syndrome of nearly simultaneous events is observed, under normal conditions, during the first ten days of June; in some years it occurs already during late May, in others it may be postponed until late June. It is well-known in classical textbooks as the "burst of the monsoon". But after recognizing the lack of coincidence between rainfall distribution, thunder-storm frequency and three-dimensional wind patterns, we see that it is actually quite a difficult job to define exactly one (and only one) date for this event at a given point. The original translation of the Arabic term "mausim" means quite generally "season"; therefore this term has originally no specific meaning like "monsoon winds" or "monsoon rains". The lack of coincidence between monsoon winds and monsoon rains is responsible for frequent misinterpretations and confusion; the onset of the rainy season is controlled, in different areas, by quite different synoptic features.

This reversal of the three-dimensional wind field is accompanied or perhaps triggered by the occurrence of anticyclonic cells in the divergence zone between the high-tropospheric easterlies and the westerlies near latitude 29° or 30°N. The average position of the subtropical jet shifts to about 40°N, with a weak anticyclonic curvature on the northern fringe of the Tibetan highlands. This rapid displacement coincides with a re-arrangement of the quasi-permanent troughs (Figure 1); instead of the weak cyclonic curvature of the subtropical jet near 90°E (Bengal trough) we now observe two rather marked troughs just upstream and downstream of the Tibetan block : the Pamir trough (near 65°E) and the west Chinese (or Szechwan) trough (at 100 - 105°E).

We might remark at this point, without further explanation, that nearly simultaneously the quasi-permanent secondary trough over eastern Europe (centred around 30°E) disappears, together with a rapid decrease of the number of blocking anticyclones above north-western Europe, a consequence of Rossby's well-known stationary wave formula. This causes a marked singularity of weather in large parts of Europe, unfortunately misnamed the "European summer monsoon" [4]. Furthermore, at this time the occurrence of a quasi-stationary anticyclonic cell above the cool Okhotsk Sea together with the sharpening of the Szechwan trough is responsible for the occurrence of "Bai-U" - rains above central and northern China and Japan, mainly produced by weak cyclones running along the marked baroclinic frontal zone ("Pacific Polar Front") [19]. The difficulty in defining one (and only one) "onset" of these Bai-U-rains as well as of the Indian Monsoon is obviously one of the causes why Arakawa [2] could find no definite time correlation between both events. While these two events are certainly related in a dynamical sense to the events between Pamir and Szechwan, this is probably not the case with respect to a third event : the onset of Arizona summer rains with apparently many parallels to the simultaneous developments in the Punjab. These large-scale teleconnexions deserve a comparative investigation.

The usual distinction between an Arabian branch and a Bengal branch of the south-west monsoon is not correct. In both areas westerly winds of the lower troposphere - mostly 250-290° - converge, along a slowly displacing convergence line, with a deep current from east-south-east, which extends right up to the easterlies of the upper troposphere (Figure 3). At the southern edge of this convergence - which forms part of the main ITCZ (northern branch) and the equatorial pressure trough - isolated cyclonic disturbances frequently travel from east-south-east to west-north-west, producing much rain in their southern and western sections. To a large extent these "monsoon depressions" are responsible for the bulk of the summer rains in the interior of the Indo-Pakistan subcontinent. Their forecast depends mainly on sufficient knowledge of the rather complicated three-dimensional wind field in that area up to at least 200 mb. How far these disturbances can be followed during their earlier track from the east is not sufficiently known. But apart from these low-level cyclones, frequent strong convective rains are observed in two regions : in Bengal and Assam, where the low-tropospheric south-west flow permanently converges with the easterlies (including orographically forced lifting at the Khasia Hills), and at the steep escarpments of the western coasts of both peninsulas. But even here large variations from day to day occur, probably related to variations of $\mathrm{div}\,\mathbf{v}$.

On the average, the boundary between the extra-tropical westerlies and the easterlies above the south-west monsoon (Figure 2) is situated between 400-100 mb (7-16 km) near 30°N, i.e. just above a large part of the Himalaya mountains. At the same time the subtropical jet is situated at latitude 40-42°N, i.e. above the Tarim Basin, as revealed by the Chinese aerological network with a remarkable constancy. The boundary between both currents is marked by well-defined anticyclonic cells, frequently centred in the south-eastern portion of the Tibetan highlands. Sometimes the travelling upper troughs of the westerlies may penetrate, near 200 mb, to about latitude 26-27°N, but hardly ever farther south. If, in such a case, a low-level monsoon depression approaches from east-south-east, it can be intensified and steered into a northerly direction and eventually merge with the trough. Then torrential rains, floods and landslides are observed in the Himalayas, while the divergence of the west-south-west flow above the peninsula produces widespread subsidence and suppression of convective activity. This is at least one mechanism responsible for the well-known monsoon breaks [12, 17]. In fact, if we disregard the relatively small areas of orographically forced convective rains and of permanent convergence in the north-eastern portion of the subcontinent, we may safely say that over the largest portion of the Indo-Pakistan area the summer rains are produced by well-differentiated synoptic events, and cannot be conceived as a more or less steady climatic feature. Even the quasi-permanent anticyclonic cell above south-eastern Tibet [6, 7] can be swept away by a travelling westerly trough with a cold air outbreak across Tibet; but it recovers after two to three days, sometimes being reinforced by warm air advection.

On the other hand, the track of these shallow monsoon depressions is controlled by the upper flow, or better by integrating the wind field horizontally and vertically with respect to pressure and taking into account the well-known meridional variation of the Coriolis parameter $\beta = df/dy$. Under normal conditions they are therefore steered from east-south-east to west-north-west, only gradually diminishing in intensity and rainfall productivity, mostly as fairly symmetric vortices near the 850 mb level. Apparently lifting and (consequently) rainfall reach a maximum in their southern section; there is hardly sufficient evidence of definite air-mass differences in their area. Generally speaking, air-mass differences during the monsoon season above the subcontinent are much smaller than in middle latitudes and hardly detectable in the lower troposphere. However, in the upper troposphere we observe a remarkable baroclinic structure where the "equatorial" air above 8°N is about 8-11°C cooler than the "subtropical" air above the heat centre at 28-30°N. This reversed temperature gradient is correlated with an extremely persistent *"Tropical Easterly Jet"* [9], centred near latitude 15°N, one to two km below the tropical tropopause. This easterly jet is of a remarkable persistence from day to day [8], with only occasional fluctuations of the wind velocity ("pulses") having a duration of three to six days and varying between about 40 and more than 100 knots in the centre. These pulses are apparently correlated with the intensity and portion of the Tibetan anticyclonic cell.

Nevertheless climatic features are by no means unimportant in the large-scale *mechanism* of the *summer-monsoon rains* in southern Asia. We list only a few of them :

(a) The reversal of the temperature, pressure and wind field of the middle and upper troposphere is preceded by the gradual warming of northern India, the Tibetan highlands and the adjacent highlands. Here we have to distinguish two main sources of potential energy :

1. The flux of *sensible* heat into the air from the elevated heat source of the arid (western and central) section of the Tibetan highlands. Here all terms of the heat balance can be assumed to be nearly equal to those in the adjacent arid lowlands of Central Asia; sufficient evidence for this assumption has been presented by Zuev [20] for the Lake Karakul area of the Pamir, at an altitude of 4,000 m.
2. The release of *latent* heat from the enormous quantities of rain falling on the superhumid mountain areas of Bengal, Assam and Upper Burma, with an estimated area-averaged value of latent heat for the cloud layer of 900-1,200 Langley/d, i.e. more than the global radiation at the surface can yield. This effect has been suggested generally [5] as adding to the anticyclonic curvature of the upper westerlies along high mountain ridges; due to the rapid decrease of moisture with height it will most increase the thickness of the lower troposphere.

   The effect of the direct warming of air above the Tibetan highlands has been stressed by Flohn [3, 6, 7] and strongly supported by Murakami [11], who obtained from his computation an anticyclonic cell in south-east Tibet. However, it should not be overestimated; recent aerological data* show that the highest temperatures are restricted to the southern fringe of Tibet, i.e. above the Himalayas, and that the reversal already starts gradually during May. Certainly the early start of the summer rains in the north-eastern part of the subcontinent - much before the reversal of the wind field - and the release of latent heat during that time contribute

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* When comparing the aerological averages obtained from the Indian and the Chinese network, it should be borne in mind that there exists no direct radiosonde comparison, and that the Indian 12 GMT ascents (17-18 h local time) are certainly warmer than the Chinese 00 GMT ascents above Tibet. In such circumstances, the use of the thermal wind equation as additional evidence and check is necessary; the axis of the (subtropical) anticyclonic belt between the westerlies and easterlies above 400 mb (along about 30°N) best describes the area of the highest average temperature.

substantially to the early formation of the quasi-permanent anticyclonic cell in the same region and, consequently, to the reversal of the tropospheric wind systems.

(b) In the arid north-western part of the subcontinent (Sind, Rajasthan) the aridity is maintained even during the monsoon season, when moist air with an almost constant dew-point near 25°C sweeps across with southerly winds from the coast to the foothills of the Himalayas. Rain occurs only during a few days, when monsoon depressions travelling from the east or south penetrate this area. On all other days - i.e. during more than 90 per cent of the season - the permanent and steady monsoon flow is divergent, turning from south-west above Jodhpur and Gwalior to south-south-east above Jacobabad, and therefore subject to large-scale subsidence, reducing the vertical extension of the moist layer to about 1.5-2 km, and its cloud cover to shallow Stratocumuli. This divergence can be understood if we take into account the average position of the pressure trough with its anticyclonic curvature from eastern Arabia to the Punjab and the Indo-Gangetic plains, which forces the frictional low-level winds to diverge (Figure 3).

(c) The remarkable Föhn effect on the eastern side of the West Ghats is well-known : while near the crest of the hills the seasonal rainfall reaches 6,000 mm (Mahabaleshwar with a frequency of 29-31 days a month from June to September), we observe only 20-40 km east of the crest not more than 600-800 mm, mostly produced by a few travelling synoptic disturbances. In some of the deepest valleys of the Himalaya Mountains - even in the rainiest areas north of Assam - the valley bottom is almost arid, as demonstrated by the vegetation [18], since the diurnal (day-time) local circulations always control the pattern of vertical wind components, of clouds and rain. This is especially true in the deep meridional gorges of Upper Burma, in spite of the high cloudiness and moisture content of the air during late spring and summer below the quasi-permanent anticyclonic cell in the upper troposphere. The slight anticyclonic curvature of the lower westerlies crossing the Ghats (Figure 3) might also be related to the permanent release of latent heat.

(d) The distribution of land- and sea-breezes controls a large part of the convective activity. The frequency and extent of these diurnal circulations along all the coasts of the subcontinent deserve much more attention, together with their effect on weather and especially on the diurnal cycle of rainfall. During the season of the strong south-west monsoon, these diurnal circulations along the coast are to a large extent weakened or even suppressed. During the remaining seasons, the quasi-geostrophic flow near the surface is much weaker, the diurnal radiation cycle is more effective due to low cloudiness and the diurnal circulations are much more regular and effective than in summer.

The "retreat of the monsoon" during September and October [16] seems to be not merely a mirror of the events during the onset in early June. The large-scale reversal of the wind field is somewhat more gradual and relatively slow, but low-level cyclones still cross the peninsula and may be steered in a northward direction, causing veritable cloudbursts and severe floods. Due to the gradual shifting of their tracks, they more often have the opportunity to develop over ocean areas into full-size warm core hurricanes, notably over the Gulf of Bengal. From October to December, tropical hurricanes and other cyclones of minor intensity are fairly frequent here; they can almost certainly be tracked along their path from the east. They are responsible for the late fall rains on the east coast (and over the south-central part) of the peninsula, as well as for the rainy season on all east-facing coasts of south-east Asia. In contrast to spring, they are relatively rare (but not absent) over the Arabian Sea. Since the north-east flow itself is shallow and mostly stable, at least north of about latitude 12°N, its effect on rainfall is small. The fall rains along the east coast are also synoptic events, quite irregular (6-12 days a month) and subject to large variations from year to year.

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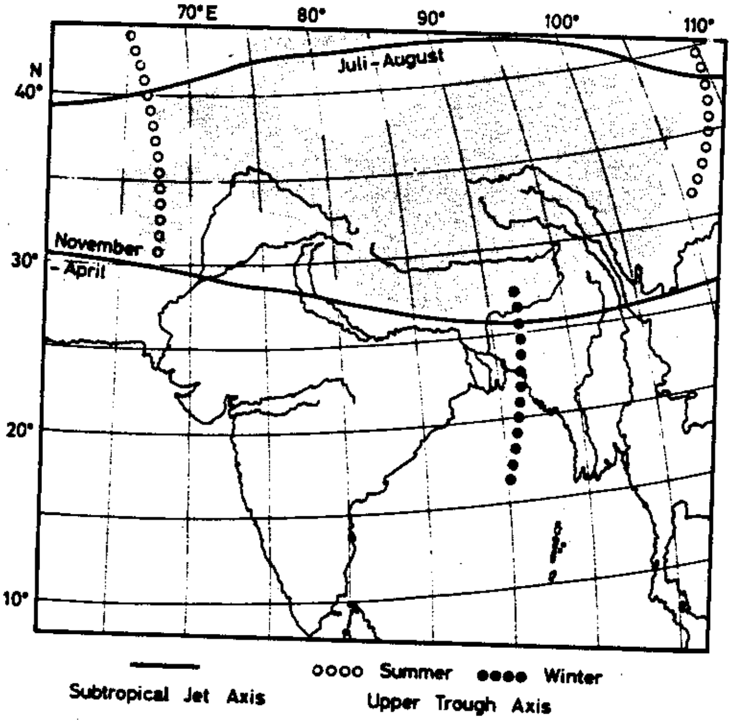

Figure 1 - Position of the subtropical jet and the quasi-permanent troughs during summer and during the other seasons.

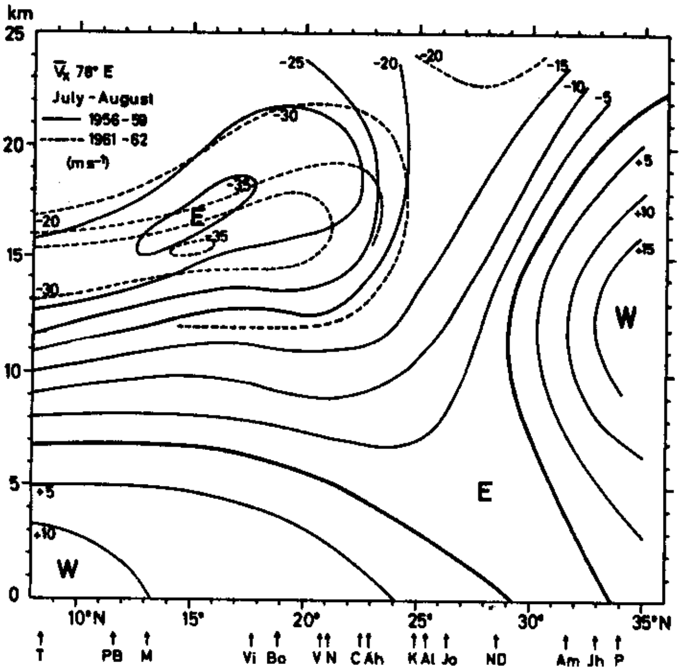

Figure 2 - Meridional cross-sections of zonal winds, during July and August, along longitude 78°E.

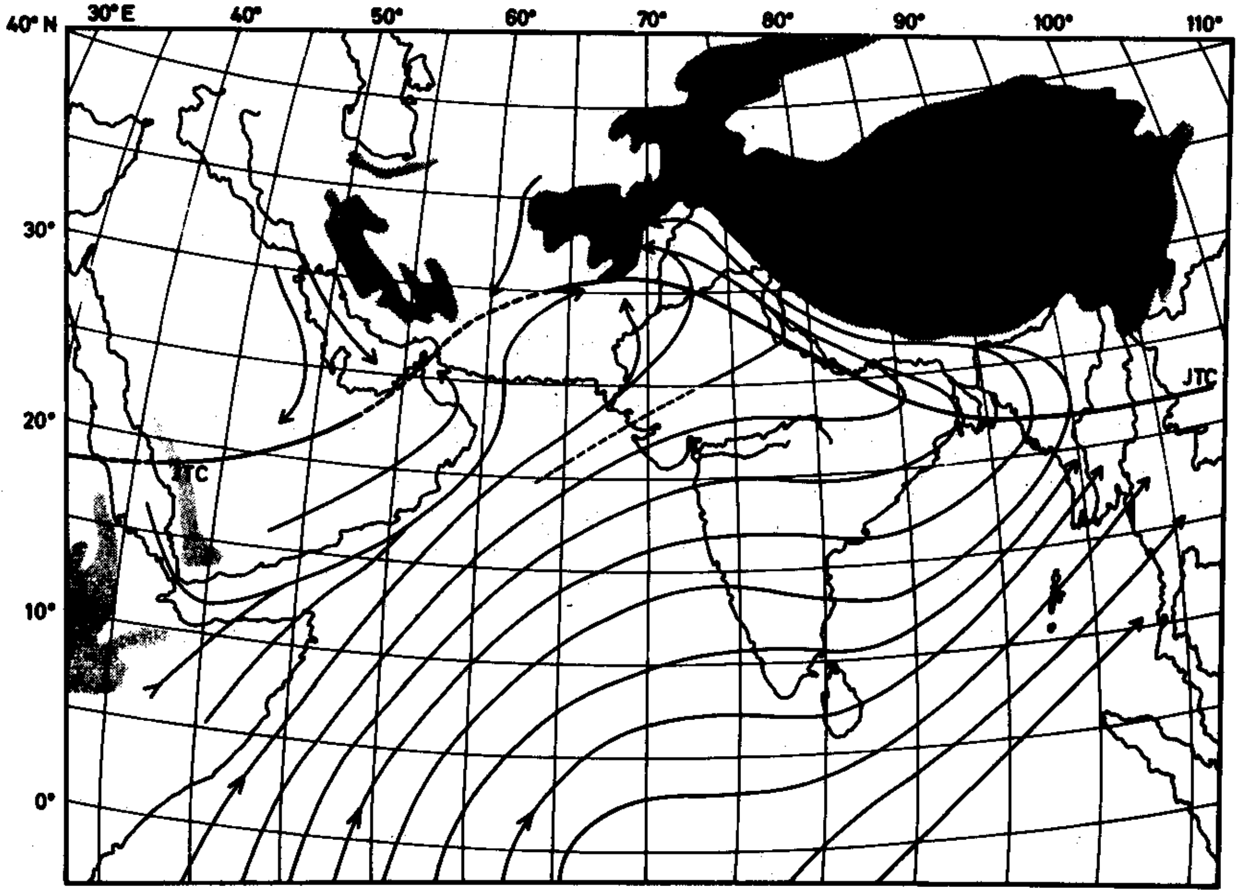

Figure 3 - Position of the monsoon pressure trough (= NITC) and resultant streamlines near 900 mb during summer.

INTER-TROPICAL CONVERGENCE ZONE AND METEOROLOGICAL EQUATOR

by

H. Flohn

The lecture given under this title was based on a lecture published in the proceedings of the Joint ICAO/WMO Seminar, Cairo - Nicosia, 1961, WMO Technical Note No. 64 - High-level forecasting for turbine-engined aircraft operations over Africa and the Middle East. (See also "African synoptic meteorology" by D.H. Johnson, in the present volume.)

NOTES ON A SYNOPTIC CLIMATOLOGY OF THE NEAR EAST

by

H. Flohn

This lecture was based on the study of agroclimatology in semi-arid and arid zones of the Near East by G. Perrin de Brichambaut and C.C. Wallén, published in WMO Technical Note No. 56, A study of agroclimatology in semi-arid and arid zones of the Near East.

SEASONAL AND LONGER-PERIOD CHANGES IN THE DESERT LOCUST SITUATION

(with a note on a tropical cyclone affecting southern Arabia in 1948)

by

R.C. Rainey

Previous lectures have dealt with the effects of meteorological factors on locusts on the meso and synoptic scales; we now approach the climatological scale, considering seasonal and longer-period changes in the Desert Locust situation over the thirty-million km^2 of its distribution area as a whole. The basic locust data are provided by the continuous record of the current locust situation which has been maintained in London, at what is now the Anti-Locust Research Centre, for the past 34 years. The special methods which have been evolved for the systematic mapping and analysis of all available locust reports, from all infested countries, are described in a subsequent lecture. The earlier results of this work, presented in a series of memoirs [3, 4, 6, 18, 19], established that areas and seasons of breeding (Figure 1) are in general areas and seasons of rainfall and indicated further that the spectacular and quasi-regular long-range migrations of the flying swarms in general have the effect of transporting the young swarms away from areas in which the seasonal rains have finished, and into new areas, commonly hundreds and often thousands of kilometres away, where the seasonal rains are beginning, and where the young swarms will in their turn mature and breed. Previous lectures, and WMO Technical Note No. 54, have presented the evidence on which the basic mechanism of these migrations is regarded as downwind displacement, towards and with zones of low-level convergence; and relevant aspects of the climatology of these areas are presented by Professor Flohn.

