Monitoring of Rainfall in Relation to the Control of Migrant Pests [and Discussion]

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Monitoring of rainfall in relation to the control of migrant pests

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Of all climatic parameters, rainfall has the greatest variability in space as well as time. It also has the greatest influence on the breeding and behaviour of migrant pests, supplying the moisture needed both for their development and for the growth of vegetation to sustain a population. Soil moisture controls both processes directly but cannot be adequately surveyed even by remote sensing techniques, so we rely upon water balance models to interpret rainfall measurements and to forecast pest populations.

Both terrain and rainfall are very inhomogeneous on the kilometric scale, a scale which is not matched by observations either from conventional raingauges or current meteorological satellites. Modelling the effects of rainfall must take account of these inhomogeneities, and the processes involved will be discussed. However, it is clear than more detailed studies of rainfall–habitat interaction are needed to derive soil moisture from rainfall estimates by using knowledge of the microtopography. Such relationships must be capable of being generalized so that future monitoring by satellites, essential to give complete and uniform coverage, can be realistically interpreted.

1. INTRODUCTION

Knowledge of rainfall, or any other meteorological variable, is only one among many information inputs to the complex decision-making system which is involved in the monitoring and control of migrant pests. The aim of the system is to find, at the earliest possible time, those populations of pests which will increase to significant proportions. Locating such populations is the major problem in operational crop protection against migrant pests (World Meteorological Organization 1988), and for this purpose the meteorological information, together with a variety of biological and geographic information, must be fed into a model which incorporates what is known of the processes governing the population dynamics and also migration. The aim of such a model is to predict the pests' behaviour, and so to maximize the chance of discovering swarms with the minimum of effort.

To make the complex information/decision-making system as efficient as possible, we must first identify the information requirements, and the characteristics of the information which is available. As these never fit the initial statement of the ideal requirements an iterative process ensues, in which supply and demand are progressively modified until they match as well as possible. This paper discusses this matching process for information on rainfall in relation to the search for, and the prediction of migrant pests, with particular reference to the Desert Locust in Africa and Arabia. In this case rainfall is the meteorological factor whose variations are predominant: temperature and humidity are also important, but they vary less dramatically and are in any case often closely correlated to rainfall variations. In the migratory periods wind observations are clearly vital, but they play a relatively minor part in the dynamics of the build-up of local plague populations.

2. REQUIREMENTS FOR RAINFALL INFORMATION

Rainfall itself is not, of course, a very important parameter in pest prediction; what we generally need to know is the moisture distribution in the uppermost 300 mm or so of the soil, and, if it were possible to map this, we would have the information we need directly. However, this is not a realistic prospect, for even the most ardent proponent of microwave remote sensing will not promise to provide information with the required discrimination and spatial resolution from operational satellites within the next decade or two. For the foreseeable future we must continue to rely on observations of rainfall amounts as the input to soil moisture models, although there may be special circumstances where information on surface wetness may be both attainable and of interest.

As has been known for a long time (Popov 1958), water equivalent to about 20 mm of rainfall must be present in the typical, sandy soils of the relevant regions, to induce female Desert Locusts to lay their eggs, and then for these to absorb sufficient moisture for hatching to take place. The rate of development of the eggs decreases quite rapidly with temperature, but so does the rate of evaporation, and the initial quantity of water required in the soil to lead to successful hatching may not vary greatly. The other water requirement before a population can expand is for the growth of vegetation to sustain the emergent hoppers. Where no substantial vegetation is present at the time of laying, a minimum available soil moisture of 20 mm or so of rainfall is again a suitable threshold level to support vegetation development sufficient to give a risk of population expansion.

3. RAINFALL OBSERVATIONS

Until recently, the only method available for the measurement of rainfall was the raingauge. If it is well sited and maintained a raingauge can tell us the amount of rain which has fallen at that point with an accuracy of around 5% (HMSO 1981; Robinson & Rodda 1969). What is less well known is what the gauge can tell us about the rainfall distribution in the surrounding area. In detail, this depends on the climatological characteristics of a region, in particular the nature of the rain-producing systems. From observations made with a dense, regular network in Niger we derived figure 1, which shows the best estimate of the rainfall from a single storm, averaged over a square of increasing area centred on a gauge. Also shown are the confidence limits associated with this estimate which are substantially independent of the rainfall amount (Flitcroft *et al.* 1989). If the gauge departs from the centre of the area, or the area is enlarged, the 'corrections' to be applied increase. However, this result cannot be extrapolated far because of the assumption included in the underlying model that all points in the area considered have experienced some rainfall.

Up till now, it has been customary to estimate the rainfall at a particular point within a raingauge network by interpolation between the observed values, more or less regardless of the time and space scales involved. Given the variability within individual storms, and the rarity of rain events in many of the areas of our current concern, the assumption of continuity that lies behind this isohyetal analysis is dangerous even for seasonal total rainfall. For individual rain events, the rate at which the correlation between station rainfalls decreases with separation (figure 2) shows that for sites more than 20 km or so from a gauge the best estimate of a daily fall may be the mean rain per rainday, established from climatology, and not the fall recorded

