WORLD METEOROLOGICAL ORGANIZATION

COMMISSION FOR AGRICULTURAL METEOROLOGY

CAgM Report No. 73

EXTREME AGROMETEOROLOGICAL EVENTS

Prepared by

CAgM-X Working Group Members: G.J. Benson, D. Dambe (Chairman), T. Darnhofer, R. Gommes, G.N. Mwongela, D.E. Pedgley, V. Pérarnaud

WMO/TD-No. 836

Geneva, Switzerland

July 1997

TABLE OF CONTENTS

SUMMARY

The Working Group on Extreme Agrometeorological Events was composed of the following rapporteurs:

(a) Rapporteur on measures to monitor and predict the effects of agricultural drought;

(b) Rapporteur on agrometeorological inputs to measures to alleviate the effects of drought and to combat desertification;

© Rapporteur on agrometeorological information for locust control;

(d) Rapporteur on agrometeorological information for the monitoring of the spread of animal diseases;

(e) Rapporteur on the specific aspects of natural disaster which affect agricultural production and forecasts, particularly wildfires, hurricanes and severe local storms.

This summary gives an overview of the reports from the five rapporteurs, and from the additional papers that are found essential to provide more information. Due to the nature of the overall theme of the Working Group (Extreme of Agrometeorological Events), a report produced by Dr R. Gommes (FAO) was adopted as part of the introduction to the working groups' theme. The paper generally addressed world wide extreme agrometeorological events, giving statistics of both human and agricultural losses, and examples of episodes that occurred in several countries.

The rapporteur on measures to monitor and predict the effects of agricultural drought, starts her report by describing drought severity, as not only dependent on the duration, intensity, and geographical extent of a specific drought episode, but also on the demands made by human activities and by vegetation on a region's water supplies. The rapporteur goes on to define and describe the meteorological, agricultural and hydrological drought. The report identifies the most important meteorological indices that characterize drought as precipitation, potential evapotranspiration, and precipitation minus potential evapotranspiration. These determine the available soil-moisture in the soil; which is one of the most important tool to monitor drought. The report then describes the drought monitoring system in France, which uses the soil water balance model. Soil water balance is monitored every ten days in all synoptic stations, with the aim of providing early warning to the relevant authorities, once significant soil water deficits are detected. Finally, the report concluded by pointing out the most important tools used to fight against agricultural droughts:

- irrigation in area that have adequate water supply;
- growing of drought resistant plants that are adapted to the prevailing climate and soils;
- planting during the bet planting period;
- the amelioration of the maximum available water content.

The rapporteur on agrometeorological inputs to measures for alleviating the effects of drought and combatting desertification, adopted definitions agreed upon the International Convention to Combat Desertification (INCD). The method of collecting information from member countries by means of questionnaires is unsuccessful because there are very few responses received. The rapporteur has to rely on the available literature, and inputs from available experts on specific topics, to produce the report. The report reviews and summarises the available literature on drought and desertification. The drought monitoring system in Botswana is given as a an example; emphasising the role of agrometeorology in drought monitoring, and its effectiveness as an advice to policy makers, the implementors and the farming community.

Professor Williams and Professor Bolling produced a summary report providing additional information on the interactions of desertification and climate. Their report provides supplementary information on the agrometeorological inputs and measures to combat desertification. Botswana's experience on desertification are also outlined and a summary of the INCD case study is included in the appendices. Finally, recommendations are made to the CAgM.

A rapporteur on agrometeorological information for locust control reports on ten representative of locust species, their breeding and movement. The report describes how rainfall, temperature and wind affects locusts and discussed the potential of meteorology for improving the monitoring, forecasting and control of locust populations. The operational preparation and use agrometeorological information for lost control was also discussed in the report.

Questionnaires are sent to countries that are at risk of locust infestation, but also about a fourth of the countries that are sent the questionnaires responded. The information received from the countries at risk of infestation use agrometeorological advice to monitor and control locust. Lastly, the report recommends that an improved co-operation between national meteorological and locust control services, and the provision of information that is, or can be, produced routinely and therefore requires little or no additional resources, would contribute most to the improved monitoring and control of locust. Rapporteur on agrometeorological information for monitoring the spread of annual diseases reports on the epidemiological study of Lumpy skin disease (LSD) in Kenya, and its possible correlation on its spread to weather factors. The report concentrates on a period when there is a massive outbreak of LSD (between 1989-91). The result of the study is not conclusive as far as the massive spread of LSD in Kenya when correlated with weather factors. However, rainfall and wind flow pattern are possible contributing factors in the spread of insect vectors that are responsible for the spread of LSD. The rapporteur finally recommends that a further investigation on the weather aspect of the disease on infestation should continue.

The rapporteur on the specific aspects of natural disasters which affect agricultural production and forests, reports extensively on the review of methodologies for assessing economic and social inputs of extreme events as well as an overview of the categories of natural disasters including meteorological, geological and epidemiological events. However, the main thrust of his report is on wild land fires, severe local storms and hurricanes. Other mentioned are hailstorms, tornadoes, thunderstorms and heavy rainflash flooding (associated with severe local storms); storm surges, heavy rains/flood associated with hurricanes. Though river flooding is mentioned, it is not a major focus of the report of the rapporteur.