Besides these characteristic seasonal alternations of invasion and evacuation, shown by Desert Locust infestations of all countries, there are major longer-term changes in the overall level of infestation. Thus, for example, Dr. Esfandiari indicated to us the severity of the 1962 locust invasion of Iran, with serious crop damage reported in a number of ostans both in the north-east and the west, when swarms also reached the Soviet Union for the first time in thirty years, as Mr. Starostin described (pp. 234-235); and Mr. Mazumdar's beautiful radar photographs (Figures 2-8, pp.170-182) provide unambiguous evidence of one of the largest Desert Locust swarms ever adequately assessed, over Delhi in July 1962. Now (December 1963), on the other hand, the overall level of Desert Locust infestation is probably lower than at any time in the past 24 years. Preliminary results of an analysis of such evidence as is available on the role of natural causes and of control measures in bringing about this dramatic change in the overall situation have directed attention to several occasions (most recently in Pakistan in September - October 1962), in which an important proportion of the overall locust population appears to have been concentrated by meteorological factors into relatively limited areas in which recent developments in the techniques of control had made possible control operations which in scale and in nature are likely to have been more effective, by orders of magnitude, than any control operations undertaken in these same areas up to a few years previously [11].

However, it must immediately be emphasized that Desert Locusts have been at a very low level before (Figure 2, ref. [20]) under circumstances to which it can be shown that early attempts at locust control are unlikely to have made any appreciable contribution. The problem of establishing what are the conditions leading to a recrudescence of the plague after such a period of recession is of course of basic importance to all countries concerned. The available evidence is inevitably fragmentary, especially for the earlier years, but it has been found possible to reconstruct the outline of a coherent and potentially instructive story for the most recent of the earlier periods of plague recession.

Swarms were reported during 1948 and 1949 only in 16 and 10 territories, the lowest figures so recorded since 1940. By the end of 1948 (Figure 3), when there had been two complete months (September and November) without any report, confirmed or otherwise, of either swarms or hopper bands anywhere in the whole distribution area of the species, the plague was, at the time, believed to have died down [14] and an "interplague period" of relative inactivity of the species was thought to have begun.

In February 1949, however, swarms appeared without warning in eastern Arabia, in the Oman, and oviposited during March. The resulting hopper bands developed into a number of young swarms, which appeared in May, and a resurgence of the plague followed, both in Indo-Pakistan, where there may have been a build-up of local locust populations as well as a probable incursion from the Oman in late May, and in the Arabian peninsula, where swarms in all probability from the Oman also entered the Hadhramaut, the West Aden Protectorate and the Yemen in late May. By October 1949 an international conference of Desert Locust experts at Karachi had concluded that a new plague was developing [17].

The events of 1948 and 1949 are accordingly of particular interest in relation to the dynamics of Desert Locust plagues. The earliest indication of the locust developments in the Oman was a local report of a "loose mixed (i.e. pink and yellow) swarmlet" at Mudafin during the first week of February 1949; and a week later the explorer Wilfred Thesiger saw loose concentrations of late instar hoppers, with pink and yellow adults, in the lower reaches of Wadi al Ain. The pink colour implies young adult locusts with a history of gregarious behaviour during at least the latter part of their nymphal development, while the associated yellow adults are likely to have been survivors of the parent generation; and their colour suggests that they had spent at least part of their adult life as swarms. Temperatures in this part of the desert during the winter months were found to range from 7° to 13° at sunrise, and to reach about 27° at noon [15]. From evidence of the rates of embryonic and hopper development* recorded at roughly comparable temperatures elsewhere in the interior of Arabia (the Hail and Lina areas in the early spring of 1952 and 1953) the egg-laying which gave rise to the late instar hoppers and young adults at Wadi al Ain can be inferred to have taken place about ten weeks previously, i.e. during November 1948.

Looking back into the earlier history of 1948 for potential participants in this breeding, the first possibility is represented by a report, also by Thesiger, of numbers of scattered mature locusts, at Buraimi, in the Oman, in April 1948, following rains across the northern sands during February and March of that year.

In behaviour and in bodily proportions these locusts were in the solitary phase (see WMO Technical Note No. 54, section 1.2); and it is known, from field observations and laboratory studies, that such solitary-living locusts (either in hopper or adult stage), if brought by environmental factors to within range of mutual perception, can become conditioned to react gregariously to each other, and, if in sufficient numbers, to produce hopper bands and swarms, associated with characteristic changes in physiology, anatomy and colour. This transformation from the solitary to the gregarious phase, termed gregarization, has been found to be of very great importance in certain other species of locust, of which swarms are known to disappear entirely for years at a time. Gregarization certainly occurs, and is of obvious potential importance in the case of the Desert Locust also, although so far swarms of this species have rarely, if ever, disappeared altogether from the entire area.

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* I am indebted to Miss Z. Waloff for the use of her compilation of field records on this point.

In this particular case, it is clearly possible that the progeny of the solitary locusts seen at Buraimi in April 1948 may have participated in the breeding which took place not far away in the Ain area, six months later, although populations of Desert Locusts, even in the solitary phase, appear to be characteristically mobile [12, 21].

Much further afield, the last large-scale swarm breeding of 1948 took place between February and May in Morocco, with some breeding during this period in Mali and in the Fezzan also. In Morocco, young swarms are likely to have begun to appear by early May, and were reported in numbers, with some damage, from early June onwards, but had all disappeared from the country by late July. In other years swarms produced at this season in north-western Africa have regularly appeared to move southwards into Mauritania and Mali and often subsequently eastwards, in some years reaching as far as Sudan and possibly Eritrea by July. In 1948 swarms were reported from early June in Mauritania, later in the month in Mali, and from mid-June in the Sudan and Eritrea, after these latter territories had been clear since the previous autumn. Most of these reports referred to immature swarms (which in Eritrea first appeared during a spell of south-westerly winds) though some mature swarms were also reported, but no breeding was recorded, and the swarms had disappeared from these territories by the end of July. There were, however, newspaper reports of swarms (not necessarily of the Desert Locust) in Upper Egypt in August (there had also been a limited hopper infestation on the Mediterranean coast of Egypt in June and July); and there was a report of a swarm in the Ethiopian highlands in early October.

Meanwhile, gregarious breeding on a limited scale had also taken place during the spring on the Saudi Tihamah, together with some gregarization following solitary breeding, and leading to the formation of young swarms, of which there were a few reports in late April and at the beginning of May; no further locust activity was recorded during 1948 in Saudi Arabia until scattered solitary locusts were seen on the Tihamah towards the end of the year. Further east again, there was gregarious breeding in Pakistan, on the Baluchistan coast, in July and control operations against hopper bands in this area continued into August.

Thus only three months before the November breeding in the Oman, of which Thesiger saw the concluding stages, there had been gregarious locust populations, in the form of hopper bands large enough to justify control operations, in Baluchistan only 600 km away to the east; and between one and six months prior to the November breeding, and some two thousand kilometres to the west, there had been swarms, a number of them immature, in several different countries around the Red Sea. Between the Red Sea and Baluchistan is the Rub al Khali, at this time one of the least known parts of the whole of the earth's surface. Since Desert Locust swarms have on occasion travelled more than three thousand kilometres in a month (see, e.g. WMO Technical Note No. 54, p. 67), and can moreover live as adults for six months before breeding, it is now clear, from the locust evidence alone, that what was regarded at the time as the beginning of a new outbreak took place not so very far away, either in distance or in time by Desert Locust standards, from what had appeared to be the end of the previous plague.

Circumstantial evidence to bridge the crucial but relatively narrow gap which thus remains in the locust record has been provided by consideration of what is known of the corresponding weather. Although no systematic or instrumental records of weather exist for the interior of southern Arabia at this period, Thesiger [15], in the course of camel-journeys in this area between October 1948 and March 1949, noted that during the last week of October 1948 there were exceptionally widespread and heavy rains across the eastern sands of the Rub al Khali from the Trucial Oman almost to the Hadhramaut. The corresponding synoptic charts of the areas were accordingly examined by the writer (initially at Karachi in November 1950) for evidence of any corresponding disturbance, and it was immediately found that an exceptional tropical cyclone, which had been detected near the Maldive Islands on 19 October 1948, had reached the Arabian coast on 25 October near Salala, and subsequently affected Trucial Oman. Meanwhile, and quite independently (and without any knowledge of Thesiger's information), an account of this cyclone had been prepared in the Aden Meteorological Office [2]. Figure 3 shows the successive positions of the centre of the cyclone, as deduced at Aden from the normal routine meteorological observations made in the area, together with the information collected by Thesiger, mainly from local Bedu, on the extent of the rains of late October, which is clearly consistent with the inland track of the cyclone as inferred from the synoptic evidence.

The weather experienced along the track of the cyclone is illustrated by observations made at the aerodrome at Salala, beginning on the 23rd, two days and some 750 km ahead of the passage of the centre, with an unusual wind of 45 km/hr from the north at 16.00 (local time), a time of day at which a south-easterly sea-breeze may usually be expected. Distant lightning was noted at 22.00 that evening, and the following morning (24th) the northerly wind, still blowing at 35-55 km/hr, brought rising sand and reduced visibility to 2 km. At 11.00 intermittent drizzle began, developing by late afternoon into intermittent moderate rain, falling through a persistent thick haze which obscured the sky, and becoming heavy though still intermittent in the late evening. The following morning (25th), the persistent northerly wind, of near-gale force (55 km/hr at 10.00), which had already caused damage to local shipping and airfield buildings, abruptly died down at 11.15, though drizzle continued; at 11.20 the wind veered to the south, suddenly freshened again, "began to blow corrugated iron sheets about the camp as if they were autumn leaves", and was recorded as south-westerly 45 km/hr at 13.00, 55 km/hr at 16.00 and 80 km/hr (strong gale) at 19.00. On the morning of the 26th the wind had abated, and there were breaks in the cloud cover after 10.00 hr but further rain and drizzle fell during the day and until 05.00 on the morning of the 27th, making a total of 157 mm recorded over the four days, comprising successive daily totals of 48, 41, 43 and 24 mm; the normal total annual rainfall at Salala, averaged over a 12 year period, is 81 mm. In the hinterland the information collected by Thesiger shows that the rains extended eastwards from Wadi Qinab for some 700 km, to beyond Mughshin, where flood damage occurred. At Masira, 640 km to the north-east away from Salala and from the track of the centre of the cyclone, there was heavy rain all night on the 24/25th, totalling 19 mm and accompanied by strong easterly winds, still 45 km/hr from ENE (cf. also ship reports for extent) at 07.00 on the 25th, but recorded as veering to SSE at 08.00 hours as the rain stopped. At midday on the 26th rain was reported by an aircraft over the Gulf of Oman, extending for 400 km along 25°N, while at Sharjah, on the Trucial coast of the Persian Gulf, 19 mm were recorded on the 25/26th, and rain was again reported on the 28th. At Abu Dhabi in late October, Thesiger was "delayed by a torrential thunderstorm, which flooded a large part of the island and rendered the salt flats impassable to camels", and, en route to Buraimi on 1-4 November, noted that "the rain had formed extensive lakes on the flats among the dunes, and promised bountiful grazing in the months to come"; the rains had been experienced over an area extending from Buraimi to Sabkhat Mutti, 400 km away to the west.

The observations available in this particular case are inadequate for any quantitative investigation of the convergence involved, but some indication of the scale of these effects has, however, been provided by a series of studies [1, 7, 13] on one particular southern Indian Ocean cyclone, from the Mozambique Channel, which moved inland across Malawi, Rhodesia and Zambia between 16 and 20 February 1950, at a latitude (15°-18°S) and a speed (13-14 km/hr) closely comparable with the Arabian cyclone just described, and also giving a roughly comparable rainfall; a total of 145 mm fell in three days (13-16th) at Antonio Enes on the Mozambique coast over the period of the passage of the cyclone, followed by a well-documented average daily fall of 52 mm over an inland area of 155,000 km^2 on the 18th and 19th, with indications that precipitation of this order had persisted for four or more days. There was also considerable similarity between the wet-bulb temperatures recorded at Salala, which remained between 22° and 23° for at least 12 hours during the passage of the cyclone, and the wet-bulb potential temperatures, between 21° and 22° from the ground up to at least 7,500 m above sea-level, recorded at Salisbury in Rhodesia during the radiosonde ascent on 18 February 1950, which was regarded as representative of the inland rain-area.

It was shown that the total water-vapour content of the atmosphere at the time, as indicated by this radiosonde ascent, was equivalent to only 36 mm of liquid water; and that evaporation and transpiration were not likely to have returned more than about 5 mm of the rainfall per day to the atmosphere. In order to maintain the observed rate of precipitation, the wind-system must therefore have been such as completely to replace, once in every twenty hours or so, the whole of the air over the rain area, up to a great height; and this was shown to require a net inflow component of the wind, near the ground, of the order of 7 km/hr around the perimeter of an area 440 km in diameter. Airborne particles constrained to remain near the ground would be concentrated by such convergence, within a period of four days, by an average factor of five over an area of more than 10^5 km^2. Despite the points of resemblance between the Rhodesian disturbance and what is known of the Arabian cyclone, differences such as those between the topography of the Rhodesian plateau, at altitudes of about a thousand metres above sea-level, and that of the eastern Rub al Khali, at a hundred metres or so, must obviously limit any possible quantitative relevance of the Rhodesian finding to the Arabian case; but it may nevertheless be suggested that these findings provide at least some indication of the order of magnitude of the convergence involved on the latter occasion.

The area just considered, 440 km in diameter, represented only the central part of the Rhodesian disturbance : and, for considering possible effects of the Arabian cyclone on the distribution of locust populations, it would be of particular interest to know from how far away the inflowing air may have come. The area over which surface winds were affected by the Arabian cyclone (and from much of which it can accordingly be suggested that air and any airborne locusts may have been drawn in) extended from the Gulf of Oman to beyond the southern Red Sea, where both at Assab, in southern Eritrea, and Perim the persistent south-easterly winds characteristic of this season of the year were interrupted by an exceptional two-day spell of northerlies and north-westerlies on the 25th and 26th (Figure 4).

The meteorological evidence thus strongly supports the suggestion, from the direct locust evidence, that locusts from swarming populations in the Red Sea area and/or in Baluchistan may have participated in breeding in the eastern Rub al Khali in November 1948, in addition to any remaining local solitary population, which would, moreover, have been subjected to marked concentration at the same time; and the widespread rains will have provided extensive conditions suitable for the multiplication of all locust populations concerned. These conclusions were endorsed by an FAO panel of locust experts to which an outline of this evidence was submitted in 1956 [5].

The exceptional nature of the weather system concerned is illustrated by the fact that no more than 25 of these Arabian Sea cyclones had been traced further west than 60°E over a preceding period of about a hundred years [8]. Two of those described reached the Arabian coast during the twenty years prior to 1948; and there are indications that both may have had effects on the corresponding locust situation comparable in some respects with those recorded in 1948-1949.

Thus at the end of September 1929, a cyclone which had been detected four days previously near the Laccadive Islands reached the Arabian coast between Salala and Masira. The Desert Locust plague was widespread at that time [16]; in addition to infestations over much of Africa, young swarms were appearing in India during September, and there had been other swarms in Iran during August. Thus there may well have been locust populations available to be drawn into the cyclonic wind-system; and the possibility that there may have been undetected breeding in the unknown interior of south-eastern Arabia receives some support from the fact that flights of pink locusts were observed in the region of Muscat after an appropriate interval, at the beginning of December 1929 [9], with mature swarms in the Oman in February.

Another cyclone originated near the Laccadive Islands (or possibly further east) in November 1940, and subsequently crossed the Arabian coast to the west of Merbat (i.e. in the vicinity of Salala), after which it was believed to have recurved to the north-east and died out. Over the open sea it gave hurricane winds, estimated to have exceeded 160 km/hr, and there were very heavy rains on the Hadhramaut coast (86 mm at Mukalla on the 13th). In the summer of 1940, after several years of general recession of the Desert Locust plague, swarms had bred in Rajasthan and Sind.

Some of the resulting swarms of the next generation reached Makran in early November and, under the influence of the cyclone, again, may well have bred in the interior of south-eastern Arabia (in addition to the breeding known to have occurred in December on the Iranian coast opposite Oman), since immature swarms appeared in numbers along the Batina coast towards the end of February 1941, and were in fact said to have come from the interior. These swarms may have contributed significantly to the re-expansion of the plague which occurred in 1941.

The interpretation given for the Desert Locust history of 1948-1949, and for the part which may have been played in it by the cyclone of October 1948,* is thus consistent with such corresponding evidence as is available for earlier years.

There is no suggestion that other major recessions of the Desert Locust plague have necessarily followed a course closely comparable with the events of 1948-1949; there had been for example a considerably longer period of relative recession between 1934 and 1940 (Figure 2); and the current overall level of Desert Locust populations (late 1963) is probably lower than it was at any time during 1948-1949. Nevertheless, the history of this latter period provides grounds for hoping that synoptic meteorology and the relationships it has already shown with the distribution and movement of locust populations will continue to assist in the interpretation and forecasting of developments in the current locust situation during periods of recession as it already has during periods of major infestation.

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* These were the main grounds for the warning which was issued by the Desert Locust Information Service in June 1963 following the movement into southern Arabia of the tropical cyclone described by S.A. Mazumdar (p. 141). On this occasion, however, no locust infestation could subsequently be found in Arabia - perhaps to be regarded as indirect additional evidence of the very low level of locust populations throughout the area affected by this cyclone. A year later, a reappearance of swarms in India and West Pakistan, after a gap of some months, closely followed the movement inland of a cyclonic depression, to which the attention of the locust control organizations of India, Pakistan and Arabia had been drawn by the Desert Locust Information Service.

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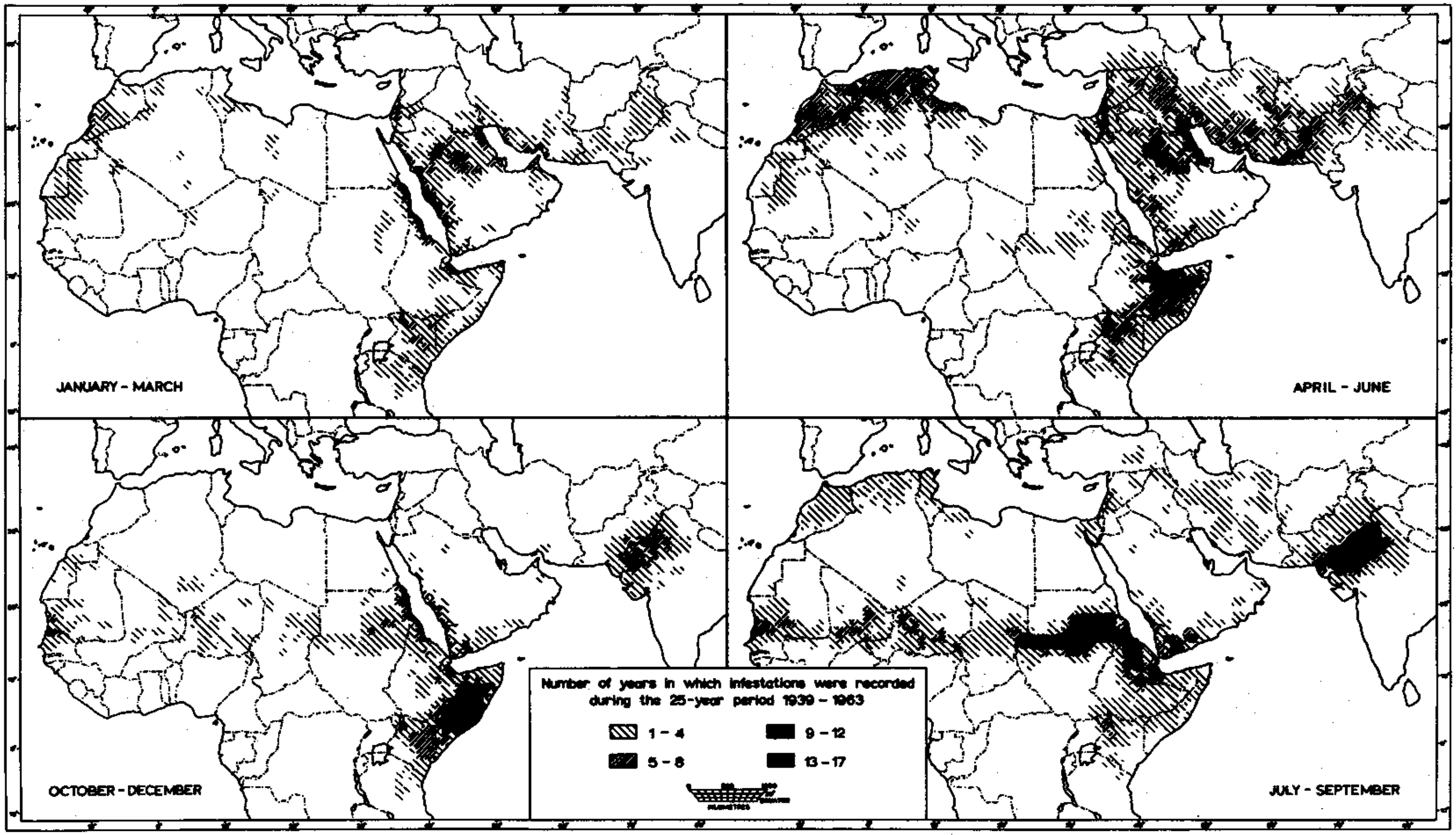


Figure 1 - Frequency of Desert Locust Hopper Band Incidence

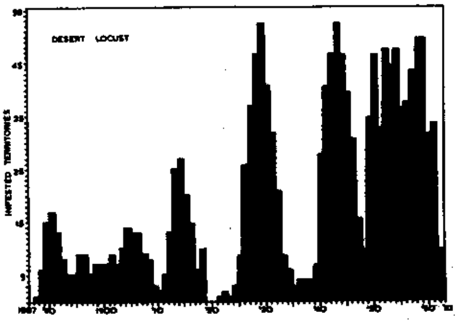


Figure 2 - Year-by-year fluctuations in areas infested by swarms.