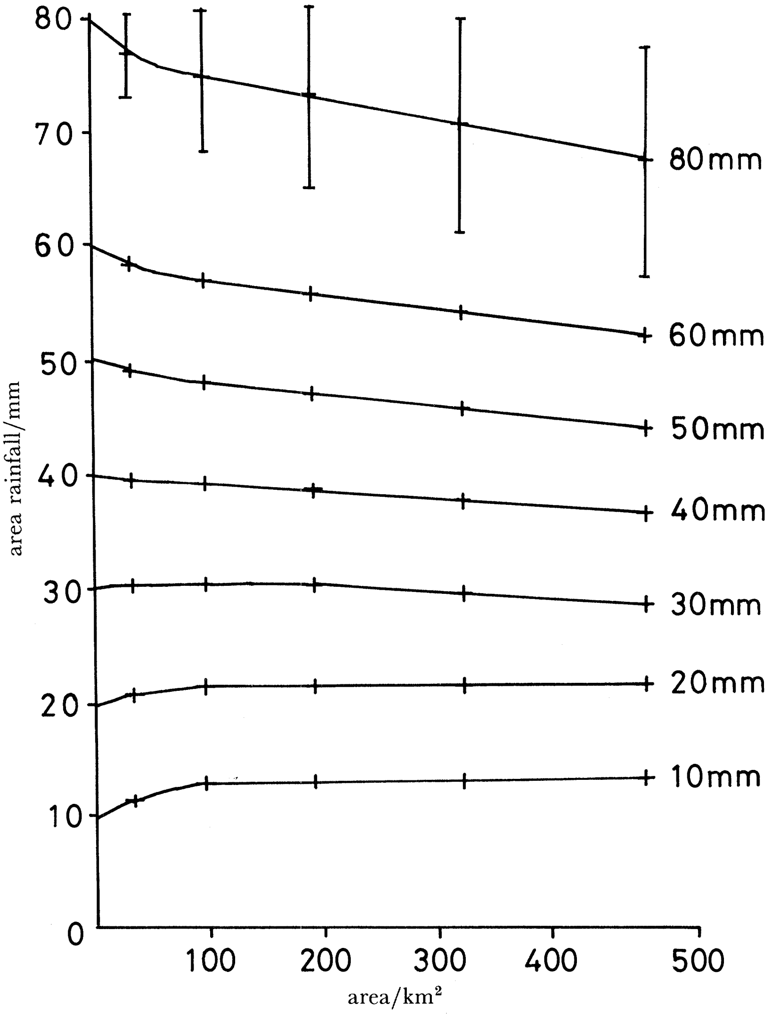

FIGURE 1. The best estimate of area average rainfall for a single storm for an area centred on a single raingauge, shown as a function of the size of area and the rainfall. The error bars include 90% of cases for recorded falls of 80 mm (after Flitcroft *et al.* 1989).

at the nearest gauge. Some of the results of comparisons between satellite estimates and gauged amounts of rain confirm this warning (Snijders 1990). The rate of decay of correlation with distance, shown in figure 2, affects the quantitative results, including those of figure 1: however, calculations (not reported here) based on samples of data from other dense networks suggest that figure 2 is not typical of seasonally or semi-arid regions of Africa, where the majority of the rain comes in heavy falls from deep convective cloud cells (Sumner, 1983). An accurate account of the sporadic rainfall, whether for monitoring water resources or migrant pest potential, thus requires an impracticable number of gauges, higher even than the 1 per 1000 km^2 recommended by WMO (1983). An additional requirement is for daily reports, implying also an unrealistic network of communications.

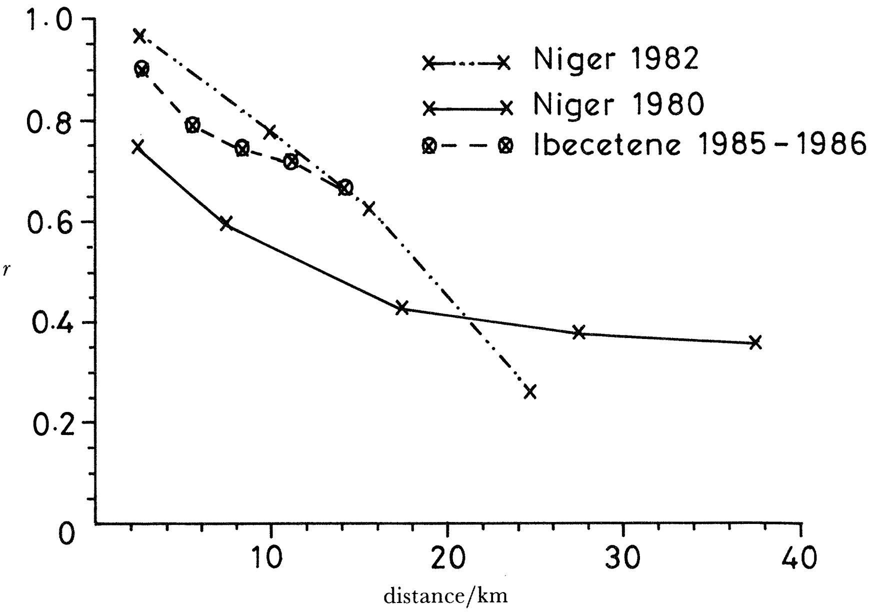

Figure 2. Correlation between daily rainfalls recorded at gauges with increasing separation in Niger. Each point is the average of a number of pairs of stations within certain distance intervals. Only occasions when rain fell at both stations are included (after Flitcroft *et al.* 1989).