In an effort to report accurately an assessment of impacts of extreme events, the rapporteur enumerated two major constraints viz lack of any systematic methodology, acceptable to meteorologists, economists and planners and more importantly, there are inadequate information within member countries on impacts of specific phenomenon or events. The rapporteur then recommends that the CAgM Working Group on Extreme Meteorological Events should undertake a survey of accepted method of assessing economic and social benefits of such events with a view to select and implement the preferred approach on the part of WMO Members. It is also recommended that CAgM Working Group on Extreme Events jointly develop a standard approach to case studies which are useful for investigating the economic and social impacts of extreme events.

CHAPTER 5

AGROMETEOROLOGICAL INFORMATION FOR LOCUST CONTROL

by D.E. Pedgley

5.1 SUMMARY

The dependence on weather for breeding, development and movement of ten representative locust species is summarised in paragraph 5.3.

The potential of meteorology for improving the monitoring, forecasting and control of locust populations is outlined in paragraph 5.4.

The operational preparation and use of agrometeorological information for locust control is discussed in paragraph 5.5.

Recommendations to improve the application of meteorology for locust control are made in paragraph 5.6. These are based largely on improved cooperation between meteorological and locust control services, and the provision of information that is, or can be, produced routinely and therefore requires little or no additional resources.

5.2 INTRODUCTION

Locusts are various kinds of grasshoppers having the ability to change their behaviour from scattered individuals to dense, cohesive swarms that can travel hundreds or thousands of kilometres. Sudden arrival of swarms in crops can threaten severe damage and loss of yield. Because their formation and movement are greatly affected by the weather, the occurrence of swarms constitute and extreme agrometeorological event.

Swarms result from crowding but their method of cohesion is not understood. Frequent contact between individuals can lead rapidly to gregarious behaviour - usually at an early stage in the life cycle, before wings develop. Crowding results from breeding, from shrinking of the habitat, or both. Breading needs to be widespread, over thousands of square kilometres, if many swarms are to form, for swarm densities are typically tens of millions of locusts in a square kilometre.

Many species of grasshoppers sometimes produce swarms. Those that do so most frequently and over large areas are the greatest threat to agriculture. The following have been selected to illustrate:

(a) Their wide geographical occurrence;

(b) Differences of behaviour between species;

(c) Variations in weather influences on behaviour.

The Desert Locust (*shistocerca gregaria*) is perhaps the most widely known. Swarms of this species have repeatedly invaded some 60 countries in northern, western and eastern Africa and in southwestern Asia. Several other species affect parts of Africa, notably the Migratory Locust (*Locusta migratoria*), the Red Locusts (*Nomadacris septemfasciata*) and the Brown Locust (*Locustana pardalina*). The Migratory Locust also occurs in MadagascarEurope and Asia, and in Australia, where the Australian Plague Locust (*Chortoicetes terminifera*) is a major pest. A relative of the Desert Locust, the South American Locust (*Schistocerca cancellata*) can invade six countries in that continent. There are other species with more restricted distributions or that rarely give species with more restricted distributions or that rarely give rise to swarms, e.g., the Moroccan Locust

(*Dochiostaurus maroccanus*), the Bombay Locust (*Nomadacris succincta*), the Sahelian Tree Locust (*Anacridium melanorhodon*) and the Senegalese Grasshopper (*Oedaleus senegalensis*).

Swarm incidence varies greatly from year to year. When there are many swarms of a given species, perhaps in many countries, there is a **plague**, but when there are few or no swarms there is a **recession**. Plagues take several generations to develop but then may last from one to many years; they are separated by recessions lasting from years to decades. During a recession, locusts are still present but they are far fewer and widely scatted, doing little or no harm. Individual locusts then behave like the many species of non-swarming grasshoppers to be found in crops and grassland. However, locusts in large numbers, even in the absence of swarms, can still cause considerable damage to crops and grazing. During a plague, swarms spread widely, invading areas of major agricultural production within, but more particularly around, the areas of origin.

Locusts live mostly in arid or semi-arid areas; they have adapted to the erratic seasonal rains typical of such areas to produce the vegetation on which they need to feed and shelter for survival. Their rate of development increases at higher temperatures, and swarms in flight are carried downwind in all but light winds. This profound dependence on the weather for breeding, development and movement has been well studied for a few locust species. Our understanding is summarised in the next paragraph for the ten above-mentioned species; more detail can be found in the publications listed in the references. The potential of meteorology as a contribution to controlling locust populations, based on this understanding, was discussed in depth at a workshop held in Tunis in 1988, prompted by invasion of northwest Africa by Desert Locust swarms in the previous year. This potential is outlined in paragraph 5.4, followed in paragraph 5.5 by a discussion of the operational preparation and use of meteorological information. From the results, some recommendations are made in paragaph 5.6 to improve the application of meteorology to locust control.

5.3 WEATHER AND LOCUSTS

Weather effects on the breeding, development and movement of the Desert Locust have been studied for decades and the results have long been applied to forecasting and control of the species in many countries. These effects are described first, followed by the other species mentioned.

