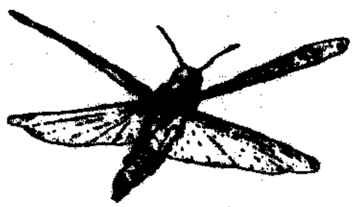
WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 54

METEOROLOGY AND THE MIGRATION OF DESERT LOCUSTS

Applications of synoptic meteorology in locust control

by R. C. Rainey



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Anti-Locust Memoir 7

Anti-Locust Research Centre
London, England

WMO

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- To promote the establishment and maintenance of systems for the rapid exchange of meteorological information;
- To promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics;
- To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;
- To promote activities in operational hydrology and to further close co-operation between Meteorological and Hydrological Services;
- To encourage research and training in meteorology and, as appropriate, in related fields, and to assist in co-ordinating the international aspects of such research and training.

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FAO Desert Locust Information Service, Anti-Locust Research Centre, London
(Desert Locust Survey, East African High Commission, 1949-1958)

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Foreword

During recent years the World Meteorological Organization has been collaborating with the Food and Agriculture Organization of the United Nations, the Anti-Locust Research Centre in London, and other organizations in programmes aimed at the application of meteorology to the effective control of the Desert Locust. A WMO technical assistance mission was based in Nairobi, Kenya, from 1955 to 1960 to collect and analyse meteorological data for the period May 1954 to May 1955 inclusive. Observations of Desert Locust swarms for the same period were collected and analysed at the Anti-Locust Research Centre. The two sets of data were then compared, primarily with a view to establishing the relationships between swarm displacements and meteorological factors. The main results of this work are presented in this report by Dr. R. C. Rainey, together with the results of some other cognate investigations.

I should like to take this opportunity of thanking Dr. Rainey for having prepared this most valuable report. Grateful acknowledgement is made to the Director-General of FAO and the Director of the Anti-Locust Research Centre for their co-operation in this project, to the Director of the East African Meteorological Department for the facilities provided to the WMO mission and to all the meteorological services which contributed the data required by the mission. Thanks are also due to the head of the WMO mission, Mr. C. I. H. Aspliden, who is the co-author of chapter 3, and to his colleague Mr. J. Cochemé, some of whose contributions are specifically mentioned in the report. Finally I should like to thank Mr. D. H. Johnson, of the British Meteorological Office, for his constructively critical and detailed examination of the final draft based on his wide knowledge and experience of tropical meteorology.

D. A. Davies

(D.A. Davies)
Secretary-General

Geneva, 1963

Summary

Relevant aspects of the biology and behaviour of the Desert Locust, still a serious problem in the agricultural development of more than thirty countries of Africa and south-western Asia, are briefly outlined. Data on the direction of hour-to-hour displacements of individual swarms, now available from aircraft observations, are shown to agree with the direction of the corresponding winds, at the levels of the flying locusts, with a root-mean-square difference of 15°. The resulting tracks followed from day to day by individual swarms are accordingly found to differ widely according to the nature of the wind-field concerned ; thus swarms in quasi-uniform wind-fields showed progressive, systematic displacements, in striking contrast with repeated reversals of directions (at times resulting in tracks with closed loops), shown in correspondingly more complex wind-fields.

The migration and breeding of Desert Locusts, over the whole area from the Canary Islands to India and from Iran to Tanganyika, for a complete individual year of widespread infestation, are described in detail in relation to the synoptic meteorology of this area and period, studied in corresponding detail by the WMO Technical Assistance Mission for Desert Locust Control. Attention is drawn to all synoptic features which have so far been found significant in relation to locust movements, in this and other years.

The movements and distribution of Desert Locusts, on the scales of synoptic and meso-meteorology, are shown to be determined to a very large extent by the low-level wind-fields involved, within the range of limiting conditions for flight. The down-wind displacement of flying locust populations implies a corresponding association of low-level convergence and divergence respectively with the concentration and dispersal of such populations, as well as with the weather encountered by them. A basis is thus provided for the use of current synoptic charts and of meso-scale meteorological observations in the interpretation and, particularly, in the short-term forecasting of locust movements, in all countries concerned with the Desert Locust. Such guidance is becoming increasingly necessary with current developments, both in the techniques of locust control (particularly the rapidly extending use of aircraft), and in the organization of the various national, regional and international aspects of control operations.

Résumé

La présente Note technique expose d'abord brièvement quelques aspects de la biologie et du comportement des criquets pèlerins, insectes qui continuent d'entraver sérieusement le développement de l'agriculture dans une trentaine de pays d'Afrique et du sud-ouest de l'Asie. Elle montre que la direction dans laquelle se déplacent certains essaims, qu'il est maintenant possible de connaître d'heure en heure grâce aux observations aériennes, correspond à la direction des vents qui soufflent aux niveaux où volent ces insectes, avec un écart quadratique moyen de 15°. On constate donc que les trajectoires suivies par les essaims varient considérablement d'un jour à l'autre selon la nature du champ de vent : dans des champs de vent quasi uniformes, le déplacement des essaims était progressif et systématique, alors que dans des champs de vent plus complexes ces essaims changaient à plusieurs reprises de direction (leurs trajectoires allant parfois jusqu'à former des boucles complètes).

La Note technique décrit en détail les migrations des criquets pèlerins et leur reproduction dans l'ensemble de la zone comprise entre les îles Canaries et l'Inde et entre l'Iran et le Tanganyika. Cette description, qui porte sur une année entière au cours de laquelle était infestée toute la plupart de cette zone est rattachée aux analyses synoptiques de cette zone pendant la même période, analyses qui ont fait l'objet d'une étude aussi détaillée dans le cadre de la mission d'assistance technique de l'OMM chargée de la lutte antiacridienne. L'attention du lecteur est attirée sur toutes les caractéristiques synoptiques qui se sont révélées jusqu'ici significatives dans les migrations de ces insectes au cours de cette année-là et d'autres années.

Les déplacements et la répartition des criquets pèlerins, considérés à l'échelle de la météorologie synoptique et de la mésométéorologie, sont déterminés dans une très large mesure par les champs de vent à basse altitude dans les limites des conditions permettant les vols. Le déplacement des populations d'acridiens dans le sens du vent indique qu'une convergence et une divergence à basse altitude sont associées respectivement à une concentration et à une dispersion de ces populations, ainsi qu'aux conditions atmosphériques rencontrées par celles-ci. On dispose donc d'une base pour utiliser les cartes synoptiques du temps présent et les données mésométéorologiques en vue de l'interprétation des mouvements d'acridiens et, en particulier, pour la prévision à courte échéance de ces mouvements dans tous les pays intéressés. Ces indications deviennent de plus en plus nécessaires en raison des progrès qui sont accomplis tant dans les méthodes appliquées à la lutte antiacridienne (l'usage des aéronefs à cette fin s'accroît rapidement) que dans l'organisation de cette lutte sous ses divers aspects nationaux, régionaux et internationaux.

Краткое содержание

Кратко излагаются соответствующие аспекты биологии и поведения Пустынной Саранчи, что до сих пор представляет из себя серьезную проблему в сельскохозяйственном развитии более чем тридцати стран Африки и юго-западной Азии. Приводятся данные о направлении ежечасных перемещений отдельных стай саранчи, полученные с самолетных наблюдений. Это направление согласуется с направлением соответствующих ветров на уровне летящей саранчи с квадратным корнем среднего из квадратов отклонений равным 15°. Соответственно установлено, что направление перемещений, которому день ото дня следуют отдельные стаи саранчи, значительно меняется в зависимости от характера соответствующего поля ветра ; так стаи в относительно однообразных полях ветра перемещаются в одном направлении в противоположность к повторяющимся отклонениям направлений (иногда в виде замкнутых петель), наблюдаемым в соответственно более сложных полях ветра.

Детально описываются миграции и размножение Пустынной Саранчи на всей территории от Канарских островов до Индии и от Ирана до Танганьики за полный год, когда наблюдалось ее широкое распространение. Эти явления описываются в связи с синоптическими условиями данного района и периодом, который в соответствующих деталях изучался Миссией Технической Помощи ВМО по Контролю за Пустынной Саранчой. Обращается внимание на все синоптические явления, оказавшиеся важными в связи с движением саранчи в те или иные годы.

Движение и распределение Пустынной Саранчи в синоптических масштабах и масштабах мезо-метеорологии определяются в значительной степени соответствующими полями ветра на низких уровнях и в пределах условий, позволяющих полет. Перемещение летящей саранчи по ветру указывает на соответствующую связь конвергенции и дивергенции на низком уровне соответственно с концентрацией и разрежением стай саранчи, а также на существование зависимости таких перемещений от условий воздействующей на эти стаи погоды. Таким образом выработана основа для использования текущих синоптических карт и мезо-масштабных метеорологических наблюдений для интерпретации, и в частности, для краткосрочного прогноза движения Пустынной Саранчи во всех странах, подверженных ее воздействию. Необходимость в таком руководстве возрастает в связи с имеющимися успехами как в технике по контролю за саранчой (особенно быстрое расширение использования авиации), а также и в организации национальной, региональной и международной оперативной деятельности по контролю за саранчой.

Resumen

La presente Nota Técnica expone brevemente los aspectos particulares de la biología y del comportamiento de la langosta, insecto que sigue entorpeciendo gravemente el desarrollo de la agricultura en más de treinta países de Africa y del suroeste de Asia. Parece que la dirección de desplazamiento de los enjambres, que se puede ya conocer de hora en hora gracias a las observaciones efectuadas a bordo de aeronaves, coincide con la dirección de los vientos imperantes al nivel a que vuelan los insectos, con una diferencia media cuadrática de 15°. Se observa igualmente que el trayecto recorrido por las nubes de langosta varía considerablemente de un día a otro según la naturaleza del campo de viento de que se trate : en campos de viento casi uniformes el desplazamiento del enjambre es progresivo y sistemático, mientras que en campos de viento más complejos los enjambres cambian varias veces de dirección (a veces su trayectoria llega incluso a formar un círculo completo).

En la Nota Técnica se analizan con detenimiento las migraciones de las langostas y su reproducción en el conjunto de la zona comprendida entre las Islas Canarias y la India, y entre el Irán y Tanganyika. Este análisis, relativo a un año completo en el transcurso del cual toda esa zona estuvo infestada, es relacionado con las observaciones meteorológicas efectuadas por las estaciones sinópticas de esa misma zona durante el mismo periodo, observaciones que, además, han sido objeto de un estudio detallado dentro del marco de la Misión de Asistencia Técnica de la OMM encargada de la Lucha Antiacridiana. Se señalan a la atención del lector todas las características sinópticas — que se han considerado hasta ahora que influían en las migraciones de esos insectos — registradas ese año, y otros años.

Los desplazamientos y la distribución de la langosta, considerados desde el punto de vista de la meteorología sinóptica y de la mesometeorología, están determinados en gran parte por los campos de viento que se registran a una altitud baja, dentro de los límites de las condiciones en las que los vuelos son posibles. El desplazamiento de las poblaciones acridianas en el sentido del viento supone que la convergencia y la divergencia a poca altitud van asociadas respectivamente a una concentración y a una dispersión de esas poblaciones, así como a las condiciones atmosféricas que encuentran. Se dispone pues de una base para utilizar las cartas meteorológicas actuales y los datos meteorológicos para la interpretación y, especialmente, para la previsión a corto plazo de los desplazamientos de esos insectos por todos los países interesados. Esas indicaciones resultan cada vez más necesarias a causa de los progresos que se realizan tanto en lo relativo a los métodos de lucha antiacridiana (cada vez se utilizan más las aeronaves), como en la organización de la lucha en el ámbito nacional, regional e internacional.

FIGURE 1

The main geographical distribution of the Desert Locust

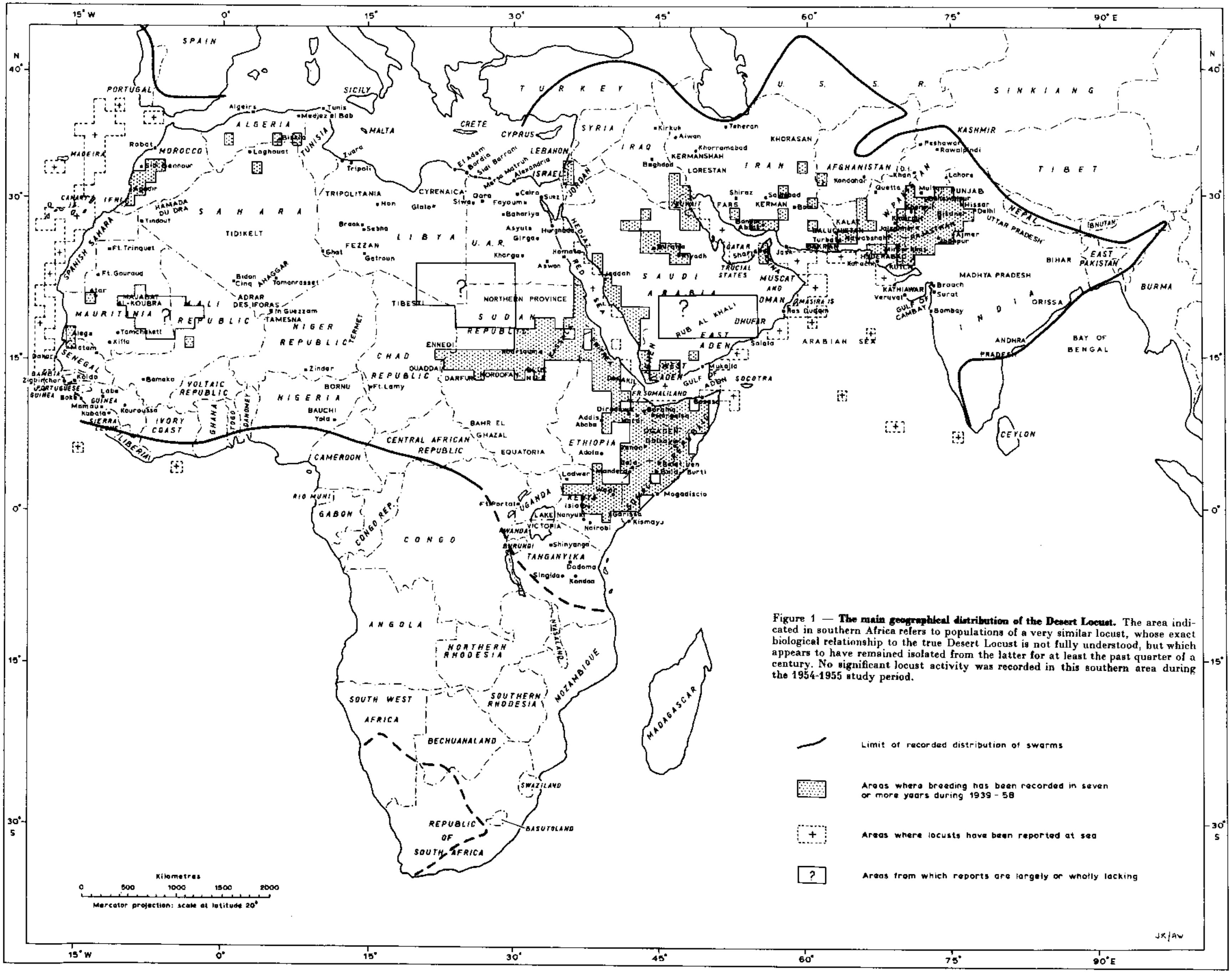

Figure 1 — **The main geographical distribution of the Desert Locust.** The area indicated in southern Africa refers to populations of a very similar locust, whose exact biological relationship to the true Desert Locust is not fully understood, but which appears to have remained isolated from the latter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

INTRODUCTION

The Desert Locust, *Schistocerca gregaria* Forskål, a plague of much of Africa and the Middle East (Figure 1) since the beginning of history, remains one of the most serious agricultural problems of this region ; during a single recent year chosen for detailed study (see chapter 3), crop damage by the Desert Locust was recorded in 23 countries, and in Morocco alone was estimated at a value of 13 million U.S. dollars [79, 138]. The problem arises both from the actual quantity of the living insect material involved, and from the mobility which this material exhibits. The order of magnitude of the mass characteristic of the swarms of winged adult locusts (Plate I) was also illustrated by an experimental aircraft-spraying

Photo A. J. Wood.

Plate I — Part of a large Desert Locust swarm, covering an area of approximately 130 km², at Hargeisa in the Somali Republic ; 3 August 1960.

Some of the magnitudes involved were illustrated by counts of dead locusts made in representative sample-areas following the application to this swarm of 38 tons of concentrated insecticide from the air over a period of six days [49]. The counts demonstrated a kill of some 20,000 tons of locusts, representing probably the greater part, but certainly not the whole, of this particular swarm.

operation, at Maktau in Kenya in February 1955, in which a quick-acting insecticide was applied along spray-runs planned to provide a systematic sample of a settled swarm, and counts of the resulting dead locusts were subsequently made in representative sample areas. These counts demonstrated that this particular swarm, which covered at the time an area of 20 km^2, comprised a total of some 10^9 locusts and would accordingly have weighed about 2×10^6 kg [63, 95]. There were at that time several hundred square kilometres of such swarms in Kenya and Tanganyika alone ; heavy invasions can amount to thousands of square kilometres of swarms in a single territory [112]; and it has been shown, by laboratory studies [16, 150] that such locusts, actively flying, can be expected to eat about their own weight of vegetation daily.

A heavy locust invasion can accordingly involve daily feeding-rates of the order of 10^8 kg of plant material. At present most of the food of these swarms is provided by wild vegetation, since only a very small proportion of the whole area subject to invasion by the Desert Locust is actually cultivated (3 per cent of the total land area in Kenya, for example). The progressive increase in the area cultivated, however, notably that associated with the development of irrigation in arid regions [137] correspondingly increases the economic threat presented by the Desert Locust ; and in a number of countries crop-losses due to the Desert Locust during the last decade have in consequence exceeded any previously recorded in these countries [27].

Concerning mobility, the particular swarm sprayed at Maktau, for example, had travelled a distance of 70 km during the two preceding days ; and, on a different scale, young swarms produced in the northern Arabian peninsula in early May 1954 had reached the Niger Republic by the beginning of June, a displacement of some 3,500 km in about a month (p. 67). Displacements on this latter scale — which is approached by some Desert Locust swarms in most years — mean that every one of the sixty countries subject to invasion is, from time to time, attacked by swarms produced thousands of kilometres beyond its own borders. On the other hand, even the most frequently invaded countries can be free of swarms for periods of several years ; and forecasts of such swarm movements can accordingly be of the greatest possible value both in the forward planning and in the day-to-day conduct of control operations.