4. Rainfall estimates from remote sensing

To gain an overview we must turn to remote sensing from satellites, which provide impartial and simultaneous data but never the actual information which is required. The potential and limitations of the methods available have been reviewed broadly by Barrett & Martin (1981) among others. More recently we have reviewed the current state of operationally established rainfall estimation over Africa and its neighbours (Milford & Dugdale 1990), which relies almost entirely upon the statistical relationships between cold, deep cloud and rainfall. The optimum threshold to use for classifying a cloud as 'cold', and the regression parameters to use, depend on the region of interest, the time of year, and possibly other variables such as cloud type and characteristics of the season so far, which have yet to be parameterized effectively. In spite of this, such rainfall estimates are being used to provide hydrological information as a routine, and also inputs to food early warning systems, such as that in the Sudan. We now describe the information which may be obtained from such systems if they are optimized for migrant pest monitoring and control purposes.

The requirement that a system be fully operational makes it very desirable to acquire the data from the satellite and process it automatically, and to pre-calibrate all numerical steps. In the case of short period rainfall, frequent views are needed, and this limits us at present to geostationary satellites, such as METEOSAT which is located some 36000 km above 0° N, 0° W. Currently the only input to our rainfall estimates is the thermal infrared (TIR) channel on Meteosat: the addition of data from the water vapour band (5.7–7.1 μm) has made only small improvements to the accuracy of the final outputs (Turpeinen *et al.* 1987), and too much of the storm activity occurs at night for the visible channel to make a useful contribution. While Meteosat provides the area coverage and hourly images which we need, well registered by European Space Operation Centre (ESOC) before they are retransmitted, the spatial resolution is limited to 5 km at nadir, and about 7 km near the horizon in Saudi Arabia, for instance. The latter area is also covered by the Indian satellite INSAT, a similar satellite around 70° E: if the INSAT data were available for general use, combining the two data sets would give improved information in principle.

Although the rainfall estimates are being made within the Africa Real Time Environmental Monitoring using Imaging Satellites ARTEMIS system in FAO, Rome, a project primarily designed to help in migrant pest control (Hielkema, this symposium), the calibrations have not yet been optimized for this purpose for any particular area. Up till now the calibration process has consisted of collecting the durations of cold cloud (CCD), by using three different threshold temperatures, over a number of raingauge stations. Ten-day totals of CCD are compared with measured falls, first in contingency tables to select the best threshold and then by linear regression to provide a conversion from CCD to a rainfall estimate. We have found that both the threshold and the regression coefficients vary geographically. Operational programs include smoothing procedures to eliminate abrupt changes in the outputs appearing at the edges of the calibration zones, and interpolation to compensate for missing data (within limits).

The credibility of the system depends on its ability to provide useful estimates of rainfall in real time, and we therefore spend much effort on validating these in years subsequent to those which have provided the calibration data. Table 1 shows an example of the results. Even though about half the residual variance is due to the non-representative nature of the raingauge (see Flitcroft *et al.* 1989), it is still so large than the estimates are not likely to be useful as inputs to localized crop production models. Here, however, we are concerned with discriminating falls within 1–3 days above a certain threshold and figure 3 shows that we may indeed be able to provide such information with significant success. A substantial amount of time is needed to optimize the information and then to test that any preliminary result is robust enough to be used operationally.

TABLE 1. VALIDATION OF 10-DAY RAINFALL ESTIMATES, NIGER, JULY 1985, 1986 AND 1987

(Calibration used: $R = 0$ when $D = 0$, otherwise $R = 4.52D + 5.1$ mm where D is CCD in hours below −60 °C. Rainfall categories used: 0, 1–10, 11–20, 21–30, 31–40, 41–60, 61–80, 81–100, etc. in mm.)

year	number of obs	exact category	1 category out	2 & 3 categories out	> 3 categories out	% ⩽ 1 categories out
1985	327	69	106	132	20	54
1986	309	68	106	109	26	56
1987	318	60	121	109	28	57

We must recognize that the statistics based on a single radiometer channel are fundamentally limited by their inability to distinguish convective from layer cloud, specifically cirrus. Averaged over large enough areas or lengths of time this may not be too important if the ratio of the types remains constant. Texture analysis could help, but we may well have to wait for the advent of additional infrared radiometers on geostationary satellites to deal with this problem in a fully automatic system. Meanwhile, we have shown that hourly images are needed to obtain the maximum useful information from the method (Milford & Dugdale, this symposium). Direct validation of area average of daily rainfalls is difficult because of the need for many gauges in the area. Some indirect confirmation of the estimates is gained from our use of the satellite data as input to hydrological catchment models, but this is also at a relatively early stage (Hardy *et al.* 1989).

Rain	Cold cloud < 4 h	Cold cloud ≥ 4 h
< 10 mm	1488	73
≥ 10 mm	22	60

(*a*) July 1987

Rain	Cold cloud < 3 h	Cold cloud ≥ 3 h
< 10 mm	1320	135
≥ 10 mm	40	117

(*b*) August 1987

FIGURE 3. Sample contingency tables to show discrimination between falls < or > 10 mm. In July, rainfall ≥ 10 mm was measured within 1.5% of pixels showing less than 4 h cold cloud (below −50 °C) and 45% of those showing ≥ 4 h. Both tables are for stations north of 14° N and threshold −50 °C. Rainfall over a period of three days including the day of cold cloud is included.

Considerable research has been carried out on other methods of observing rainfall by remote sensing, and some of these may have useful applications in particular situations. For example, radar monitoring of rainfall can be used in the study of individual systems such as squall lines, but the limited coverage of a radar set prevents the method being viable as a general monitoring tool. Microwave instruments, whether active or passive, mounted on aircraft or satellites, are also under development but will, for the foreseeable future, give too low resolution and too infrequent views for operational use where large areas have to be monitored for brief, intense storms.