5.3.1 Desert Locust (*Schistocerca gregagria*)

Females lay clusters (pods) of about 100 eggs in moist soil at depths between about 5 to 15 cm. Moisture at these depths is essential for full development of eggs, otherwise they desiccate; moisture in the top 5 cm does not affect development. About 25-30 mm of rain, or the equivalent in run-off, is usually sufficient for full egg development. Heavier falls may be needed if soil is to remain sufficiently moist for egg laying up to several weeks later. However, too much rain can kill locust eggs by exposing them on the soil surface, by washing them out of the ground, or by causing them to rot.

Flying locusts that reach an area of moist soil will usually mature sexually in about one week and egg laying starts soon after. Widespread rain leads to widespread synchronous egg laying and subsequent hatching. Because rains are seasonal in the Desert Locust invasion area, so breeding is seasonal. In the north (from northern Africa to the Middle East), breeding takes place on the winter and spring rains accompanying eastward-moving atmospheric disturbances of temperature latitudes. In the south (from western to eastern Africa) it is on the summer (monsoon) rains associated with westward-moving disturbances. In the east, over parts of the Indian sub-continent, breeding can occur in both seasons, and the same is true around the southern Red Sea, which has the most complex seasonal rainfall and breeding in all the invasion area.

Swarms can form widely within the recession area if rains are adequate. There are no restricted outbreak areas but plagues start more often in the borders of highlands where there can be substantial run-off in many outward-radiating valleys (the central Sahara and around the southern Red Sea, Gulf of Aden and Gulf of Oman). A succession of seasonal rains, falling in different regions but linked by flight of successive generations of locusts, can lead to a plague. Breaks in the succession can weaken or end a plague upsurge. Swarms reaching the outer parts of the invasion area, where rains are more reliable, may breed successfully and produce more swarms. In this sense a plague is self-perpetuating.

Temperature affects locusts development rate and locust flight. Duration of egg development (from laying to hatching) decreases at higher temperatures (of soil at egg depth, but his is will related to air temperature at screen level). It varies from about 11 days at mean air temperature 30-35°C to about 45 days at 25°C. Winter temperatures may be low enough to inhibit development. Immature stages (hoppers) develop in 30-40 days, again faster at higher temperatures, and flight becomes possible in a further 10 days. A rainy season is usually long enough for one generation, sometimes two, but rarely three.

Swarms usually start flying during the morning and settle towards sunset. The night is spent roosting, usually on vegetation, although flight can continue in very hot weather. In cloudy weather, the threshold temperature for take-off is about 20°C, but about 25°C if flight is to be sustained. Locusts bask in the morning sun to raise their body temperature; hence take-off and flight in sunshine can occur with air temperatures as low as 15°C.

Winds affect locust take-off and flight across country. Mean speeds greater than about 5 m/s (about 15 km/h) inhibit take-off, which ten occurs in the lulls between gusts. Because the flight speed of an individual, about 3 m/s, is often less than the wind speed, flying locusts are usually taken downwind. Because swarms often roll across country, with part settled at any one time, their speeds are never greater than, and usually only a small fraction of, the mean wind speed in the layer from the ground to swarm top. During sunny weather, when swarms tend to be cumuliform owing to atmospheric convection, tops reach one or two kilometres above the ground, but seldom higher because the air there is too cool for flight. Towards sunset, or in cloudy weather, swarms tend to be stratiform and close to the ground.

Daily flight durations are often 5-10 hours in warm weather, leading to daily displacements of 100-200 kilometres in a week occur. Downwind displacements of several thousand kilometres between seasonal breeding areas are common - e.g., Sudan to Morocco, or India to Yemen. In the presence of moving atmospheric disturbances, however, displacement trajectories are more complex. They can be markedly different from that expected from the average wind flow for the time of year; and loops can result in zero displacement after several days flying. In the cooler months, northward movements are particularly extensive on spells of warm southerly winds ahead of eastward-moving disturbances.

Where wind direction has a regular diurnal variation, as near coasts and mountains, trajectories can be saw-toothed. Sea breezes usually prevent day-flying swarms from moving out to sea, but strong off-shore winds can take swarms to distant islands (e.g. Cape Verde Islands and Canary Islands), although many individuals may drown on the way. Persistently convergent winds bring swarms closer together and may lead to merging, but such winds do not seem able to form swarms out of scattered populations - density changes are too great. Spreading downdraughts from rainstorms can temporarily trap moving swarms; moreover, swarms do not always move when winds and temperatures allow - hence there may be other, as yet unknown, environmental controls.

Solitary (non-gregarious) locusts fly at night, but flight duration, and therefore displacement distances, are poorly understood. Surface winds at night can be light and unrepresentative of winds at flying heights. If there is a night-time wind acceleration near the top of the temperature inversion (a so-called low-level jet) then downwind displacement may be several hundred kilometres in a night, leading to surprise infestations in areas previously clear.

In any one year, only part of a seasonal breeding area becomes infested because not all winds may be favourable for bringing locusts there from their sources; moreover, subsequent rains may be inadequate. The sequence of events during build-up has been different in each of the few plagues that have ben examined in detail. Plague decline occurs naturally through failure of rains or windborne movement out to sea, but there are probably other reasons, as yet unstudied, e.g., predation, parasitism, and reduced fecundity after many gregarious generations. Whether control has been more than just a contributory factor in Desert Locust plague decline is still matter of debate.