The systematic collection and analysis of locust reports from all affected countries, which first made possible the provision of such forecasts of swarm movements, was begun in 1929 under the direction of Dr. B. P. Uvarov at what subsequently became the Anti-Locust Research Centre, and these analyses soon provided evidence of a useful degree of seasonal regularity in the distribution, movements and reproduction of swarms. Thus for example Morocco has been invaded by swarms during 16 of the past 22 years (1941–62) ; in each of these 16 years the first invading swarms were reported between 28 September and 1 November ; and in half of these years of invasion the first swarm was reported between 9 and 22 October. By 1943 experience of this quasi-regularity had made it possible to begin the issue of a regular monthly summary of the current Desert Locust situation incorporating a brief forecast, in very general terms, of probable developments in the overall situation during the next few months. The value of these forecasts has become widely recognized, and has led to their being sponsored, since 1958, by the Food and Agriculture Organization of the United Nations, as part of an international Desert Locust Information Service (now included in the U.N. Special Fund Desert Locust Project). It has, however, long been appreciated that the purely historical approach, utilizing only the evidence of the current locust situation and the experience provided by locust situations recorded at the corresponding season in previous years, while thus providing a useful indication of the range of possible developments during the coming season, commonly gives no indication of the onset of unusual developments, and often furnishes little or no guidance on the day-to-day and hour-to-hour movements of individual swarms, which with the rapidly extending use of aircraft are now becoming of major importance in the tactical direction of control operations. The potential importance of meteorological factors in relation to the biology of locusts, as of other insects, had long been recognized [136]; it was soon found that areas and seasons of breeding by the Desert Locust were in general areas and seasons of rainfall [17, 19, 33, 137, 141], and work at about the same time in India [111] directed attention to some of the associations between swarm movements and synoptic meteorology. Research on the mechanism of swarm movements, with particular reference to weather factors, has accordingly been actively pursued, both in the field and by cartographical studies. In 1951 work on both these lines led to the formulation of the hypothesis that the major movements of Desert Locust swarms take place down-wind, towards and with zones of convergent surface wind-flow, and that such a mechanism might account for much of the close and apparently purposeful association found between swarm movements and the distribution of the rainfall which is essential for successful breeding [92].

It was, however, immediately obvious that the possibility both of adequate testing and of ultimate exploitation of such a hypothesis were severely limited by the underdeveloped state of the synoptic meteorology of much of the area concerned ; and the co-operation of the World Meteorological Organization was accordingly sought, through the good offices of Mr. D. A. Davies, at that time Director of the East African Meteorological Department and President of the WMO Regional Association for Africa (RA I). Consideration of the evidence then available on the part played by meteorological factors in swarm movements led the first session of Regional Association I, at Tananarive in 1953, to express the view that the further development of the application of synoptic meteorology to the forecasting of locust movements was economically one of the most important of the fully-formulated problems of applied meteorology in the African Region. A specific Tananarive recommendation on this point, subsequently implemented by WMO, led to the establishment of the WMO Technical Assistance Mission for Desert Locust Control.

After a preliminary appraisal of the problem [55], and consultations between WMO, the Desert Locust Survey, and the Anti-Locust Research Centre, it was decided that the objectives of comprehensive tests of existing hypotheses of the relationship between swarm movement and weather, and of detailed studies on the relevant aspects of the synoptic meteorology of the region, could best be approached by a co-ordinated investigation, in the fullest possible detail, of the whole of the available data, both on weather and on locusts, for a complete year. The year beginning May 1954 was selected for this purpose, as a year of widespread and heavy Desert Locust infestations, providing examples of most of the types of swarm-movements which had so far been recognized [26]. The study-period was subsequently extended for a further month to include certain swarm-movements of particular interest which occurred during May 1955.

In addition to the work of the WMO Mission, extensive evidence, of a kind not previously available, on the hour-to-hour and day-to-day movements of individual swarms in relation to meteorological factors on the meso-scale, has been secured since 1951 by intensive air reconnaissance, particularly that made possible in eastern Africa by additional light aircraft which were made available by FAO to the Desert Locust Survey during 1953–56. These data on the movements of individual swarms, so far largely unpublished, are summarized in chapter 2, both as evidence of the respective roles of locust behaviour and of meteorological factors in the mechanism of swarm displacement, and to assist directly in the provision of meteorological guidance in field operations concerned with the location, assessment and control of swarms.

Chapter 3 presents the detailed chronological study of locusts and weather during 1954–55, provided by the work of the WMO Mission on the macro-scale, and furnishing a comprehensive test of the 1951 hypothesis. This study, in conjunction with the meso-scale results of chapter 2, also incorporates the fullest interpretation so far achieved of the detailed geographical pattern of Desert Locust migrations. Attention is directed, in the course of chapter 3, to all synoptic features which have so far been found significant in relation to the distribution and movements of locusts, utilizing in addition to the results of the Mission experience also available from other years. This includes recent findings of the Desert Locust Information Service, made possible by the current daily synoptic charts of the whole infested area which for the past two years have been utilized to assist in the interpretation of the current locust situation and in forecasting its future development.

CHAPTER 1

RELEVANT ASPECTS OF THE BIOLOGY AND BEHAVIOUR OF THE DESERT LOCUST

In the same way that a meteorologist responsible for aviation forecasting needs at least some acquaintance with the operating characteristics of the aircraft which he serves, the provision of the meteorological requirements of locust control needs the same kind of acquaintance with the relevant aspects of the biology of the locust. This involves consideration not only of the flight performance and behaviour of the individual locust, but also of other aspects of its biology, which establish conditions of continuity which assist very considerably in the interpretation of the inevitably incomplete current data (see pp. 55, 56 and 65) available on the overall locust situation. Thus a report of locusts at any of the conspicuously distinct stages of their life-history, successively from eggs to wingless hoppers, to newly-fledged, to immature, and finally to mature egg-laying adult locusts again, necessarily implies the previous presence of the corresponding earlier stage, within limits of time and distance which can be at least approximately specified. Moreover, each locust report similarly represents a potential source of locusts at the next stage of their life history.

1.1 Life-history

The adult locust is a large insect, with a wing-span of 10–15 cm and a weight of 1–3 gm, which lays its eggs in moist sand or soil, at a depth of about 5–10 cm. The egg of the Desert Locust, when it is first laid, contains less than half the quantity of water present in the young locust at hatching [126]. This has the effect of minimizing the demands made by egg-laying on the water-resources of the female locust, as compared with most other egg-laying land animals, of which the egg is laid with an initial water-content sufficient for the whole of embryonic development [80]. As a result, however, the further development of the locust egg is entirely dependent on the presence of free soil-water which it can absorb, and which also commonly promotes the growth of the vegetation on which the young locusts subsequently feed. From a review of field and laboratory data on oviposition and on relevant soil properties, soil moisture equivalent to approximately 20 mm of rain has been indicated as a necessary, though not sufficient, condition for oviposition [67]. Since the major breeding* areas of the Desert Locust are characterized by a scanty and erratic rainfall, typically averaging between 80 and 400 mm per annum [67], with coefficients of variation** of about 70 per cent [82, 89, 106], successful breeding necessarily implies a very considerable degree of co-incidence of parent locusts with rainfall, both in time and place — though the fact that eggs can be successfully laid through as much as 8 cm of dry sand, overlying a moist layer [88], means that soil moisture provided by rains which fell a number of weeks previously can still be utilized. Sexual maturation is commonly delayed (sometimes for as much as six months) until the locusts have encountered the onset of the corresponding seasonal rains, though the physiological mechanism of this effect is not yet known (p. 76). Egg-laying has been recorded in the field at air-temperatures ranging from 22° to 34°C [87, 88].

The duration of the egg-stage varies greatly with temperature, from ten weeks at a soil-temperature reported as averaging 19° at a depth of 10 cm, to two weeks at a corresponding temperature of 34° [109]. During the 1954–55 study period, for example, recorded durations of egg-development ranged from 63

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* The term "breeding" is commonly used to include the presence of young stages (eggs or hoppers) as well as the actual processes of mating and egg-laying.

** Standard deviation as a percentage of corresponding mean value.

days during February-April 1955, near Laghouat in Sahara, down to 10 days during November-December 1954 near Garissa in Kenya. Much more restricted ranges of duration have however been found to be characteristic of particular breeding-areas and times of year ; and this degree of regularity has been utilized to provide forecasts, e.g. of dates of hatching and of subsequent appearance of swarms, for planning control operations. Thus for example some 23 records of egg-laying during the months of October and November of 1950-54, in an important breeding area comprising the adjoining parts of Ethiopia, the Somali Republic and Kenya, all gave hatching within 10–14 days, with 13 of the 23 cases between 13 and 14 days. Illustrations of consistent differences in this respect are provided by the topographical diversity of western Iran, where for example the 22 days of egg-development recorded for the first hatching in the Aiwan district of Kermanshah ostan in 1962, and the same duration similarly recorded for the first hatchings in this ostan in 1954, may be contrasted with the two-month periods of egg-development recorded in the Khorramabad area of Lorestan both in 1959 and in 1962 [100].

The young locust hatches from the egg as a wingless nymph or "hopper", initially about a centimetre in length and about 20 mg in weight, which feeds actively, grows, and moults five times before reaching the fully-winged, adult stage, usually some five to six weeks later. At each moult there are characteristic changes in form and in colour-pattern, as well as in size, which enable these five successive stages (instars) to be readily distinguished.

Soon after hatching, the hoppers, if close enough together, begin to react gregariously to each other, to assemble into dense groups [25, 42], and characteristically to march together as coherent bands which can cover distances ranging from 3 to 25 km [25, 103] during the five to six weeks between hatching and the final moult.

1.2 **Swarming and solitary phases**

Locust hoppers which become isolated from their fellows, by effect of environment or of laboratory experiment, begin within a few days to lose the colour-pattern characteristic of gregariously-living hoppers (yellow or orange ground-colour, associated with a black pattern which appears to become particularly extensive at low temperatures), and to assume instead a uniform green colour. At their final moult, such solitary-living hoppers give rise to adults which in bodily proportions as well as in colour-pattern are sufficiently different from the adult locusts typically found in swarms to have been formerly considered a separate species. This process is known as dissociation, and the two contrasting types of locust (both of hopper and of adult) characteristic respectively of solitary-living and of gregariously-living individuals, are known as the phases *solitaria* and *gregaria* [135].

Conversely, locusts of phase *solitaria*, brought by environmental factors to within range of mutual perception, can become conditioned, sometimes within a matter of hours [24], to react gregariously to each other, and once again to produce hopper bands and swarms, associated in due course with the reversal of the changes in colour pattern and subsequently of bodily proportions observed during dissociation. This transformation of phase *solitaria* to phase *gregaria*, termed gregarisation, is of the greatest possible importance in certain other species of locust (such as the Tropical Migratory Locust, *Locusta migratoria migratorioides* R. & F., and the Red Locust, *Nomadacris septemfasciata* Serv.) of which swarms can disappear entirely for years at a time. Thus in these species production *de novo* of potentially damaging swarms, from individuals which for many generations have led solitary, unobtrusive and harmless lives, is believed to be the vital step in the outbreak of a new plague of these locusts after years of quiescence in all countries. In these species, moreover, this process of gregarisation appears only to be possible in certain restricted outbreak areas, covering a few thousands of square kilometres as against the tens of millions of square kilometres invaded by swarms at the height of a plague. This made possible, some twenty years ago, the beginnings of the International African Migratory Locust Organization and the

International Red Locust Control Service, leading to the suppression at source of all subsequent potential outbreaks of these species [36, 37].

The basic problem of the Desert Locust, on the other hand, has recently been found to differ in certain important respects from those of the other two species [26, 29, 94]. In the records of every individual country concerned, plague periods, with swarms, can be clearly distinguished from periods of years without them ; but, when the entire area liable to invasions, from India to the Atlantic and from Tanganyika to Turkmenia, is considered as a whole, swarms of the Desert Locust have been recorded somewhere or other in every year since 1887 (except 1921 — which nevertheless provided a record of gregarious breeding in the Sahara). Furthermore, even during years when the number of countries reporting swarms has been at a minimum, individual countries have been heavily infested, and swarms have still been reported from a number of widely separated areas. Finally, solitary-living locusts have been found [111] to occur at densities commonly of the order of only 10 to 10^3 per km^2 ; and the locusts even in a single small swarm (10^8 in 1 km^2) can outnumber, by an order of magnitude, one of the largest populations of *solitaria* so far assessed [146] — for which, moreover, some possibility of swarming parentage cannot be excluded.

Accordingly, while from time to time further Desert Locust swarms are undoubtedly produced from populations of locusts which have at least temporarily been solitary-living [48, 71–73, 111, 132, etc.], it is probable that any formation of entirely new swarms from locusts which have been solitary-living for several generations is at least in most years quantitatively insignificant compared with the continuing production of swarms from earlier swarms. The process of gregarisation *de novo* might of course become of greater importance in any circumstances in which swarming populations of the species had been drastically reduced, either by natural causes or by control measures.

1.3 The flight performance of the individual locust

After the final moult the young adult, known as a fledgling, is initially capable only of weak descending flight, until the completion of the development of the flight-muscles and the hardening of the wing-structure after another week or so. Thereafter, and for the remainder of adult life, which may extend over six months or more — more than two years under laboratory conditions [116] — the flight performance is characteristic and impressive, particularly during the red "immature adult" stage (prior to sexual maturation) in which much of the long-range migration occurs. Thus in laboratory studies on the physiology [151] and aerodynamics [46] of locust flight, and on spraying techniques [154], individual locusts have flown for hours at a stretch on an aerodynamic balance in a wind-tunnel, enabling air-speed and endurance to be recorded under conditions of sustained flight, with the locust developing aerodynamic lift comparable with its own weight. The power for flight is provided by the oxidation of fat [150] ; and an upper limit for the potential duration of continuous flight, without feeding, is accordingly set by the maximum size of the fat-reserves, in relation to the rate of consumption of fat in steady flight. Both have been estimated by laboratory investigations [150], and indicate a maximum endurance of the order of twenty hours of continuous flight.

Locusts are capable of sustained flight only within a range of conditions corresponding, in the laboratory in the absence of significant radiation, to air temperatures between 25° and 35° [151]. In nature the internal temperature of locusts can at times be more than 10° above the corresponding air temperature, with the effects of the metabolic heat produced within the flight muscles, as well as of solar radiation, contributing significantly to their thermal balance [106]. Thus while at night, and in the absence of sunshine by day, sustained flight has been recorded in the field only at air temperatures above about 20° [113, 148], comparably sustained flight has been seen in sunshine at temperatures down to 17° in Kenya [40] and to 15° in Morocco, where some flight activity has been observed down to 9° [115]. Few field data have been recorded on a comparable upper limit, but aircraft observations in the Sudan and the Somali Republic have provided circumstantial evidence of a marked reduction in visible flight activity at air temperatures above 40° [28, 101].

Concerning the speed of flight, it was concluded from laboratory data [151] that the average air-speed during steady horizontal flight in nature would probably be between 13 and 15 km/hr, while in other wind-tunnel studies [154] locusts flew at air-speeds which ranged from 9 to 23 km/hr and averaged 12 km/hr; somewhat surprisingly, air-speed was practically unaffected by variations in laboratory air temperature within the range 25° to 35° [151]. In field studies of the behaviour of locusts in swarms, a photographic technique of double exposure [122], using a camera directed vertically upwards into a swarm from the ground, has been developed to record objectively the orientation and the direction and speed of displacement of the individual flying locusts, as in Plate II, and thus to provide direct estimates of their air-speed. Such estimates [107], taking appropriate account of corresponding vertical gradients and turbulent fluctuations of the wind, gave mean air-speeds of about 20 km/hr for low-flying locusts (below 35 m) in each of three swarms studied in East Africa in early 1955 (10 and 17 February at Mtito Andei, Kenya ; 2 March at Korogwe, Tanganyika). This figure, while in reasonable agreement with earlier field determinations of locust air-speeds by more approximate visual methods [39, 148], is higher than most of the laboratory values just quoted. However, during these wind-tunnel studies [57, 151] it was observed that initial air-speeds, at the start of flight in the laboratory, were generally higher than the values already given, averaging 17 km/hr and occasionally reaching 20 km/hr, and subsequently declined, to the lower "cruising speeds" quoted, within half an hour or so after the start. In view of the characteristically intermittent nature of the flight of the individual locusts in all the swarms in which air-speeds have been determined in the field, together with the fact that the individuals studied in this respect were necessarily flying relatively low, it is probable that many of the individual field values of air-speed related to locusts which had very recently taken off. The mean air-speed found during such a series of observations, therefore, might well be higher than a corresponding cruising value. Apart from their active flapping flight, locusts are frequently seen to glide, at air-speeds roughly comparable with those exhibited in flapping flight, and at sinking-speeds of the order of 1 m/sec [96]. Both take-off and landing directions are typically into wind [148].

1.4 The flight behaviour of locusts in swarms

Since Desert Locusts are thus capable of sustained flight at an air-speed of some 15 km/hr, swarm-displacement in any direction relative to the ground would be physically possible at wind-strengths less than this figure, provided the flying locusts assumed and maintained the appropriate orientation or "course". Now flying swarms are conspicuously characterized by a strikingly uniform orientation of neighbouring locusts; for example 189 out of the total of 193 flying locusts recorded in the photograph used in Plate II were heading towards ENE, E or ESE. Moreover, a similar orientation is often maintained over considerable periods by flying locusts passing an observer ; and Plate II, for example, was one of a series of 17 photographs, taken at regular 20-second intervals, every one of which likewise showed a marked predominance of easterly orientations. It had therefore long been implicitly assumed that direction of displacement of swarms was determined by uniform and persistent orientation of the flying locusts ; and, in the past, factors determining their orientation were accordingly actively sought [50, 152, etc.].