Reverting to current meteorological satellites, the Advanced Very High Resolution Radiometer (AVHRR) data from the National Atmospheric and Oceanic Administration (NOAA) satellites has spatial resolution of 1.1 km (in place of 5 km or more) but this does not make up for the poorer frequency (four observations per day at most, in place of 48). These data were the basis for an interactive scheme for anti-locust operations in northwest Africa (Barrett 1979), but the system was not used for long enough to provide independent evaluation of its accuracy. More recently, the Bristol group (Barrett *et al.* 1989) advocated the use of varying amounts of data from geostationary and/or orbiting satellites, according to the area and time span to be covered. For large areas and 10-day periods days are classified as having rain/no rain and a climatological rain/rain-day figure applied. The interactive interpretation of images, together with detailed local knowledge, may well improve localized estimates, particularly where topographic effects are substantial, for instance in the coastal strips on either side of the Red Sea.

Finally, we should refer to the possibility of observing where rain has fallen through the reduction of the amplitude of the diurnal temperature wave at the earth's surface. Much effort has been expended on the general methodology, but it has not yet been shown to be operationally viable anywhere. However, locust recession areas may offer the most favourable sites for testing the technique because of their small amounts of vegetation. The main drawbacks are the difficulty of establishing when an area is free of cloud, a small amount of which will reduce the temperature observed as an average over a whole pixel, and also the fact that the method can discriminate water in the surface layers of a sandy soil up to a few mm (Milford 1987) but cannot differentiate between 10 and 20 mm. Quantification of the reduction in amplitude is also hampered by uncertainty over the moisture content of the atmosphere, and hence in the correction to be applied to the apparent surface temperature reported by the satellite.

For an automatic system the images must be processed to reveal the changes from the minimum reflectivity in the visible, and the maximum midday temperatures, both mapped to include variations across the scene due to the terrain (rock, soil or sand for example). If information on the areas where it was probable that some rain had fallen in the previous 24 h were particularly helpful, it might now be possible to use a dedicated image processing system to alert an operator to areas which merited closer study. A combination of such a system with the cold cloud statistics may improve the chance of locating the areas most at risk from a locust population explosion. At the least, some areas may be shown with some certainty to have received no rain.

5. Moisture in the soil

We have said that it is the moisture in the soil, which is important for both locust eggs and vegetation growth. If it is known how much rain has infiltrated into the soil, and what the physical properties of the soil are at different depths, there is now little difficulty in using a numerical model to compute the distribution of water with depth at some later time (Campbell 1985).

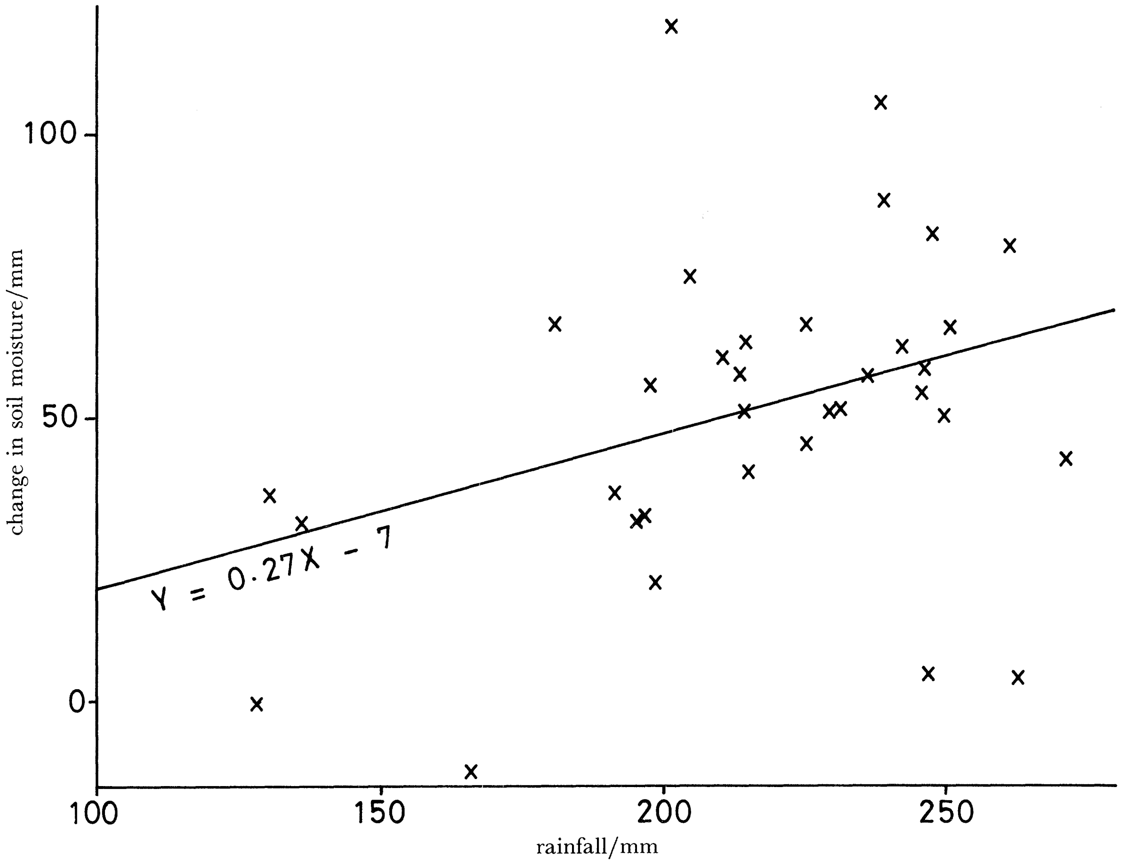

Figure 4. Change in soil moisture storage against total rainfall over an eight-week period. Observations are from a regular grid, with 2 km spacing. Ibecetene, Niger, July–August 1985.