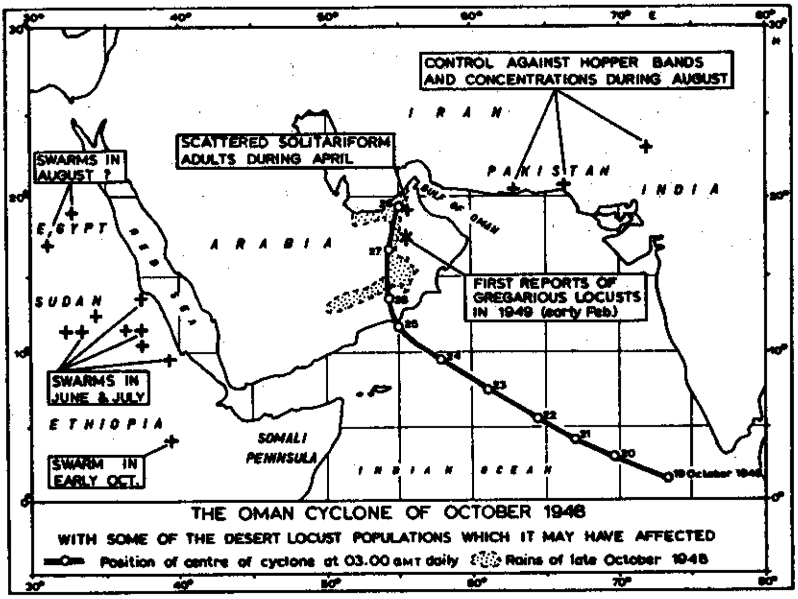


Figure 3

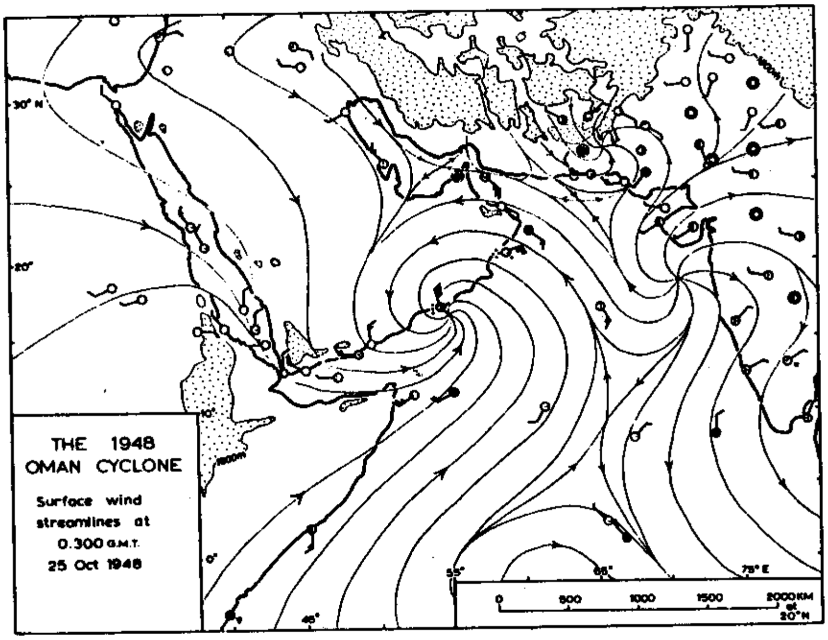


Figure 4

NOTES ON MIDDLE-SCALE MOTIONS AFFECTING LOCUST SWARMS

by

R.S. Scorer

1. THERMALS

1.1 Definition

A thermal is a mass of buoyant air rising through surroundings of lower temperature.

1.2 Origin

Thermals originate largely over places where the temperature is higher than in the neighbourhood. For example, dry areas, higher ground (also sources of heat such as fires, etc.). When there is a moderate or strong wind the situation is more complicated and no attempt is made to discuss the matter here.

When the ground temperature is rising there is a superadiabatic layer at the bottom (depth 20 to 200 m according to circumstances), then a layer of almost neutral stability up to the condensation level, and then a layer in which the lapse rate is about the wet adiabatic (Figure 1).

A portion of the superadiabatic layer begins to rise where it bulges upwards and is replaced by colder air which pinches it off below. Temporarily at least the place where the thermal originated is covered with colder air, and cannot continue to send up thermals (Figure 2).

1.3 Development

When the thermal is isolated from the superadiabatic layer, it quickly assumes the form typical of a thermal. This is shown in Figure 3. w denotes the rate of rise of the top of the thermal and the velocity distribution relative to the thermal is shown in multiples of w. The buoyant air in the thermal circulates in such a way that it all passes through the mixing region at the top in the time taken for the thermal to rise about 1½ diameters. The whole interior thus becomes diluted.

The size of the thermal increases linearly with height and so we can write

$$z = nr \qquad (1)$$

if r is the radius of the largest horizontal section and z is height from a suitable origin, which is usually at about the altitude of the ground.

The volume increases in proportion to r^3 (and is equal to $m\,r^3$). About half the air taken in is mixed in over the top surface where the thermal is turbulent and knobbly, and the other half is entrained into the base in laminar flow and passes up the middle into the mixing region from below. This is how the updraught in the middle, although ascending faster than any other part of the thermal, does not have any temperature excess over the surroundings.

The velocity w is given by

$$w = C(gBr)^{\frac{1}{2}} \tag{2}$$

where C is a constant and B is the buoyancy given by

$$B = \Delta\theta/\theta \tag{3}$$

where θ is the potential temperature in degrees absolute, and $\Delta\theta$ the mean excess inside the thermal.

Since the total buoyancy is constant

$$Br^3 = \text{constant} \tag{4}$$

and so

$$w \propto r^{-1} \propto z^{-1} \tag{5}$$

But thermals are not isolated, and are continually amalgamating with each other. The result is that the areas of updraught and downdraught remain approximately constant and the number of thermals decreases upwards. If the upward flux of buoyancy decreases with height (because the air is being warmed) then it is given by

$$Bw = A - \alpha z \tag{6}$$

where A represents the rate at which heat is leaving the gound and α the rate of warming of the air. In that case, instead of (4) we have (6), and combining it with (1) we get

$$w = C\left(g\frac{z}{n}\frac{A - \alpha z}{w}\right)^{\frac{1}{2}}$$

or

$$w \propto (Az - \alpha z^2)^{1/3} \tag{7}$$

Thus if no warming is taking place in a layer (i.e. all the heat is passing through and is warming layers above) α is zero and w increases upwards, while if the air is absorbing much of the heat $(A-\alpha z)z$ decreases as z increases, and so the updraught strength decreases upwards.

1.4 Numerical values

These formulae are not valid near to the ground before the thermals have taken on their correct shape. Above about 100 m they are usually fairly good. The numerical values are not quite the same for all thermals. In the table below useful working values are given with the range within which the values vary from one thermal to another. The mode of release is usually the cause of differences between thermals. Extreme values outside the ranges given can occasionally occur.

Quantity	Working value	Range in practice
C	1	0.7 - 2
n	4	3 - 6
m	3	2.5 - 4

These are dimensionless numbers. To compute the buoyancy or updraught within a thermal (2) may be used as in the following example :

if $g \simeq 10^3$ cm sec^{-2}, $r = 2.7 \times 10^4$ cm, $= 270$ m, $w = 3 \times 10^2$ cm sec^{-1}, $= 3$ m sec^{-1}, $\theta = 300°$K, then

$$\Delta \theta = 300 \frac{9 \times 10^4}{10^3 \times 2.7 \times 10^4} = 1°C$$

1.5 Cloudy thermals

On arriving at the condensation level a thermal becomes visible as a small Cumulus cloud. The mixing region then becomes a region where evaporation and loss of buoyancy occur, so that the material from the mixed region cannot enter the base of the thermal and is left behind as a tower of cloud below the thermal. The air circulating inside the thermal is gradually decreased until the evaporation affects it all and then it ceases to rise. To build a large cloud several thermals must rise into the same region, gradually making it damper and so reducing the rate of evaporation.

It should be noted that the environment of the clouds is stably stratified and so the air no longer inside the active part of the thermal soon arrives at its equilibrium level.

1.6 The sub-cloud inversion

By "an inversion" we mean a shallow layer in which the stability is very large. Thus an inversion is a ceiling for thermals, and is often visible as a large top or the top of a cloud layer.

Since air is rising through Cumulus bases, there is a descent of air through the condensation level somewhere. Often this descent occurs between the clouds and so stably stratified air is introduced into the layer below the condensation level. Only the most buoyant and largest thermals penetrate this layer; the smaller ones flatten out below the condensation level (Figure 4). The clouds will therefore be found over the best thermal sources only, although there will be convection up to the sub-cloud inversion elsewhere.

If the downdraughts are far away, as might be the case in a region of convergence where the upward motion is concentrated in the thermals, there will be no sub-cloud inversion. There will usually be a haze top near to the condensation level because convection will be much more widespread below this level than above it. Locusts may be carried up to the haze top even over places where there are no Cumulus and even when there are Cumulus in other places.

2. ANABATIC WINDS

Upslope winds are most strongly developed by solar heating when the air mass is stably stratified. The stratification has the effect of canalizing the heat put into the air up the slopes in a continuous stream.

Sometimes Cumulus are seen above hills in this continuous stream of thermals, but if there is a strong inversion below mountain top level, or when the convection stops at the snow-line, the air ascending the slope spreads out from the convection layer on the slope, across the low ground as a flow compensating the breeze towards the foot of the mountain (Figure 5).

By means of the complete anabatic circulation, all the air mass, although it is stable, becomes filled with pollution if there is a source of it on the valley floor. Although there are no thermals, haze spreads out over all the low ground, but locusts do not.

3. EFFECTS OF WIND

3.1 Effect on thermals

Thermals rising through wind shear are distorted and diluted more rapidly than thermals rising through calm air. But there is one interesting result of wind shear which is important : the air descending to the ground, as a thermal rises out of the superadiabatic layer, is moving faster than that layer; it therefore tends to act as a micro-cold front with the cold air descending on one side of the thermal only so that it lifts air of the superadiabatic layer of the ground on the opposite side. In this way a slowly moving source of thermals may be produced (Figure 6).

3.2 Effect on anabatic flow

Except when the wind is very strong anabatic flow may continue up a lee slope against the direction of the general wind. An eddy is thus formed on the lee side of a mountain and convergence towards the point of separation takes place (Figure 7).

3.3 Downslope wind

When the air is stably stratified very strong downslope winds are produced on the lee side and there is a likelihood that the air on the windward side may be blocked, with anabatic flow up the windward face of a mountain. Although the wind is in the same direction over the whole surface of the mountain, there may nevertheless be a barrier to the transport of locusts at the inversion (Figure 8).

3.4 Lee waves

Accompanying the strong downslope winds there is often a series of lee waves with a wavelength, typically, between 5 and 20 km. Under the crests of these waves the wind is much feebler than under the troughs so that wind measurements may not be representative. Under very strong waves there may even be rotors with a reversed wind at the surface; but it is unlikely that they will occur frequently enough to be an important factor in the aggregation of locusts (Figure 9).

4. TURBULENCE

4.1 Thermal turbulence

This kind of turbulence is composed of the motions due to many thermals interfering with one another. It is very complicated near the ground, but the main effect is to disperse airborne particles upwards, then horizontally, and finally downwards.

4.2 Mechanical turbulence

This is the motion produced when the air moves over uneven ground, buildings, trees, etc. It is very difficult to separate this motion from thermal turbulence in the air near the ground, but at higher levels it is unimportant by comparison with thermal turbulence.

4.3 Convergence effects

It is usual to think of turbulence as a mechanism which causes the dispersal or diffusion of any smoke or other particles which are in the air, and it is natural to think of it as an agent which would cause the dispersal of locusts. But there are two factors which cause the opposite result. First it must be noted that a small swarm is not broken up or dispersed by a very large eddy; it is moved along bodily by it. Secondly a very large swarm is affected to only a negligible extent by small eddies : they cause a small amount of diffusion at the edges of the swarm but have no important effect within the swarm. Therefore, the eddies which affect a swarm most are those whose size is comparable with the size of the swarm - whatever that size may be. Such eddies will tend to break up and disperse a cloud of smoke whose size is the same as the size of the swarm. But on examining the nature of the motion we observe that eddies which are important in the air near the ground can only disperse a layer of particles, which are initially near the ground, in the upwards direction. Every upcurrent must be accompanied by converging motions below, and since the locusts tend to fall down through the upcurrents they are not carried in appreciable numbers into the diverging part of the eddies. The consequence is that the eddies always have the effect of aggregating, not dispersing, swarms of locusts (Figure 10).

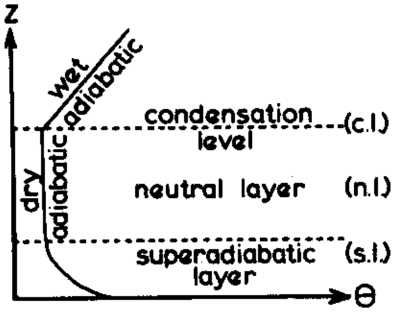


Figure 1

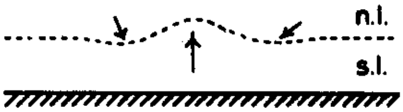


Figure 2 (i)

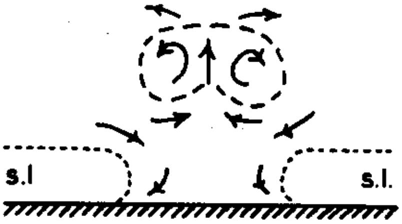
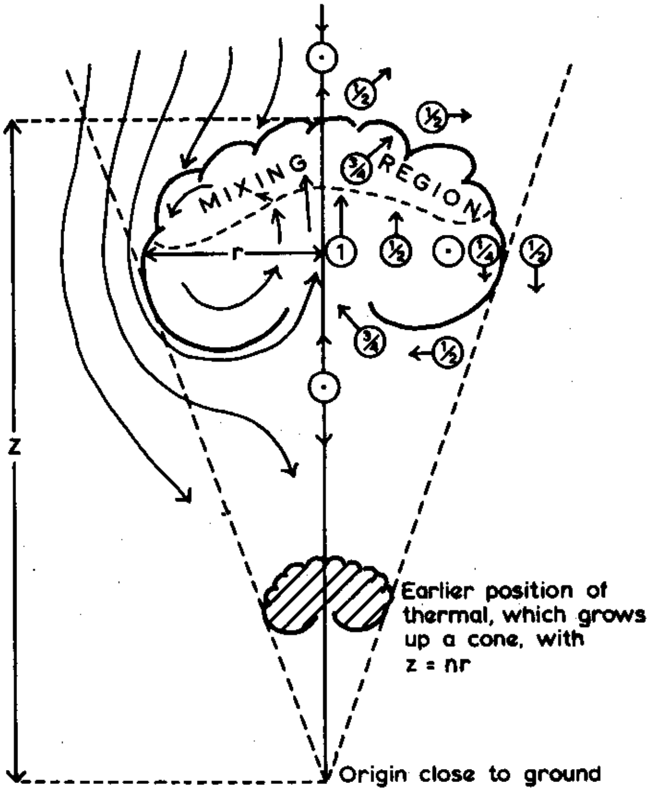


Figure 2 (ii)



Air motion relative to thermal given as multiples of rate of rise, w, of thermal top; to obtain flow pattern relative to ground an upward velocity of w must be added.

Figure 3

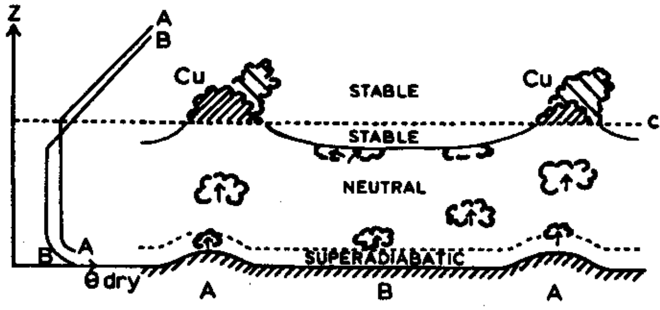


Figure 4

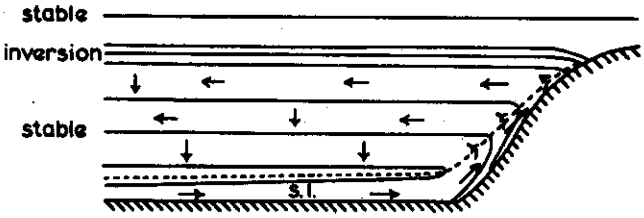


Figure 5

Figure 6

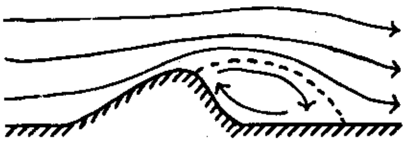


Figure 7

Figure 8

Figure 9 (i)

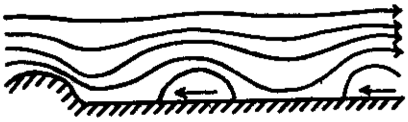


Figure 9 (ii)

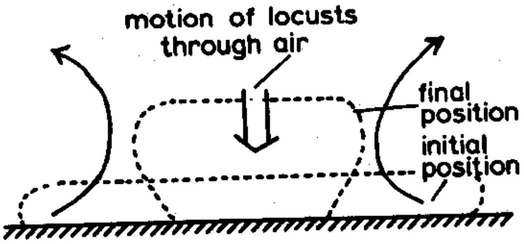


Figure 10

THE SEA BREEZE FRONT AND MOVEMENT OF LOCUST SWARMS

by

D.E. Pedgley

A flying swarm of locusts moves with the wind in which it is embedded. Consequently, a number of swarms in a given area will tend to accumulate along any line of convergence which happens to be present in the wind field over that area. Such a line of convergence restricts the movement of a swarm.

Lines of convergence occur not only on the broad synoptic scale, such as in the equatorial trough over North Africa during the northern hemisphere summer, but also on the meso-synoptic scale. An example of the latter is the sea-breeze front which develops diurnally along coastlines as a result of the differential heating of land and water. If the existing large-scale pressure pattern produces only a weak wind-flow near the coast then a well-defined boundary develops between the air flowing inland from the sea and the air already existing over the land. This is because the speed of the sea-breeze, usually some 10 to 15 knots, is greater than that of the wind over the land, so that strong convergence occurs at the leading edge of the sea air as it advances inland.

This convergence maintains large gradients of temperature and humidity at the edge of the advancing sea air, which thus takes on the character of a front - the sea-breeze front /1,2,3/. Relative humidity changes are especially well defined, a hygrograph trace showing a sudden change in slope, even though the magnitude of the humidity change may be only a few per cent. A series of hygrograph stations maintained along a line perpendicular to the coast can be very useful in determining the movement of the front /4/.