During aircraft spraying trials in Kenya in 1952, however, when four successive flying swarms (Figure 2) were kept for several days under close observation from slow-flying light aircraft [102], it was first noted that, with the possible exception of brief periods at the beginning and end of the day's displacement, no common orientation ever appeared to become established throughout an entire swarm. Under repeated observation from the air, each swarm was seen to comprise a number of groups of flying locusts, with a common track often recognizable within each group, but with the widest possible diversity of track between different groups, giving an impression of a meshwork of interlacing streams ; two observers noted that there were at times conspicuous differences in the way in which the sunlight was reflected off the wings of different groups, again implying differences of orientation. Seen from the ground, successive flying groups were in fact observed on occasion to pass overhead in opposite directions [120]. Direct photographic evidence of the variability of orientation, shown from time to time at the same point during the passage of a swarm, was secured on one occasion, and is summarized, in relation to the corresponding direction of displacement of the swarm as a whole and to the wind at the time, in Figure 3, which also illustrates the degree of uniformity of orientation seen in some of these groups. In such circumstances it did not seem likely that the orientation of the flying locusts could have been of much importance in determining the direction of displacement of the swarm as a whole (Plate III). Moreover, observations of uniformly-orientated groups of flying locusts have not merely repeatedly failed to provide any indication of the corresponding direction of displacement of the complete swarm ; such observations could at times fail to show whether a swarm as a whole was even moving at all. Thus despite the considerable flight activity shown by the individual locusts in Plate II, for example, the swarm as a whole was effectively stationary (p. 52) ; 24 hours after this photograph was taken, the swarm was still occupying much of the same area, covering about a square kilometre, on which it had been seen settling two days previously ; and, in visual observations from a hilltop overlooking the swarm, streams of flying locusts, indicating marked uniformity of orientation within the stream (as in Plate II), were repeatedly seen to approach the edge of the swarm and then to fail to pass beyond it.

It was realized, in 1952, that the observed continued coherent existence of these swarms (Figure 2 ; maintained in spite of the potentially disruptive effects of atmospheric turbulence as well as of the diversity of orientation of the flying locusts themselves — see below) appeared to imply the existence of some reaction having the effect of deflecting inwards groups of flying locusts when they reached the perimeter of the swarm. The only suggestion of direct evidence on this point available at that time had been provided by a single observation on a small low-flying swarm which had been seen from the air in the Isiolo area on 13 February 1951. At about 13 hrs, while the swarm was flying down-wind in a narrow stream about 1 km long, and giving an impression of a predominantly down-wind orientation over the greater part of its length, a marked diversity of orientation was noted among the flying locusts over the first fifty or sixty metres back from the head of the swarm, and further described [134] as suggesting "counter-marching", with a considerable proportion of the flying locusts in this part of the swarm apparently heading in the opposite direction to those in the main part of the swarm.

In 1954 and 1955 systematic photographic recording of the orientation of flying locusts, in a number of the swarms located and followed by the aircraft, was undertaken by ground parties, with the main purpose of securing evidence on this postulated "edge effect", as potentially a major manifestation of the gregarious behaviour of the locusts. This was in fact achieved [107, 143] ; photographic evidence of "counter-marching" was provided by observations made during the passage of the leading edge of a number of travelling swarms, where the lower-flying locusts showed a marked predominance of orientations in a direction opposite to that of the displacement of the swarm as a whole ; a specific example is illustrated in reference 143. Conversely, orientations at the trailing edge were in general agreement with the direction of displacement of the complete swarm. Finally, locusts approaching the flanks of travelling swarms, both singly and in groups, have been observed visually, on a number of occasions and by several different observers, to turn back as they reached the perimeter of the swarm. Marching locust hoppers have similarly been observed to turn back on arrival at the perimeter of their band [131]. Evidence of the effectiveness of the cohesion often so maintained in swarms was provided by observations of a virtually complete absence of locust stragglers after the passage of such swarms even across thick thorn bush [99], though, on the other hand, stragglers were frequently found in stands of tall grass, an exceptional habitat

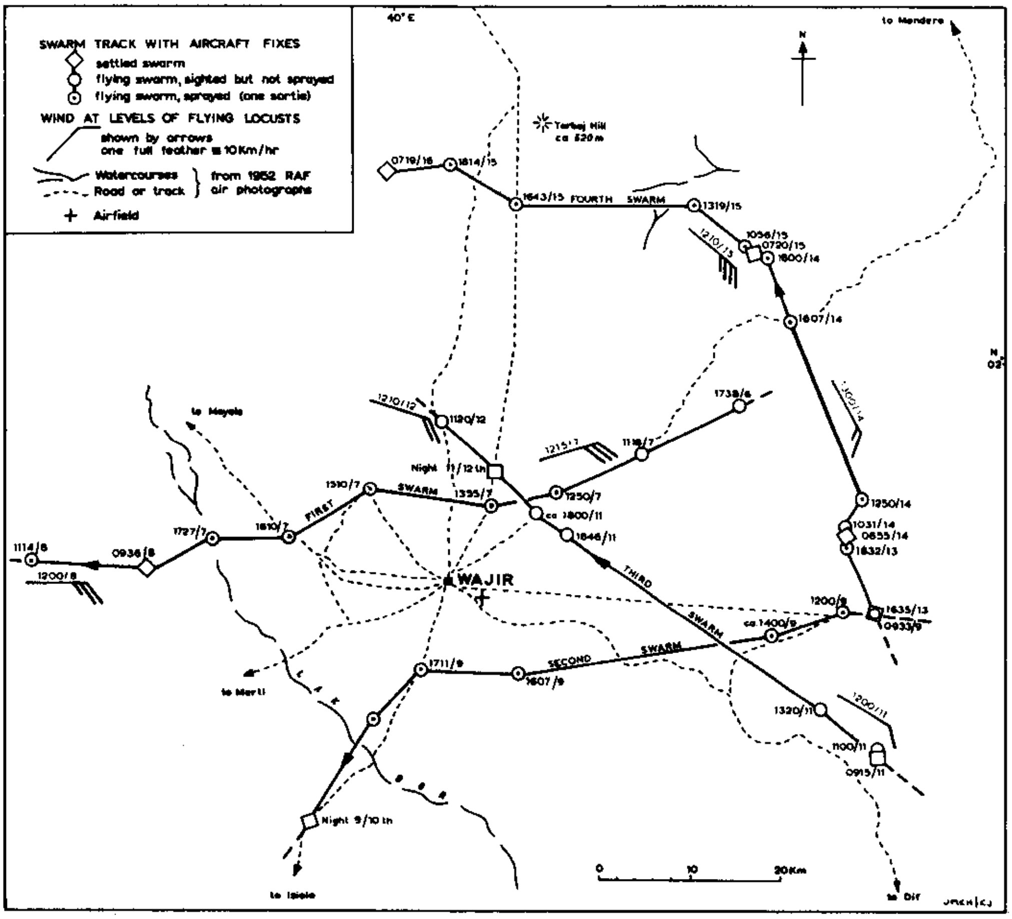


Figure 2 — Movements of individual Desert Locust swarms near Wajir, Kenya, February 1952 : effects of day-to-day variations in wind-direction. Note special key for wind-speeds in this and subsequent figures.

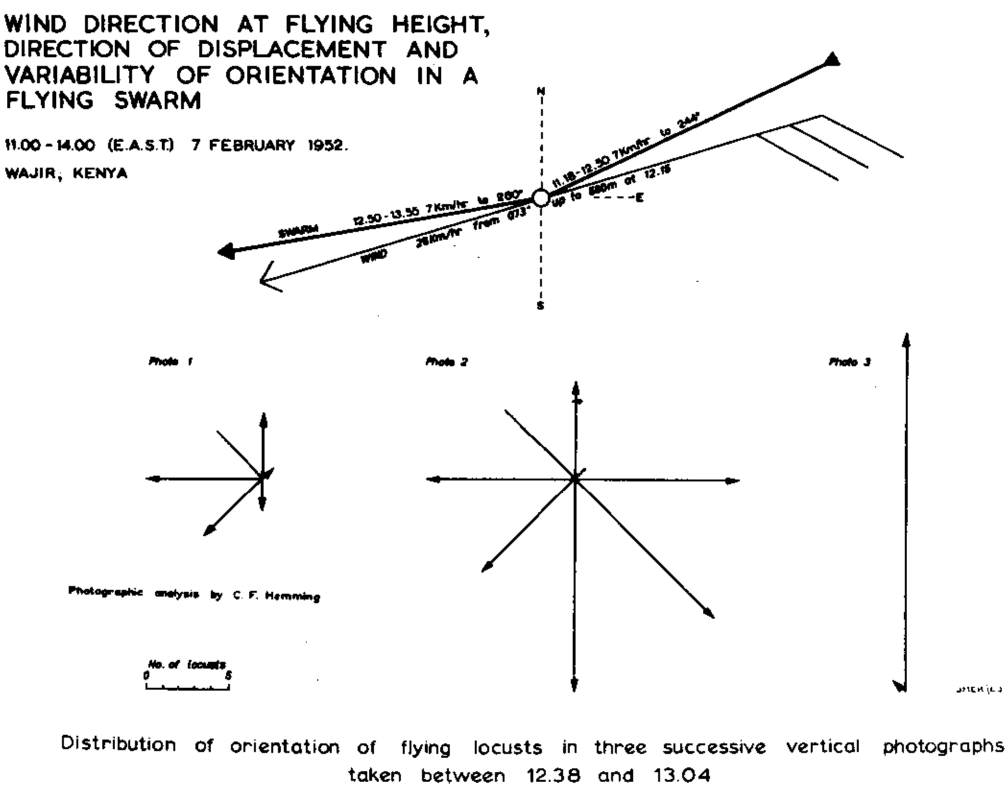
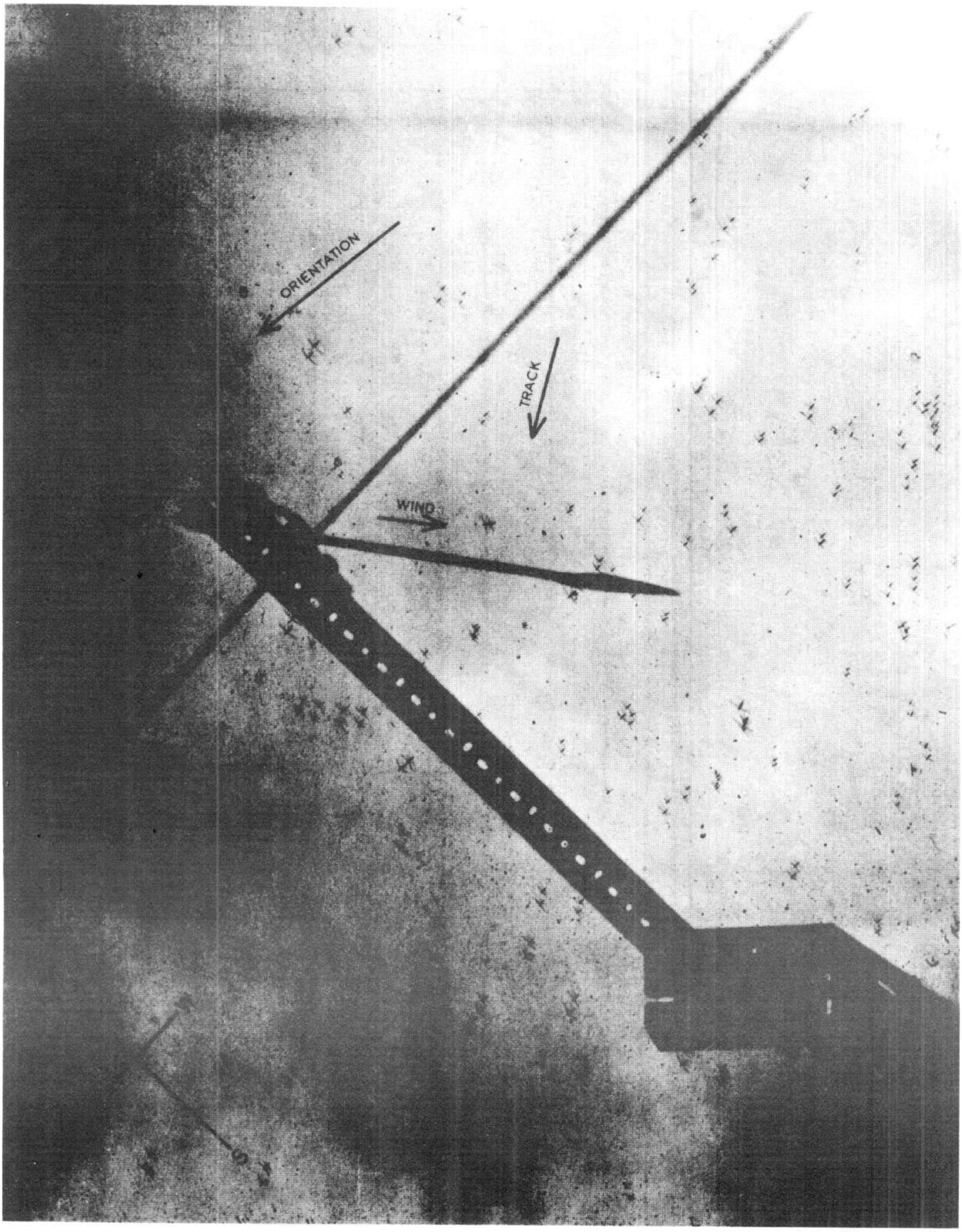
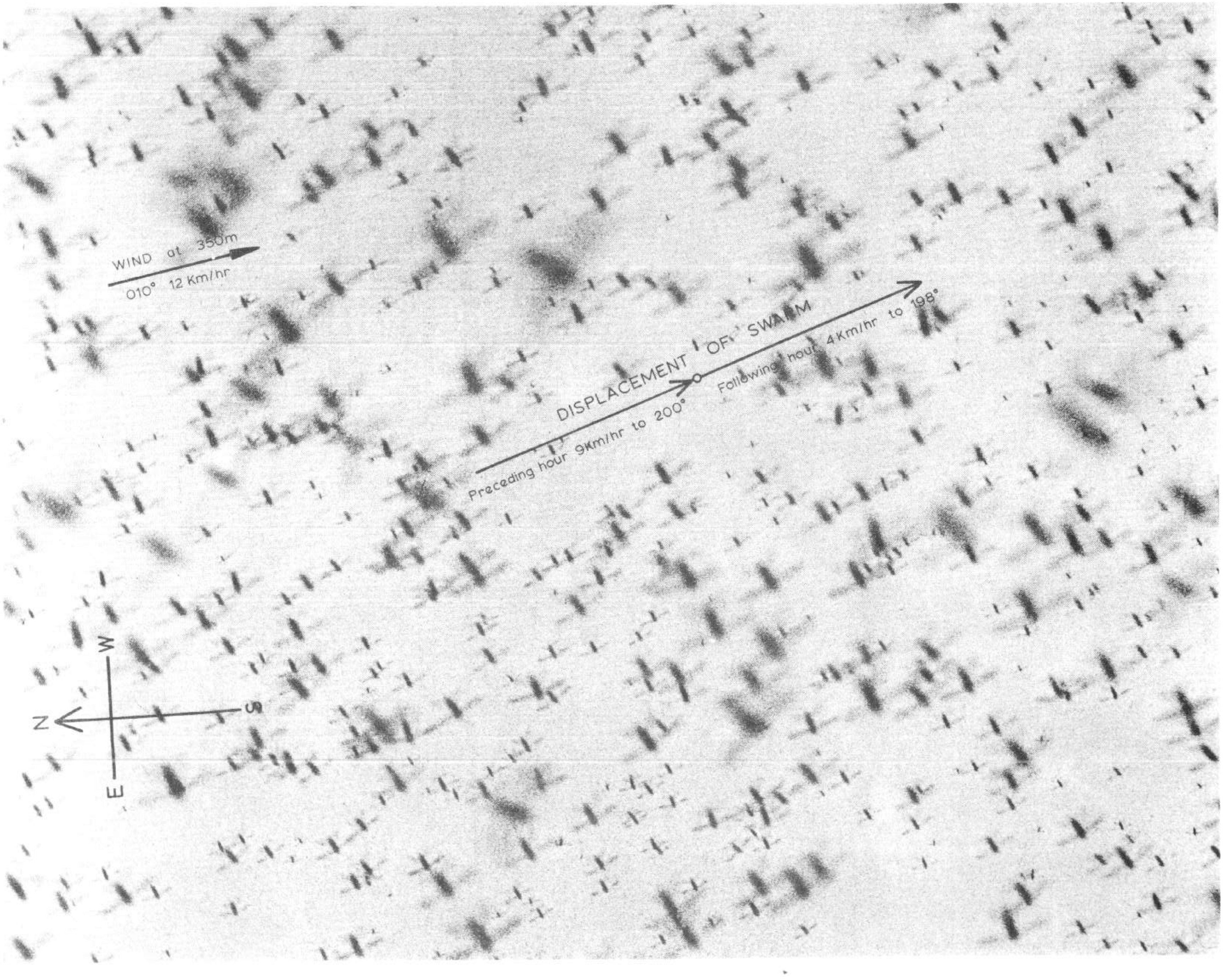


Figure 3 — Orientation of flying locusts in relation to wind and direction of displacement of a swarm.

Plate II — Group of flying locusts in a swarm at Marangu on the lower slopes of Kilimanjaro, in Tanganyika [107]; photographed vertically upwards from the ground by a double-exposure technique [122] giving two successive exposures each of about $^1/_{500}$ second separated by an interval of $^1/_{50}$ second; 1310, 22 February 1955.

Despite the degree of uniformity of orientation shown within such groups of flying locusts (which persisted at this point for at least six minutes), and the low wind-speed (7 km/hr) relative to the air-speed of the locusts (shown by the small angle of drift between their orientation-"course" — and their direction of displacement relative to the ground-"track"), the swarm as a whole remained effectively stationary on the same site for at least a further day, with the groups of flying locusts repeatedly seen to fail to pass the perimeter of the swarm (pp. 10, 52).


ORIENTATION
TRACK
WIND


WIND at 350m
010° 12 Km/hr
DISPLACEMENT OF SWARM
Preceding hour 9Km/hr to 200°
Following hour 4 Km/hr to 198°
W
N
S
E

in which these reactions would appear to break down [106]. Rough quantitative assessments have been made of the potentially disruptive effects successfully opposed by a particular swarm (Figure 8) which maintained an approximately constant area of 60 km^2 during a displacement of 370 km across central Kenya over a period of nine days. In these conditions turbulence could have been expected to disperse a cloud of completely inert airborne particles, in area and vertical extent similar to the swarm, at a rate corresponding to doubling the cross-wind diameter of the swarm in a time of the order of six hours [96].

There is some evidence on the sensitivity of the sense-organs which are available to provide the instrumentation required to enable flying locusts to react to each other. Thus electrical responses have been demonstrated in the nerves from the locust eye [10], evoked by movements of a small light-source through as little as 0.1°, which is the angle subtended by the length of a locust at a distance of about 30 m. Furthermore, the sound emitted by a flying locust has been found to evoke a demonstrable electrical response from the tympanal organ of a second locust, though the distance over which one locust can hear another in flight under field conditions is likely to be only of the order of 2 m or less [44]. The range of spacings of flying locusts observed in swarms (from the order of 10^{-3} to 10 locusts per cubic metre), and the continued cohesion of many travelling swarms, would thus be consistent with possible behaviour reactions operating to keep each locust within visual range of its neighbours, while perhaps avoiding their wakes [70, 97].