5.3.2 Migratory Locust (*Locusta migratoria*)

This species occurs widely over the plains of Africa, Europe, central and souther Asia, and Australia, but plagues have originated from limited and well-defined areas of flood plains, the deltas of some major rivers and some areas of impeded inland drainage. The last plague in Africa (1928-41) started in the flood plains of the central Niger River, in Mali, subsequently spreading all over sub-saharian countries.

Seasonal rains generally allow two generations, but more often only one near the cool northern limits of its range, where the winter is spent as dormant eggs in the soil. The retreating floods of the central Niger River provide a large habitat for two further generations during the dry season. It is this particular geographical occurrence of out-of-phase seasonality of rains and flooding that probably determines the source of African plagues. In other parts of the distribution area, drought years lead to crowding on the flood plains as water levels fall, and hence an association with swarm formation and even plague initiation.

Locust movements within the flood plains are not always related to winds, perhaps because solitary (non-gregarious) locusts fly at night and they may avoid spells of strong winds. During plagues, however, judged by studies of the last plague in West Africa, swarms fly by day and are taken downwind in the same way as the Desert Locust, travelling over 100 kilometres in a day. As a result, movements are generally northeastwards during the monsoon and southwestwards during the harmattan (trade wind) season, leading to an ever-wider distribution. The greater latitudinal range of movement than around the flood plain sometimes allows three generations in a rainy season. In Australia, swarms have appeared in Queensland following scrub clearance. Similarly in Philippines, plagues have started in Mindanao where grasslands have followed forest clearance. Swarms from there have spread across the archipelago, even crossing the sea to reach Taiwan.

Considerable reduction of flood plain habitats, resulting from agricultural development, has greatly reduced the risk of plagues in some outbreak areas, e.g., the central Niger River and the Yellow River flood plain of eastern China.

5.3.3 Red Locust (*Nomadacris septemfasciata*)

This species is confined to Africa. As with the Migratory Locust, swarms develop in flood plain grasslands with impeded drainage. Plagues originate only from limited outbreak areas in eastern Africa. During the last plague (1930-44), swarms spread from there to reach most countries south of the Sahara.

Development is slower than in the previous two species, so there is only one generation a year. Adults remain sexually immature during the dry season, followed by a long maturation period with onset of the next rainy season. Egg laying and hatching are therefore not synchronised. Swarms fly by day but near the ground. They are taken downwind, but flight duration seems to be only a few hours so daily movements are only a few tens of kilometres. This flight behaviour, contrasting with the two previous species, may be related to an apparently higher flight threshold temperature.

Attempts to control the Red Locust by reducing the size of its flood plan habitats in eastern Africa have been unsuccessful.

5.3.4 Brown Locust (*Locustana pardalina*)

This species is confined to southern Africa. As with the Desert Locust, there are no outbreak areas but, unlike that species, its eggs are drought resistant, and indeed some eggs laid by solitary Brown Locusts remain dormant for up to a year or more. In this way it takes advantage of the erratic rains of the Karroo, in southwestern Africa, where it thrives. However, adequate rains can lead to as many as three generations in a season. When swarms form they are day-flying, travelling downwind over 100 kilometres in a day, and spreading as far as 16°N. Because of control measures, swarms are now rarely encountered, although large and damaging non-swarming populations still occur.

5.3.5 Moroccan Locust (*Dochiostaurus maroccanus*)

This species occurs widely in the semi-arid areas of the Mediterranean basin, and eastwards to Afghanistan. There is one generation a year, developing on the abundant vegetation following winter and spring rains, and the new generation appears in early summer. Swarms fly by day but movements are local and long-distance flights are rare. Drought-resistant eggs are laid during the summer and lie dormant until hatching in the following spring. Its economic importance as a pest has declined because expansion of agriculture has generally reduced the availability of egg-laying sites.

5.3.6 Bombay Locust (*Nomadacris succincta*)

This is a species of southern and southeastern Asia. Sometimes it occurs in large numbers, particularly in areas of forest cleared for cultivation, but it has been seen to swarm only in India, and even there not since 1927. Like the Moroccan Locust, it has one generation a year, but overwintering is in the immature adult stage, with egg laying at the beginning of the rains.

5.3.7 Australian Plague Locust (*Chortoicetes terminifera*)

This species is confined to Australia. Outbreak areas occur in the semi-arid interiors of Queensland, New South Wales and Western Australia. Widespread spring rains there cause overwintering eggs to hatch. Plagues develop rapidly (in 2-3 generations) and frequently (almost every other year, on average) but they are short-lived.

Swarms fly by day in light winds and near the ground; with flight speeds similar to the Desert Locust, such winds lead to small daily movements (10-20 kilometres) in comparison with other species. Long-distance movements, in contrast, take place at night, when non-swarming populations fly at heights up to a kilometre above the ground. Those moving on spells of warm north winds ahead of eastward-moving disturbances can travel several hundred kilometres in a night and rapidly reach the crop-growing areas of the southeast, where they may reach swarms and nature quickly on the rains accompanying the disturbances. Sometimes they cross the sea to Tasmania. Movements westward are also possible but they have been poorly recorded.