If the prevailing broad-scale, on-shore wind already exceeds some 10 to 15 knots, then the convergence is weak, and the sea-breeze front is correspondingly diffuse or non-existent. However, a sea-breeze front can also develop with off-shore general winds. If the component of this wind perpendicular to the coast is less than about 15 knots then the front is particularly well defined, but it penetrates inland only slowly, reaching a distance of perhaps 20 to 30 miles from the coast by late afternoon. During the evening, as the sea-breeze circulation dies away, the front returns towards the coast, eventually moving out to sea. But this will occur only if the off-shore wind maintains its speed. Normally this wind decreases quickly late in the day, once the night-time temperature inversion near the ground starts to develop. If there is a rapid decrease of wind speed the moist sea air can persist as a stagnant film perhaps only 30 m (100 ft) deep whilst above it the off-shore wind continues with little alteration. Where the off-shore wind component perpendicular to the coast exceeds about 15 knots, the front does not develop, or else it remains almost stationary near the coast.

It is important to realize that the front moves inland at a speed slower than the breeze itself/5/, and this seems to be especially true not only when there is an off-shore general wind but also even with on-shore winds during the mid-afternoon when the front has advanced some tens of miles inland. This is because the leading edge of the advancing air rises, once it has been heated sufficiently by contact with the land, and returns seawards relative to the front.

Whenever the prevailing wind tends to carry flying swarms out to sea, it is clear that the development of a sea-breeze front could prevent this happening. Indeed, the front is particularly effective because it is best developed during the afternoon, at just that time when locusts are most likely to be flying because of high air temperatures. Even if a swarm moves out to sea during the morning it might well return landwards later once the sea-breeze has developed.

A reverse wind circulation can develop along the coast at night when the air over the land becomes colder than that over the sea. This is the land breeze. It is generally a much weaker and shallower system, and because the necessary air temperatures are low, locusts are unlikely to be flying, so it is of little significance in determining their movement.

During the northern spring, eastward movement of swarms from Morocco and Algeria can take place along the north coast of Africa under the influence of pressure disturbances moving eastward either over the Mediterranean Sea or across southern Europe. Cold fronts of these disturbances move steadily eastward across Libya and Egypt towards the Levant. Ahead of each cold front, winds are mainly southerly, and in March to May are hot and dry - the Ghibli of Libya and the Khamsin of Egypt. Behind each cold front, winds become generally cool and moist from the north-west, although if westerly they can still be dry and warm. If the southerlies are not too strong, sea-breeze fronts develop along the coast, preventing any extensive seaward movement of swarms, which thus tend to accumulate near the coast. Their eastward movement is small ahead of the cold front, but once it has passed, the north-west winds allow eastward movement to occur. Just ahead of the front, over a belt some hundreds of miles wide, the southerlies may be too strong for a sea-breeze to form. However, swarms swept out to sea might well return if they are first lifted in the convergence zone accompanying the front and later fall back into the north-westerlies beneath the frontal surface. This fall back will occur after the locusts have been lifted to a level where the lower temperatures are unfavourable to flapping flight.

A series of disturbances, typical of this area from March to May, can thus cause considerable eastward displacement of swarms, by means of a series of pulses, perhaps crossing the whole area in a week or two.

The topography of the coastline has an important controlling effect on the sea-breeze /6,7/. Where mountains are close to the coast (as in western Cyrenaica), there is little inland penetration. Where the coast is low-lying (for example, the Gulf of Sidra), the sea-breeze should penetrate well inland, but an escarpment (as in eastern Cyrenaica) may limit this penetration. The front can reach such an escarpment even with a strong off-shore general wind if the latter develops only during the morning. In this case the hot land air rides smoothly out to sea over the top of the relatively stagnant cold film which has persisted near the coast since the previous night. Also, in regions where the coast changes direction suddenly, two sea-breezes are possible. Thus a place situated in the angle of the coast will have a breeze from that coast which is aligned closest to the direction of the off-shore broad-scale wind.

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MESURES METEOROLOGIQUES AU SOL ET EN ALTITUDE

Principes et recommandations

par

N. Gerbier

1. Un des rôles principaux du météorologiste, qui accompagne une unité aérienne de recherche opérationnelle, est d'étudier le milieu dans lequel évolue ou a évolué le "criquet pèlerin".

Il ne faut pas oublier que ce "milieu" est à trois dimensions. De ce fait, les mesures en surface doivent être complétées par des mesures aérologiques en altitude. De plus, il est indispensable de définir ces moyens en fonction de l'échelle à laquelle le météorologiste doit travailler.

Dans cet exposé, nous nous limiterons à l'échelle micrométéorologique ou échelle "locale". Il importe, en premier lieu, de choisir les appareils destinés à mesurer les différents paramètres météorologiques, à savoir : pression, température, humidité, vent.

1.1 Pression : Tant en surface qu'en altitude, l'appareil à utiliser est le baromètre. Les calculs de hauteur ou d'altitude seront faits, après le vol, en tenant compte des gradients verticaux de température et d'humidité. Au sol, on peut utiliser des baromètres très précis et sensibles. En vol, le baromètre "type avion" donne une précision de l'ordre du millibar, ce qui est suffisant pour nos mesures.

Recommandations :

i) Ne pas employer l'altimètre simple qui est trop imprécis.

ii) Ne pas oublier de brancher le baromètre sur une prise de pression statique avant le décollage.

1.2 Température : La mesure de la température est plus délicate. Elle nécessite pour nos mesures des instruments précis, sensibles et à temps de réponse rapide.

Les thermomètres à mercure, à alcool, ou à lame bimétallique ont un temps de réponse assez lent : de 30 secondes à une minute. Pour cette raison, nous leur préférons les thermomètres électriques et en particulier les "thermistances".

Certaines de ces sondes thermo-électriques sont comparables entre elles (sondes thermopiles) et ont un temps de réponse très court : une à deux secondes; grâce à une boîte de commutation, nous pouvons utiliser dix sondes à la fois, placées à des endroits ou à des niveaux différents. Deux exemples de mesures sont donnés dans la deuxième partie de cet exposé. De plus, par suite du court temps de réponse de ces sondes, il est inutile de faire des paliers lors des sondages par "avion".

La correction de température, due à la vitesse de l'avion, doit être calculée. Elle est faible pour des avions lents, de l'ordre de 0,2 à 0,3°C. Cependant, quel que soit l'instrument de mesure utilisé, il faut prendre des précautions pour mesurer les températures tant en surface qu'en altitude. Il est indispensable que les mesures soient comparables entre elles en un même lieu.

Recommandations :

i) Les sondages successifs par "avion" devront se faire à la verticale d'un même lieu, en faisant de larges spirales et en corrigeant la dérive due au vent.

ii) Tenir compte de l'état du sol et de l'heure. Ainsi en plaine, un sondage de température ne sera représentatif que s'il est effectué dans le même milieu. Eviter de couper des thermiques puissants ou appliquer des corrections, en faisant des paliers traversant les thermiques, de façon à avoir une idée exacte du gradient horizontal de température. Si non, vous verrez apparaître sur votre diagramme des inversions, isothermies, ou des gradients suradiabatiques qui ne seront pas représentatifs de la masse d'air dans laquelle vous évoluez, mais plutôt de l'entrée ou de la sortie d'un thermique, au cours du vol.

iii) En pays montagneux, si le vent est assez fort (supérieur à 15 noeuds au niveau des crêtes) et que l'air est stable, un sondage sous le vent de la montagne doit se faire obligatoirement au niveau des points d'inflexion des ondes de ressaut (vitesses verticales maximales) ou au voisinage de la ligne des vitesses verticales nulles (crêtes ou creux d'ondes) pour donner une représentation exacte de la structure verticale des "masses d'air".

iv) Pour l'étude qui nous concerne, la hauteur maximale à atteindre, lors du sondage "avion", se situe entre 2.000 et 3.000 mètres, en s'attachant plus particulièrement à la tranche 0 - 1.000 mètres.

1.3 Humidité : En surface, la mesure de l'humidité ne pose pas de problème particulier. Les instruments classiques, tels que psychromètre, hydromètre à aspiration, hygromètre enregistreur, sont satisfaisants pour ce type d'étude.

En altitude, lors des sondages par avion, c'est encore le psychromètre type "avion" qui est le plus utilisé. C'est un instrument précis à condition de laisser les températures se stabiliser, ce qui nécessite des "paliers" ou une faible vitesse propre et une vitesse ascensionnelle (au plus égale à 2 m/s) de l'avion. Il existe actuellement des hygromètres basés sur le même principe, mais avec des thermomètres à temps de réponse plus court "type hygrophyle" qui évitent cette perte de temps.

1.4 Vent

1.4.1 Vent en surface : La mesure n'offre pas de difficulté au point de vue instruments qui doivent être précis et enregistreurs (anémomètres et girouettes électriques).

Recommandations :

i) Choisir avec soin l'emplacement de la girouette et de l'anémomètre en tenant compte de la proximité des obstacles artificiels et naturels, tels que maison, hangars, rideaux d'arbres, etc.

ii) Placer ces appareils à une hauteur suffisante, par exemple deux mètres, si l'endroit est bien dégagé.

iii) Se munir d'un anémomètre à main en cas de déplacements rapides et de courte durée.

1.4.2 Vent en altitude : La mesure du vent en altitude a une grande importance dans notre étude, aussi faut-il y apporter le plus grand soin. La couche d'air que l'on doit étudier se situe entre le sol et 3.000 mètres, en apportant toute notre attention, nous le répétons, à la tranche 0 - 1.000 mètres, qui est sous l'influence directe de la couche terrestre, zone où les effets "sol" et "orographique" sont prédominants. Il en résulte que ces sondages doivent être rapprochés dans le temps et dans l'espace par suite de la variation diurne de la température, de la grande diversité du sol superficiel, du relief (effets de brises) et parfois de la proximité des côtes (brises de terre et de mer dans la couche 0 - 600 mètres). Les mesures du vent peuvent se faire depuis le sol ou en avion.

1.4.2.1 Depuis le sol : Le moyen le plus précis est le "radar". Malheureusement, son utilisation est peu commode, parfois impossible dans les régions désertiques où nous travaillons. Le théodolite est le moyen le plus pratique et le plus utilisé, cependant son emploi demande certaines précautions. En effet, l'on suppose que la vitesse ascensionnelle du ballon est constante; si cette hypothèse n'est pas mauvaise pour les sondages effectués en plaine. lorsque l'air est stable, elle est beaucoup moins bonne au cours de la journée, lorsqu'il existe de forts thermiques (convection), et s'avère fausse en pays montagneux (ascendances au vent, fortes descendances sous le vent des crêtes, courants ondulatoires et sous-ondulatoires sous le vent des chaînes de montagnes). Seuls, dans ce cas, les sondages à deux théodolites donnent des résultats satisfaisants.

Recommandations :

i) Faire les sondages à un seul théodolite en plaine avant et après la convection (matin et soirée).

ii) Employer aux autres heures deux théodolites, si possible.

iii) En pays montagneux, utiliser les fumées, fusées, le déplacement des nuages (direction et vitesse) et les mesures par avion.

1.4.2.2 Par avion : L'avion peut être équipé d'instruments classiques de navigation. Dans ce cas, il n'y a pas de difficulté. Malheureusement ce n'est pas souvent le cas pour les avions que nous utilisons, par suite de la faible dimension de ces appareils et de l'absence de moyens "sol" dans les régions où nous travaillons. Dans ce cas, l'installation à bord d'un dérivomètre est intéressante.

En l'absence de cet appareil, nous recommandons la méthode suivante :

i) Choisir un point de repère précis.

ii) Spiraler en se laissant dériver à 600 mètres au-dessus du sol.

iii) Voir au bout d'un certain temps (20 à 30 secondes par exemple) la direction prise par l'avion par rapport au point de repère initial. On obtient ainsi la direction du vent.

iv) Choisir un axe facilement repérable, parallèle à cette direction, prendre sur cet axe deux points facilement repérables et chronométrer le temps que l'on met pour aller de l'un à l'autre vent arrière, en spiralant. On obtient ainsi la vitesse du vent.

1.5 Conclusion : Un météorologiste doit obligatoirement accompagner une unité de recherche opérationnelle dans un double but :

i) Assurer la sécurité des avions, en collaboration avec le service météorologique du pays où se trouve l'unité.

ii) Etudier le milieu dans lequel évolue le criquet pèlerin (ponte, larve, adulte au sol et en vol) ou dans lequel il serait susceptible d'évoluer, en s'attachant plus particulièrement aux mesures de température et de vent, en fonction des moyens dont il dispose. Même si ces moyens sont faibles ou rudimentaires, il ne doit jamais perdre de vue que c'est de l'exactitude de la "mesure" que dépend le succès des études expérimentales futures qui seront la base de toute théorie. Le théoricien ne peut faire aucune hypothèse valable, aucun calcul, si les mesures sur lesquelles il compte sont sujettes à caution.

2. Exemples de mesures de la température en surface et en altitude

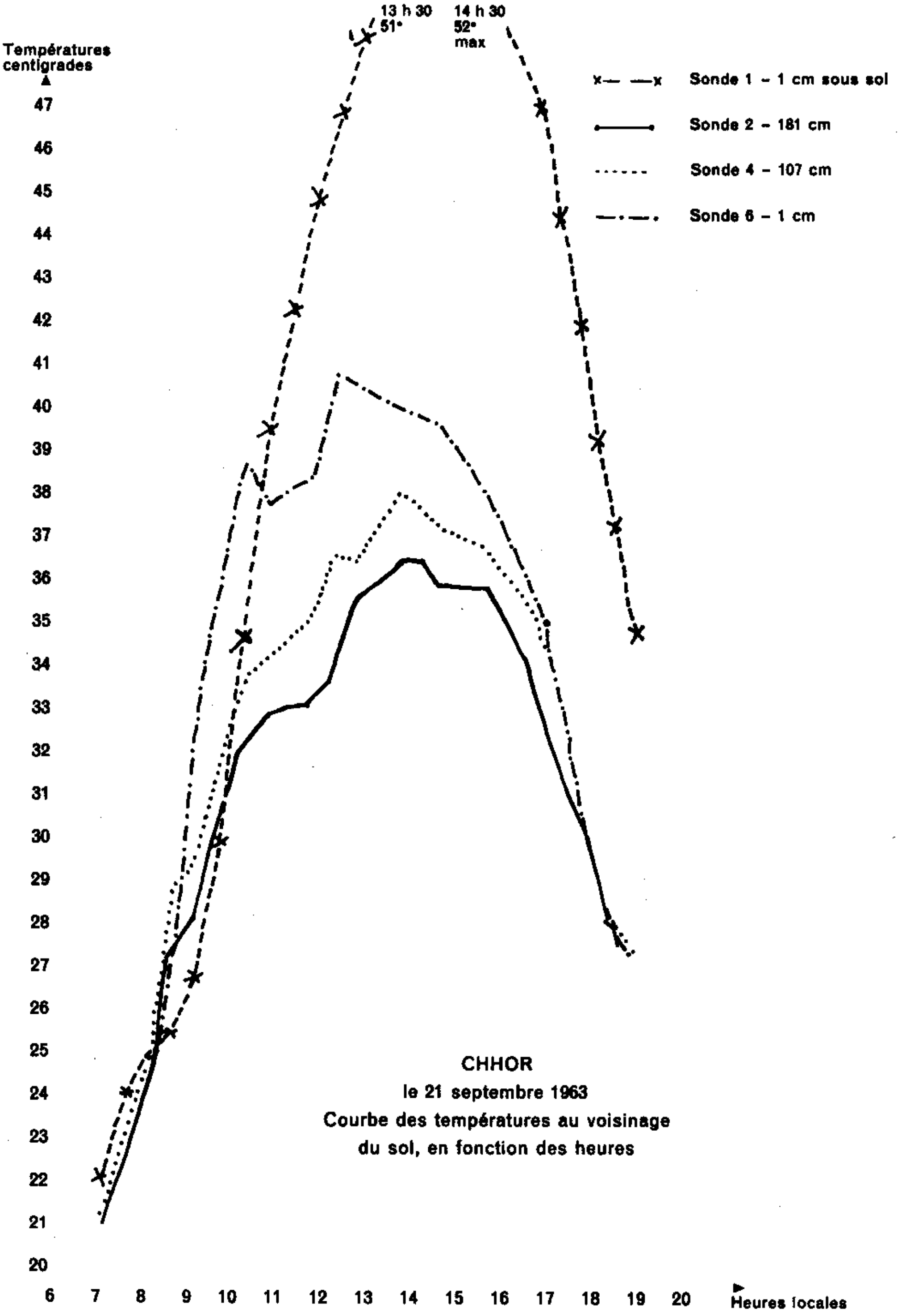
En relation avec les opérations de pulvérisations effectuées à Chhorr au courant de septembre 1963, nous présentons les diagrammes de variation de température des 21 et 22 septembre 1963 (figures 1 et 2). En comparant le diagramme moyen des vitesses de vent en surface (figure 3) et ceux des températures en fonction des heures, nous voyons une relation étroite entre stabilité au voisinage du sol et vent faible, qui détermine la période permettant la pulvérisation dans les meilleures conditions.

De même, à plus grande échelle verticale, l'analyse du sondage par avion du 22 septembre (Chhorr), par exemple, indique une évolution du gradient vertical de température entre le sol et 600 mètres, due à la variation diurne de la température (figure 4).

A 07 h 35, heure locale, le sondage A B C est stable absolu.

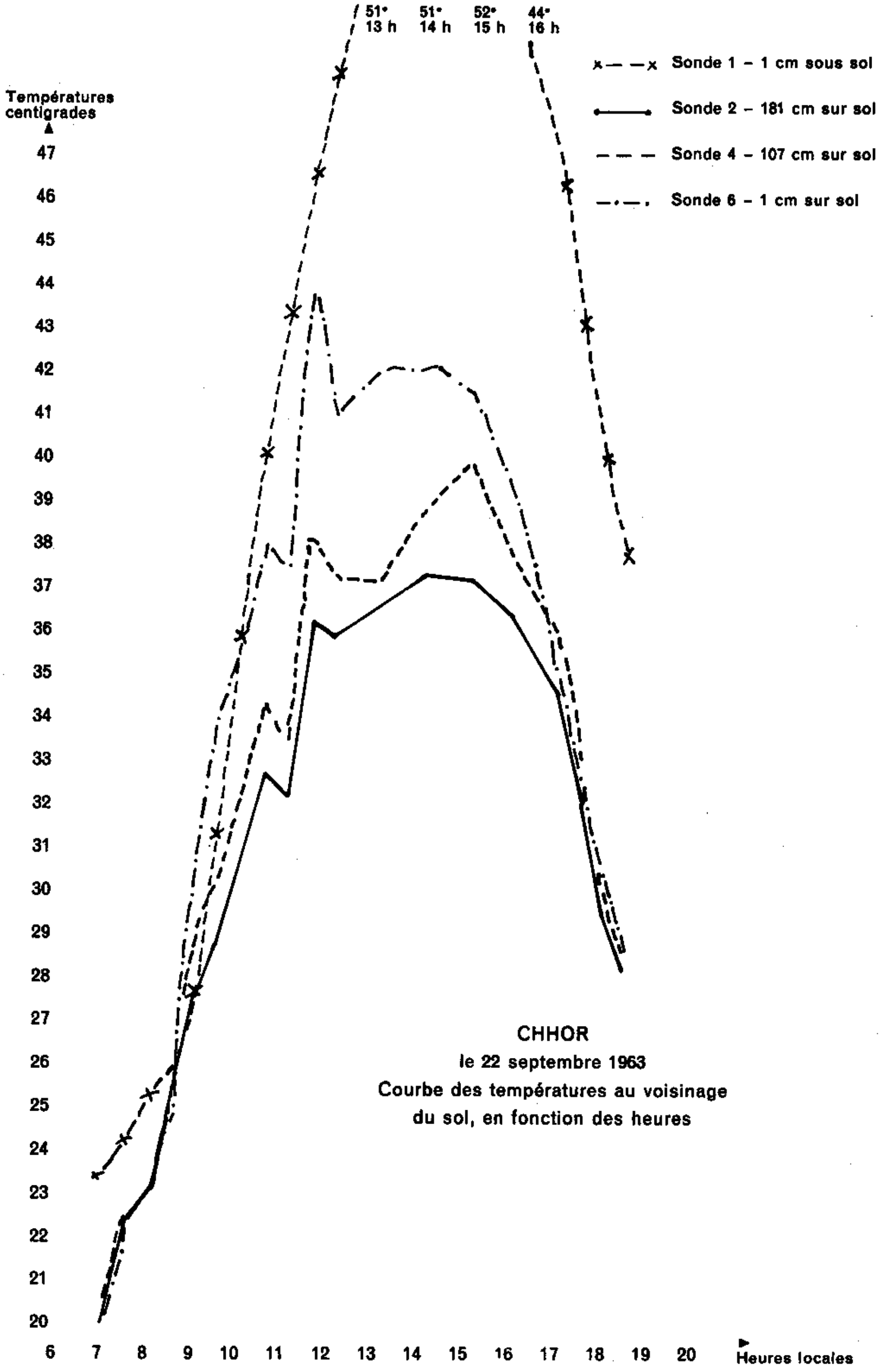
A 10 h 35, heure locale, le sondage est devenu G C (gradient adiabatique). De même, à 07 h 35, le vent était calme au sol et se renforçait rapidement dans la tranche d'air stable A B C au-dessus de 100 mètres. A 10 h 35, par suite de l'homogénéisation par brassage turbulent, le vent augmentait au sol et diminuait de 300 à 600 mètres.