A substantial proportion of the individual photographs in every series exhibited an obvious predominant orientation (Plates II–III) which was at times shown at flying heights up to the corresponding limit of photographic resolution (several hundred metres), and with a degree of uniformity of orientation illustrated by standard deviations of orientation which were sometimes as low as 13°, as in Plate II [21]. A consistent predominant orientation was often maintained throughout a number of successive photographs, over periods sometimes as long as 20 minutes. However, on no occasion on which serial photographs, taken throughout the passage of a swarm, have so far been examined, was a single consistent orientation predominant throughout the swarm. On the contrary, there were, consistently, striking differences in the predominant orientations recorded at different times at a single point within each swarm, and between different points at the same time ; and in four different swarms, which were travelling at ground-speeds ranging from 2 to 7 km/hr, the predominant orientations recorded at different stages during the passage of each swarm ranged over all four quadrants of the compass.

Flying swarms vary in vertical extent from a few metres to several thousand metres, with the spacing of the locusts in them ranging from more than ten locusts per cubic metre down to the order of one locust per thousand cubic metres, and very commonly with a proportion of the locusts temporarily settled on the ground beneath those in flight. The maximum height of flight is often attained in the afternoon, with the topmost locusts sometimes within 150 m of the upper limit of dry convection from the ground, but on other occasions, particularly with smaller swarms, remaining well below this limit [96]. In somewhat exceptional circumstances, it appears to be just possible for the heat exchange of the flying locusts themselves to affect the development of convective turbulence within a large swarm [96, 97]. Swarms commonly but not invariably [113] settle at night, while solitary locusts on the other hand appear to fly mainly by night [146].

Plate III — **Part of a photograph of a group of flying locusts in a passing swarm, viewed vertically upwards from the ground, with the corresponding direction and speed of displacement of the swarm as a whole, and the wind at the time at a level representative of the flying locusts [107] ; Kanga, Kenya, 1625, 10 February 1955. Height of topmost locusts, by aircraft observation, 720 m above ground ; wind at half this height estimated by interpolation between wind of 063° 8 km/hr at 2 m and wind of 327° 15 km/hr at base of Fc at 1950 m [98], from same series of photographs ; see Appendix.**

Despite the impression of instinctive purposefulness given by such a uniformly-orientated group, all swarms so far studied in this respect have been found to consist at any one time of large numbers of such groups, with the widest possible diversity of orientation between groups, resulting in a directly down-wind displacement of each swarm as a whole, as shown.

CHAPTER 2

DISPLACEMENTS OF INDIVIDUAL LOCUST SWARMS IN RELATION TO METEOROLOGICAL FACTORS ON THE MESO-SCALE

Further evidence of the very limited role of the orientation of the flying locusts in the displacement of the swarm has been provided by observations of the hour-to-hour and day-to-day movement of individual swarms in relation to the corresponding winds. Such records were secured for the first time by detailed analyses of aircraft observations in Kenya in 1951, and subsequent experience, in the course of aircraft spraying trials and operations against swarms, has provided a considerable body of evidence on this point, still largely unpublished. Since these results cast some doubt on the recorded findings of earlier ground observations (section 2.1.3.1), it is necessary to present the new material in some detail, and to give critical consideration to the probable limitations of these various methods of observation, both ground and air. Except where otherwise indicated, the data presented in this chapter (2) relate to sexually immature swarms.

2.1 Estimates of instantaneous velocity of complete swarms and of the corresponding winds

For the detailed study of the relationship between individual swarm movements and wind, a basic set of observations would, ideally, comprise an instantaneous value of the direction and speed of displacement (i.e. velocity) of the whole swarm, relative to the ground, together with a corresponding value for the instantaneous velocity of the air in which the swarm was at that instant flying. The velocity of the swarm as a whole must represent the vectorial mean velocity at that moment of all the locusts in it ; and the corresponding wind is of course the net, overall effect of all the varying air movements relative to the ground, occurring at that instant throughout the swarm.

Because of the very large number of photographs which would be required to sample adequately the diversity of orientations exhibited even by the lower-flying locusts in a complete swarm (in addition to the uncertainty due to locusts flying above the upper limits of photographic resolution), it has not yet been possible to secure sufficiently representative records of the flight behaviour of the individual locusts in a flying swarm to give a net, overall direction of displacement approximating to that of the swarm as a whole. The only available evidence of the direction and speed of displacement of complete individual swarms is accordingly that provided by successive fixes of the position of each swarm. Relative to the scale of swarm displacements over periods of months and distances of thousands of kilometres, some of the observations now available on the direction and speed of movement of swarms, over periods of the order of an hour and distances of a few kilometres, can be regarded as acceptable approximations to instantaneous point values ; and in a number of cases, where several such observations were made on the same swarm within a few hours (see e.g. Figure 3 and Table I) the agreement between the successive estimates of swarm velocity provides direct justification for this approximation.

The accuracy of the estimate of the velocity of a swarm which is provided by two successive fixes of its position depends of course in the first place on the accuracy of these fixes, and it has accordingly been found necessary to undertake a re-analysis of each flight-log, in much more detail than was needed at the time merely to maintain contact with the swarm, and incorporating for example the standard corrections to compass bearings and, particularly, to indicated air-speed (for air density and for position error) as well as taking account of all available evidence on the winds encountered. Furthermore, the length of the displacement of a swarm (usually assessed in terms of the movement of its centre) must be not only large compared with the accuracy of the individual fixes but also at least comparable with the length of the swarm. A minimum interval of time is accordingly needed to provide a useful estimate of the velocity of the swarm ; and this interval, moreover, will be related both to the size and to the speed of displacement of the swarm, longer intervals being required both for larger and for slower moving swarms.

This limiting period may, in turn, affect the relevance of the corresponding wind observations, provided in most cases by a single, relatively instantaneous pilot-balloon ascent ; the longer the period needed to provide adequate evidence of the velocity of the swarm, the greater the possibility that the wind may change with time in such a way as to make such a single observation unrepresentative of the whole period under consideration.

In contrast with the cases already mentioned as indicating relatively constant swarm velocity, over periods of hours and distances of tens of kilometres, other cases, considered in sections 2.2.2 and 2.2.3, provide evidence of marked changes in the direction and/or speed of displacement of swarms, on a scale of hours and kilometres ; and no satisfactory estimates of swarm velocity can yet be quoted for such conditions.

2.1.1 *The most fully-documented observations*

It is convenient to begin with the detailed consideration of occasions when the direction of displacement of the swarm and the corresponding wind were most firmly established, by records of individual hour-to-hour swarm displacements for which instrumental observations of wind were available within a distance of 100 km, for heights representative of the observed vertical extent of the swarm, and either between the times of the two successive swarm-fixes used, or, at worst, within 1½ hours before or after this period. Moreover, cases with evidence of marked changes ($> 90^{o}$) in the direction of the wind or of swarm displacement in the area and period under consideration, together with those for which the successive fixes were either closer together than the linear dimensions of the swarm (and therefore unsatisfactory as evidence of direction of displacement), or, on the other hand, not made within the same day (and accordingly subject to potential uncertainties of shorter-period changes in wind and/or swarm movement), are deferred, with other less completely documented cases, for consideration in subsequent sections.

The present material has furnished a total of 49 cases, of which details are tabulated in the Appendix, satisfying these somewhat drastic criteria, and thus providing direct, objective evidence of the direction and (in 42 cases) speed of the displacement made good by a swarm relative to the ground, together with the strength and direction of the corresponding wind, taken as the vectorial mean wind between the level of the topmost locusts on each occasion and that of the ground, and computed from each appropriate upper-wind observation. The areas represented by these observations are Borama district, in the Somali Republic, and, in Kenya, the districts of Garissa, Isiolo and Wajir, in the Northern Province, of Kitui, Machakos and Masai, in the Central Province, and of Kwale in the Coast Province. Relative to the total material available, from over ninety swarms followed, however, this number of cases is not large ; they do not include any fully-mature swarms ; and they relate, moreover, to predominantly fair weather, with isolated showers seen in the distance on only four of these occasions, since the evidence on the more erratic swarm movements, considered in later sections, includes most of the observations made in rain or unsettled weather. In other respects these 49 cases sample a wide range of conditions, relating to swarms ranging in size from 0.03 to 150 km^2 and in vertical extent from 15 to 1,690 m above the ground, observed in winds from 6 to 34 km/hr and air temperatures from 15^{o} to 37^{o}, and over terrain varying from the thorn-bush plains of the Kenya lowlands, 100–300 m above sea-level, to the rugged mountains and deep valleys of the north-western Somali Republic, with summits up to 1,800 m, and the open grasslands of the Kapiti plains at 1,500–2,000 m in the Kenya highlands. While 32 of these

49 cases relate to swarms sprayed with insecticide during or prior to the displacement recorded, most of these operations were on a scale which, with the insecticides and techniques then available, was small in relation to the size of the swarm (p. 46) ; only in three of these cases (15.1.1952, 22.1.1953 and 15.2.1955) was there reason to believe that anything approaching half of the locusts concerned had received lethal spray doses up to the end of this displacement ; and on two occasions (including 15.2.1955) a direct comparison of the track made good by the target swarm with that of a neighbouring unsprayed swarm showed differences of only 3° and 6° (Table I and Figure 10).

All these results, summarized in Figure 4 and presented in detail in the Appendix, show directions of movement within the down-wind quadrant, with the directions of swarm displacement showing a root-mean-square difference of only 15° from the corresponding wind-directions. In half of the cases the direction of displacement was in fact less than 10° from directly down the corresponding wind ; and the largest departure recorded from directly down-wind movement was 34°. Moreover, in all five cases in which this difference exceeded 25° the data were in some respect (see Appendix) less satisfactory than most of the other observations of this series ; in two of these cases the establishment of the position of the swarm was known to have been only approximate, and in the other three cases the corresponding wind-observation used is likely to have been less relevant than usual, owing to the height of flight of the swarm (p. 19) or to the place and/or time at which the wind was observed. Thus two of these latter observations were made at a distance of more than 55 km from the swarm, in one case 1½ hours before the time of the first fix and in the other only 5 minutes after it, while in the third case there were intervening mountains rising to 300 m above the level both of the pilot-balloon station and of the lower flying locusts.

It is not possible to make any rigorous direct comparison of the differences actually found, between the direction of swarm displacement and that of the corresponding wind, with the differences to be expected by chance from random errors of observation, since no systematic replication of the observations of swarm-displacement nor, at the time, of those of the corresponding wind, was practicable. Some indication of the degree of reproducibility of such estimates was however provided by a few occasions on which more than one observation of the velocity of swarms and of the corresponding winds were made within a limited area and period. On one occasion independent observations of the direction and speed of displacement of two different swarms and of the corresponding winds at two neighbouring pilot-balloon stations were, by chance, all made within a radius of 45 km and a period of just over four hours. Table I shows the results found, together with those for another occasion when two successive observations of the velocity of a single swarm were made within a similar period and a radius of 75 km, together with pilot-balloon ascents at three different neighbouring stations.

Table I *Reproducibility of estimates of velocity of locust swarms and of the corresponding wind*

	Direction and speed of displacement of swarms			Wind between ground and level of topmost locusts				
11 February 1955 (Fig. 11)								
(i)	1100–1345	185°	7 km/hr	(1110	Mtito Andei	003°	9 km/hr)	up to
(ii)	1255–1525	191°	6 km/hr	(1210	Makindu	024°	9 km/hr)	800 m
17 February 1955								
(iii)	1450–1545	205°	7 km/hr	(1330	Voi	036°	23 km/hr)	
	1545–1720	215°	5 km/hr	(1415	Makindu	020°	21 km/hr)	up to
				(1740	Mtito Andei	035°	34 km/hr)	150 m *

* Observations made with un-tailed balloons ; speeds indicated are accordingly subject to the uncertainties of possible vertical air movements.

On both these occasions the two estimates of swarm-velocity agree to within 10° in direction and 1–2 km/hr in speed. The corresponding wind directions show ranges of 21° and 16° on the two occasions, which may at least to some extent represent real trends in space and time ; linear interpolation between these wind-observations on this assumption, to provide an estimate of the actual wind at the position of each swarm, does in fact give a wind-direction which for these occasions agrees to within 3° with the corresponding direction from which the swarm was moving. The very close agreement indicated by these particular cases, however, may well have been partly fortuitous, in view of the quasi-random turbulent fluctuations in wind which are shown even by pilot-balloon ascents made in rapid succession at the same station.

Evidence of the magnitude of these fluctuations, under conditions approximating to those of the swarm observations, was provided by a short test series of tailed pilot-balloon ascents, planned with the guidance of the late C. S. Durst and undertaken by A. J. Wood in an area (Mtito Andei), at a time of year (February 1956) and at times of day (1100–1200, 1330–1430 and 1600–1700) corresponding to those of a number of the best documented observations of swarms during the two preceding years. Precipitation was however noted at Mtito Andei on six of the 28 days of the 1956 test series, indicating conditions considerably more unsettled than were encountered during the 49 swarm observations being considered, and accordingly with possibly more variable winds. During this test series, it was found that a determination by pilot-balloon of the direction of the vectorial mean wind between ground-level and a representative height of 800 m differed from the result of a similar determination made ten minutes later by more than 10° on 48 out of 94 such occasions, and gave a root-mean-square difference of 16.4° for these successive observations. This indicates a figure of $16.4/\sqrt{2}$, or 11.6°, for the standard deviation of the distribution of such observations, about the corresponding mean wind averaged over a ten-minute period, attributable to the combined effects of observational errors and of wind-fluctuations within this period. Such observational errors and wind-fluctuations, if regarded as roughly representative of those involved during the swarm observations, would have accounted for about half of the total variance found between the direction of swarm displacement and of the corresponding wind, leaving a root-mean-square of about 10° to represent the combined effects of errors and fluctuations in swarm-track and of any real differences between swarm-track and corresponding wind-direction (together with the variation of ten-minute mean winds about the wind as averaged over the period, usually of several hours, between successive swarm-fixes).

The agreement between the direction of swarm-displacement and of the corresponding wind was thus very close, giving an overall bias with a mean value of only 5.4° and a standard deviation of 14°, though with this number of observations the bias is in fact statistically significant ($P < 0.02$). It has not been possible to establish with certainty the mechanism of this small bias, though it appears to have been particularly associated with the highest-flying swarms (Figure 4), for several of which the direction taken by the swarm corresponded more closely with the winds experienced by the more numerous lower-flying locusts than with the winds as averaged throughout the whole vertical extent of the swarm (see Appendix).

It is therefore concluded that the differences found, between the direction of swarm displacement and that of the corresponding wind, are no more than are to be expected from the evidence available on the errors of estimation involved in obtaining completely comparable values of both ; and that none of the differences found are to be interpreted as evidence of any real departure from directly down-wind displacement.

Consideration may next be given to the speed of the corresponding winds, in order to see to what extent these down-wind directions of displacement may have been physically imposed on the swarms by wind-speeds in excess of the air-speeds of which the locusts are likely to have been capable. Such an effect has been suggested as one cause of down-wind displacement [148], and has often been regarded as the main mechanism involved [50, 153, etc.].

The 49 present records of direct down-wind displacement include observations made at wind-speeds down to 6 km/hr, with 7 records at wind-speeds less than 9 km/hr (corresponding to a probable minimum air-speed for sustained free flight [151]), a further 19 observations at wind-speeds up to 15 km/hr (a probably conservative value for a cruising speed which could be maintained for many hours), and a further 8 records at wind speeds up to 20 km/hr, corresponding to the air-speeds found for low-flying locusts in some of these actual swarms. The remaining 15 observations were made at wind-speeds between 21 and 41 km/hr; but these speeds, like the others just quoted, all relate to winds averaged over the whole vertical extent of the corresponding swarm, from the ground upwards, while considerably lower wind-speeds will always have occurred near the ground, even in the open, with still lower values in bush and woodland.

The strongest wind recorded during this series of swarm displacements, 41 km/hr up to the level of the topmost locusts at 600 m, was on an occasion, already mentioned, with the swarm among mountainous terrain 30 km from the pilot-balloon station, while the corresponding wind at about 2 m among the lowest-flying locusts during this displacement was found to be only 13 km/hr. The next strongest winds recorded in this series were two observations of 34 km/hr (one given by an untailed ascent), up to 150–300 m over thorn-bush terrain, with corresponding values of 11 and 14 km/hr at 2.4 m. The strongest wind recorded at low levels during this whole series of swarm observations was 21 km/hr at 2 m on the open Kapiti plains (1558–1650, 23 January 1954); and even on this occasion it was noted that the lowest flying locusts, particularly those taking off from the ground, were just able to make perceptible headway against the wind [142].

It is accordingly doubtful whether the wind was strong enough, in any of these 49 cases, to impose a down-wind track on really low-flying locusts, within a metre or so of the ground, by exceeding the air-speed of which they were capable. On occasions (Hargeisa area, August 1957) when swarms have been observed directly experiencing sustained wind-speeds in the vicinity of 40 km/hr, likely to be strong enough to exceed the air-speed of locusts even at the lowest levels, flight activity was in fact conspicuously absent (until the wind dropped), even in bright sunshine at air temperatures above 20°, an effect which had also been noted in 1952 [142]; in lighter winds swarms have often been seen in sustained flight in sunshine at air temperatures below 20° (p. 8).

Turning now from the direction to the speed of displacement made good by these swarms, the ground-speeds found ranged from 1½ to 16 km/hr, with a median value of 6 km/hr; ground-speed of swarm is plotted against wind-speed in Figure 5, and indicated as a percentage of the corresponding wind-speed in Figure 4. A value of 100 per cent thus corresponds to the ground-speed to be expected of completely inert airborne material; and, with down-wind directions of displacement, the flight activity of the locusts might be expected to give some increase on this figure. In actual fact, only two of these 42 values of ground-speed exceed the corresponding wind-speed, and then only by 1 km/hr, a difference likely to have been within the limits of observational error. It is clear from Figures 4 and 5 that the range of directions and speeds of displacement actually shown by these swarms, in relation to the corresponding winds, covered only a small proportion of the range physically possible with the air-speed of which the locusts are capable. Thus there was no record of displacement in an up-wind or cross-wind direction, which would have been physically possible, even at the flying heights observed, on half the occasions studied. Moreover, while the direction of displacement was down-wind in all cases, there were none in which ground-speed appreciably exceeded wind-speed, although ground-speeds up to 3½ times the corresponding wind-speed could have been made good by continuous flight with down-wind orientation. Furthermore, in most cases the ground-speed of the swarm was in fact less than half the corresponding wind-speed.