At this stage we must consider the problems of representivity again: all quantities derived from satellite observations are averages over the pixel of the particular radiometer in use, with some blurring because no registration of images can be better than to the nearest pixel. Even if the rainfall were uniform across a pixel we would find that the amount infiltrating into the soil was not uniform. This is shown in figure 4, where the change in soil moisture storage (as measured with a neutron moisture probe) bears little relation to the rainfall measured at exactly the same spot. A subsequent experiment confirmed the importance of the local slope and surface characteristics: local run-off within the pixel scale was indeed substantial, but was reduced by the presence of vegetation, or by breaking up the 'pan' which tended to form on the surface of the sandy soil at this particular station.

6. INTERPRETATION OF RAINFALL ESTIMATES

We have discussed the use of contingency tables to select criteria which delimit areas where there was little chance that significant rain has fallen, or there was a substantial chance that rain has fallen. More detailed interpretation of the rainfall estimates from satellites is based on analyses of the spatial distribution of falls of different amounts. On a large scale, comparable to the grid squares of general circulation models of the atmosphere, we may use the variability of the cloud itself. For increasing CCD (and hence estimated area average rainfall) figure 5

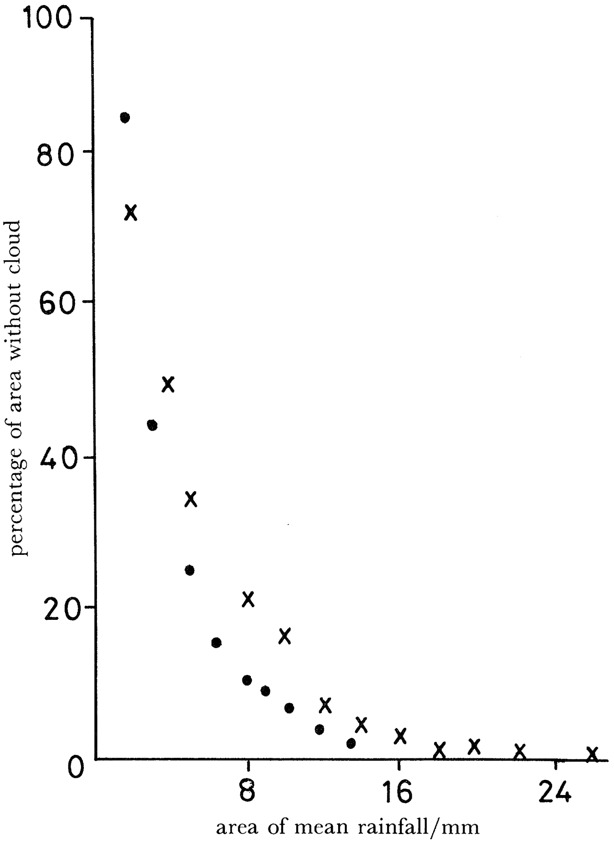

FIGURE 5. Proportion of a grid square without cloud as a function of area mean rainfall estimated from daily cold cloud duration. 200 km grid, Niger, July 1985, threshold −60 °C. 100 km grid, Niger, July 1987, threshold −50 °C (after Dugdale 1989). (×, 200 × 200 km grid (1985); ●, 100 × 100 km grid (1987).)

shows the fraction of an array of 20 × 20 Meteosat pixels which experience no cold cloud over the 24-h period, and, we assume, no rain. Figure 5 also includes figures for a 40 × 40 array (Dugdale 1989).

With each pixel cold cloud duration we associate a distribution of point rainfalls, as deduced from our dense gauge networks. The resultant distribution of point falls corresponding to mean falls over a grid square of 3, 7.5 and 15 mm are shown in figure 6 (Dugdale 1989). We see, for example, that for an area mean of 15 mm some 20 % of the area would experience a fall of 20 mm or more, sufficient to meet the criterion for locust proliferation. This result applies regardless of the source of information on the area mean.