Ce phénomène est classique par régime non perturbé; il faut en tenir compte pour le choix des heures et altitudes de pulvérisation.



CHHOR
le 21 septembre 1963
Courbe des températures au voisinage
du sol, en fonction des heures

Figure 1


51° 13 h
51° 14 h
52° 15 h
44° 16 h
x— —x Sonde 1 - 1 cm sous sol
Sonde 2 - 181 cm sur sol
— — — Sonde 4 - 107 cm sur sol
—·—· Sonde 6 - 1 cm sur sol
Températures centigrades
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
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24
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10
11
12
13
14
15
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20
Heures locales
CHHOR
le 22 septembre 1963
Courbe des températures au voisinage
du sol, en fonction des heures

Figure 2

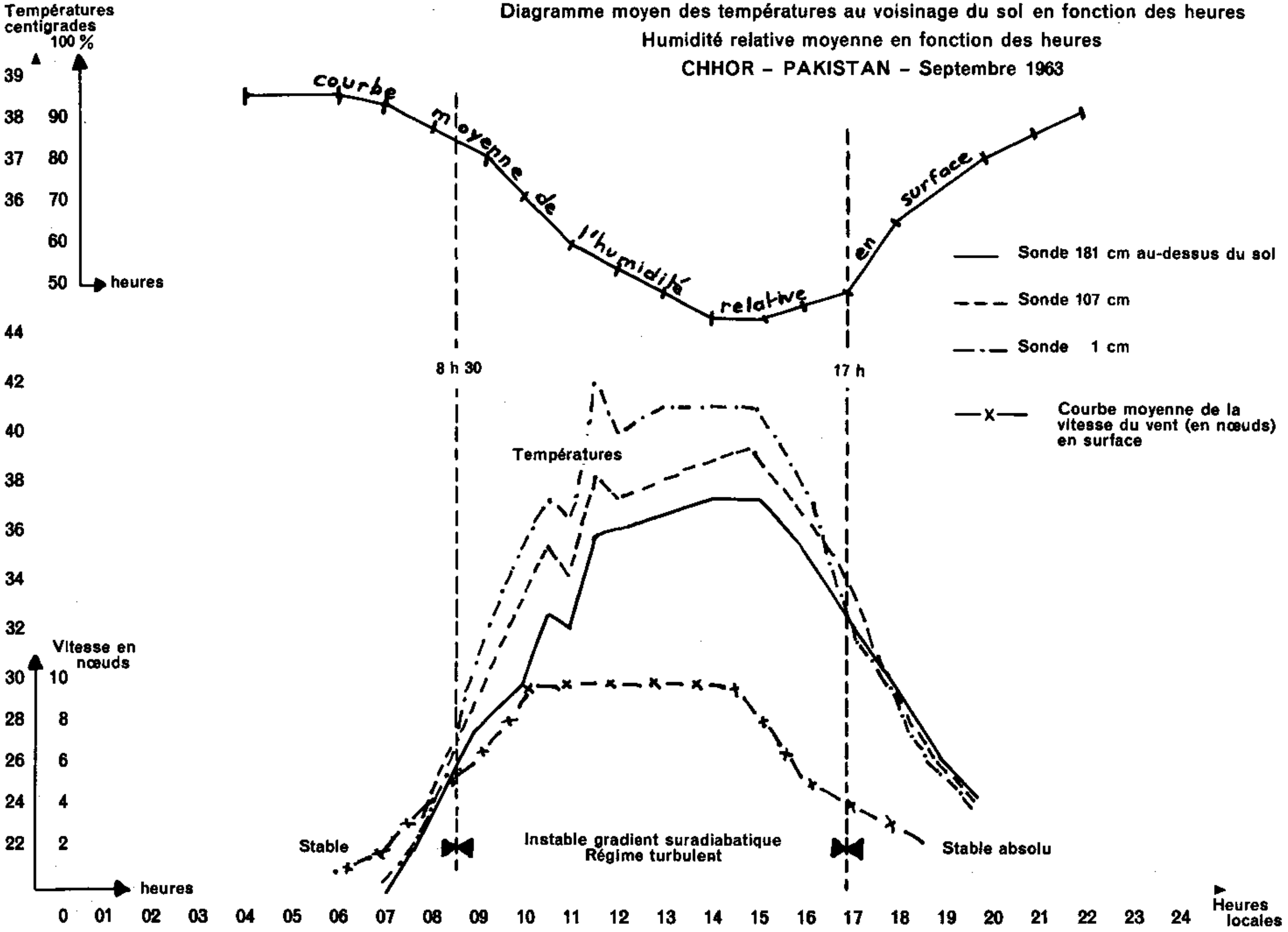
Diagramme moyen des températures au voisinage du sol en fonction des heures
Humidité relative moyenne en fonction des heures
CHHOR - PAKISTAN - Septembre 1963
Températures centigrades
100 %
39
38
37
36
90
80
70
60
50
heures
44
42
40
38
36
34
32
30
28
26
24
22
Vitesse en nœuds
10
8
6
4
2
0
heures
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Heures locales
courbe moyenne de l'humidité relative en surface
8 h 30
17 h
Sonde 181 cm au-dessus du sol
Sonde 107 cm
Sonde 1 cm
Courbe moyenne de la vitesse du vent (en nœuds) en surface
Températures
Stable
Instable gradient suradiabatique
Régime turbulent
Stable absolu

Figure 3

CHHOR
le 22 septembre 1963
Sondage de température
par avion

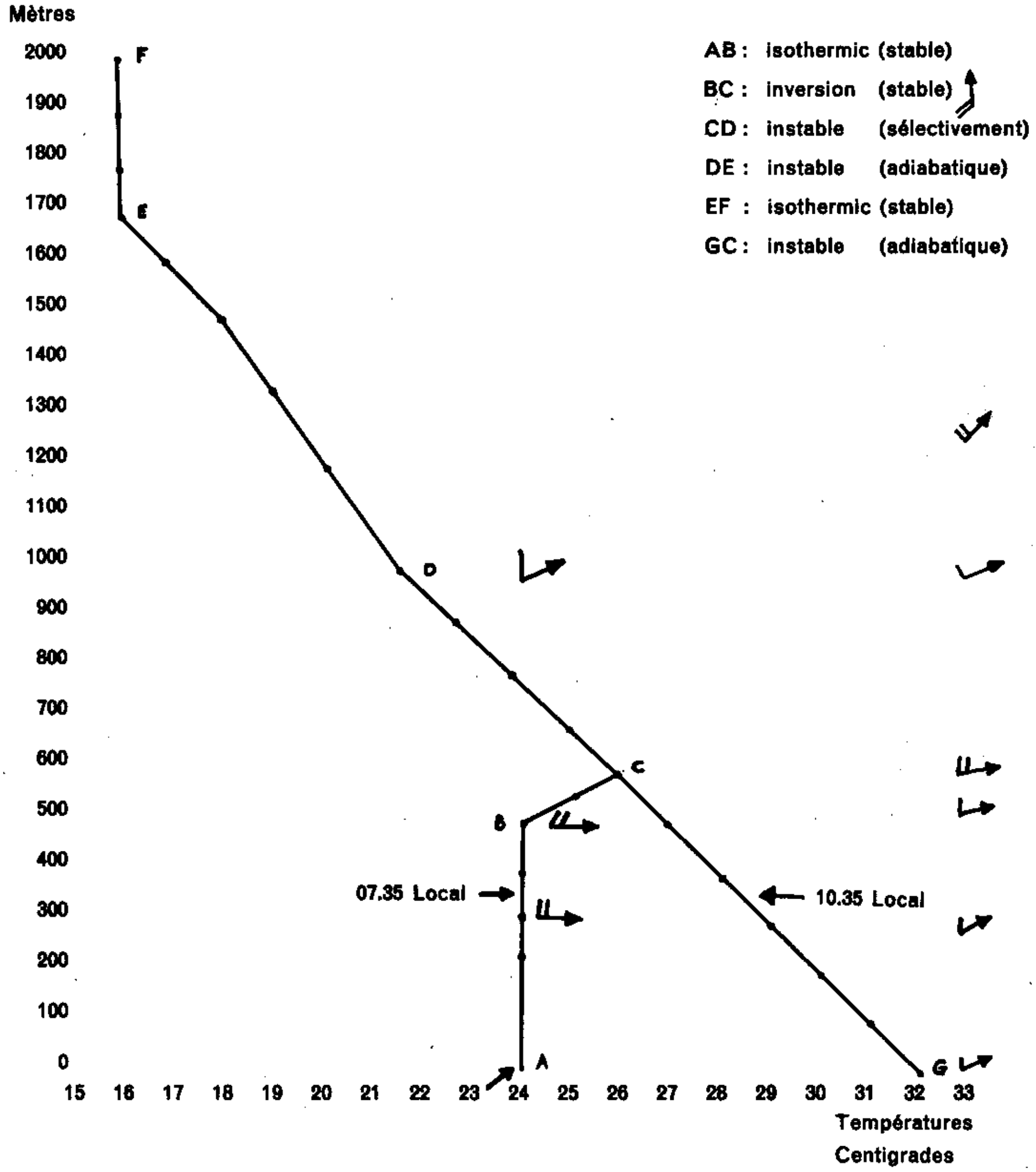

Figure 4

LOGISTICS AND STRATEGY OF DESERT LOCUST CONTROL

by

R.J.V. Joyce

1. INTRODUCTION

In the control of troublesome and harmful insects the entomologist and other scientists engaged are faced with a multitudinous variety of problems, each of which is unique. The final objective is frequently clear, though too often lost sight of. In the field of crop protection the objective is an increase in the financial return per unit of investment, whether this be money, or man or machine power. The problem then is to reduce the pest population to a level of economic insignificance and this sometimes, as in the case of some mosquitoes, tsetse fly, or for example some coffee pests, means virtual eradication. In other cases, high populations of pests are economically tolerable though it may be necessary to ensure that such high populations do not coincide in time or place with a vulnerable stage of the crop.

The Desert Locust problem differs from most others in the field of insect control in that it is not possible to define with any precision its economic significance.

Over a number of years, the average crop loss in any country from the Desert Locust is rarely large and is certainly exceeded by a considerable number of crop pests which receive very much less attention and publicity. From time to time, however, on rare, but so far unpredictable, occasions, damage of a catastrophic nature occurs which may upset national, local or domestic economy (depending on the scale of the catastrophe) in a manner comparable with other disasters such as flood and earthquake.

With regard to a pest which is always present, governments and farmers take cognizance of a possibly reduced crop yield, unfortunate, but nevertheless amenable to investigation and correction in economic terms. Locust attacks, however, may disrupt personal, local or national life in a way that it is impossible to anticipate or budget for, or even to insure against.

Broadly speaking, pests may be divided for control purposes into three categories:

(i) Pests whose control is an individual responsibility because the cost of control is recovered in increased private returns; for example, fruit-tree pests, most cotton insects, etc.

(ii) Pests whose control is a local responsibility because they breed on common land, or far from the crops they subsequently damage; for example, sunn pest, tsetse fly, etc.

(iii) Pests whose control is an international responsibility because they breed and move over wide areas so that events in one country affect rapidly events in other countries.

The Desert Locust is an outstanding example of the latter type of pest, and one of the most encouraging features of recent years is the universal acceptance of the principle of the indivisibility of the Desert Locust problem. That is to say, Desert Locust control must, in the long run, be organized over the whole invasion area because locust events in any one country very rapidly determine locust events in all other countries affected by the plague, possibly in some with catastrophic results.

In this paper, I shall attempt to enunciate the general nature of the Desert Locust problem and the required characteristics of control organized on the scale dictated by the indivisibility of the problem.

2. THE NATURE OF THE DESERT LOCUST PROBLEM

2.1 Scale

The first quantitative attempts to define the scale of the Desert Locust problem were made by R.C. Rainey [2] who estimated by photographic techniques and corpse counts following spraying, between 100 and 200 million locusts per square mile, or about 50 million locusts per km^2. Assuming each locust weighs about 2-2½ grammes, the weight of a Desert Locust swarm is thus estimated at about 100 tons of live insects per km^2. Rainey [2] describes how 50 swarms with a total area of about 500 square miles, which invaded Kenya in January 1954, were enumerated and measured by aerial reconnaissance. He calculated that the invasion represented 50,000 million or 100,000 tons of locusts. Similarly, R.J.V. Joyce [1] estimated from mortality counts that four swarms which entered the northern region of the Somali Republic at the end of July 1960 contained 16,400 million individuals, though their density, estimated later by assessments of mortality achieved by spraying, varied from 20-150 million locusts per km^2. On the average, swarms at the time of aerial reconnaissance between June and August 1960 contained about 50 million locusts per km^2 and a total of over 17,500 km^2 of such swarms were recorded in 173 sightings made during 69 daily sorties. When account was taken of the fact that many swarms had been seen on more than one occasion, the number of invaders was estimated at the order of 100,000 million locusts or nearly 200,000 tons of live insects covering at the time of reconnaissance some 2,000 km^2. Half this invasion was in the form of daily sightings of swarms covering more than 300 km^2, each consisting of more than 30,000 tons of locusts. This invasion is the largest which has been estimated and enumerated in eastern Africa, but not necessarily the largest which has occurred.

Methods of describing the magnitude of locust invasions used by other locust control organizations are so diverse that it is difficult to arrive at an objective estimate of the numbers which have been involved in operations in other parts of the Desert Locust invasion area. Consideration of the numbers of toxic doses which have been used in Morocco and have evidently resulted in the destruction of the greater part of the invading locust population suggests that operations in this country have been conducted against populations of a similar order of magnitude to those described from eastern Africa. The country which in recent years has suffered from the heaviest invasions of Desert Locusts has been Pakistan. The distribution of swarm sizes reported by the Pakistan Locust Control Department in their monthly summaries may be used to infer the size of swarm production in India and Pakistan during the summer of 1961 when so much serious crop loss was suffered, making only the assumption that this distribution is similar to that recorded in eastern Africa.

The distribution in sizes of reported swarms indicates that there was a 95 per cent chance that the total population exceeded 800 km^2 but was less than 2,500 km^2 of swarm containing about 50 million locusts per km^2. That is to say, the devastating swarms in India and Pakistan in 1961 were of the same order of locust numbers as those in eastern Africa in 1960, that is about 100,000 million locusts or about 200,000 tons of live insects.

As a first approximation then, with regard to the control of Desert Locust swarms, the control effort must be such as to be able to disperse insecticide in sufficient quantities to destroy populations of the order of 100,000 million locusts.

2.2 Mobility

The mobility of Desert Locust populations has been fully described in previous lectures and the evidence in particular supplied by Rainey [3] shows that it is the exception rather than the rule for locusts to breed less than 500 km from their place of birth. The detailed analysis of swarm movements during the period 1954/1955 studied by Rainey and Aspliden illustrates vividly how uncontrolled breeding in one country may rapidly affect other countries several hundreds or even thousands of kilometres away. It is not my purpose to enlarge upon this aspect of the mobility of the Desert Locust by giving further examples, but rather to emphasize another problem arising from mobility which must be considered in relation to the organization of control.

The size of the target which I described earlier, as measuring from time to time from between 100,000 and 600,000 hectares, would present a formidable problem in insecticide control, even if it were considered as a static area, for example, a crop which had to be sprayed in a limited period of several days or weeks. The problem of locust control, however, is further complicated by the facts :

(i) The target is highly mobile, moving 50-100 km per day;

(ii) The total invasion frequently occurs in a relatively brief space of time, sometimes in as short a period as a month but rarely longer than three months;

(iii) The swarms are unevenly distributed in time, so that very large targets may be available for only a few days followed by relatively long periods when no targets are present;

(iv) Targets are variable in size.

This problem of distribution of swarm population was investigated in eastern Africa using data collected during the large-scale invasion of the northern region of the Somali Republic between June and August 1960. The sizes of 55 swarms considered to have been measured most accurately were listed in order of ascending magnitude and the total, 12,000 km^2 was 73 per cent of the total coverage recorded. When the percentage of the total coverage contributed by each swarm size was plotted on log probability paper, the resultant curve did not differ significantly from linearity indicating a log normal distribution of swarm sizes. The median size of swarm was calculated at 50 km^2, that is 50 per cent of the swarms exceeded 50 km^2 in size. However, half the total population which invaded the Somali Republic during this period was in the form of swarms occurring in a single day covering more than 300 km^2 and these represented only 8 per cent of the total number of swarms recorded.

A similar analysis was also made of the daily occurrence of swarms of various sizes. These were found to be also log normally distributed, so that on 50 per cent of the 81 days of observation a swarm coverage of nearly 200 km^2 was sighted. A swarm coverage of more than 300 km^2, namely half the invasion, was sighted on 24 days between June and August. That is to say, there was a 30 per cent chance that half the total population of locusts might be sighted on any single day during the period. This type of distribution of locust swarms in relation to size and time has been found to be typical of invasions of eastern Africa. The implications are that if a swarm invasion of, say, 100 km^2 is expected, then in order to provide the control forces with a 95 per cent chance of destroying the invaders from a single base, it would be necessary to construct the control force so that it is able to destroy in a single day a population of at least 35 km^2. The demands on the control force are eased if the swarm invasion occurs over a prolonged period of time and displacement of swarms is slow.

2.3 Cohesion

The cohesion of Desert Locust swarms has been described by previous speakers, and theories have been put forward as to the possible mechanism by which the cohesion is maintained. It remains only to emphasize that the Desert Locust problem exists because of the cohesion of Desert Locust populations, so that the necessity to elucidate the factors which cause or assist this cohesion is one of paramount importance. Were the whole of the world's population, during the peak of a plague, postulated at something of the order of 10^{11}-10^{12} locusts, randomly distributed over the 50 million km^2 available to them, they would not constitute a pest of economic importance. Locusts become important only when they occur in swarms, under which conditions they are able to inflict characteristic catastrophic damage. It is also significant that only under these conditions of high density are the locust swarms amenable to chemical control. The identification of the conditions under which such high density is obtained provides the key to Desert Locust control. It may be said, moreover, that whatever part is played by the locusts themselves in terms of their behaviour, practical experience suggests that, by and large, highly dense targets suitable for aerial spraying are rarely recorded except under conditions of low-level wind convergence on either the meso-or synoptic scale. Moreover, though during the transition of populations from one major area of wind convergence to another the identity of these populations may not be entirely lost, swarms tend to move with extreme rapidity (as graphically displayed by the charts prepared by Rainey) and further may be of an extremely low density. The identity therefore of semi-permanent zones of wind convergence, acting as a sink where locusts may accumulate and remain for relatively long periods, provides the first necessary condition for rational control.

2.4 Multiplication

The existing data of multiplication rates was reviewed in the last report of the Desert Locust Survey, together with field data on natural mortality. It was concluded that death, especially that occurring just after hatching, has been observed so frequently in the field and in the laboratory, that it is possible that the 23 per cent of population lost to parasites and predators recorded by Stower and Greathead on the Eritrean littoral (W.J. Stower and D.J. Greathead [47]), represents a maximum survival amongst Desert Locust populations when predators and parasites are largely ineffective. The problem of control is to destroy that proportion (about 20 per cent) of the progeny not succumbing to egg-parasites, dessication, inviability and other accidents.

This survival, though small, represents a multiplication rate of between 10 and 20 times in a single generation and carries with it several important implications from the point of view of control. Of greatest importance is the fact that a population may multiply 10^2 to 10^4 in a single year, each generation being possibly separated from the next by hundreds or thousands of kilometres, so that a recession may transform to a plague in a period of 12 months.

3. THE REQUIRED CHARACTERISTICS OF A CONTROL ORGANIZATION

Having defined the nature of the Desert Locust problem it is now possible to consider the required characteristics of a control organization tailored to match the unique difficulties and opportunities which the problem presents. First the scale of the problem must be matched by an adequate striking power; secondly the mobility of the target must be matched by at least an equal mobility of the control forces; thirdly, the consequence of the concentration of locusts in certain areas of wind convergence must be matched by the ability of the control organization to mount operations of adequate concentration in such areas; and lastly, the ability of the locust to multiply at a considerable rate in successive generations dictates the need for sustained effort against each successive generation by the control organization.