The low ground-speeds thus found must have been due in part to the characteristically intermittent nature of the flight of these locusts, of which considerable numbers were nearly always to be seen temporarily settled beneath even the most actively flying swarm. In the large, high-flying swarms which have been

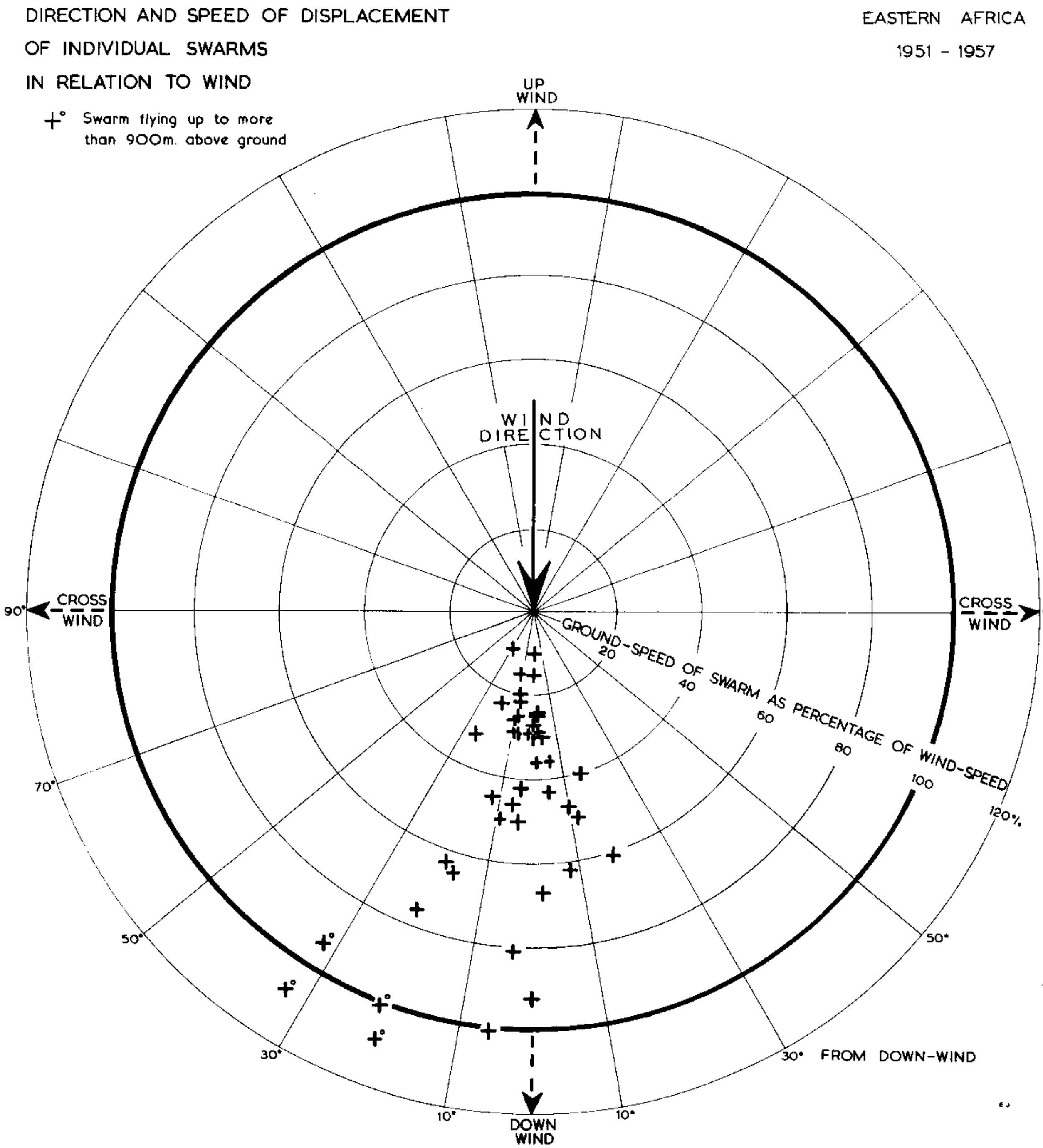


Figure 4 — Direction and speed of displacement of individual swarms in relation to wind.

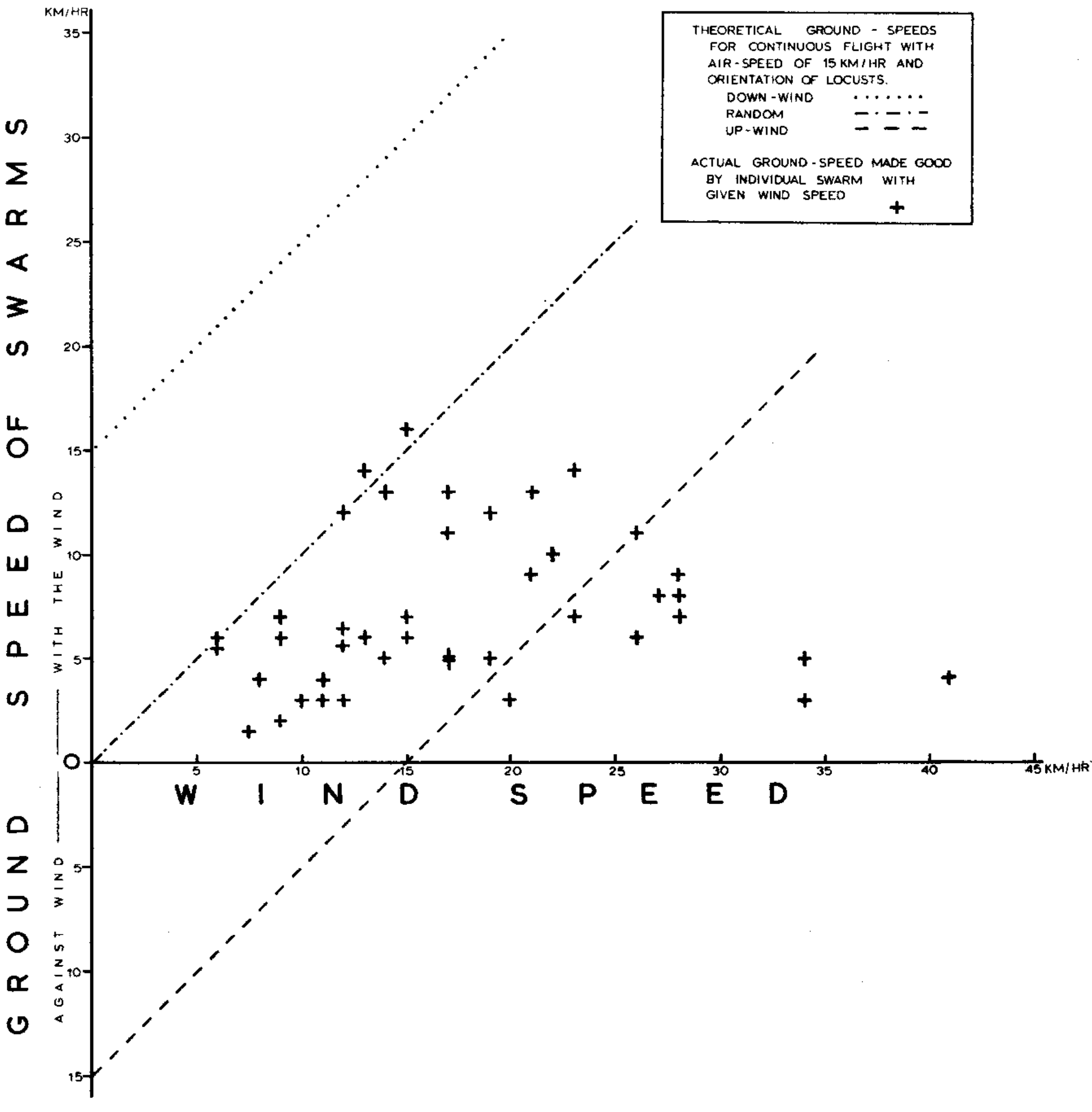


Figure 5 — Ground-speed of individual swarms in relation to wind-speed.

observed travelling at speeds close to that of the corresponding wind, with wind-speeds which ranged from 6 to 15 km/hr, it is suggested that the higher-flying locusts, effectively randomly orientated, act as pace-makers for those taking off again after temporarily settling beneath the swarm ; in such a swarm the flying locusts as a whole must clearly have shown some net preponderance of down-wind orientation. In a swarm travelling at a ground-speed substantially less than the corresponding wind-speed, on the other hand, it is suggested that the proportion and/or the height of flight of the randomly-orientated flying locusts may be insufficient to dominate the ground-speed of the swarm as a whole, though still determining its direction of displacement ; and in some such swarms there may even be some preponderance of up-wind orientations, since such a preponderance has been shown to be involved in enabling some locust populations to remain effectively stationary for extended periods despite flight in quasi-unidirectional winds [106].

Since within none of the swarms so far studied in this manner can the flying locusts have maintained any effectively consistent orientation — neither up-wind, cross-wind nor, in all probability, even down-wind — conscious navigation, comparable with that demonstrated by homing birds, appears to have been most unlikely. On the other hand, there is evidence that it was the actively gregarious behaviour of the flying locusts, one of the most striking characteristics of their biology, causing them to turn inwards at the perimeter of the swarm, which was responsible for maintaining the continued coherent existence of at least some of these individual swarms, despite the potentially disruptive effects both of atmospheric turbulence (p. 15) and of the diversity of orientation between the different groups of flying locusts in the interior of the swarms [96]. Direct observations (p. 10) suggest that such inwardly-directed flight took place all round the perimeter of each swarm, so that it could accordingly be without effect on the net displacement of the whole swarm.

2.1.2 *Other evidence*

Observations on swarms more than 100 km from the nearest upper-wind station were made on several occasions for which there is evidence of winds sufficiently similar, at two or more such stations in different directions from the swarm, over distances of several hundred kilometres, to suggest comparable conditions at the swarm. One such case was that of a swarm (including mature as well as immature locusts) which was followed by aircraft during 8–10 July 1954 in the course of spray-trials conducted by the Research Division of the Sudan Ministry of Agriculture in northern Kordofan [75, 162] ; see also p. 74. Two successive fixes of the position of the swarm, north-west of Sodiri, given by the first two spray sorties on the morning of the 9th, cover a period during which upper-wind observations were made both at El Obeid, 280 km south-east of the swarm, and at El Fasher, 360 km west-south-west of it. The swarm, which covered an area of 80 km^2, in cloudless weather with a wind recorded visually as light south-westerly, was flying up to 450 m above the ground, and the corresponding winds up to this height at 11 hours were 240° 28 km/hr at El Obeid and 235° 7 km/hr at El Fasher.

Between 0915 and 1115 the swarm made good a displacement of 20 km on a track of 072°, which was only 12° from down-wind in terms of the pilot-balloon observation at El Obeid, and 17° from that at El Fasher, both over 250 km away. These south-westerly winds were relatively shallow, extending only to about a thousand metres above the ground, with easterlies at higher levels, and the surface Inter-Tropical Front (p. 31) was probably within a few hundred kilometres to the north, though synoptic stations are lacking in this area ; a *haboob* was experienced the same day at Sodiri. The terrain was comparatively flat, between 500 and 900 m above sea-level over the whole area, which might perhaps be expected to have contributed to the uniformity of the wind-field.

Although among mountains both the wind-fields and the directions of swarm movement are often conspicuously affected by the terrain, as for example [90, 100] among the parallel Zagros ranges in western Iran in spring (when the higher points are still snow-capped), there have been other occasions on which winds and swarms appeared at least temporarily to have been unaffected by considerable topographical obstacles. A particularly striking example was provided by an immature swarm sprayed on a limited scale (3,500 litres 20 per cent DNC) in flight in the Usambara mountains in northern Tanganyika on 15 February 1954 (Figure 15), and will be recorded in some detail. Between 1445 and 1700 the swarm, 7×3 km in extent, moved from a position over the valley floor 12 km north of Korogwe, up the eastern flank of the massif, across the plateau near Bungu, and down again on the western side, involving an ascent of at least 800 m and a descent of similar extent within a distance of 11 km and a period of 2 $^1/_4$ hours. The track made good by the swarm between 1445 and 1700 (and closely maintained for a further hour across the lowlands, until it settled for the night around Mombo) was 307°, and dead locusts attributable to these spraying operations were subsequently reported along this track, at the villages of Dindila (1,250 m above sea-level) and Masasa (460 m) and around Mombo (400 m). During this movement the locusts flew at heights ranging from that of the valley floor, at 300–500 m above sea-level, to a maximum of 1,700 m A.S.L. for the topmost locusts flying above the plateau at 16 hours. One pilot-balloon ascent was made that afternoon at each of four meteorological stations in the surrounding area. The nearest of these stations was Mombasa, on the coast 170 km away to the north-east, where at 1530 the wind between 300 and 1,700 m above sea level was within 13° of the direction from which the swarm moved. At Voi, 180 km to the north and at an altitude of 560 m, the wind at 1200 between ground-level and 1,700 m was within a degree of the direction of displacement of the swarm. At Dar-es-Salaam, on the coast 220 km to the south-south-east, the wind at 1600 between 300 and 1,700 m above sea-level was 14° from the direction of swarm displacement. Finally, at Dodoma, 320 km to the west-south-west and at an altitude of 1,120 m, the wind at 1230 between ground-level and 1,700 m was 38° from the direction of swarm-displacement. At all four stations, these markedly uniform winds, from between easterly and south-easterly, extended up to at least 3,000 m above sea-level on this occasion, and may accordingly be expected to have completely submerged the Usambaras, with their highest point at 2,230 m.

Surface wind-directions at the swarm, noted from the air on three occasions between 1600 and 1710, were all between east and south-east ; and the only other wind-records available from the vicinity, surface observations at Amani and Tanga at 1430, were both south-east. Weather in the area was mainly fair or partly cloudy, with little precipitation to imply disturbance of the uniformity of the wind-field, and with generally small amounts of Cumulus, not lenticular. The base of $^1/_8$ Cumulus over Mombo was already as high as 1,800 m (above sea-level) at 1045, and, from the dry and wet-bulb temperatures (29° and 20°) recorded at Amani, at an altitude of 860 m, at 1430, cloud-base by this time is likely to have been at about 2,400 m above sea-level, above the highest summits. It may therefore be suggested that, under the influence of dry convective turbulence, the general south-easterly flow over the area could be expected to have penetrated well down into the valleys of the Usambaras ; temperatures over the mountains were much higher than in the Iranian cases mentioned.

The next occasion on which a wind-field of comparable uniformity was recorded from the area was on 3 March, with afternoon winds from between north and north-east at all four pilot balloon stations up to the top of each ascent, at 1,200–2,700 m above sea-level ; and this was in fact the day of a major exodus of locusts from the Usambaras (where swarms had been present since 22 January), in the form of a swarm, reported near Korogwe at mid-day on the 3rd (Figure 15), which in the course of the next five days moved 120 km away to the west.

Mention must also be made of the best available evidence secured on the direction of displacement of an individual sexually-mature swarm in relation to wind ; as indicated elsewhere (p. 53), the circumstances of these operations provided few opportunities for observations on such swarms. This particular swarm was sighted twice in the course of a single reconnaissance flight in southern Kenya on 12 March 1954, its yellow colour in conspicuous contrast with the red of the immature swarms which had been under observation throughout the previous 2½ months. The first sighting, at 1535, was 5 km on 163°

from Narok, and the second, at 1620, was 5 km on 212° from Narok, giving a displacement of about 4 km towards about 280°. Surface winds at Narok were recorded as SE at 1530 and S at 1630, with a pilot-balloon observation at 1305 giving southerlies near the surface becoming east-south-easterly at 300 m above the ground. While these wind observations do not fully satisfy the criteria of section 2.1.1, they are at least sufficient to indicate a down-wind sense for the direction of displacement. It had previously been suggested [50, 141, etc.] that mature and immature swarms might move differently in relation to wind-direction ; no evidence of such a difference has been found (see e.g. pp. 23, 51, and chapter 3).

2.1.3 *Implications of down-wind swarm movement*

2.1.3.1 *Note on earlier field observations*

While all authorities now appear to accept down-wind displacement as dominating the long-range movements of Desert Locust swarms [36, 52, 137, 145, 153], some attention must be given to an apparent discrepancy, on a smaller but still potentially important scale, between the consistently down-wind direction of all 52 individual swarm-movements demonstrated by the air observations presented in the preceding sections, and the fact that up-wind and cross-wind movements of individual swarms were repeatedly recorded during ground observations in earlier field studies on this point — including some by the present writer [40, 50, 148, 152, etc.].

The first possibility to examine is, of course, whether the aircraft data may merely have been insufficiently extensive to have encountered cases of up-wind and cross-wind swarm-movement such as were reported during the earlier studies. The limitations of the range of conditions covered by the hour-to-hour movements presented in sections 2.1.1 and 2.1.2 have already been indicated (p. 17) ; and considerable importance accordingly attaches to the data of sections 2.2, provided by the track followed by each individual swarm throughout the period of days (sometimes weeks) for which the aircraft were able to maintain contact with it, as evidence of the extent to which the relationship between swarm-movement and wind-direction indicated by the hour-to-hour observations is likely to have been maintained throughout these longer periods. Considered as a whole, these aircraft data are in fact probably more extensive, in total numbers both of individual swarms seen and of separate observations, than the whole of the earlier ground studies combined, and comparable with them in the overall range of areas and seasons sampled. Nevertheless, in some cases the shortage or absence of aircraft data is due at least in part to difficulties (such as of weather and terrain) inherent in this method of observation, and might therefore be suspected of concealing or at least of under-representing any types of behaviour which might be particularly associated with such conditions. A similar objection in principle applies also to ground observations, in which conditions in which swarms are most readily accessible from the ground must likewise be over-represented. The best available answer to these valid objections (see also p. 53) of in-adequately representative sampling in these field observations (both ground and air) is the comprehensive approach of chapter 3.