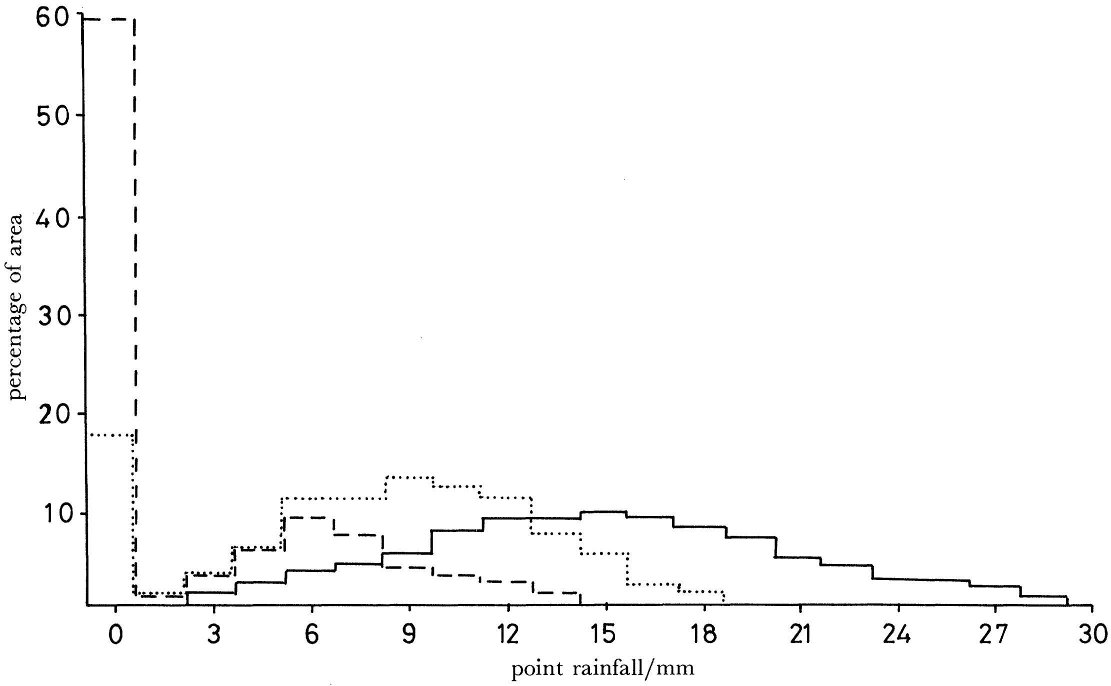

FIGURE 6. Proportion of a 100 km grid square receiving different daily rainfall amounts when area average is 3 mm (---), 7.5 mm (....) and 15 mm (—). Distributions are calculated from the distribution of cold cloud amounts for given average, and the distribution of rainfall observed for each cloud amount (after Dugdale 1989).

A further important factor which has yet to be quantified is the extent to which rainfall is concentrated into a limited part of an area by the topography, for instance where we find soil in wadis between impervious rocks. Even a light average fall over a satellite pixel may thus provide 20 mm of soil water over a fraction of the area, and therefore conditions suitable for Desert Locusts to lay, and also for vegetation growth. Relations between the rainfall, whether observed with a dense gauge network or estimated from satellite, and the range of soil moistures to be found in particular sites must be established. Vast areas have to be covered, so no doubt we must turn to remote sensing techniques to survey them. However, the interpretation of earth resource satellites with this particular purpose in mind has not yet been carried out: it is therefore apparent that studies of such rainfall–habitat interactions are needed if we are to predict the effects of rainfall in specific areas, particularly the fringes of the desert.

7. Summary and prospects

We have been discussing the means available for obtaining information on the rainfall and soil moisture content, a vital component in the prediction of the development and movement of populations of migrant pests. All the discussion on rainfall can be applied to other meteorological data to some extent, although the spatial variability of temperature abnormalities, for example, is much less extreme than that of rainfall. The difficulties of providing the actual information required for the predictive models are manifest, and there is a continuing and major task to match the information that can be supplied on a regular and reliable basis to the decision-making processes of the control operations. In every case the need for coverage on a continental scale means that optimal use must be made of satellites, both as instrument platforms and for communications. The revolutionary developments in satellite and computer technology already enable us to provide information of a quality and quantity which was unthinkable twenty years ago, and much of this is now being used in migrant pest control.

Much work remains to be done to improve the information we can provide to the teams monitoring migrant pests. Techniques for deducing rainfall and soil moisture from satellites have a long way to go, requiring better interpretation of data from existing radiometers as well as the development to routine operational stage of newer instruments. In particular, we must learn much more about how to combine the data from several different instruments.

We need to improve our knowledge of the reaction of biological systems, including both flora and fauna, to different environmental conditions. We have emphasized the Desert Locust in this paper, but influences on other grasshoppers, armyworm and quelea birds are equally important. These reactions, and hence the exact environmental information we need will only become clear from detailed, localized studies.

Finally, the idea of 'Integrated Pest Management' should be emphasized, although perhaps not in quite the way this term is commonly used. Better information will only lead to better control of migrant pests if the system is planned and operated as a coherent whole. The acquisition, processing and delivery of meteorological data is one vital component, but it serves no useful purpose unless it is matched to field data, modelling and guidance to pest control operations which are maintained at an adequate level of readinesss. Systematic study of the overall process is at least as important as research into any individual component.

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Discussion

K. A. Browning, F.R.S. (*Meteorological Office, Bracknell, U.K.*). Dr Milford described the use of cloud top temperature as a proxy for surface rainfall measurements. I'm sure he would be the first to acknowledge that this approach must be applied with caution: not only does the relationship need to be tuned for different regions and/or seasons, but in many areas it breaks down altogether. Thus in very arid regions a lot of the rain may evaporate before reaching the ground, whilst in some other regions much of the high cloud may be frontal cirrus and unrelated to heavy rain. A study by Turpeinen *et al.* (1987) has shown, for example, that a useful relationship exists for Kenya but that the technique does not work for Morocco and Tunisia.

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E. C. Barrett (*University of Bristol, U.K.*). The use of regional regressions in the ('Tamsat') method described in some detail seems to work reasonably well in the western Sahel, a region of relatively simple topography and climatic zonation, but seems likely to be less than effective where topography, climate and weather are more complex.

The problem of cirrus recognition is important, for thick cirrus can masquerade as deep rain cloud. The authors say that '...we may well have to wait for the advent of additional infrared radiometers on geostationary satellites to deal with this problem in a fully automatic system', but the Adler/Negri technique is well suited to this task, although it would require local calibration for efficient application.