5.3.8 South American Locust (*Schistocerca cancellata*)

This species is confined to South America east of the Andes between about 17°S and 43°S. Like the Desert Locust, it requires moist soil for egg laying. Because there is a single, but long, season of erratic rains over most of the invasion area, breeding is seasonal, with usually two generations in a year. Winter, the dry season, is passed as sexually immature adults. Plague outbreak areas are in the drier, western part of the invasion area, but breeding can occur anywhere over vast plains as well as in the inter-montane basins of the west.

Swarms fly by day, when air temperatures exceed 20°C, but less in sunny weather. In hot weather, swarms are cumuliform and tops can extend to more than one kilometre above the ground. In all but light winds, swarms are taken downwind. During the winter, low temperatures greatly restrict movement, but in spring longer flights become more frequent, particularly in spells of warm north winds ahead of eastward-moving disturbances. Maturation can be delayed for many months but egg laying starts where locusts meet soils wetted by early rains. Locusts of the new generation spread widely and breed again. By the time the second generation is flying wind directions are less variable. A semi-permanent summertime heat low is present them, centred over northwestern Argentina, and swarms tend to be taken towards it, not only from Argentina but also from any neighbouring countries that may have been invaded, but some may not reach there before lower temperatures again restrict flight. Although there is a considerable redistribution of locusts during the year, there is a region of northwestern Argentina where the species is always present.

Plagues have been frequent in the past but control of swarms in recent years has prevented their development.

5.3.9 Sahelian Tree Locust (*Anacridium melanorhodon*)

This species is confined to the open woodland of the Sahel, as well as eastern Africa and the Arabian peninsula. As with the Bombay Locust, there is one generation a year, with the dry season being passed in the immature adult stage. Eggs are laid in moist soil at the beginning of the rains. Hoppers and adults feed on trees, and at night. Swarms fly by night, but little is known about distances flown although individuals have been caught more than 100 kilometres out to sea.

5.3.10 Senegalese Grasshopper (*Oedaleus senegalensis*)

This species, which can occur over an area as vast as that of the Desert Locust, seldom produces swarms, but severe damage is threatened in years when large numbers appear. It has been studied extensively in West Africa, where three generations develop on the monsoon rains, each in a different latitude zone between 10°N and 18°N, and each taking about two months. The first generation appears in the south following early rains. It develops from eggs that have lain dormant in the soil during the dry season. Resulting adults are taken at night on the southwest monsoon winds and breed further north. The resulting second generation is also taken downwind, to breed in the northern parts of the invasion area. When the third generation is ready to fly winds have reversed to the northeast harmattan (trade wind) and the habitat is drying out. Adults are therefore taken south (sometimes out to sea) and females are triggered by shortened day length to lay eggs that stay dormant through the dry season, some of them up to several seasons.

5.4 METEOROLOGY FOR LOCUST CONTROL

The aim of locust control is to prevent the appearance of numbers large enough to cause serious damage to crops and grazing. Preventing a plague, or at least reducing the size of a plague that has started, is particularly important because of the huge numbers involved and their great mobility. Although the effects of weather on locusts vary somewhat between species, as the previous paragaph has shown, the main effects are clear. **Rainfall** largely determines the extent and intensity of breeding. **Temperature** affects the rate of development of all stages in the life cycle - eggs, hoppers and adults - as well as the duration of flight. **Wind** affects the direction and speed of locust flight and the tactics of spray application from an aircraft or a ground vehicle.

It follows that locust control services can plan monitoring, forecasting and control more effectively by making use of meteorological information for estimating:

(a) Where breeding is likely to occur;

(b) When the next generation is likely to be flying;

(c) Where and when that generation is likely to reach areas at risk of invasion;

(d) Effects of weather on logistics of control - the moving of staff and materials as well as the application of insecticide sprays against hoppers and swarms, both on the ground and from the air.

The following meteorological information can be used for making these estimates.

5.4.1 Rainfall

Daily and weekly (or 10-daily) totals from gauges within areas where locusts are known or are likely to be present. If these areas are unknown, gauges from the whole locust are within the nation may be needed. Daily totals are more valuable than weekly ones because they increase the precision of estimates of timing of breeding. Records are needed promptly because the locust life cycle can be as short as to months. Evenso, late reports are still valuable for subsequent reassessment of events. So, too, are monthly totals, which may not be available from some gauges until breeding has finished.

Satellite-derived estimates of rainfall (usually 10-daily). Although their reliability varies geographically, they are valuable because from the gauge network. In areas of few or no gauges, they may be the only source of quantitative information.

Warnings of the occurrence of widespread heavy rains and run-off that might contribute to a plague upsurge. Such rains are often associated with readily recognisable synoptic weather systems, on either surface or upper charts. The warnings may add considerable to field reports from the control service's own staff. (Areas and quantities that are critical can be agreed in advance with locust control services).

Warnings of the occurrence of a sequence of widespread and heavy rains spaced about one generation apart. They can be particularly useful is assessing the likely number of generations in a rainy season, and hence the rapidity of plague development.

Warning of continuing poor rains in drought years. They can help in the assessment of risk of a plague developing in those species that breed on contracting flood plains.