3.1 Striking power

Experience over the past decade has demonstrated, vividly on some occasions, that from time to time the bulk of the world's population may be concentrated in a limited region or indeed even in one country. There have been occasions, for instance during 1960 in the northern region of the Somali Republic, when it has been possible to estimate approximately the numbers of locusts which are involved in such concentrations. On this occasion it was estimated that the population, which had largely bred on the Long Rains (April, May, June) in the Rift Valley of Ethiopia, consisted of something of the order of 10^{11} adults. This population was largely destroyed by the application of toxic doses of the order of 2×10^{12} representing some 200,000 litres of concentrated insecticide. It should be added, however, that formulations are available for applying the same number of toxic doses in an even more concentrated form so that the same result might have been achieved by the use of 50,000 litres of insecticide. Moreover, there are theoretical reasons and field data to support the view that under the circumstances where most of the insecticides have been applied to adult locusts in eastern Africa, the number of locusts killed increased geometrically with the toxicity of the insecticide. That is to say, that if x locusts are killed per litre by gamma BHC (toxicity coefficient 3×10^6 per litre) about $20x$ may be expected from diazinon (toxicity coefficient 36×10^6 per litre). As a first approximation, then, it may be suggested that the required striking power of a control organization is an ability to apply insecticide containing toxic doses of the order of about 5×10^{12} to adults, or alternatively, possibly toxic doses of the order of 3×10^{12} to adults and a similar number against hoppers. This is a scale of application of toxic doses which has hitherto rarely been achieved and effectiveness assumes no greater efficiency than has been shown to result from the application of quantities equal to almost 50 per cent of this amount.

3.2 Mobility

Rainey and Sayer have pointed out that during periods of rapid re-disposition of locust populations which occur regularly, swarms are often in so dispersed a condition as to be unsuitable as aerial targets for control. These periods of rapid re-disposition are alternated by comparatively long periods when swarms of Desert Locusts are relatively static for weeks or months in areas of persistent wind convergence. Though such areas may be widely separated in space, the general region of their occurrence is predictable. Only aircraft match the mobility of locust swarms, and only by aircraft can the necessary striking power in terms of toxic doses to be applied be achieved. It follows then that the mobility of aircraft in a control organization must be in no way impeded by administrative requirements or by problems of supply. Certain items of anti-locust equipment and supplies, such as aviation fuel, insecticide, mechanical transport, accommodation, stores, etc., cannot be transported by aircraft and must be made available on the spot. It is therefore necessary to reproduce such facilities as are only semi-mobile in areas where operations are expected, so that the aircraft and crew may arrive at any base at the speed dictated by the aircraft alone, and become operational within a few hours of arrival. This mobility can be achieved and has, in fact, been achieved in eastern Africa, where control operations on a very considerable scale have been mounted at bases separated by as much as 1,000 miles in the time necessary for the aircraft to fly between the two bases.

3.3 Concentration

Concentration effort is dictated by the log normal distribution of swarms in space and time described earlier. If the scale of probable invasion is known, and estimates of this may be made by methods described elsewhere, it is possible to select a chosen degree of chance that sufficient control potential is available at any one base, or succession of bases, to allow for the application of the required number of toxic doses to largely destroy the invaders. This concentration of control effort must take account of the fact that, for example, if a swarm invasion of, say, 100 km^2 is expected then it is necessary for control potential to be available to destroy in a single day a population of at least 35 km^2. Similar calculations may be made for swarm invasion of any other size.

3.4 Sustained effort

A Desert Locust population may breed two or three, or sometimes four times in a single year, and on each occasion has the opportunity of multiplication by 10 to 20 times. Consideration of this fact together with the evidence already referred to of natural mortality enables certain conclusions to be reached with regard to the control effort needed to reduce the population at the end of one such season to a level below that at which it started at the beginning of the season. Thus it may be shown that, in a population with multiplication rate of times 10 in a single generation, if 50 or 75 per cent of the parents are killed by control measures, it would still be necessary to destroy 85 or 80 per cent of the hoppers in the following generation to achieve a reduction of population at the end of the breeding period. Similarly, if in any year locust populations are able to breed twice and two spraying campaigns are conducted against parent swarms in which say 50 or 75 per cent of the adult locusts are killed in each, then in order to achieve the reduction of that population, 60 per cent of the hoppers must also be destroyed during each breeding cycle.

The control force must therefore be not only mobile with respect to being able to concentrate in areas where adults become quasi-stationary, but also to be able to follow the surviving adults to their breeding areas and conduct an effective and complete hopper campaign against the progeny.

This formidable task of matching the striking power, mobility and concentration of sustained effort with the scale, mobility, cohesion and reproductive capacities of the Desert Locust throughout the invasion area, which extends over more than 50 million km^2, requires a very high degree of organization, and demands the application of the most advanced scientific operational methods if it is to be brought to a successful conclusion. I will now discuss how these problems may be met and the current approach of the Desert Locust Control Organisation for East Africa to them.

4. INFORMATION AS THE BASIS OF EFFECTIVE ACTION

4.1 The nature of information required

The basic information required for the rational planning of a large-scale control operation is an estimate of the numbers in the populations to be attacked so that provision may be made to bring to bear on these populations the appropriate number of toxic doses to ensure their destruction to the chosen level. Quantitative survey of Desert Locust populations thus constitutes the basis for effective control action. It is hardly necessary to emphasize that this quantitative survey is by no means an easy task. Not only are exceptionally large areas involved, but also these areas must be surveyed in a very short time, which may be weeks or at the most a couple of months. Various means, however, are available which make survey, even on this scale, a practical proposition and these will now be discussed.

4.2 Convergence and quantitative survey

Survey for swarms of Desert Locusts which, as has been pointed out by Rainey and Sayer, may under favourable conditions often be seen from distances of up to 60 km, offers the most favourable opportunity for quantitative survey. Both these speakers, however, have emphasized the protean nature of the structure of Desert Locust swarms and the importance of high density not only in determining the swarms as suitable targets for control, but also of ensuring their visibility at a distance. Whatever may be the mechanism of swarm cohesion, it has become evident in practice that by far the best opportunities of finding locust swarms during aerial survey are under those conditions when they have been condensed into high density structures through low-level wind convergence. Such systems of convergence may be detectable on a synoptic scale, or may be determined by meso-scale phenomena, such as sea-fronts or through local topography and possibly insolation. Such areas where convergence is occurring, or may be expected, must be identified, and must constitute the main, indeed probably the sole, areas for intensive search.

It is unfortunate that the distribution area of the Desert Locust is poorly served by meteorological observation posts, and meteorological forecasters have great difficulty in determining and predicting zones of wind convergence on the synoptic scale. Recent experience in eastern Africa, where aerial survey has been concentrated in convergence zones charted by the East African Meteorological Department, has shown that even under conditions where upper-wind data are at a minimum, it is possible to obtain useful guidance from the Meteorological Services.

Aerial surveys in these general areas of wind convergence may however provide additional meteorological data which, if transmitted to the analysis centre, provide opportunities for the meteorological forecasters to improve the delimitation of areas of convergence.

A fundamental aspect of the organization of Desert Locust control should include this element of feedback, whereby the reconnaissance aircraft operating under the guidance of meteorological forecasters, collects further data so that guidance may be improved.

Analysis for and forecast of zones of convergence may also be helped by the more adequate use of local resources, such as the transmission to meteorological stations of surface wind observations by local police, and army stations equipped with radio. Sayer has already pointed out how plans to make use of these resources are well advanced in southern Arabia. More sophisticated sources are also available, such as that referred to by Rainey, of the use of satellite data on the cloud cover which is accessible to most national meteorological departments.

The control organization must of course possess adequate means of transmitting the data it has collected during its survey flights and of receiving the analysis from the meteorological analysis centre. An efficient and fully utilized radio network therefore becomes of prime importance, together with, for preference, receipt by facsimile receiver of specially prepared charts showing low-level wind convergence.

4.3 Quantitative survey for hopper populations

Quantitative survey of hopper populations is equally important to quantitative survey of swarms. This is required not only for the immediate purpose of organizing the control of hoppers, but also so as to have prior warning of the scale of swarm production in important source areas.

Though a considerable body of data exists, collected over the last decade, on the occurrence of hopper populations, little work has so far been conducted on the detailed analysis of these data. There is no doubt that the distribution of hopper populations differs in important respects in different parts of the distribution area. For example, a preliminary analysis of the data on hopper distribution in the Sudan Republic during the years 1950-1958 has revealed that some 300,000 km^2 are liable to be infested during the six to eight weeks between August and September. Though areas of high frequency breeding may be readily detected, nevertheless the distribution of infested areas is extremely scattered, so that in order to have detected 95 per cent of the infestations which were in fact reported, it would have been necessary to have searched in this limited period something of the order of 200,000 km^2. On the other hand, in the Ogaden Province of Ethiopia, infested areas tended to be far more grouped, so that not only did the discovery of a single infestation indicate a high degree of chance of the presence of other infestations in the area, but also the occurrence of an infestation at any one time implied a high degree of probability that other infestations would develop in the same area at a later date in the same season and in subsequent seasons. Such detailed investigations on the distribution of hopper infestations provide the foundation for the rational planning of quantitative survey for hoppers.

Once the form of the hopper distribution is known it is possible to construct on well-established principles of industrial sampling procedures by which a degree of probability is selected to ensure, on the one hand, that no areas infested beyond a tolerable level escape detection and, on the other hand, that no area is passed as infested which contains less than the tolerable population level. Sampling procedures used in eastern Africa based upon these considerations have enabled a rate of search for hopper bands of 2,500 km^2 per aircraft per morning to be achieved. Sampling procedures may be made even more economical by introducing sequential techniques. They may also be adopted to enable the number of hopper bands discovered in a traverse to be used to compute the total hopper population in the area.

4.4 Locust reports from other sources

In this account no mention has so far been made of the traditional sources of information on Desert Locusts, namely, from ground sources which may include scouts, police, local administration, as well as locust control teams. It is not my wish to decry the value of these reports or to discourage their transmission. These reports often provide the first indication of the presence of Desert Locusts in an area, and are particularly valuable because aerial surveys cannot be conducted all the time in all places. Nevertheless, all such ground reports must be treated with circumspection, and must be checked by aerial or ground survey before they can be translated into quantitative terms. It should be mentioned also that ground reports may frequently be erroneous and misleading and, when they emanate from non-technical sources, should carry little weight until they have been checked and confirmed.

5. UTILIZATION OF INFORMATION

5.1 Data on scattered populations

The record of a single locust seen during aerial survey is of value in the analysis of a locust situation. Aerial survey in times of recession may be planned so as to select a level of probability that the discovery of the single locust in an aerial survey indicates that the area is populated beyond a tolerable level. Conversely, such surveys indicate that where this tolerable level is not found, that is, when no locusts are discovered in surveys of appropriate intensity, the probability of population not exceeding the stated level varies inversely with that level; this calculation assumes that all significant locusts are flying and therefore are likely to be seen by aircraft, but solitary Desert Locust populations are reported not to behave in this fashion. Ground surveys alone can determine the level of such solitary populations, but it is arguable whether the limited area which can be covered by ground survey teams can increase our knowledge of the Desert Locust population to a significant extent, except at high and possibly uneconomic cost.

5.2 Data on swarm populations

Since aerial survey cannot be continuous in any one area and there is no means of determining whether any one swarm is the same as that observed on any other occasion, particularly in view of the ephemeral nature of Desert Locust swarms under such conditions as those described by Sayer, statistical techniques are required for the analysis of data collected by aerial survey on Desert Locust swarms in order to reach an objective estimate of locust numbers. Such techniques have been developed in eastern Africa, and have been shown to provide reasonably satisfactory results. They have the further advantage of providing a basis from which the effects of control of populations on locust numbers may be inferred.

As I have emphasized elsewhere, the value of quantitative survey is to enable predictions to be made of the locust numbers to be attacked so that control operations may be rationally planned, guided and adjusted. It should be the objective of the organization to plan its surveys in such a way as to enable predictions of this type to be made with the maximum possible accuracy. The data which are at present available, though of low quantitative value, in the form of hopper reports, reports of egg-laying swarms, swarm reports, information of scattered Desert Locust populations, etc., compiled by skilled or semi-skilled locust personnel, can be used with advantage to give an overall picture of Desert Locust situations in terms of the orders of magnitude of populations and population changes. For example, a method was presented to the Third Symposium organized by the Special Fund Desert Locust Project for processing the data of egg-fields reported on standard Desert Locust Information Service (D.L.I.S.) forms, so that the pattern of development of infestations could be predicted. Quantitative estimates may be made, at a later stage, using these data to interpret the significance of even a single reconnaissance flight in relation to the probable total swarm production in a source area. Again, despite very large errors in the reporting of hopper bands on the standard D.L.I.S. forms in relation to the numbers and sizes, the data may also be used quantitatively to produce further independent information on the magnitude of the Desert Locust infestation. Recent examination of the data so collected over a number of years suggests that, rather surprisingly, there is no significant difference between the mean size of hopper bands of various ages. In view of the difference in density of young compared with old instars this constancy of band size must represent natural mortality and, if substantiated, may have biological significance. Though there is considerable variability around the mean size, the data from eastern Africa giving a coefficient of variability of the order of 20 per cent, it is possible that satisfactory estimates of hopper populations may be obtained by a simple arithmetical process.

For the greatest economy of effort, control operations must be designed to reduce most efficiently the Desert Locust population to a tolerable level. This level will vary according to circumstances, and methods of calculating have still to be developed. The objective, however, implies a knowledge of :

(i) The population to be controlled,

(ii) The numbers of locusts killed by control operations,

(iii) The numbers surviving control operations.

Natural mortality will then be 1 - (2+3).

Only when Desert Locust control is constructed upon such methods involving the calculation of locust numbers and the effect of control upon them, based upon quantitative survey, can locust control be said to be effectively and economically organized.

6. ORGANIZATION OF EFFECTIVE ACTION

The calculations of the requirements of a particular Desert Locust situation, as revealed by quantitative survey, enable rational plans to be made to provide the control organization with all the supplies necessary for it to achieve the desired results, namely the reduction of the Desert Locust population to a pre-selected level of tolerance. In planning such operations the dictates of aircraft mobility must be fully borne in mind so that this important attribute can be exploited to the full. This involves the reproducibility of material and equipment which is not transportable by air and the planning and development of carefully calculated procedures for refilling supply dumps in accordance with estimated and actual consumption. These supply problems constitute an interesting field for operational research using principles already well established and proven in industry and other fields. Work along these lines has already started in eastern Africa, and estimates have been prepared of the probability of the utilization of toxic doses from selected bases during the period of time defined in terms of time required for replenishment. A similar approach may be made to the whole field of supply from the provision of vehicles, vehicle spares, tyres, aircraft etc., including the construction and use of airfields, placing the whole of the operation on a strictly scientific basis.

7. FUTURE DEVELOPMENTS

A rudimentary beginning only has yet been made on the organization of Desert Locust control along scientific lines. Even the superficial examination of the problem that has been given in this lecture reveals at once glaring deficiencies and omissions which it should be the object of urgent research to correct. I will now briefly refer to some of the developments which are considered by the Desert Locust Control Organization (DLCO) to be of the greatest immediate importance.

7.1 Quantitative data on wind convergence

The work described by Cochemé is of the greatest importance in demonstrating how quantitative studies of wind convergence may provide predictions on where there have been adequate concentrating factors to transform a scattered Desert Locust population into one of suitable density to become at once of economic importance and a target for control. Though in many parts of the Desert Locust distribution area it is difficult to foresee a time when sufficient coverage can be provided for wind data to enable quantitative estimates of convergence to be achieved, it is necessary and desirable to plan in the direction of increasing such observations. This can be accomplished at the national level, once administrators can be convinced that the understanding of the weather processes in their country is of fundamental importance to its economy. There are, however, many areas where the cost of maintaining permanent meteorological stations would be prohibitive in view of the lack of opportunities for agricultural or industrial development. Such areas include much of southern Arabia and much of the southern Sahara which are of profound importance in locust ecology. Nevertheless, meteorological data from these areas would be of tremendous value not only in the control of the Desert Locust but also in identifying areas of convergence which, I understand, meteorologists now consider to be the key to forecasting rainfall in the tropics. Efforts should therefore be made to encourage the development of long-range meteorological flights by fully instrumented aircraft in areas which are inadequately covered by ground stations. Such flights, perhaps organized under the auspices of WMO and FAO, would provide data which could be broadcast to all countries for inclusion on the synoptic charts issued by central forecasting services. Desert Locust control organizations should be prepared to make their contributions to the cost of conducting such surveys, though it would be unfair to expect the whole of the expenditure for this purpose to fall on such organizations.

For these data to be of maximum use to Desert Locust control as well as to the central forecasting offices, it would be highly desirable for them to be subjected to quantitative analysis so that the amount of convergence occurring in any area may be known from day to day. Such procedures would, I am told, require advanced electrical computing equipment, and it is desirable that plans be made at an early stage for the installation of such equipment at an appropriate meteorological department, or university, in the tropics. Access by locust control organizations to the data provided by such quantitative analysis must of course be assured, and the organization of Desert Locust control must take into account the need for financial contribution to such a valuable source of information to provide guidance in their surveys.

7.2 Quantitative surveys for locust infestations

Long-range survey for Desert Locust swarms is at present handicapped by the difficulties of sizing swarms seen at a distance. In short-range surveys this difficulty may be surmounted by the survey aircraft diverting from its course and measuring the swarm size by the appropriate traverses. This is the procedure adopted in eastern Africa, and no doubt elsewhere. Long-range aircraft, however, cannot with safety divert in this way from their flight plan, and such survey would have enhanced value if sizing of swarms could be achieved automatically. Feasibility studies on the use of radar for swarm detection have been made by the Anti-Locust Research Centre, London, in collaboration with Sayer, and it would appear that suitable radar already exists which can be expected to give recognizable echoes from even low-density swarms at distances up to 50 km. The major problem at the moment is to acquire and fit such radar to a suitable aircraft, the aircraft at present available for locust control probably being too small and having insufficient electrical generating capacity, and to acquire field experience in its use. It is very much to be hoped that the United States, who through its Regional Insect Control Project has given such notable help in Desert Locust control, can be persuaded to assist in this important work.

Similarly, quantitative survey for hopper bands is now limited by the short period of time when hopper bands are visible to an airborne observer. This is due to the habits of the hoppers in relation to temperature, vegetation and other dispersing factors in the environment. When hoppers are grouped together, such as when basking under bushes in the early hours of the morning, all instars are clearly visible in thick bush as well as amongst scattered vegetation. This period of basking may however be brief and when marching begins, hoppers, though present in large numbers, may be invisible from the air. In an age where, in Mr. Kruschev's words, guided missiles may shoot down a fly in space, it is surely not beyond the ingenuity of mankind to devise a means by which hopper bands may be automatically recorded by electronic devices fitted to survey aircraft. This problem has been put to the Anti-Locust Research Centre, London, as well as to the United States Department of Agriculture, Washington, and both authorities tend to agree that methods based upon detection of infra-red radiations from locusts are worth investigating. The project must be regarded as long-term and an expensive one, but should be given the greatest possible encouragement by FAO and other locust control organizations throughout the distribution area.

One of the most glaring deficiencies in quantitative survey is an objective measure of swarm density. So far, the methods used to determine this important parameter have been based upon vertical photographs taken by ground observers or by spraying swarms to destruction and counting corpses. What is needed for quantitative survey as well as for efficiency in control is an objective measure of the variability of density within a swarm in flight, and preferably at different levels in the swarm. In eastern Africa attempts are being made to develop a device, suspended below the aircraft, through which locusts fly and which records automatically the number of locusts thus traversed. Other methods deserve investigation, in particular aerial photography using perhaps infra-red sensitive films.

7.3 The future organization of Desert Locust control

In this account I have attempted throughout to emphasize that information is the basis for effective control action. Once adequate information suitable for quantitative analysis is available, then effective action may take a variety of forms and may be executed on a national, regional or international scale. The control organizations, on whatever scale, must also regard themselves as a means of feedback of information to the information service.

The indivisibility of the Desert Locust problem demands the centralization of all locust information. A suitable embryonic structure is available in the form of the present Desert Locust Information Service and it should be the object of international endeavour to strengthen the capabilities of this service, particularly in respect of enabling it to provide quantitative information, and where possible, quantitative forecasts. But an information service is as good only as the information which it receives. For DLIS to acquire this increased capability it must have access to :

(i) The best possible charts on the distribution of low-level wind convergence and current data on the quantitative divergence occurring throughout the Desert Locust invasion area. The source of this information has already been discussed and depends not only on the strengthening of national Meteorological Services but also on the institution of long-range meteorological flights over uninhabited areas, and the transmission, computation and analysis of these data at an appropriate centre;

(ii) Quantitative information on Desert Locust swarms and hoppers, provided by a specially equipped serial reconnaissance survey unit having access for reconnaissance purposes to any part of the distribution area which the information service considers to constitute a danger spot;

(iii) Immediate access to information from all sources, including national locust control or crop protection teams, of hopper and swarm infestations in the forms now accepted as standard, but transmitted by radio or teleprinter instead of by post.