The potential of passive microwave as a complement to visible and/or infrared data at least for cirrus discrimination and visible/infrared technique calibration is not afforded the recognition it richly deserves.

The use of collateral data (e.g. from raingauges and radar) should be promoted wherever possible. The best results are likely to stem from the systems which use the most, not the least, types of input data.

Twenty years after the first satellite rainfall monitoring schemes were proposed, much has been learnt about the physical and practical problems with which this field is fraught. However, progress towards operational implementation of such schemes has been much slower and more piecemeal than the science and technology could sustain. It has been estimated that each year one third of the total global food crop production is damaged or destroyed by insects. We owe it to mankind to increase our efforts to reduce such undesirable effects by using satellite-based techniques wherever this seems likely to be beneficial.

J. R. Milford and G. Dugdale. We entirely agree with Dr Barrett that information derived from satellites has been underexploited. This is partly because the time and effort required to move from the research and case study stage to the incorporation of any technique in an operational system has been consistently underestimated, and hence underfunded. In addition, collaboration between local scientists in developing countries has often been poor when they find themselves competing for aid projects and prestige: in this context the donor governments and international agencies have not always set a good example.

We welcome the opportunity to clarify the rationale of our current work in collaboration with the U.K. Overseas Development Administration. We are convinced that if information on rainfall is to be used by non-meteorologists we must provide a virtually automatic system which will deliver easily intelligible products with the utmost reliability. This is particularly true where the information is needed on a limited number of occasions each year, and over a huge area, as in the monitoring of migrant pests in Africa and Asia. Interpretation of the products must be straightforward, and the limits to their accuracy well defined.

We make absolutely no claim to have invented a technique for rainfall monitoring: rather, we are using existing ideas in the engineering of operational systems to match the requirements outlined above. We chose to use the cold cloud statistics method and we are trying to see how far it can usefully be refined. Our main research is on the comparison with other methods, including surface gauges, and on the interpretation of the products. In the process we must educate the technicians who will operate the system, the meteorologists who interpret it and the final users. Only when a truly operational system is established can we decide which of many possible additional techniques would be viable for delivering further information to specific users. Until then we are likely to remain limited to the simplest, and admittedly simplistic techniques.

In the context of this particular meeting our paper emphasized the interpretation of the primitive technique because it is already in operational use, or about to be so, in a dozen centres in Africa. We are already including collateral data where it is appropriate, particularly in the hydrological applications.

With regard to other techniques that were mentioned in the comments, none of these seem to be ready for operational implementation for migrant pest monitoring, for a variety of reasons. Radar is invaluable for research but cannot cover the extensive areas involved in monitoring. Satellite-borne microwave has a great long-term future, but the 20% accuracy predicted for TRMM hardly meets the need as it refers to monthly totals averaged over an area of 10^5 km^2 or more. Turpeinen *et al.* (1987) used a very small sample of data, and we hope to follow up their work with a larger sample in the near future. Finally, our interpretation of Negri and Adler's papers differs from that of Dr Barrett: for example they state that 'One-parameter models were as effective in explaining the variance of cloud volume rainrate as multiparameter methods...' (Negri & Adler 1987). None the less, we hope that texture, pattern and information from other satellites will improve the overall accuracy of operational systems in due course.

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C. G. Collier (*Meteorological Office, Bracknell, U.K.*). This paper provides a useful summary of the importance of rainfall in monitoring the behaviour of migrant pests. The authors note the particular usefulness of satellite data in providing estimates of rainfall over wide areas. Indeed, they stress that conventional raingauge observations cannot hope to satisfy the requirements for widespread continuous coverage.

Although the paper does stress the potential and limitations of satellite methods of measurement, the main method employed, that of estimating the duration of cloud tops below a certain temperature threshold, is presented rather uncritically. It is correctly pointed out that the optimum threshold used depends upon location and season; in addition it will depend upon the type of cloud observed.

Recent work by Brown & Cheng (1989) supports the earlier conclusions of Lovejoy & Austin (1979) that a correlation of visible and infrared data is overall a better measure of rainfall than using visible alone, which in turn is better than by using infrared alone. Of course, visible data are not available at night and substantial rainfall may occur at night. Recently, Vejen (1989) has found that use of water vapour imagery may enhance rainfall estimation techniques. Likewise, the differences between channel 3 (3.7 μm, near infrared) and channel 4 (11 μm, infrared) of the AVHRR instrument flying on the NOAA polar orbiting satellites may be used to differentiate between water and ice cloud. Although data from channel 3 are not available on the current Meteosat, it is possible that Meteosat Second Generation will provide measurements at this wavelength.

Perhaps the most exciting development recently has been the use of microwave frequencies from the Special Sensor Microwave Image (SSM/I) instrument flying on the U.S. Department of Defence Meteorological Satellite Programme (DMSP) satellite. Early results (Barrett *et al.* 1988) by using the different polarizations available at a frequency of 85.5 GHZ are very encouraging. Unfortunately it is unlikely that such an instrument will fly on a geostationary satellite for many years. However, plans are well advanced to fly an active radar system in low earth orbit to provide data for use with such passive microwave radiometers. This project, known as Tropical Rainfall Measuring Mission (TRMM) (Simpson *et al.* 1986), aims to provide monthly estimates of rainfall in the tropics with an accuracy over land of 20%.

Although these new developments may, in the long run, provide more accurate estimates of rainfall than existing satellite techniques, the use of geostationary satellite data will remain the basis of practical operational procedures for measuring rainfall. However, the use of infrared thresholding alone should be regarded as only a first step. The use of procedures based upon multi-spectral analysis are likely to bring worthwhile improvements.