Forecasts of widespread and heavy rain likely in the coming few days. They can provide valuable preparation time for control teams in the field.

5.4.2 Temperature

Daily mean temperature, for calculating development rate and the date when flight of the new generation is likely. Soil temperature at egg depth is preferable for egg development calculations, but an alternative is screen-level temperature, where its relationship with development (both eggs and hoppers) is known. Again, prompt delivery is essential if the calculations are to be made in time for the results to be useful. But late reports can be used in any subsequent reassessment of events.

Daily maximum temperature, for calculating flight duration of swarms.

Daily temperature at sunset (or the nearest synoptic hour), for estimating the possibility of take-off by non-swarming locusts before long-distance night flights.

Warnings of the occurrence of spells of temperatures markedly different from the seasonal mean - they may indicate an increase or decrease of either development rate or flight duration.

Warnings of the occurrence of temperature persistently too low for development - they are useful for estimating prolonged development, particularly by overwintering eggs or adults, with implications, for example, in timing the deployment of control teams in the field.

5.4.3 Wind

Daily maps of the windfield, for estimating the direction and (in combination with estimates of flight duration) distance of daily swarm movements. A representative time would be the nearest synoptic hour to 1200 or 1500 local time. The surface map would be suitable on most occasions, but the 850 mb map would be needed when high daytime temperatures encourage flight within a deep layer of the lower atmosphere, or when swarms are in mountainous country (where the 700 mb map may be more appropriate).

Daily maps of the windfield at 500 m above the ground at night for estimating direction and distance of night fight. A representative time would be the balloon-sounding time nearest to midnight. In its absence, daily maps of the windfield at sunset would be a substitute, particularly if some guidance can be given on the likely diurnal variation up to dawn at flying heights. A less reliable substitute would be a daytime map.

Warnings of the occurrence of persistent and strong coastal winds blowing from land to sea - they may carry large numbers of locusts to islands or to mass drowning.

Warnings of the occurrence of spells of winds markedly different in direction and/or temperature from the seasonal mean - they may indicate the occurrence of unusual or unprecedented locust movements to areas not usually at risk or at risk earlier than normal.

Forecasts of disturbances accompanied by such winds, particularly spells of warm poleward-blowing low-level jets (south in the northern hemisphere, north in the southern hemisphere) ahead of cold fronts, known for their associated long-distance and rapid movement of swarms by day and of non-swarming locusts at night.

Forecasts of winds for spraying. The aim of **air-to-air** spaying of a flying swarm is to release a cloud of droplets just unwind. Because the swarm moves slower than the wind, the cloud passes through it, from rear to front. Early and late in the dat are the best times, when swarms are densest. The aim of **air-to-ground** spraying (ob both adults and hoppers) is to place the minimum necessary insecticide on the vegetation and locusts, not on the ground where it would be wasted. Spray is applied across wind but avoiding turbulence, so again early and late in the day are usually the best times. **Ground-to-ground** spraying for hopper control is in the form of strips on the vegetation laid across wind, again avoiding turbulence.

This list includes advice (warnings and forecasts) as well as data. Most, if not all, should be available routinely within national meteorological services or through international exchange, not just from agrometeorological sections but also from aeronautical sections. Hence, additional resources are not needed to provide this information to locust control services. Indeed, a locust control service is an example of a user of meteorological information whose requirements can be met largely with standard products. The type, amount and frequency of information can be agreed in advance between the two services. How far such information is currently provided is assessed in paragraph 5.5, based on replies to a questionnaire.

5.5 CURRENT USE OF METEOROLOGICAL INFORMATION FOR LOCUST CONTROL

In an attempt to survey the current use of agrometeorological information in countries at risk of locust infestations, a questionnaire was sent to 119 Members of the WMO Commission for Agricultural Meteorology. These Members were selected on the grounds that there had been infestations of locusts at some time in the past. Of the 27 replies, 13 stated that either there were no locusts and therefore no meteorological input to control, or outbreaks were so rare as not to warrant any input. In one country a forecasting service is currently being built up. An analysis of the remaining 14 replies follows. Further valuable accounts of the operational provision of information by 8 Members has already been published by WMO - CAgM Reports 36 (1991) and 53 (1992).

5.5.1 Reports and guidance material used in the preparation of agrometeorological information for locust control

Nine Members use locust situation bulletins prepared nationally, regionally or internationally (FAO), but five not use such bulletins. There was no mention of any guidance obtained from publications describing either the effects of weather on locusts or the use of meteorological information in locust control.

5.5.2 Information provided by locust control

All 14 Members provided information, usually at 10-day, 15-day or monthly intervals, or when requested. In one of them, synoptic reports and charts, and satellite imagery were provided 3-hourly. Members providing information were:

climatological normal	13
current synoptic reports	11
climatological charts	9
synoptic charts	9
forecast charts	9
satellite imagery	8

5.5.3 Organizations receiving information

The principal recipients were:

national plant (crop) protection (production) departments (services/divisions/organizations)	12
regional locust control organizations	4
other regional organizations	3
FAO	2

Information was sent mostly by fax (6) or mail (6), and rarely by messenger (2), radio (1), telephone (1), telegram (1), or e-mail (1). It was used to assist in monitoring, forecasting and controlling locusts, usually more than one species in a given country.