It should be the objective in the organization of Desert Locust control, and in particular of the information service, that crises and emergencies and unexpected happenings never occur. There should be continuous access to all available Desert Locust information from all parts of the distribution area and guidance available for control teams well in advance of the time when operations are to be necessary.

Since at any time the bulk of the world's population of Desert Locusts may be concentrated in a limited area or in a single country, and this concentration may well be of such numbers as to overwhelm any conceivable control potential which a country could maintain on a permanent basis, an aerial striking force of adequate potentiality is essential to supplement the national effort. Such a striking force, operating preferably under FAO, and supported by contributions from all countries affected by the Desert Locust problem, should be able to conduct control wherever the information service considers that the greatest impact can be achieved.

Such a centralization of information, and of striking power, becomes all the more important during a period of recession. The control potential which is available now throughout the whole of the distribution area of the Desert Locust is so overwhelmingly large that if it could be concentrated on to any residual population of Desert Locusts which shows signs of resurgence, the Desert Locusts would never again have an opportunity of building up into the unmanageable numbers which have occurred in the past. The question is where to search for these potentially important residual Desert Locust populations. Limited ground surveys designed to provide population estimates have been conducted on the Red Sea littoral of the Sudan and Ethiopia for many years past, and more extensive surveys by Indian and Pakistani teams in the Rajasthan Desert are a regular routine. The continuous existence of Desert Locust populations in these areas is doubtless due to the persistence of wind convergence in them. Undoubtedly, during appropriate conditions of convergence scattered Desert Locust populations may be found and indeed are found over the greater part of the distribution area and this is far too large to be covered by ground survey except at prohibitive expense. Aerial survey guided by meteorological data, preferably of a quantitative nature, will enable such areas potentially suited for concentration to be investigated. It should be emphasized that locusts are of economic importance (and suitable as targets for control) only when they are present in sufficiently high density. It may be true that high populations of solitary locusts may occur in areas suited for their survival and reproduction. If these are in crop areas they will be reported and can be destroyed. If they are in uninhabited desert areas they will not be reported nor do they constitute an economic problem. They will however be found by aerial survey once the population condenses into swarms.

During the present recession the major problem is obtaining information, particularly quantitative information. Once the problem of control may be defined in terms of toxic doses to be applied, adequate resources are available from regional and national sources to destroy any infestation that is likely to arise, and FAO has the capability and authority to organize necessary action.

It is my firm conviction that the permanent control of the Desert Locust is technically possible. It is a great tribute to FAO that, through their efforts over the last decade, the principle has been accepted that the Desert Locust problem is indivisible. It is through their guidance and encouragement that the control effort of national organizations has been strengthened to a more realistic level than was ever possible in the past, and that regional organizations have been created, or are in the process of being created, which can augment the national effort. The problem that now remains, to keep the Desert Locust under permanent control, is one of developing international co-operation, indeed integration of effort, on a scale so far achieved in very few fields. The organization of Desert Locust control to obtain a permanent solution to the problem presents a tremendous challenge to the United Nations and its specialized agencies which I believe they will be prepared to accept and surmount successfully.

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ORGANISATION DE LA LUTTE ANTIACRIDIENNE

Emploi des moyens aériens

par

J. Roy

Tout travail d'organisation d'unités devant intervenir sur le terrain doit être précédé d'une étude détaillée du problème à résoudre et de son contexte. Puis il convient de choisir les moyens, de préciser leurs techniques d'emploi et de définir les méthodes de travail. Il faut ensuite recruter et éventuellement former le personnel et, enfin, examiner très soigneusement les questions de financement et de gestion de ces unités.

Ce sont là des règles générales qui restent valables dans tous les cas, mais qui sont particulièrement difficiles à adapter d'une façon satisfaisante au problème particulier de la lutte antiacridienne.

En effet, les conditions de travail dans la lutte antiacridienne changent considérablement d'une région à l'autre et, dans une même région, d'une année à l'autre.

L'accessibilité du terrain aux véhicules, l'étendue et la qualité du réseau routier varient considérablement dans l'immense zone envahie par le criquet pèlerin.

Les installations de stockage sont généralement élémentaires et fort éloignées les unes des autres. Les ateliers permettant l'entretien des matériels sont souvent dispersés et insuffisamment équipés.

Les approvisionnements divers, et en particulier en pièces de rechange, posent fréquemment des problèmes difficiles à résoudre.

Par ailleurs, les caractéristiques des invasions varient considérablement au cours des années. La réputation et l'étendue des pontes, par exemple, ne sont jamais identiques d'une année à l'autre.

De plus, les techniques et les méthodes de lutte sont naturellement fort différentes lorsqu'il s'agit de s'attaquer à des larves aptères ou à des adultes ailés.

Cependant, l'un des handicaps les plus graves provient du fait que, à certaines époques, certains pays sont submergés par le fléau pendant que, dans d'autres, les services antiacridiens restent inoccupés.

Ces quelques considérations permettent de se rendre compte de l'ampleur, de la diversité et de la complexité des problèmes que pose l'organisation de la lutte antiacridienne sur l'ensemble de la zone d'invasion du criquet pèlerin. Autrefois la lutte antiacridienne consistait presque exclusivement à assurer une protection rapprochée des cultures. C'était une lutte défensive et peu efficace. Progressivement, une meilleure connaissance des différents aspects du fléau et l'amélioration des moyens de lutte permirent d'entreprendre des actions offensives.

Le propre de la lutte antiacridienne est actuellement de détruire le criquet pèlerin partout où il peut manifester une activité dangereuse dans son immense habitat, entre l'Atlantique et l'Himalaya.

Il est évidemment impossible de détruire l'espèce et de procéder ainsi à une véritable éradication du fléau. Ce que l'on cherche, c'est essentiellement à connaître à tout moment l'importance de la population acridienne et le danger potentiel qu'elle représente, afin de tenter d'intervenir en temps utile pour prévenir tout développement du fléau. Ceci impose nécessairement le maintien, sur tout l'habitat du criquet pèlerin, d'une énorme organisation de surveillance et de lutte en perpétuel état d'alerte.

Cette façon de procéder peut sembler peu rationnelle, mais il ne semble pas que l'on puisse envisager d'autre solution tant que l'on ne sera pas en mesure de prévoir à coup sûr où et quand des actions préventives doivent être menées pour empêcher toute reprise du fléau, et tant que l'on ne disposera pas des moyens permettant de mener à bien ces interventions sans risque d'échappées.

Bien entendu, dans l'état actuel du problème, l'organisation de la lutte antiacridienne doit être capable d'attaquer les insectes aux différents stades de leur existence et d'assurer aussi bien la protection des cultures que la destruction massive des populations grégaires.

La lutte antiacridienne doit ainsi faire face à des tâches multiples dans des conditions de travail extrêmement variables. A cet effet, la lutte antiacridienne dispose d'un arsenal de moyens que nous pouvons passer en revue et dont nous pouvons examiner l'emploi en fonction des différentes catégories de travail à effectuer. La prospection antilarvaire en région cultivée ne pose pas de problème bien particulier. Dans les zones de culture, les signalisations sont généralement abondantes et leur transmission se fait dans des délais raisonnables. Bien entendu, les renseignements recueillis sont souvent sujets à caution et doivent être vérifiés. Le réseau routier est généralement suffisant pour permettre des contrôles rapides par un personnel compétent.

En régions dites désertiques, c'est-à-dire très peu peuplées, l'on se trouve devant deux cas. Ou bien le terrain est praticable aux véhicules, ou bien il ne peut être parcouru par des moyens terrestres. Dans le premier cas, l'emploi de véhicules effectuant des prospections systématiques durant les périodes d'infestation possible représente une solution valable. Cependant, la lenteur relative de telles prospections peut aboutir à un certain retard dans les interventions de lutte proprement dites et finalement conduire à des échappées d'insectes parvenant au stade ailé avant qu'il soit possible de les détruire. L'emploi de l'avion s'impose lorsque le terrain est impraticable aux véhicules. Cependant, dans certains cas, la détection des bandes larvaires à vue directe à partir des avions est extrêmement difficile et parfois totalement impossible, particulièrement lorsque les insectes en sont encore aux premiers stades larvaires. Là encore, il peut en résulter un certain retard dans l'exécution des traitements insecticides avec toutes ses conséquences. Cette question des prospections est extrêmement importante. La détection rapide des pullulations larvaires est indispensable si l'on veut être en mesure d'effectuer la destruction des insectes avant qu'ils ne parviennent au stade ailé. En période de rémission, des prospections insuffisantes ou tardives peuvent être à l'origine d'un nouveau développement du fléau qui peut devenir alors rapidement incontrôlable.

Il convient ensuite de détruire les insectes en s'attaquant aux pullulations larvaires partout où elles sont détectées. Pendant que les concentrations d'insectes seront attaquées par des moyens terrestres ou aériens, travaillant en formations groupées afin d'obtenir un meilleur rendement des matériels, il sera indispensable d'assurer la protection rapprochée des cultures pouvant exister dans la zone envahie. Cette protection des cultures pourra être assurée par les cultivateurs eux-mêmes, au moyen d'un matériel léger, simple d'emploi et de lots d'insecticides peu toxiques, distribués avant toute invasion prévisible. Des véhicules équipés d'exhaust nozzle sprayer pourront utilement renforcer cette protection en effectuant des pulvérisations en larges cercles concentriques autour des groupes de cultures afin d'éviter des invasions successivesde bandes larvaires ayant pris naissance dans les zones non cultivées.

Le traitement des pullulations larvaires couvrant de larges zones peut être entrepris soit par moyens terrestres lorsque le terrain est praticable aux véhicules, soit par moyens aériens.

Cependant, l'emploi de l'avion ne peut se concevoir qu'en traitements systématiques avec l'épandage d'insecticide en larges bandes parallèles sur le chemin de progression des larves. Le traitement des pullulations dispersées ne peut être économiquement entrepris qu'au moyen de véhicules attaquant les bandes larvaires l'une après l'autre. Il s'agit là d'un travail généralement long et dont le succès reste lié à la possibilité de détecter les bandes larvaires isolées. Ce genre de problème de lutte n'a pas encore trouvé, en réalité, de solution vraiment satisfaisante.

Si l'emploi de l'avion pour le traitement des zones étendues, fortement infestées par les bandes larvaires, doit être vivement recommandé, il n'en reste pas moins que l'efficacité des unités aériennes constituées d'avions légers dépend dans une large mesure du bon fonctionnement du support terrestre qui leur est indispensable. En effet, les avions légers, qui comprennent les appareils susceptibles d'emmener de 200 à 700 kg d'insecticide, ne peuvent intervenir économiquement que dans un rayon maximal de 20 à 40 km environ autour des pistes de ravitaillement. Il est donc indispensable de transporter par voie de terre l'équipement nécessaire au fonctionnement de l'unité et à l'hébergement du personnel jusqu'à une distance réduite des lieux de traitement, et des insecticides et carburants jusqu'aux pistes d'envol situées à une distance ne dépassant pas 20 à 40 km des points où devront être effectuées les pulvérisations.

Par ailleurs, le bon fonctionnement d'une unité aérienne de ce genre dépend de la parfaite coordination des travaux divers revenant à l'échelon terrestre. Ces travaux sont les suivants :

- Prospection des zones infestées.
- Préparation des pistes d'envol.
- Repérage et balisage des voies d'accès aux pistes d'envol.
- Approvisionnement en insecticides, carburants et fournitures diverses.
- Mise à bord des avions des insecticides et carburants.
- Balisage des zones de traitement (éventuellement).
- Entretien mécanique du matériel roulant et des avions.

Une bonne coordination de ces différents travaux ne peut être obtenue que grâce à un réseau radiophonique d'un fonctionnement correct et continu.

Il est certain que la conduite d'unités composées d'avions légers en campagne de lutte antilarvaire est difficile et demande la plus grande attention. De plus, le court rayon d'action utile des avions légers et l'important support terrestre qu'ils requièrent représentent deux inconvénients majeurs. L'on en est arrivé à considérer que l'emploi d'avions d'un plus fort tonnage pourrait être une excellente solution, en particulier dans les cas où l'approche des approvisionnements dans les zones fortement infestées rencontre des difficultés trop importantes à l'époque des interventions.

Cependant, si l'avion lourd permet de s'affranchir des servitudes d'un échelon terrestre difficile à mouvoir, son utilisation n'est pas sans présenter certains inconvénients. En particulier, l'on ne peut songer à l'employer sur des surfaces inférieures à plusieurs dizaines de milliers d'hectares d'un seul tenant. Par ailleurs, ce genre d'appareil n'est économique d'emploi qu'au-dessus d'un minimum annuel d'heures de vol imposant pratiquement son utilisation à longueur d'année.

La lutte contre les adultes ailés pose des problèmes beaucoup plus difficiles à résoudre que la lutte antilarvaire. Si la détection des insectes en vol peut être effectuée aisément à partir d'avions légers volant à basse altitude et situant la position des essaims se détachant sur le ciel, leur destruction par pulvérisation est beaucoup moins aisée. Lorsque les circonstances le permettent, il est parfois possible d'attaquer les essaims posés, mais cela ne se produit que lorsque les basses températures d'hiver maintiennent les insectes au sol pendant la journée, durant un temps suffisamment long pour permettre l'intervention des avions.

Pendant la plus grande partie de l'année, les essaims sont extrêmement actifs et volent pratiquement pendant toute la durée du jour. La pulvérisation des insecticides à l'intérieur de ces essaims pose alors des problèmes techniques qui ne sont pas tous résolus. Sur le plan opérationnel, on peut espérer que l'avion lourd sera susceptible d'apporter une solution à l'attaque de cibles aussi mouvantes.

Avant de clore ce chapitre, il est bon de noter que le choix des moyens de lutte dépend également d'un certain nombre de facteurs qu'il ne faut pas sous-estimer et qui sont brièvement rappelés ci-dessous :

- Polyvalence des matériels qui devront pouvoir être employés à d'autres travaux au cas où les opérations antiacridiennes ne justifieraient par leur plein emploi.
- Possibilité de financement en ce qui concerne aussi bien l'achat des matériels eux-mêmes que celui des pièces détachées indispensables à leur bon fonctionnement (problème de devises étrangères).
- Disponibilités en personnel spécialisé susceptible d'obtenir un rendement convenable des différents équipements.

Est-il nécessaire d'ajouter qu'un bien meilleur rendement des moyens antiacridiens existants pourrait être obtenu par la voie d'une coopération plus étroite entre les services nationaux et régionaux, en particulier par l'envoi plus fréquent de matériels et de personnels, à certaines saisons de l'année, vers les régions envahies, à partir de celles où les services antiacridiens restent inoccupés.

DESERT LOCUST CONTROL METHODS WITH PARTICULAR REFERENCE TO THE THEORY AND PRACTICE OF AIRCRAFT SPRAYING AND TO METEOROLOGICAL FACTORS

by

H.J. Sayer

1. INTRODUCTION

A considerable change in the technique of Desert Locust control has taken place in the last decade or so as a result not only of more effective insecticides and improved application machinery but also because of the increased appreciation of the effect of meteorological factors on the movement and behaviour of locusts. Some of the most important changes have come about by taking advantage of the meteorological environment and exploiting it to the disadvantage of the locust.

The advent of powerful synthetic organic insecticides after the Second World War did not at first bring any great change in the then accepted optimum methods of control, which were mainly dusting and baiting. The new insecticides were exploited essentially for their greater safety in use, having a low mammalian toxicity compared with their predecessor, arsenic. Vast armies of men, vehicles and application machinery were still necessary to distribute the large quantities of materials, and the problem of locust control was, fundamentally, a problem of logistics. Realization that the greater part of the transport problem was involved in the carrying of inert materials (1,000 tons of poison bran bait contain only one ton of insecticide) led to a consideration of the possibility of applying the insecticide to the normal diet of locusts, the vegetation of the bush. Repeated experience in the field had shown almost complete lack of effectiveness of dry dusting under many conditions, and showed in South Africa that gamma-BHC applied as a dry dust was one-eighth as effective as when it was sprayed as an emulsifiable concentrate in water.

The change to liquid spraying was confused and development retarded by the retention of many of the concepts of spraying normally used in crop spraying. The idea that the insecticide concentrate should be diluted with some other liquid, usually water or diesel oil, tended to persist, and there was an obsession to think in terms of a minimum dosage of insecticide per ground area. It has been shown that under the climatic conditions normally associated with Desert Locust habitats, the evaporation of the diluents from the spray droplets results in a loss of deposition of the insecticide. Using concentrated oil solutions of insecticide specially formulated to be highly involatile and adopting drift spraying resulted in most of the insecticide being deposited on the sparse vegetation. By this means, extremely small quantities of insecticide formulations were shown to give effective and persistent control, especially if applied by the technique (to be described later) of "barrier" spraying, as low as one gallon per square mile. The thousands of tons of bait can now be replaced by a few hundred gallons of spray : instead of searching for and applying bait to each individual hopper band, as is required by the non-persistent bait, a highly infested area can be "barrier" sprayed and left for the hoppers to march through the spray barriers, thus reducing further the operational costs. In order to apply these very low dosages of spray, a simple ground sprayer has been devised which utilizes the exhaust gases of a light desert vehicle.

Along with the improved methods of ground control, aerial spraying techniques have developed considerably over the last decade. By the early 50's, a great deal of basic work had been carried out both in the field and in the laboratory, notably by Gunn, Wootten and Sawyer. The use of aircraft by the then Desert Locust Survey in East Africa has permitted the expansion and development of this original work. The constant search for better insecticides and formulations, the improvement of spraygear and spraying techniques, have led to the acceptance of aerial spraying as a major weapon in the control of the Desert Locust.

The vast areas subject to invasion by the Desert Locust, generally with poor ground communications, together with the mobility of swarms, can only be realistically matched by a control method which has similar mobility and is largely independent of ground communications, i.e. aerial control. In the following, therefore, only aircraft control methods will be discussed, especially as aircraft offer a proven means of survey far more accurate and rapid than has been obtainable by ground-based units. Before any planned attack can be made on locusts, it is necessary to know where to expect an invasion well in advance, and this anticipation is nowadays a matter of experience and survey. It is convenient, therefore, to consider control methods as two separate parts, (a) survey, and (b) control. Since the author is most familiar with the control problem of Eastern Africa, this area will be used as a basis for illustrations but this does not preclude other regions of the Desert Locust invasion from having a similar fundamental problem.

2. SURVEY

The experience of years established a routine of control in East Africa, but since the advent of aircraft, it has become very clear that the annual locust cycle is a very large meteorological phenomenon. Moreover, the meteorological factors, which in the tropics cannot be dissociated from geographical factors, have largely determined the pattern of control. The appreciation of the displacement of swarms down-wind(post-frontal movement) to concentrate under the influence of zones of wind convergence has led to the establishment of a forecast system for wind convergence, and aerial surveys are directed towards these convergence zones since the likelihood of finding swarms at certain periods of the year is greatest in the areas of wind convergence. Moreover, as will be shown later, locusts in the semi-static zones of wind convergence are the most vulnerable.

3. CONTROL TECHNIQUE

Commercial types of spraygear (boom-and-nozzle, spinning cage) produce a range of droplets about a mean diameter, but this range is less with the spinning cage gear than with the boom-and-nozzle. At the moment, with both types of spraygear, the increase of emission rate produces an increase in drop size. With the drop size commonly used in locust control, the droplets assume their terminal velocities within a metre of the point of emission. Thence the trajectories of the droplets are the resultants of the terminal velocities and of the wind. The importance of non-volatile spray formulations has been realized in locust control for many years, since, if volatile solvents are present, these will evaporate very rapidly from the droplets, reducing drop size and thus terminal velocities, which, in the extreme, may result in very low deposits. There are two types of basic spraying techniques in use, air-to-air and air-to-ground. Wind tunnel experiments have shown that a flying locust has approximately twice the droplet, pick-up area as that of a settled locust. For this reason and also because of the lack of competition for spray by vegetation and the lack of shielding, air-to-air spraying can be the most efficient spraying possible, all other things being equal. The most important factor involved in all spraying is locust density, flying or settled. It has been shown that for flying locusts, the number dosed to a specific level is almost directly proportional to the flying density. Correspondingly, since it is necessary to dose a settled locust to a minimum dose per unit area, the same dosage rate is required whether there are one hundred locusts or only one per square metre. Clearly, then, it is most desirable to know the conditions which produce high density locusts, flying or settled, and a knowledge of such conditions should be a major part of the training of aircraft control units.