The next ten years or so will see a significant increase in the number of ground based digital weather radars in Africa. Systems are already being planned in Botswana, Malawi, Lesotho and Zimbabwe, and some north African countries already have radar networks. These systems should provide additional data with which to tune satellite measurement techniques. I concur with the authors that the inhomogeneity of rainfall has a major impact upon the way in which its quantity and distribution are inferred from satellite data. Further effort must be put into improving our understanding of exactly what the satellite instrumentation is measuring if inferences are to be made about soil moisture and hence vegetation growth and pest development.

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D. P. Rowell (*Meteorological Office, Bracknell, U.K.*). This contribution leads on from Dr Milford's excellent paper on the techniques and problems of monitoring rainfall, by detailing the current skill of short-range numerical forecasts of tropical rainfall. If skilful forecasts were possible, this would increase the lead time at which significant increases in pest population could be predicted. This contribution also links in with the discussion after Mr Boulahya's paper, concerning the skill of model wind (and precipitation) forecasts in the area surrounding Algeria, and also with the need to predict areas of convergence which are of course closely linked to rainfall.

The results presented here concern the prediction of rainfall in the Sahel at the height of the wet season. Verification of model forecasts was performed for three grid boxes in southern Niger, chosen because of the availability of data from a 'reasonable' number of raingauges within each box. The prediction errors shown in table 1 are for the rainfall which accumulates during the first 24 h of each of the 31 forecasts made from 12h00 G.M.T. during August 1985. It is clear that both models are unable to provide forecasts of rainfall amounts, which improve upon simply by using the climatological values. The ability of the model to forecast simply whether or not rainfall will be above or below a given threshold (2 mm) was also found to lack any useful skill (although a higher threshold is appropriate for the development of pest populations, it is thought that this is unlikely to alter the result of low skill).

Forecasts for at least a few days ahead are the main requirements, and these are clearly out of question, given the skill shown here for just the first 24 h. However, it must be emphasized that the level of skill varies with season and between climatic regions.

The quality of the European Centre for Medium-range Weather Forecasting (ECMWF) and U.K. Meteorological Office 850 mb wind forecasts up to 4 days ahead were also investigated. This study covered the north African region between latitudes 5° and 25° N, again for August 1985. Prediction of wind speed was very poor, but limited skill was found in

Table 1. Prediction errors for the rainfall accumulating during the first 24 h of forecasts made in August 1985

grid box	number of gauges	mean absolute error (mm/day) model forecast	 forecast of the climatological amount
		ECMWF	
15° N, 5.6° E	15	4.9	2.6
13.1° N, 7.5° E	10	4.7	6.5
13.1° N, 9.4° E	15	6.3	6.9
mean		5.3	5.3
	U.K. Meteorological Office		
15° N, 5.6° E	13	3.9	2.8
13.5 °N, 7.5° E	11	4.6	6.4
13.5° N, 9.4° E	16	5.5	6.8
mean		4.7	5.3

predicting the position of African waves (affecting wind direction) up to two or three days ahead. This skill may or may not be high enough for the purposes of forecasting pest migration. Again, it should be emphasized that skill varies with season and between climatic regions, and indeed Dr Boulahya has found the Meteorological Office forecasts to be useful up to 5 days ahead in the northern Sahara during November.

I conclude with a brief discussion of future prospects for short-range tropical weather prediction by using numerical models. There is reason to believe that significant improvements will be seen. The main problem at present is to produce a good analysis from the small quantity of data available in regions such as north Africa. Three factors will help with this: the use of automatic weather stations in data-sparse areas; better communications to enable more of the observations to reach the GTS (Global Telecommunications System) in time to be incorporated into the model analysis; the availability of satellite data more appropriate to the needs of meteorologists, and the undertaking and use of research into its objective interpretation. This is likely to be the most important factor leading to improved tropical analyses.

Finally, the parameterization of physical processes is particularly important for the evolution of tropical forecasts, and further research in this area may also lead to greater predictive power.

G. Szejwach (*EUMETSAT*, *Darmstadt*, *F.R.G.*). The paper by Milford & Dugdale stresses the importance of satellite rainfall monitoring as an indirect means of obtaining information on soil moisture at the considered scale. At the present time, it is indeed true that the method is indirect and this will remain the case until much more sophisticated remote-sensing data (including microwave imagery) become available from satellites. In this context, it is noted that satellite data obtained from a radiometer (visible, infrared, and water vapour channels) provide information on the upper part of the cloud cover from which rainfall at the surface is indirectly estimated using statistics or a physical model. Limitations are well known and most of them are indicated. They include presence of cirrus clouds in the vicinity or convective tops, global representativeness of the relationship between rainfall and cloud top temperature, as well as local, regional, topographical, temporal, and seasonal variability. Research is ongoing to try better to understand, and calibrate this relationship. One should note that most publications (including this one) address the problem of convective rain but very little has been done concerning the much more difficult problem of stratiform rain. It is possible that in the proposed application stratiform rain could play an important role in the regions considered here or in other parts of the globe. One other important parameter not considered here (or by others) related to rain and soil moisture is atmospheric water vapour.

Despite these limitations, the authors attempt to arrive at an operational and useful product related to rainfall. The research conducted by Milford & Dugdale to address the problem of rainfall estimates from satellite, and to correlate this to soil moisture, is relevant to a wide variety of meteorological and climatological studies and applications such as the one indicated in the present paper.