5.5.4 Arrangements for the preparation of information

Several members listed particular arrangements that had been made for the preparation of information. They included:

(a) Reception by fax of forecast winds and trajectories from global numerical models;

(b) Reception by PC-based station of satellite images;

(c) Comparison of 10-day rainfalls with normal and dry years;

(d) Temporary installations of observing stations in areas of swarm movement.

5.5.5 Training in the use of information

Six Members provided training of locust control staff in the use of agrometeorological information, but 8 did not. Of the 6 members, 5 provided lecturers from the meteorological services who spoke about the use of regular bulletins or of satellite imagery. One relied on seminars or workshops organized internationally.

5.5.6 Operational use of information

Members were asked to provide examples; 10 out of the 15 did so. They included:

(a) Climatological charts for specific months;

(b) Location of breeding areas in specific months;

(c) Modelling of locust phenology;

(d) Advice on specific invasions.

Concerning the value of the information provided, 4 said or implied that operational locust control would be impossible in the absence of the information. Others did not state the value, although 1 admitted to being "not sure". It is for users to judge the value.

Seven Members responded to a request for recommendations to improve the information provided. They included:

(a) Greater coverage of observing stations, including automatic stations;

(b) More frequent interactions between meteorological and locust control services, through training;

(c) Use of expert systems;

(d) Improved electronic access to data;

(e) Improved weather forecasts;

(f) Improved interpretation of satellite imagery.

These recommendations were made despite only 1 Member reporting difficulties encountered when arranging the preparation of information.

5.5.7 Research in locust monitoring, forecasting and control

Of the 14 Members replying, only 6 reported any research projects. They included:

(a) Case studies of breeding and swarm movement;

(b) Improvement of locust development models.

Three Members did not specify projects.

5.5.8 Other information of use for locust control

In response to a request for additional information, 8 Members responded. Their comments included:

(a) Publications giving results of studies by other Members or by WMO and FAO were needed;

(b) Data bases of locust outbreaks and corresponding meteorological situations would be valuable;

(c) Better understanding of drought is needed;

(d) Better satellite monitoring of breeding areas is needed.

5.5.9 Users views on the information provided

In an attempt assess the value users place on the agrometeorological information provided to them, users in the 14 Member countries responding to the questionnaire were asked for their views on that value and on any recommendations for improvements. Of the 14, 6 replied. They agreed that the information was essential to the planning and execution of locust field monitoring, forecasting and control, but various deficiencies were recognised and the following improvements suggested (not in any order of priority):

(a) Closer working relations between national meteorological services and locust control services;

(b) Provision of information in user's language;

(c) Provision of additional meteorological observing stations in remote locust breeding areas to complement the existing network, which is based mainly on urban centres;

(d) Better distribution of existing satellite-derived products (including Early Warning bulletins) from neighbouring countries and regional agencies;

(e) Provision of PC-based satellite receivers for high-resolution cloud and vegetation maps;

(f) Assistance in the preparation of high-resolution rainfall maps;

(g) Improvement of existing trajectory models.

5.5.10 Discussion of current use of meteorological information for locust control

Some Members have been providing information to locust control services for a decade or more. They have evolved collaborative and effective systems to reduce the threat resulting from swarm invasion. Accounts of these systems are given in CAgM Report No. 36. But replies to the questionnaire revealed deficiencies elsewhere. Five of the 14 Members replying did not use locust situation bulletins in the preparation of agrometeorological information for locust control. Although they provided some routine agrometeorological products, the implication hee is that there is some lack of appreciation of the types of information needed. This implication is supported by:

(a) The almost complete absence of use of publications as guidance to the information needed;

(b) The few comments made on the value of the information to users.

Climatological normals and charts are widely provided. They are certainly useful for understanding the long-term seasonal dynamics of locust populations and for long-term planning of deployment of funds, staff, equipment and other resources. However, as made clear in paragraph 5.4, 3 **daily** synoptic data and charts, supplemented by satellite imagery and forecast charts, are essential for understanding the day-to-day developments of locusts populations, particularly breeding and movement. Whereas 11 Members provided synoptic reports and 9 provided charts, they were almost always at 10-day, 15-day or monthly intervals. Only 1 Member reported provision daily. (However, the value of daily meteorological information during the invasion of Maghreb countries in 1987 and 1988 was graphically emphasised in accounts included in CAgM Report No. 53).

There seems to be a serious lack of appreciation of the fundamental importance of the daily availability of the information that is essential for maximum precision when estimating onset of breeding, duration of development to flight, and direction and distance of movement by flight. Such estimates are essential for tactical deployment of control measures based on effective monitoring of locust development and on timely forecasting of movements. It has already been said that most, if not all, of the information should be available routinely.

These implications, concerning apparent lack of appreciation by some Members of:

(a) The kinds of information needed by locust control services;

(b) The critical importance of daily information;

highlight an urgent need for improved interaction between meteorological and locust control services of some Members - a point emphasised by 1 Member and 1 user. Such interaction should include training of locust control staff, as is already undertaken by meteorological staff of 6 Members.