The evidence now available on the behaviour of locusts in swarms, however, as summarized in section 1.4, has also directed attention to the serious (and previously unrecognized) difficulties which confront a ground observer attempting to estimate the direction of displacement of a flying swarm, and which are now believed to require some re-assessment of the earlier observations. In particular, there have been the repeated demonstrations, by objective, photographic evidence, of extensive streams of strikingly uniformly-orientated flying locusts, conspicuously making good a direction of displacement, relative to the ground, quite different from — on a number of occasions diametrically opposed to — the direction of displacement, at the time, of the swarm as a whole [143, etc.]. Even with systematic photographic records taken throughout the passage of a swarm, it has not yet been possible to secure data on the orientation of a sample of the flying locusts sufficiently representative of the swarm as a whole to give a mean track corresponding with that of the complete swarm (p. 16), probably as a result of significant differences in orientation between lower-flying and higher-flying locusts as well as between the interior of the swarm and the vicinity of its perimeter. It is therefore clear that observations of the individual flying locusts seen over a more limited period may be wholly misleading as evidence of the direction of displacement of the whole swarm ; on a number of occasions (e.g. Plate II), such observations have even failed to show whether the swarm as a whole was moving at all.

Moreover, in addition to these difficulties of relating even completely objective observations of the orientation and displacement of individual locusts to the displacement of the swarm as a whole, there is also the fact that a locust swarm is an impressive sight — impressive in a way to which photography has never yet done justice. Objective visual observation is accordingly peculiarly difficult ; in particular, these uniformly-orientated groups and streams of flying locusts (e.g. Plates II and III) give an almost irresistible impression of purposefulness. It is suggested that this powerful impression may well have contributed to the assumption, explicit or implicit in earlier work [40, 50, 148, 152, etc.], that a travelling swarm is normally characterized by a single predominant orientation of the flying locusts ; early observations of circling flight and of widely differing orientations of flying locusts in different parts of the same swarm at the same time appear to have been tacitly regarded as relatively exceptional. Apparent support for this supposition of a single predominant orientation was provided by ground observations suggesting an assumption of uniform orientation by the flying locusts at mass departure from the roosting site [40, 50, 148] ; but later work [107, 143] has shown that this effect probably represents large numbers of previously settled locusts taking off at the trailing edge of a swarm and subsequently flying in the direction of their departing fellows, an effect which has repeatedly been seen not only on departure from the roosting site but also during the subsequent displacement of swarms.

The behaviour of flying locusts thus presents very considerable difficulties for the estimation of the direction of displacement of a swarm from observations made inside it. The difficulties of doing so from outside the swarm have been similarly demonstrated by evidence of the high probability of the presence of other swarms in the vicinity (in seasons of light infestation as well as during heavy invasions), and by experience of the continuously varying and often vague appearance presented by flying swarms [96], commonly providing no useful impression of distance, and at times temporarily disappearing from view altogether. Thus, while high-flying swarms are at times visible at great distances, the most careful observations on such occasions can only be expected to show whether they are moving across the field of view from left to right or from right to left. Even when a swarm passes directly over an observer, and successive bearings are taken on its upper parts as it approaches and recedes, there remain the uncertainties of the position relative to the rest of the swarm, both of the observer and of the features of the swarm on which he sights ; often he cannot be sure that his successive sightings are even on the same swarm. A single ground observer can thus rarely hope to do more than establish the general sense of displacement of a travelling swarm.

These difficulties of estimating the direction of displacement of a swarm from the ground have only been apparent since independent evidence on this point has become available by the use of aircraft. Ever since the systematic collection of records of migrating swarms was first attempted, "direction of flight" has, naturally, always been asked for, and locust control personnel and others concerned with reporting locusts in the field, had accordingly become accustomed to recording an opinion on the direction of flight of any swarm they might see, for many years before any means of assessing the accuracy of such opinions became available.

Moreover, in addition to these problems of estimating the direction of displacement of a whole flying swarm, there are the further difficulties of determining the appropriate corresponding wind, and, in particular, in the use of wind observations made within a few metres of the ground, such as have previously been made for this purpose. The first of these difficulties, which has been recognized for some time [40, 152, etc.], is that the swarms studied have often extended up to many hundreds of metres above the ground, and that wind observations are therefore required up to the level of the topmost locusts. Since 1947 such observations have been satisfactorily provided, as in the present work, by pilot-balloon ascents [148]; fortunately, difficulties originally envisaged [40] in making such observations in the vicinity of swarms in the field, such as puncturing of balloons by locusts, have not been encountered in practice. A second problem, presented by the more usual observations of surface winds, is the extent of minute-to-minute variations both in direction and speed due to atmospheric turbulence, often accentuated under the circumstances of these studies by intense insolation, dry soil-surface, and relatively low average wind-strengths. Ranges of up to 150° in wind-direction with corresponding variations of wind-speed by a factor of two have commonly been recorded within periods of minutes during the passage of a swarm. Since these turbulent fluctuations of wind may to a first approximation be regarded as random, this particular difficulty can be readily overcome by averaging a sufficient number of individual observations over an appropriate period (as for example in Plate III) : few of the earlier observations suggest that this precaution was in fact taken.

In all the earlier observations of swarm movements in relation to wind, attention was, naturally, directed primarily to the orientation of the flying locusts, and to the corresponding surface wind direction. The difficulties which can be imposed by the variability of both were illustrated by the passage of a number of swarms, during each of which the flying locusts showed at different times predominant orientations (recorded photographically) within all four quadrants of the compass and during one of which the surface wind direction, within a period of four minutes, likewise entered all four quadrants — while each of these swarms was in fact travelling at the time in a direction within 12° of directly down the corresponding mean wind.

Since the wind most directly relevant to the data available on the displacements of complete individual swarms would be a value averaged over the corresponding distance, of the order of kilometres, and time, of the order of hours, useful estimates of this wind can often be provided by routine synoptic data on the wind-field concerned ; and in fact for 27 out of the 49 sets of observations considered in section 2.1.1 the wind data were provided by the routine upper-wind observations of the local meteorological service. An early attempt to estimate, by interpolation from such routine synoptic data, the winds likely to have been experienced on particular days by a particular swarm, was made in respect of the first swarm to be successfully followed, with the help of air reconnaissance, for a period of several weeks, in the western Kenya highlands during April-May 1945 [40]. There was, however, "no similarity between the interpolated wind directions and the roost-to-roost displacements (of the swarm)" ; and the discrepancy between this negative conclusion and the positive findings of section 2.1.1 requires examination. The difficulties involved in estimating these "interpolated winds" were fully recognized at the time ... "winds near the ground must be greatly and unpredictably affected by the considerable irregularities of the surface. Thus our observations were mostly made in places within 30 miles of some ground at least 2,000 ft and sometimes 7,000 ft higher" ; and it was also pointed out, as a further complication, that these observations were made during a season of transition between the NE monsoon and SE trade régimes. A recent re-examination of the meteorological records available for this area and period has emphasized the complexity of the wind-fields concerned, with not only north-easterly and south-easterly but also westerly winds established sometimes simultaneously at neighbouring stations, and at times experienced in succession at a single station ; and the original authors have courteously indicated that they are now quite prepared to accept the over-riding importance of the complexity of the wind-field in their failure to find any relationship between their interpolated winds and the recorded movements of the swarm ; in fact, in such conditions, interpolation cannot be soundly done [35, 38].

In view of these various difficulties of observation, it is now clear that the direction of displacement of a whole swarm, relative to the corresponding wind, can only be satisfactorily established on criteria much more rigorous than have been accepted in the past.

The writer's own early records on this point [*in* 148], for example, were based on evidence which must now be regarded as quite inadequate. In most of the records of this type in the literature, the individual observations are not recorded in sufficient detail for re-assessment (hence the detail with which it has been considered necessary to present the later aircraft data on this point), but in some of these early ground records it is clear that up-wind or cross-wind swarm displacement has been inferred from observations of uniformly-orientated streams of flying locusts, such as have since been found at times to be entirely misleading as evidence of the direction of displacement of a swarm as a whole. Thus one of the best-documented of the earlier accounts [40] states, "We have seen a swarm flying straight into the wind, flying all below about 15 ft, and so dense as to conceal the bush a few yards beyond its near edge . . . and we have seen a swarm persistently flying (up to perhaps 50 ft) obliquely against the wind in such a way that its track was sometimes nearly at right-angles to the heading of the locusts", but without indicating any other evidence to show that the corresponding displacement of either swarm *as a whole* was in the direction indicated. It is still possible that these particular swarms may in fact have been moving respectively up-wind and cross-wind, but, in view of the extent to which such effects have subsequently been paralleled during observations on some swarms which at the time were effectively stationary, as well as on others which were travelling directly down-wind, such evidence alone cannot now be accepted as adequately establishing up-wind or cross-wind displacement of a complete swarm.

In no record of up-wind or cross-wind swarm displacement which has so far been seen, either in the literature or in unpublished observations, has the direction of displacement of the swarm, relative to the corresponding wind, been established by evidence of a type which can now be considered adequate; and a report on the most recent field experience in eastern Africa states, "The hypothesis constructed by Rainey (1951) of the down-wind displacement of locust swarms has now been subject to test for over ten years, and no exceptions have been definitely established (although) air movements which affect locust migration cannot always be detected on the scale plotted on to synoptic charts" [49]. On the other hand, since locusts can fly at air-speeds of 15–20 km/hr, up-wind swarm displacement, against winds of less than this speed, remains physically possible; and it is accordingly theoretically possible that adequate evidence of such displacements might still be secured in the future. In particular, attention may be drawn to the possibility that the real discrepancy between the earlier work and the present material may be no more than a reflection of the difference in scale between the two types of observation used. What appears to have been actually seen and described in the earlier work — and abundantly confirmed by the subsequent photographic studies — were up-wind and cross-wind movements of groups of locusts over distances of the order of tens to hundreds of metres. The present air observations record the displacement of complete individual swarms, over distances ranging from 84 down to 3 km, which within the limits of observational error have so far all been directly down-wind. It may therefore be suggested that it is on intermediate scales of movement, from a few hundred metres to perhaps a few kilometres, that evidence of up-wind swarm movement might still be sought — though some of the difficulty inherent in satisfactorily establishing the direction of swarm displacements on this scale has already been indicated (p. 17).

2.1.3.2 *Meteorological implications*

Before proceeding further with the evidence available on the routes followed by individual swarms, it is convenient to examine some of the meteorological implications of the down-wind displacement already indicated. In the cases considered so far, with substantially uniform wind-fields, attention has, in effect, been largely confined to wind-flow which was non-divergent, that is with no net excess of inflow or outflow across the boundary of any closed area within the region under consideration. Any surface synoptic chart, however, recording simultaneous observations of real weather over a sufficiently wide area, includes of course both areas of convergence, across whose boundaries surface winds show a net excess of inflowing air over outflow, and within which there must necessarily be a net ascent of air : and areas of divergence, across whose boundaries outflow exceeds inflow, and within which there must be a net descent of air. The process of convergence is an essential factor in the production of precipitation, while divergence is commonly associated with fair weather, with the dynamic heating of the descending air tending to disperse any cloud initially present : and much of the process of weather forecasting may in fact be considered as the recognition and characterization of areas of convergence and divergence.

From considerations of continuity, winds within the lowest kilometre or so of the atmosphere may be regarded, in general and on balance, as blowing from areas of divergence (where air will have descended from above into the stratum under consideration) ultimately into areas of convergence, where air will move up again to higher levels. Any airborne material, animate or inanimate, which (like hypothetical flying locusts of randomly-changing orientation) is without any systematic horizontal motion of its own relative to the air, must be displaced down-wind : and such movement must be, on balance, away from areas of divergence, where the early work of the WMO Mission [55] showed that regions of significant separation of air-flow into differing directions can usefully be recognized as "zones of terminal divergence", and towards areas of convergence. If such areas of convergence retain their identity for long enough the airborne material will reach them : and if this material should be constrained to remain within the lowest few kilometres of the atmosphere, as flying locusts are, it will begin to accumulate in these areas of convergence. Even in cases in which there is a component of the wind blowing right through the area of convergence, a statistical accumulation of such airborne material must still be expected, since, with an initially uniform distribution of the material, more must move into the convergence zone in unit time than moves out of it. On the other hand, in a wind-field which was confluent without being convergent, there would be no such accumulation.

From such considerations it was suggested in 1951, mainly on a basis of circumstantial evidence provided by detailed cartographical studies of particular locust situations in relation to the corresponding weather data (together with some field experience), that the major displacements of locust swarms take place down-wind, towards areas of convergence ; that swarms may in general be expected to collect in the vicinity of such areas ; and that this might provide a mechanism for the close and apparently purposeful association observed between the distribution and movement of swarms and the rainfall essential for successful breeding [92]. Thus a quarter of a century of cartographical analysis of Desert Locust records from all countries concerned with this species, has shown not only that areas and seasons of breeding are areas and seasons of rainfall [17, 19, 33, 137, 141], but also that the large-scale, quasi-regular seasonal swarm movements [26], which are so characteristic of the Desert Locust, in general take swarms from areas where seasonal rains are ending, to other areas in which the rains are beginning.

Furthermore, besides this general association of normal rainfall régime and usual breeding seasons, there are many records of locusts arriving and breeding in association with exceptional rains. Thus, for example, it was noted [4] that "In most years there is insufficient moisture and food in Sinai to support large swarms of hoppers. The peculiar feature of the present year (1929–30) was the very abundant winter and spring rainfall all over Sinai and the consequent vegetation which supplied the necessary food-plants for the enormous bands of hoppers which came from the numerous egg-deposits". This particular invasion took place between November 1929 and April 1930, and the total rainfall recorded during these six months at El Arish [45] was 152 mm, as compared with an average total of 86 mm for these months over a 25-year period ; at Ismailia the corresponding figures were 92 mm for 1929–30 and 39 mm for a 51-year normal. Desert Locust swarms have only been known to breed at all in the Sinai peninsula during seven out of the 37 years 1926–62. Again, during November-December 1949 [92], the first swarm record anywhere in Arabia after a lapse of nearly three months, at Mukalla in the Hadhramaut, with the first gregarious breeding which had been recorded in this particular area for five years, followed a rainfall of 182 mm in 36 hours at this station, for which the mean annual rainfall, over a 15 year period, is 58 mm.

Areas of convergence, however, particularly in temperate latitudes, are often elusive and ephemeral phenomena, which may appear, develop, weaken and disappear again within a matter of days and sometimes hours. Examples of such areas of convergence, which have been found important in relation to locust distribution, are those associated with the Mediterranean and Persian Gulf disturbances which provide the winter and spring rains of these regions (see sections 3.2.3.3 and 3.2.4.2). In addition to the convergence developed in association with such travelling pressure systems, Desert Locust swarms in lower latitudes also encounter semi-permanent zones within which marked convergence is repeatedly exhibited over periods of months, and which may oscillate to a relatively limited extent about a mean position, or exhibit in addition comparatively regular and progressive seasonal movements. An example of the former type is the zone of low-level convergence between south-easterly and north-westerly winds which appears to occur practically all the winter in the central Red Sea area, and to be associated with the characteristically localized winter rains of this area (see section 3.2.4.1.1).

Lastly, perhaps the most important and probably meteorologically the most controversial, is the feature (or features) known variously as the Equatorial Trough, Inter-Tropical Front or Inter-Tropical Convergence Zone, considered further in section 3.2. Opinions on the structure, mechanism and, particularly, nomenclature of this feature still differ widely. For present purposes, and throughout chapter 3, "Inter-Tropical Convergence Zone" will be used as a convenient generic term, defined merely as a zone within which there is evidence of the meeting of wind-currents from opposite sides of the Equator, and accepting that convergence is not continuously exhibited throughout the zone so defined [14, etc.] — which is moreover not even always inter-tropical.

Quantitatively, an order of value of convergence commonly recorded on the synoptic-chart scale, in association with disturbed weather, is 10^{-5} sec^{-1} [81, etc.] corresponding, in the straight flow case, to a 1 m/sec change in wind velocity, decreasing down-stream, over a distance of 100 km. For airborne particles, initially uniformly distributed, and without systematic horizontal motion relative to the air, but constrained to remain near the ground, such a value of convergence would give a net increase in the number of particles present, in a strip of given width and 100 km long in the direction of the wind, at a rate equal to the addition, in every second, of the number of particles initially present in a 1 metre length of the given width. This rate would double the number of particles in unit area in some 28 hours.

On the smaller scale of a single thunderstorm, with an inflow of surface air, during the early stages, from a distance of the order of 10 km, convergence of the order 10^{-3} sec^{-1} is found [12]. This corresponds, in straight flow, to a 1 m/sec decrease in wind-velocity over a distance of 1 km, and would double the number per unit area of the airborne particles under consideration in 17 minutes.

In addition to the effects of convergence and divergence on the large-scale distribution of swarms, considered in subsequent sections, there is also evidence that convergent wind-flow may at times have contributed to the process of gregarisation, by bringing previously solitary-living locusts from long distances into limited areas providing suitable conditions of moisture and vegetation for breeding [92], and perhaps also to within range of mutual perception [99].

Consideration has so far been given mainly to the wind-flow at the lower levels of the atmosphere, as obviously relevant to the movement and distribution of airborne material constrained to remain at these levels. In the mechanism of precipitation, also, the relative importance of the lower-level wind-flow is commonly weighted by a greater water-vapour content, since more than half the total water-vapour of the whole atmosphere occurs within the lowest two kilometres. But the production of precipitation involves a substantial depth of atmosphere (at least 2 km, commonly 5–10 km, and at times extending right up to the top of the troposphere, at about 15 km in tropical latitudes) : and such vertical development is greatly influenced by the structure of wind and moisture fields in the upper air. Moreover, active convergence at the lower levels of the atmosphere appears always to be associated with divergence at higher levels (and vice versa), the two types of flow being separated by one or more surfaces of non-divergence : the principal one of these surfaces is commonly to be found about half way up the troposphere (by weight), at some height between 3 and 5 km, though probably lower than this in situations such as that described below in the Sudan. Thus the actual distribution and intensity of precipitation, while often closely related to the distribution of convergence in the surface wind-flow [32, etc.], can at times be substantially modified by conditions above the surface, such as by any marked and systematic change of winds with height within the lowest few kilometres. In such conditions, the distribution of swarms may be expected to differ systematically from that of precipitation.