A mathematical analysis of air-to-air spraying has shown that the number of locusts dosed to any level (swarm infinitely deep) is roughly inversely proportional to the square of the dose. Thus the number of locusts sprayed to a level of L.D.10* is about 80 times the number of locusts sprayed to the L.D. 90* level. Since most of the present insecticides used in locust control are cumulative, repeated applications of sub-lethal doses will eventually accumulate to a toxic dose. This fact accentuates the importance of adding sufficient insecticide to any particular locust population once operations have started against the locusts, in order to exploit the accumulation of sub-lethal doses. If the swarm is carried away rapidly by the wind from the spray base, as frequently occurs in post-frontal swarm movement, then capitalizing on the sub-lethal doses is considerably reduced. On the other hand, if the meteorological conditions keep the swarms relatively static and permit repeated attacks from the same base, then the maximum use can be made of the sub-lethal doses. Such conditions occur when the Inter-Tropical Convergence Zone (I.T.C.Z.) is relatively static during June to September in Northern Somaliland and Ethiopia.

It has been observed that the effect of sub-lethal doses is to cause accelerated swarm movement coupled with dispersion of the locusts. Under post-frontal conditions, when the condensing factor is the gregariousness of the locusts, the wind turbulence being a dispersive factor, repeated attacks may become successively less effective owing to the reduction of density. Frontal swarms, on the other hand, are daily re-condensed by the converging winds, thus making it possible to exploit the cumulative effect of sub-lethal doses.

If one considers the annual locust cycle in East Africa, bearing in mind the above, it would appear that the optimum control situation occurs during the northern solstitial position of the Inter-Tropical Convergence Zone, when it tends to align along the escarpment area of the northern coast of Somalia. Flying locusts are concentrated here and are displaced slowly eastwards. The same locust population can be repeatedly attacked over a period and each afternoon the locusts are, in general, condensed under the influence of the front. The southern solstitial position is not so good from this point of view, since the front is not clear, there being a wide belt of unstable air across north Tanganyika and Kenya. Individual prominent land masses, such as Mounts Kenya and Kilimanjaro, create their own daily convergence zones and swarms tend to become trapped in such mountain masses at high altitude. Under these conditions, control is difficult since, although the swarms move slowly and often fly low and concentrated, the aircraft flying conditions are often bad, rough terrain with cloud at high altitude giving pilots great flying difficulties.

The two equinoctial periods, when the front moves rapidly north or south together with the associated rain belts, are periods of breeding. During this particular time, owing to the maturing swarms getting involved with the bad weather and breeding, control of adults is virtually impossible and, in any case, these old swarms are dying out and disappearing.

The control of the emergent hoppers has long been the prerogative of the ground control organizations, using a non-persistent bait which has to be applied to individual bands. The hopper phase is a more dispersed phase compared with that of the parent swarms. Thus, a flying locust population which occupied, say, a thousand square miles in June to August, can breed over an area of over one hundred thousand square miles during October to

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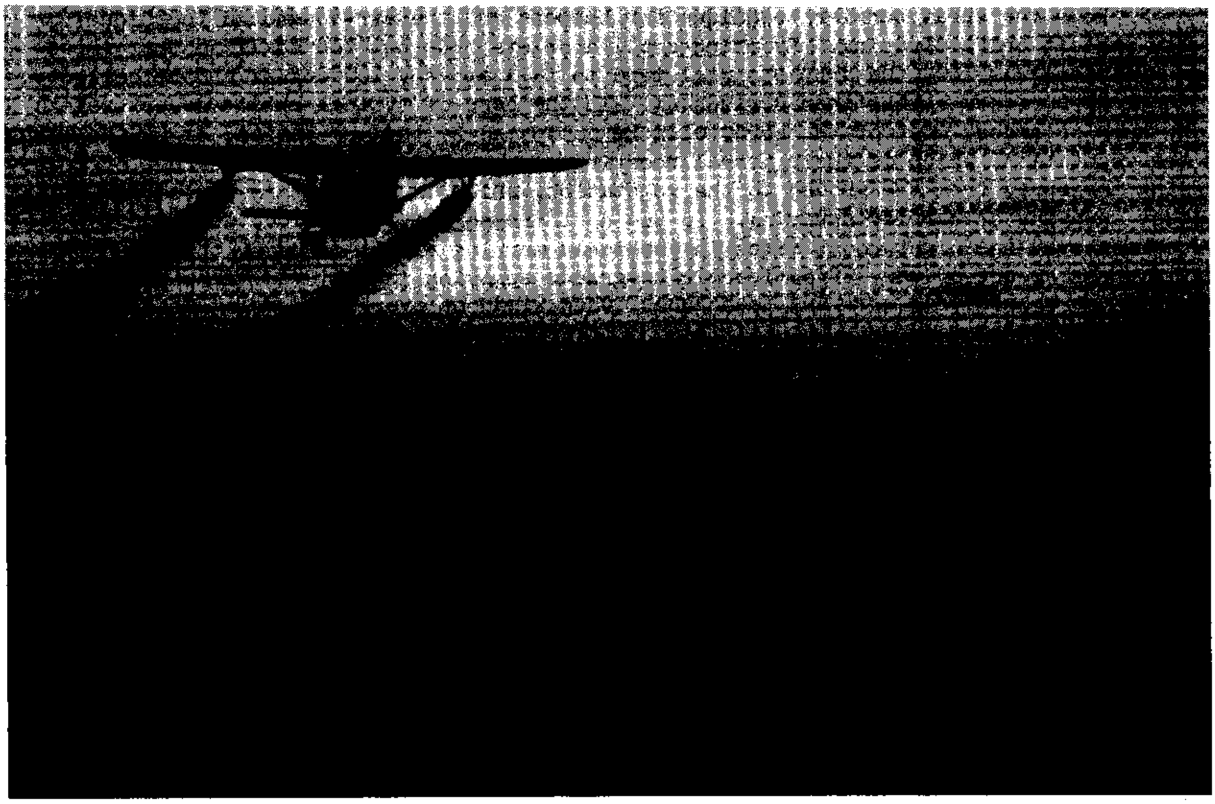
* L.D.10 and L.D.90: doses killing respectively 10 per cent and 90 per cent of locusts receiving them.



Demonstration of ultra-low-volume spraying, as used against Desert Locust hoppers; Doshan Tapeh, Tehran, 30.XI.1963

Cessna 185 aircraft of FAO Operational Research Air Unit, spraying cross-wind from height of about 10 m, using non-volatile oil solvent to give effective swathe of more than 200 m with fine drops which are largely deposited on sparse vegetation such as that on which the locust hoppers feed.

November. The problem of survey is considerably greater, since hopper bands cannot be seen from anything like the same distance away. (A swarm has been recognized in the frontal system from 60 miles, whereas hoppers can be seen from a mile or less.) Aerial survey for hopper bands is now becoming established, and a control technique for aerial spraying which exploits the wind is now available. The control method is to lay down by drift spraying, across the north-easterly wind which is becoming well established by the time of the middle instars, "barriers" of spray (fine droplets circa 100μ and concentrated, non-volatile persistent insecticides) at intervals of 5 km across highly infested areas. The term highly infested" is, again, a question of density, and much development work is still required as to when to apply the barriers. Advantage is taken of the fact that hoppers tend to displace down-wind, which by the time they are in marching bands is becoming increasingly constant in direction (post-frontal). The bands moving across successive barriers accumulate toxic doses, such spray barriers having been shown to be persistent over a period of 40 days. This technique, using only one gallon of spray per square mile, permits the rapid control of large areas of infestation, and eliminates the problem of finding and controlling individual bands, which is the most costly part of hopper control.

Both the spray barrier technique for hoppers and the air-to-ground technique for adults exploit drift spraying. By using small droplets, but not too small so that impaction efficiency is low, the droplets will tend to fall at very low angles and be collected by vertical surfaces rather than horizontal. In the case of typical sparse desert vegetation, bush or grass, most of the spray will be collected by the vegetation, or by the locusts on the vegetation, which is their normal roosting place. The wind has the effect of transferring the spray from the ground to the vegetation, which is where it is wanted for either contact spraying or barrier spraying. In the northern solstitial period, winds of 15-20 kt are common over the night-roost sites in the early morning and it is under these conditions that a great amount of very effective air-to-ground spraying is achieved, in striking contrast to the common crop-spraying techniques, when winds of over 10 kt bring all spraying to a halt.

One more possible use of the wind has been suggested when dealing with swarms which are in convergent winds. Since under these conditions swarms are being concentrated by the wind, it should be possible to apply a spray to such a system in such a way as to keep the spray and the locusts together for the longest possible period, so that droplet pick-up is a maximum. By applying a spray of about 250 microns diameter above the densest part of a convergent swarm, the spray will tend to fall into the wind updraught, and be carried up with the locusts. As the locusts fall out at the top by gliding, the droplets will tend to fall out with them, since the terminal velocity of 250 micron droplets is about the same as that of the rate of descent of a gliding locust.

METEOROLOGIE ET ACRIDIENS A MADAGASCAR

par

R. Ravoavy

Il existe à Madagascar deux grandes espèces migratrices : Locusta migratoria Capito (Saussure) et Nomadacris septemfasciata (Serville).

Nous n'examinerons que l'espèce Locusta migratoria qui est de loin plus importante que la Nomadacris septemfasciata. La multiplication de la Locusta migratoria suit une progression géométrique, tandis que celle de la Nomadacris septemfasciata peut être assimilée à une progression arithmétique.

En effet, la Locusta migratoria a plusieurs reproductions annuelles, qui découlent de l'absence de diapause imaginale, comme aussi de diapause de ponte. On n'a observé que des phénomènes de quiescence, mais qui disparaissent dès que les conditions climatiques sont favorables. Quant à la Nomadacris septemfasciata, on n'a jamais observé, à Madagascar, qu'une seule génération par an.

Il nous semble utile de donner quelques notions sur le climat de Madagascar, facteur qui conditionne la biologie des insectes.

On distingue en gros deux saisons par an :

i) l'été austral chaud, qui dure cinq à sept mois (novembre à mai) et est généralement pluvieux;

ii) l'hiver austral, durant cinq mois (juin à octobre), est généralement sec.

1. CLIMAT DE L'AIRE GREGARIGENE

L'aire grégarigène des migrateurs malgaches est située dans la région côtière du sud-ouest de l'île, limitée par l'isohyète 750 mm, d'une superficie totale de 60.000 km^2 (carte I) et située entre 21°S et 26°S.

Le climat de cette région est caractérisé par une pluviosité inférieure à 700 mm, et même, pour la plus grande partie, à moins de 300 mm. La saison des pluies y est fort irrégulière avec des précipitations orageuses suivies de périodes de sécheresse caractérisées et des écarts de températures diurnes et nocturnes fort importants. Ces phénomènes varient également d'une année à l'autre, et ce sont ces écarts importants (avec des minima thermiques très bas - voisinant quelquefois 1°C à 2°C - et des maxima très élevés - 40°C) qui caractérisent en définitive l'aire grégarigène et lui donnent ses limites géographiques.

Pour illustrer ceci, nous prenons l'exemple de la station de Tsihombe située dans l'aire grégarigène.

En saison chaude, les variations y atteignent la plus grande amplitude pour Madagascar. Celle de l'oscillation du maximum journalier est de 10,9°C, et celle du minimum journalier de 9°C. La plus grande variation du maximum pour deux jours consécutifs est de 4,8°C et celle du minimum de 6°C. L'amplitude de la variation diurne est de 3,5°C à 15,6°C.

En saison fraîche, pour la même station, on relève une amplitude de l'oscillation du maximum journalier de 10°C et celle du minimum journalier de 11,9°C. La plus grande variation du maximum pour deux jours consécutifs est de 8,7°C, et celle du minimum pour deux jours consécutifs de 8,6°C. L'amplitude de la variation diurne est de 4,5°C à 22°C.

La région grégarigène présente donc une très forte irrégularité pluviométrique et thermique. Il est d'ailleurs à remarquer que les caractères grégaires ne se développent chez les acridiens, dans le monde entier, que lorsque ceux-ci évoluent dans des régions à forte instabilité éco-climatique.

2. CLIMAT ET GREGARISATION

A l'exception de la côte est, caractérisée par une forte pluviosité durant presque toute l'année et une température à peu près homogène(21°C à 27°C) pendant les 12 mois de l'année, les quatre cinquièmes de l'île font partie de l'aire d'invasion. Ceci a été nettement observé pendant la grande invasion de 1937 à 1957, où les vols de sauterelles ont en effet occupé plus de 500.000 km^2.

3. BIOLOGIE DES LOCUSTA MIGRATORIA

Nous donnerons ci-après quelques relations entre la biologie des Locusta migratoria et la météorologie, telles que celles-ci découlent des récents travaux du Centre de recherches acridiennes de l'Institut de recherches agronomiques de Madagascar.

Dans le cas d'une humidité suffisante du sol, la durée d'incubation dépend uniquement de la température et, suivant cette dernière, des incubations variant de 12 jours en décembre à 45 jours en juin ont été observées.

Dans le cas d'une humidité insuffisante du sol, l'embryon ne peut pas effectuer son retournement et les oeufs restent en quiescence pendant quelquefois deux mois, en juin et juillet qui sont les mois les plus froids de l'année. L'incubation totale peut alors durer 90 jours et même plus. Si l'humidité du sol est inférieure à 1 pour cent, l'oeuf ne survit que peu de temps; pour une humidité supérieure à 30 pour cent, on a également enregistré la mort de l'oeuf, probablement par asphyxie.

La durée du développement larvaire varie ainsi de 24 jours en saison chaude à 63 jours en saison fraîche. Suivant les saisons, la maturation sexuelle, pour se développer, s'échelonne de 15 à 40 jours.

L'intervalle de temps compris entre la mue imaginale et la première oviposition est de 12 à 16 jours en saison humide et de 37 à 41 jours en saison sèche.

4. CLIMAT ET HOMOGENEISATION DES PHASES DE DEVELOPPEMENT

Une pluie importante mettant fin à une période sèche peut jouer un rôle à plusieurs niveaux :

i) Facteur déclenchant l'éclosion à cause de l'amollissement de la croûte de terre superficielle. - Eclosions immédiates, après la pluie, des oeufs au stade VII de Popov.

ii) Rupture de la quiescence des oeufs. - Eclosions 10 jours après la pluie (en saison chaude).

iii) Déclenchement de l'oviposition (sol favorable et maturation sexuelle chez les femelles prêtes à pondre). - Eclosions 15 jours après la pluie.

iv) Déclenchement de la maturité sexuelle des jeunes femelles.
- Pontes 10 jours après la pluie.
- Eclosions 25 jours après la pluie.

Pour la Locusta migratoria, on propose le schéma de reproduction annuelle suivant :

Octobre-novembre	Décembre-Janvier	Février-avril	Mai-septembre
1ère reproduction	2e reproduction	3e reproduction	4e reproduction
de saison chaude	de saison chaude	de saison chaude	de saison fraîche

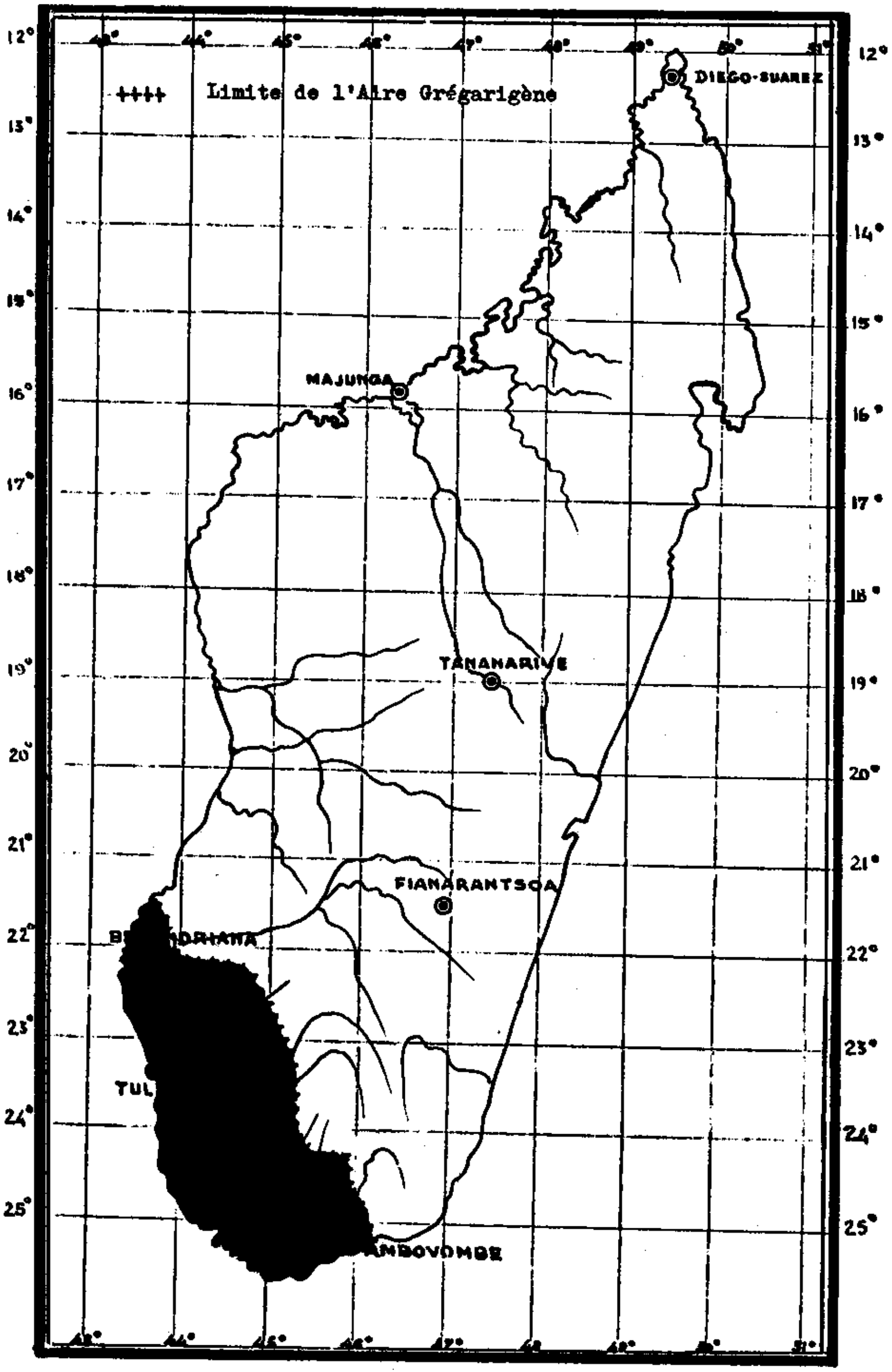
Suivant les conditions éco-climatiques, l'une ou plusieurs de ces reproductions peuvent n'avoir pas lieu et on voit donc que la grégarisation de l'espèce, prélude de l'invasion acridienne, est uniquement fonction des phénomènes météorologiques.

5. CLIMAT ET DEPLACEMENT DES ESSAIMS

Les vents dominants et les vents locaux jouent un rôle très important dans le déplacement des vols d'invasion. A Madagascar, les essaims se déplacent en général sous l'action du vent et n'atteignent jamais une altitude supérieure à 400 mètres.

Dans l'aire grégarigène, les vents d'alizé dominants sont orientés du sud-est au sud-ouest pendant la période de démarrage des essaims (février-mars), ce qui a pour effet de les amener rapidement du sud vers les régions côtières plus septentrionales et les Hauts Plateaux. Si l'alizé ne s'établit pas normalement, comme cela s'est produit en 1961-1962, la circulation des vols est perturbée et on assiste à des mouvements tourbillonnaires et à des allées et venues qui permettent des interventions plus efficaces. On a également observé une diminution des distances de déplacement des essaims lorsque ceux-ci atteignent les régions septentrionales plus élevées. Cette diminution est probablement liée à la baisse des températures en début et en fin de journée, ce qui diminue la période d'activité diurne des insectes. Une moins grande stabilité des vents dans la région des Hauts Plateaux malgaches contrecarre également le déplacement des essaims.

Ainsi donc sont établies non seulement l'influence dominante des phénomènes météorologiques (températures, pluies) sur le développement biologique de l'insecte, mais aussi l'influence des vents sur l'invasion acridienne.


++++ Limite de l'Aire Grégarigène
DIEGO-SUAREZ
MAJUNGA
TANANARIVE
FIANARANTSOA
TUL
AMBOVOMBE
12°
13°
14°
15°
16°
17°
18°
19°
20°
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43°
44°
45°
46°
47°
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49°
50°
51°

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