Despite an almost complete absence of reported difficulties encountered when preparing information for locust control, it is clear that there were serious constraints on the quality of information that could be provided. These constraints arose from:

(a) Lack of sufficient meteorological data from critical areas, either from lack of observing stations or intermittent failure of communications, nationally or internationally;

(b) Inadequacies of weather forecasts and of interpretation of satellite imagery;

(c) Lack of access to electronic data bases and expertise.

Removing these constraints is probably outside the capacity of some meteorological services. However, improvements are possible through regional and international assistance, particularly by provision of:

(a) Additional meteorological observing stations, preferably automatic with transmission via satellite;

(b) Improvements in communication links, both within and between countries;

(c) Forecasts and trajectories from global numerical models by fax;

(d) PC-based satellite receivers, geographical information systems and expert systems.

Meteorological services have recently started to assist in the reporting the presence of Locusts at synoptic stations through the introduction of coded messages added to routine synoptic reports.

5.6 RECOMMENDATIONS FOR IMPROVING THE USE OF METEOROLOGICAL INFORMATION IN LOCUST CONTROL

Some Members have provided agrometeorological information to locust control services for a decade or more, with fruitful collaboration to identify both the information needed and how it is best used. However, the survey shows that other Members could improve the information they provide. The following recommendations are intended to show how improvements can be made. They support the recommendations made by the Tunis workshop of 1988.

Where national collaboration does not exist, formal arrangements should be made to make clear what agrometeorological information is needed by the national locust control service, how it can be provided to users in the fields, and how operational decisions based on it are made to undertake not only field monitoring and forecasting but also the planning and implementation of control. The kinds of information needed will vary between countries, depending principally upon locust species and resources available to both meteorological and locust control services. Paragraph 5.4 outlined the usefulness of various kinds of information almost all of which is, or can be, produced routinely, either by agrometeorological or aeronautical sections, but there is a need to improve means of sending the information to users in the field in a format they can act upon.

Staff training - of meteorologists in the use of locust reports, and of locust staff in the use of meteorological information - should be undertaken in all countries prone to locusts so as to improve awareness of the need for collaboration. It would also clarify and overcome difficulties in the provision and use of information - e.g., insufficient data, poor communications, late delivery, wrong format. Traning could be by brief detachment of meteorologists to locust forecasting and control centres for informal in-service collaboration. Practice could be arranged through exercises during recession periods using records from a previous plague. Such training has been undertaken internationally in the past; its effectiveness needs to be assessed.

Some Members have published their experience in the operational application of meteorological information to locust control. This includes, e.g., outlines of operational procedures and how they changed in the light of experience, as well as methods to assess the relevance of information. Other Members should be encouraged to publish their experiences, in collaboration with national locust control services. In this way a body of guidance materials can be built up and all Members can benefit through discussion of how operational difficulties were identified and overcome.

Published accounts of the use of meteorological information in locust control need to be available to both meteorological and locust control services in all Member countries threatened by locusts. Some of these have been distributed widely in the past but there is little evidence of their use.

Some potentially useful routine synoptic observations are not being made available regularly, either nationally or internationally. Communications failures, resulting in missing synoptic data, sometimes at critical places, need to be reduced.

Further consideration needs to be given to installation of automatic weather stations reporting by satellite from remote locust breeding areas.

The distribution of existing satellite-derived products could be improved, both internally and from neighbouring countries and regional agencies. These include imagery of clouds, estimated rainfall and vegetation, as well as Early Warnings. Meteosat is used internationally for cloud imagery of Africa and western Arabia but Insat is not available for the remaining, eastern part of the Desert Locust area. 1 km vegetation imagery from NOAA satellites should be made available directly using PC-based receivers to aid location of the sparse vegetation upon which locusts live.

Further research needs to be undertaken and published to improve:

(a) Understanding of the effects of various kinds of weather systems on locust breeding and movement;

(b) Estimation of rainfall amount by satellite remote sensing over locust breeding areas;

(c) Use of PC-based electronic data bases for locust and weather information, with expert systems to assist forecasting locust development and movement;

(d) Application of trajectory models to forecasting swarm movements.

Much of this research requires international cooperation, but case studies of particular locust events can be undertaken nationally. Existing unfinished case studies need to be completed. Research methods are described in already published case studies for the Desert Locust but they need to be applied to other species.

5.7 REFERENCES

Centre for Overseas Pest Research (1981). Desert Locust Forecasting Manual, vols. I and II. London.

Natural Resources Institute. (1988). Locust Handbook, 2nd edition. Chatham, UK.

WMO/IESCO (1993). Reference manual of WMO Codes for Transmission of Pest Locust Data.

FAO (1994). The Desert Locust guidelines: 1. Biology and behaviour.

Centre for Overseas Pest Research. (1982). The locust and grasshopper agricultural manual. London.

WMO (1991). Meteorology and Locust Control Contributions by National Meteorological Services. CAgM Report No. 36.

WMO (1992). La météorologie au service de la lutte anti-acridienne. Contribution d'un Service météorologique national. CAgM Report No. 53.

WMO (1963). Meteorology and the migration of Desert Locusts. Technical Note No. 54.

WMO (1965). Meteorology and the Desert Locusts. Technical Note No. 69.

WMO (1988). Workshop on meteorological contributions to locust control. Tunis. (unpublished report).