A striking example of this effect is provided by the summer situation in Sudan, and in fact for much of the way from West Africa to India [20, 118, 119 and 155–159], where the surface boundary, at which humid and relatively cool south-westerly winds undercut much drier and generally warmer northerlies and north-easterlies, is some 200 to 500 km to the north of the main belt of rains, to which the over-running northerlies commonly extend [119, 129]. In this situation, illustrated by the August data presented in Figure 6, the locust swarms are correspondingly to be found well to the north of the main rains, in the vicinity of the surface boundary. This boundary is a zone of abrupt transition between the two wind systems, often a discontinuity of zero order with respect to humidity and usually narrower than the distance between neighbouring synoptic stations in the Sudan ; observations temporarily made at Wadi Seidna, 20 km north of Khartoum, have shown "on several occasions NE winds of 5–6 kt ... when simultaneously south-westerlies occurred at Khartoum" [59]. In the Sudan and the other African countries concerned the feature is commonly termed the "inter-tropical front (ITF)" or *front intertropical (FIT)* : it corresponds also to the "inter-tropical discontinuity" as defined by Recommendation 60 (CSM II)–"a discontinuity separating very hot and dry continental air from the cooler moist air from Equatorial regions" [161].

A preliminary quantitative examination of the convergence of the low-level wind-field in the vicinity of the Inter-Tropical Discontinuity in this region was undertaken by J. A. Cochemé during the work of the WMO Technical Assistance Mission for Desert Locust Control [15], by the objective computation [5], direct from the original pilot-balloon observations, of the mean divergence within each triangle provided by the stations available in the area. Daily values of divergence (and vorticity) were computed from observations made around 0800 GMT for a height of 600 m above ground-level, taken as likely to be roughly appropriate for flying locusts ; the preliminary examination was restricted to October 1954, for which month the available data were most complete. Figure 7 shows the mean monthly value of the divergence given by each triangle, together with the mean position of the inter-tropical discontinuity during the month, as located in terms of wind, humidity, cloud and weather on the daily surface charts ; corresponding monthly rainfall totals have also been added. The data show a sinuous zone of convergence, with its axis showing some similarity with the shape and position of the Inter-Tropical Discontinuity, and with positive divergence shown further to the north and south. The heaviest rains were to the south of the zone of convergence as indicated at 600 m. A further point of general interest was that the corresponding vorticity values found were only of the same order of magnitude as the divergence. This contrasts with the situation in temperate latitudes, where vorticity is commonly one or two orders of magnitude greater than divergence, but is consistent with Cochemé's subsequent findings, by a different method, in East Africa, where nearly-pure indraughts persistently found within 5° of the Equator during February 1955 gave mean vorticity values which were only about one quarter of the corresponding values of convergence [14].

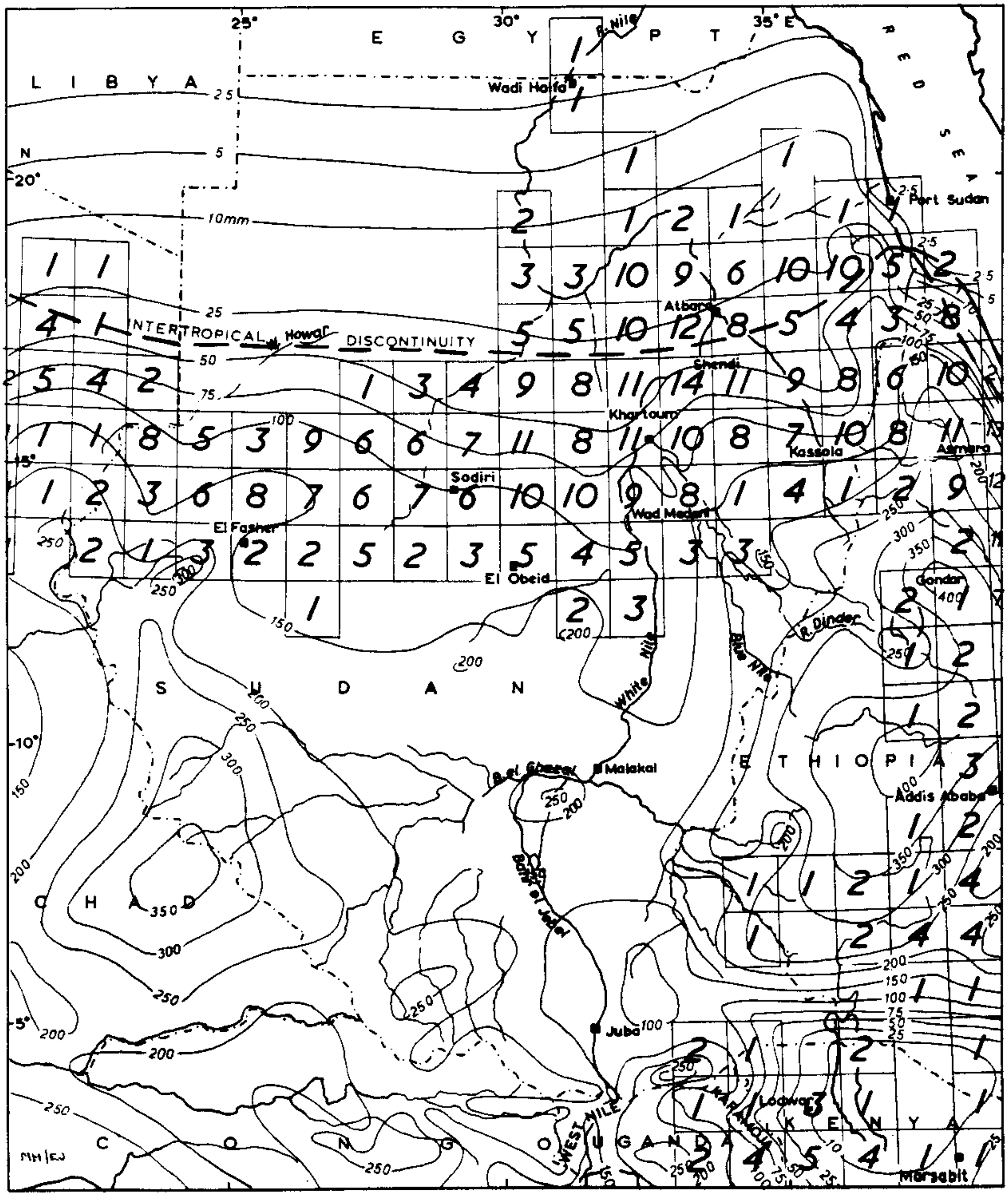


Figure 6 — Mean August distribution of swarms in the Sudan in relation to mean August rainfall and mean position of the inter-tropical discontinuity during the month [119, 158, 160].

Red figures indicate number of years during which swarms have been recorded in August in each degree-square during 1939–1958.

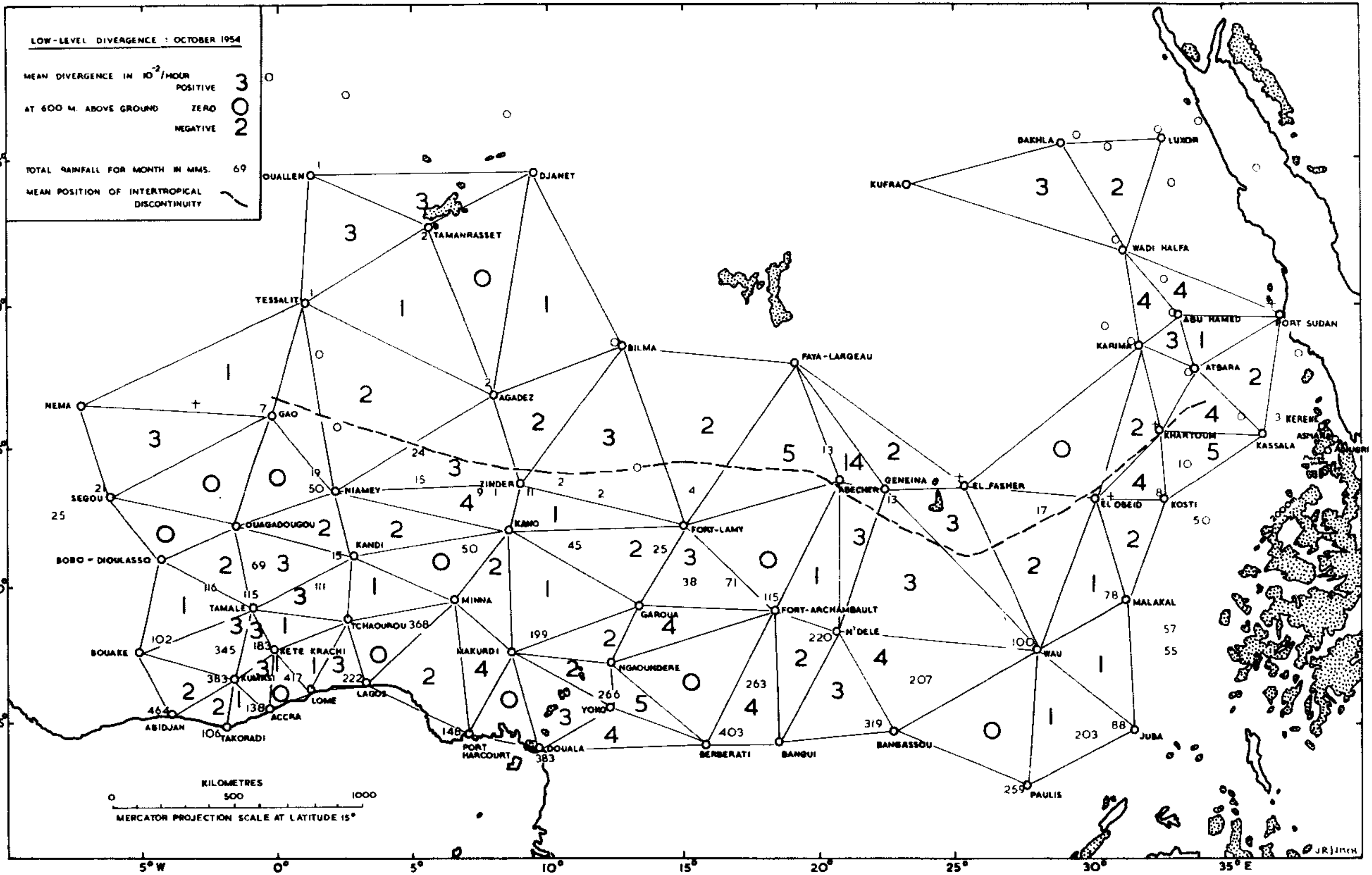


Figure 7 — Mean divergence of low-level wind-field in October 1954 in relation to mean position of inter-tropical discontinuity and total rainfall for the month [15].

2.2 Routes followed by individual swarms with particular reference to corresponding wind-fields

Following the evidence provided by the selected hour-to-hour movements of individual swarms and the corresponding wind observations, which furnish the best available approximations to instantaneous values of the velocity of the swarm and of the air in which it flew, consideration may now be given to the track followed and the geographical displacement made good by each individual swarm throughout the period for which it remained under observation. Apart from the direct relevance of such longer-period observations to the strategy and tactics of locust control, these displacements may also be considered, in relation to such information as is available on the corresponding wind-fields, as the effects, integrated over periods of days and sometimes weeks, of the swarm velocities sampled and considered in the previous section in relation to the corresponding instantaneous winds. These longer-period displacements thus provide evidence of the extent to which the relationship between swarm-movement and wind, indicated by the "instantaneous" observations, is likely to have been maintained throughout these longer periods.

The data available furnish 94 series of aircraft observations with each of these series including two or more successive fixes of position which could with reasonable confidence be attributed to a single swarm, taking into account the visibility and other relevant circumstances of each aircraft observation concerned. Objective evidence is thus provided on the direction and speed of displacement of individual swarms observed during seven years in six territories, over periods varying from hours to weeks and over distances up to several hundred kilometres. In addition, there were occasions (e.g. August-September 1957 in the Somali Republic) when numbers of swarms were repeatedly observed from the air, but in circumstances (close proximity to each other, together with indications of erratic movements and of some temporary loss of cohesion) in which it was not possible to attribute successive fixes with confidence to the same swarm. Such difficulties have been found to recur in a given area and season in a number of different years, such as in the Somali Republic at this season in five other years [49, 64, 123], and must be taken into account in considering how far the results found in other areas and seasons are likely to be of general application.

For this latter purpose, it is also necessary in general to take account of the widely differing circumstances in which different series of observations were made, ranging from intensive research on swarm behaviour, with reconnaissance aircraft and mobile ground parties available for this express purpose (as for example at Mtito Andei in February 1955), to aircraft spraying operations undertaken solely for the purpose of control (as for example at Mombo and Nginyang in 1954), with air reconnaissance necessarily primarily concerned with the location of successive suitable targets, no mobile ground observers, and many of the observations provided by pilots of spraying aircraft, flying usually alone and often under exacting conditions ; consideration has already been given (p. 18) to possible complicating effects of the spraying operations themselves. Both the frequency and the accuracy of swarm-fixes have accordingly varied greatly with the circumstances. The corresponding meteorological documentation has likewise varied, from occasions on which it was possible to undertake special observations of surface and upper-air conditions inside the swarm which was being followed, to other occasions for which not even the simplest observation of surface wind-direction was available within a hundred kilometres of the swarm.

A striking feature of these records as a whole is the contrast between the progressive, systematic swarm displacement shown by many of the data, and the highly erratic nature of the swarm movements shown by other observations. Each set of three or more successive fixes of the position of a particular swarm indicates the extent to which a consistent direction of displacement was maintained ; and the relationship so observed between the successive directions of displacement recorded for a single swarm has, on different occasions, ranged from conspicuous persistency (e.g. Figures 2, 8, 9) to almost complete reversal of the track of the swarm (e.g. Figures 12, 13, 14), sometimes within a few hours.

The relationship between the successive individual displacements of a particular swarm, and the corresponding resultant overall displacement made good, has varied, on different occasions, from progressive, long-range movement, over distances of hundreds of kilometres in a few days, to series of repeated changes of track which have in effect confined swarms within restricted areas for periods of weeks at a time, and with a number of observations of individual swarms which even continued to occupy the same site for several days at a time despite considerable flight activity. As in studies of wind-variability [8] such differences may conveniently be expressed in terms of *constancy*, defined for a particular swarm and series of observations as the ratio of the net ground displacement made good between the first and last observation of the series, to the arithmetic sum of all the individual displacements of the same series. The differences found in the effective mobility of swarms have covered a continuous range, with values of constancy from nearly 100 per cent to 0 per cent, but it is convenient to subdivide this wide range in the following manner.

2.2.1 *Progressive systematic swarm-displacements*

Systematic, progressive swarm-displacement, with constancy of direction exceeding 75 per cent and daily displacements of 5 to 130 km made good, was shown by half the swarms whose tracks have been recorded — 47 out of the total of 94 — throughout the period for which they remained under observation (ranging from 3 hours to 10 days), and, by a further 13 of the swarms studied, during part of the time they were under observation (Table II).

Persistent directions of displacement were well illustrated by the swarms which traversed southern Kenya during January 1954 (Figure 8) with the best documented period, in respect both of swarms and of meteorological data, between about the 16th, when the leading swarms had crossed the Tana river (and one, not subsequently followed, had reached the Galana), and the end of the month, by which time swarms had reached the Rift Valley in the west and the Usambara mountains in the south, having entered Tanganyika by 22/23 January along a front of more than 350 km, and aircraft operations were extended to the latter country.

These swarms were some of those which resulted from egg-laying during October and November 1953 over an area which extended for some 1,500 km south-westwards from southern Somaliland, across much of Somalia and the Ogaden province of Ethiopia, into the Northern province of Kenya, as far as the vicinity of Garissa. The first, and largest, of the swarms indicated in Figure 8, seen from the ground on 15 January north of Garissa, and the second, which for nearly a week remained some 50–150 km east of the first as they traversed the highlands, were probably among several which had previously been sighted, between the 11th and 13th, near the Kenya-Somalia border between El Wak and Dif. They are likely to have comprised locusts which had fledged in late December and at the beginning of January in the Dolo-Lugh Ferrandi-Mandera area (some 100–200 km further to the north-east, where there had been widespread egg-laying between 7 and 14 November, and from which area some escapes from control operations had been expected), probably with a nucleus of individuals up to a week or two older from still further to the north-east, and further reinforced by progressively younger individuals from progressively further south-west, as far as Garissa, where the southernmost egg-laying of this generation had been recorded between 21 and 26 November, and from which area any escapes might accordingly have been ready to join new swarms by about the third week of January. Such a "snowballing" process [121] appears to have been involved in other cases of the production of large swarms (e.g. p. 45).

The predominantly west-south-westerly displacement illustrated by Figure 8, and shown by all these swarms, over terrain ranging in altitude from less than 200 to more than 2,000 m above sea-level and almost regardless of topographical features such as the Yatta lava-plateau and the deep valley of the Athi river, give an impression of marked purposefulness, on a geographical scale, comparable with that initially given, on the scale of individual behaviour, by the uniformity of orientation often seen in

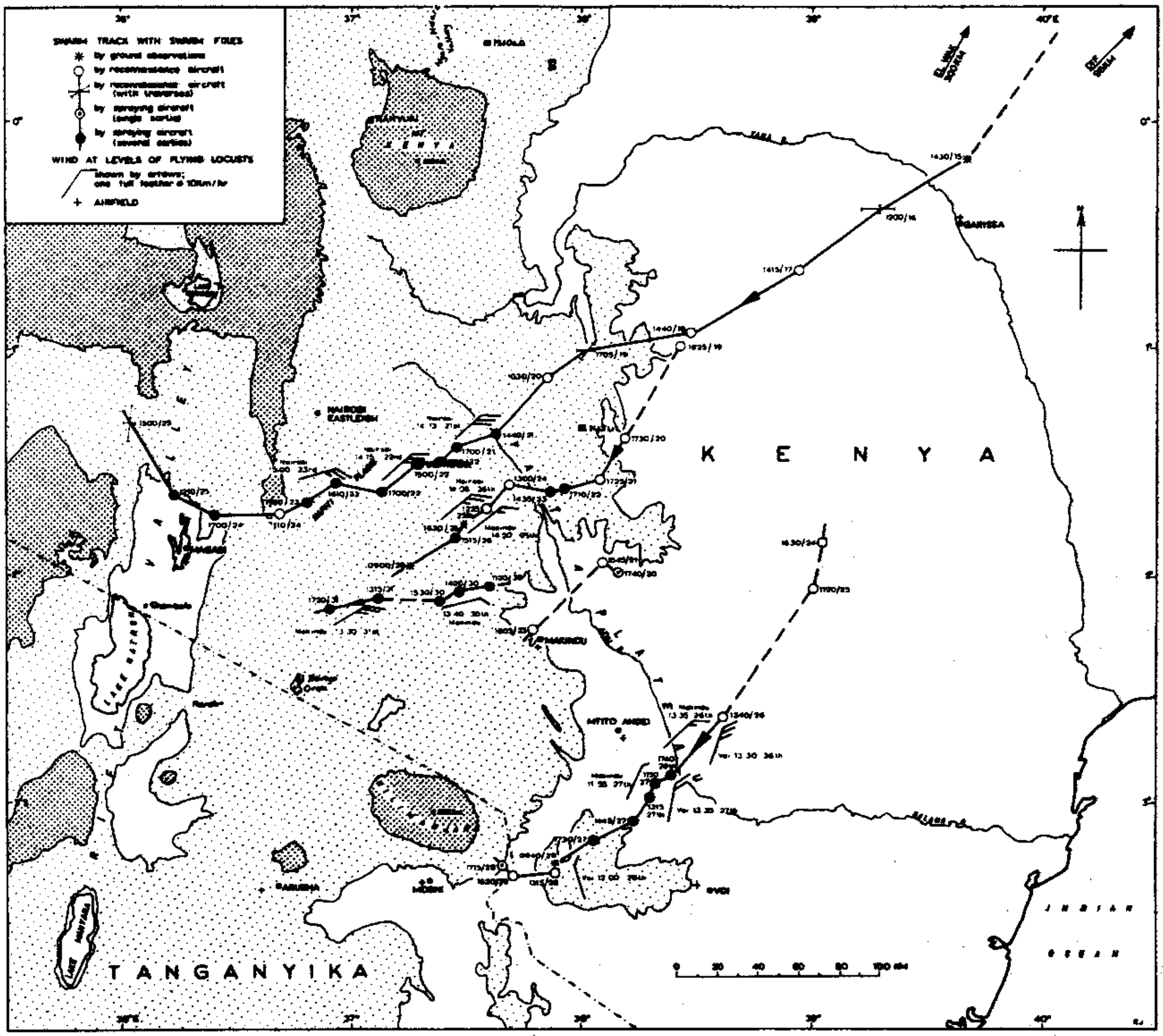


Figure 8 — Swarm movements in a quasi-uniform wind-field (NE monsoon in Kenya.)

TABLE II

MOVEMENTS OF INDIVIDUAL SWARMS SHOWING PROGRESSIVE SYSTEMATIC DISPLACEMENT DURING PART OR WHOLE OF PERIOD OF OBSERVATION

Date	*Country : province, district or area*	*No. of swarms*	*Extent of daily displacement in km*	*Predominant direction(s) of swarm displacement towards*	*Direction(s) of corresponding wind from*	*Remarks*
1951 February 13	Kenya : Isiolo	1	> 9	WSW	NE	See Appendix.
1952 February 6–16	Kenya : Wajir	4	34 to 66	WSW ; NW	ENE ; SE	Fig. 2.
1953 January 13–22	Kenya : Wajir	5	90 to 130	W	E	Indication of temporary reversal of one swarm associated with ⛈ ; refs. [1, 120].
1953 25 Sept. – 4 Oct.	Somaliland : Borama-Hargeisa	2	10 to 60	NE ; SSW	SW ; NNE	E.g. Fig. 12 ; near-reversals of swarm track with daily wind-shift ; ref. [123].
1954 January 3–16	Kenya : Wajir	10	25 to 100	NW – SSW	SE – NE	E.g. Fig. 9 ; accompanied by further 18 less completely documented swarms.
1954 ,, 15–31	Kenya : Southern and Coast provinces	5	10 to 70	WSW	ENE	Fig. 8.
1954 February 2–12	Tanganyika : Moshi-Arusha	5	25 to > 60	W – NW	S – E and SE – E	Surface winds only, for two swarms ; for other swarms, winds variable or unknown.
1954 ,, 15–17	Tanganyika : Lushoto	1	20 to 30	NW ; N	SE ; ?	Fig. 15
1954 ,, 20–27	Tanganyika : Korogwe	1	10 to 40	S ; NNW	Not known	Fig. 15
1954 March 3–8	Tanganyika : Korogwe-Handeni	1	10 to 30	WNW–WSW	Not known	Fig. 15
1954 July 8–9	Sudan : Kordofan	1	> 95	ENE – ESE	WSW ; ?	See section 2.1.2 ; partly-mature swarm ; ref. [75, 162].
1954 July 17–18	Kenya : Maralal	1	40	E	Not known	Ref. [1].
1955 January 27–31	Kenya : Garissa	2	15 to 45	W – SW	E – NE	See Appendix.
1955 February 1–15	Kenya : Coast province	3	30 to 105	S – SSW	N – NE	Figs. 10 and 14.
1955 ,, 3–18	Kenya : Mtito Andei-Tsavo	12	20 to 80	SSE – WSW	NNW – E	E.g. Figs. 10 and 11.
1955 March 3–4	Tanganyika : Mkomazi	1	> 20	S	N (surface only)	Fig. 10.
1955 ,, 6–11	Tanganyika/Kenya : Usambaras-Kilimanjaro	1	33 to c. 70	NW	SE	Fig. 10.
1955 April 4–5	Tanganyika/Kenya : Namanga-Shombole	1	> 30	WNW	Not known	Partly-mature swarm ; ref. [63].
1955 June 9–11	Sudan : Darfur	1	> 60	W ; E	E ; W	Reversal of wind and swarm-track ; Fig. 13 ; ref. [163].
1957 August 4–15	Somaliland : Borama	2	30 and > 25	SE ; E	? ; W	See Appendix.

groups of flying locusts, as in Plates II and III. Moreover, the biological significance of these particular swarm movements is illustrated by the fact that the first swarm, after making good a displacement of 350 km to the west-south-west within eight days of moving out of the limits of the breeding-area in which it had been produced, had already reached the area, around Magadi in the Rift Valley, in which egg-laying by swarms of this generation was to begin some six weeks later, in early March. While the swarms continued to fly during this intervening period, the biologically significant displacement of this swarm, between the breeding-areas of the two successive generations, may thus be said to have been effectively complete within a small proportion of the time elapsing between the two corresponding successive breeding seasons — as, in fact, appears very often to be the case.

The corresponding wind-field encountered by the swarms during this period was a strikingly uniform one, as is typical of settled NE monsoon conditions, over the whole area with the exception of the vicinity of the Rift Valley in the west (where Magadi consistently recorded surface winds from between south-west and north-west, and surface southerlies were noted at Kima on the 28th). The general constancy of wind-direction was illustrated by the 18 pilot-balloon ascents made at Makindu, near the centre of the area, between 0845 and 1515 (a period of the day within which flight activity regularly occurred) on 16 different days between 14 and 31 January. The wind found between ground-level and 500 m (i.e. 1,000–1,500 m above sea-level), heights representative of those of the flying locusts, was between northerly and easterly in all these ascents. Moreover, some proportion of the total range recorded (351° to 079°) may have represented a diurnal variation in wind-direction ; and a series of 15 daily upper-wind observations during this same period, at times between 1400 and 1445 (and accordingly likely to be much less affected by any regular diurnal variation of wind), made at Nairobi (Eastleigh) by the more accurate radar method, all gave winds at 400 m above the ground (800 mb, or c. 2,000 m above sea-level) which were from between north-east and east-north-east, within a total range of direction of 36° (042° to 078°, 13–44 km/hr). On each day these north-easterlies, with a vertical temperature-gradient approaching the dry adiabatic lapse rate, extended up to at least 3,100 m above sea-level (700 mb) — above all topographical features encountered by the swarms, and on most if not all occasions well above the level of the topmost locusts. The weather was generally fair to fine, with very little rain recorded anywhere in the vicinity of the swarms to imply disturbance of the general wind-field ; although there was a heavy thunderstorm at Moshi on the 27th, there was no rain reported between the 15th and 24th even within the same degree-square as any of these swarms, traversing well-documented areas of the Kenya highlands. Figure 8 shows, by wind-arrows drawn adjacent to each appropriate section of swarm-track, all corresponding instrumental observations of wind, at the levels of the flying locusts, satisfying the criteria of section 2.1.1, i.e. made within 100 km of a swarm for which two successive fixes were secured on the same day, with the wind-observation at a time between 1½ hours before the first of the two fixes and 1½ hours after the second, omitting cases with evidence of marked change in the direction of wind or of swarm-displacement within the area or period under consideration. The only wind-observations excluded from Figure 8 on the last criterion were those relating to the first swarm on 24 and 25 January, after it had reached the Rift Valley area, when it was between Nairobi, still recording north-easterlies, and Magadi, where surface observations (the only wind-records available) showed light winds from between south-west and north-west, and it was accordingly not possible to make any useful estimate of the corresponding wind at the swarm.

Considering the data as a whole (Table II), 50 of these cases of progressive, systematic swarm displacements took place in, and with, wind-fields likely to have been quasi-uniform ; for the remaining ten cases the data are inadequate to establish the nature of the wind-fields concerned.

The swarms recorded in Figure 8 travelled on approximately parallel tracks despite irregularities of topography, and roughly retained their positions relative to each other during these movements. Evidence of such movement in parallel by neighbouring swarms, retaining their relative position, has been secured on a number of occasions, of which one is shown on a larger scale in Figure 9 ; other examples are illustrated in Table I and Figures 10 and 14. The data provided by one of the swarms shown in Figure 9, which in four days made good a net displacement of 250 km from Bardera district in Somalia, have been used to test a series of alternative theoretical models of orientation behaviour [98], and were, for example, clearly inconsistent with any hypothesis of a uniform and constant orientation of continuously flying locusts.

In addition to Figure 8, further evidence of swarm movement with the NE monsoon flow, commonly associated with this season in Kenya, was provided by the January observations in Garissa district and the February observations in Isiolo, Coast Province, and, particularly the Mtito Andei area (Table II, Figures 10, 11, 14). Effects of day-to-day variations in wind at this season were shown by observations at Wajir, in the Northern Frontier Province of Kenya. Here, during the 1952 aircraft spraying trials [102], local pilot-balloon observations were used for the first time in planning air reconnaissance flights, to intercept swarms approaching from directions which varied from day to day, with the wind, from between north-east and south-east (Figure 2). The upper-wind observations were used to determine which sector should be searched for incoming swarms, and every swarm was in fact located — without assistance from the ground — while it was still approaching base. Early-morning pilot-balloon ascents were found particularly useful in this connexion, averaging the wind up to the estimated upper limit of convection to provide a forecast of the wind to be expected later in the day at the lower levels.

Further to the south at the same season, swarms were recorded moving across northern Tanganyika during February and early March of 1954 and 1955 in directions which likewise ranged from south-westward to north-westward, followed by a very marked north-westward move shown with the seasonal establishment of south-easterlies in March 1955 (Figure 10), representing the northward passage of the Inter-Tropical Convergence Zone.

Away to the north, beyond the Equator, and at a later season of the year, progressive systematic movements towards east or east-north-east were shown by swarms in the Sudan in July, and in the north-western Somali Republic in August, in westerly monsoon currents, and by another swarm in July in an area of north-western Kenya for which no wind-data were available.

2.2.2 *Simple changes in direction of swarm-displacement*

Marked changes in the direction of displacement were exhibited by 16 of the swarm-tracks under consideration. Eight of these cases, considered in this and the following section, were clearly associated with corresponding changes of wind ; for the remainder, wind-data are inadequate to establish the more complex wind-fields concerned.

This section deals with the simpler changes of direction, in which the swarm concerned did not re-cross its own preceding track, and the first example relates in fact to a swarm which showed an overall constancy of direction of 89 per cent (and is accordingly also included in Table II). Figure 11 illustrates the progressive change of track, from 191° to 201°, 231° and finally to 257°, exhibited during the afternoon of 11 February by an immature swarm of 8 km² with which contact was being maintained (without spraying) by reconnaissance aircraft from Mtito Andei, in weather which was fair to fine. When first located, over the Yatta plateau almost equidistant from Mtito Andei and Makindu and flying up to 800 m above the ground, the direction of displacement of the swarm, to the south, was within 3° of directly down the mean of the winds, up to 800 m, given by the corresponding midday pilot-balloon observations at Mtito Andei and Makindu (Table I) ; and a comparable track (and ground-speed) were found at about the same time for the second swarm, 70 km to the south of the first and 20 km² in extent, which was then being attacked by spraying aircraft. The final track of the first swarm, approaching Mtito Andei from the east at the end of the afternoon, was within 1° of down the corresponding wind indicated by the 1800 pilot-balloon observation at Mtito Andei. The swarm settled for the night at about 19 hr, soon after sunset. The following morning the wind had backed to north-north-west, and at about 09 hr, after 8/8 of early-morning Stratocumulus had begun to clear rapidly, the swarm moved off its overnight roosting-site on a track within 12° of down the new wind. By noon the wind had veered again, to the north, and the swarm was now moving southwards, within 4° of down the noon wind. These last two displacements were each only 4 km — no more than the length of the swarm in flight — and the corresponding estimates of the direction of displacement are therefore likely to have been less accurate than those found the previous day, but the 20° change in direction which they indicated was again in the same sense as the corresponding 36° shift in wind-direction shown by the two pilot-balloon observations.

On 8 February, a temporary incursion of westerly winds from Tanganyika into southern Kenya was shown by the early-morning pilot-balloon observation at Voi, and by a brief spell of fresh south-westerlies noted during the afternoon at Mtito Andei, with scattered showers moving from the west. This exceptional westerly break in the predominantly north-easterly wind régime of this area and period, described in more detail in section 2.2.3, was associated with an exceptional easterly movement shown at the same time by four swarms with which contact was then being maintained — three small ones in the Tsavo area and the larger one in Coast Province ; the latter had already exhibited an almost complete reversal of track between the 4th and 7th, near the Tanganyika border, where north-easterly winds had already given place to south-westerlies. Again, a month later, the dramatic north-westward swarm movement out of the Usambaras in early March, as already mentioned, was immediately preceded by a very marked veering to south-easterly of the winds over much of Kenya, corresponding with the passage of the Inter-Tropical Convergence Zone.

Repeated marked changes of track in the vicinity of the Inter-Tropical Convergence Zone, at the beginning of its return seasonal movement, were illustrated by two swarms followed in Somaliland in late September 1953 [123] ; the daily weather régime at Hargeisa during these observations was described as "At sunrise (0545) fairly calm conditions existed, but by 0700 a fresh south-westerly had become established ... By the end of the morning the wind had veered and at noon calm conditions preceded the establishment of a north-easter during the afternoon, which brought always a certain amount of cloud and sometimes a build-up with heavy local storms towards the end of the day" [120].

The swarm illustrated (Figure 12) had roosted near Borama on the night of 25/26th, and was located in flight near Touligagto at 1315 on the 26th. At Hargeisa a change in surface-wind, from south-westerly to northerly, was noted at about 1330 ; and between 1618, when contact was again made with the swarm, and 1745 the swarm was found to be travelling on a track of 193°, representing a change of direction of at least 90° from its track earlier in the afternoon. On the 27th again, the abrupt change of direction of the swarm, from the easterly displacement made good between the 0930 and 1314 fixes to the south-south-westerly displacement shown after 1314, corresponded with a change-over from a light westerly wind noted on take-off at Hargeisa at 1230 to a calm recorded on landing again at 1326, followed by a light easterly at the airfield at 1340 and a light north-easterly at 1420 [1].

A reversal of track from a westerly to an easterly direction of displacement was shown by a swarm near Lake Baringo in the Rift Valley of central Kenya, in late June 1954, in a probably highly complex wind-field (p. 51).

Erratic local displacements have been shown by swarms in the immediate vicinity of thunderstorms, near Wajir in January 1953, near mount Meru in February 1954, near Moshi in February 1955, and in Darfur in June 1955.

2.2.3 *Complex changes in direction of swarm-displacement*

The tracks of four of the swarms under consideration showed, on six occasions, complex changes of direction, causing the swarm to cross its own previous track, with a consequent constancy of 0 per cent, in striking contrast with the purposeful-looking progressive tracks described in sections 2.2.1. The

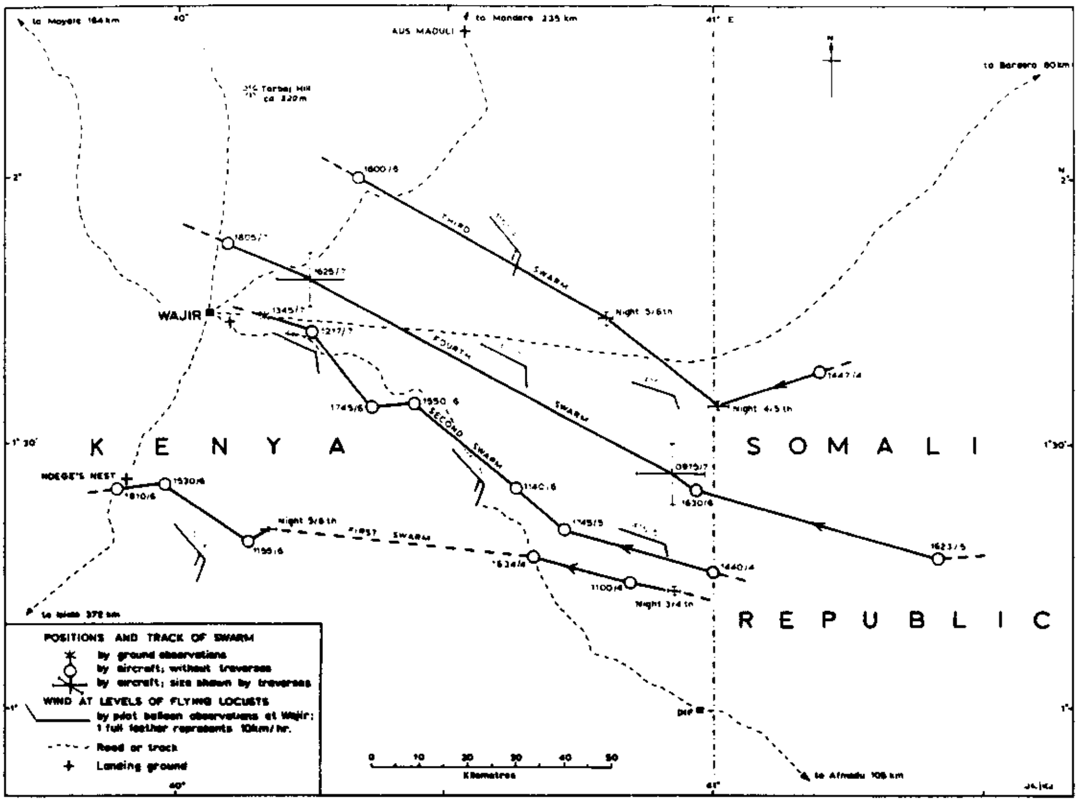


Fig. 9 Neir

Figure 9 — Local swarm movements in a quasi-uniform wind-field.

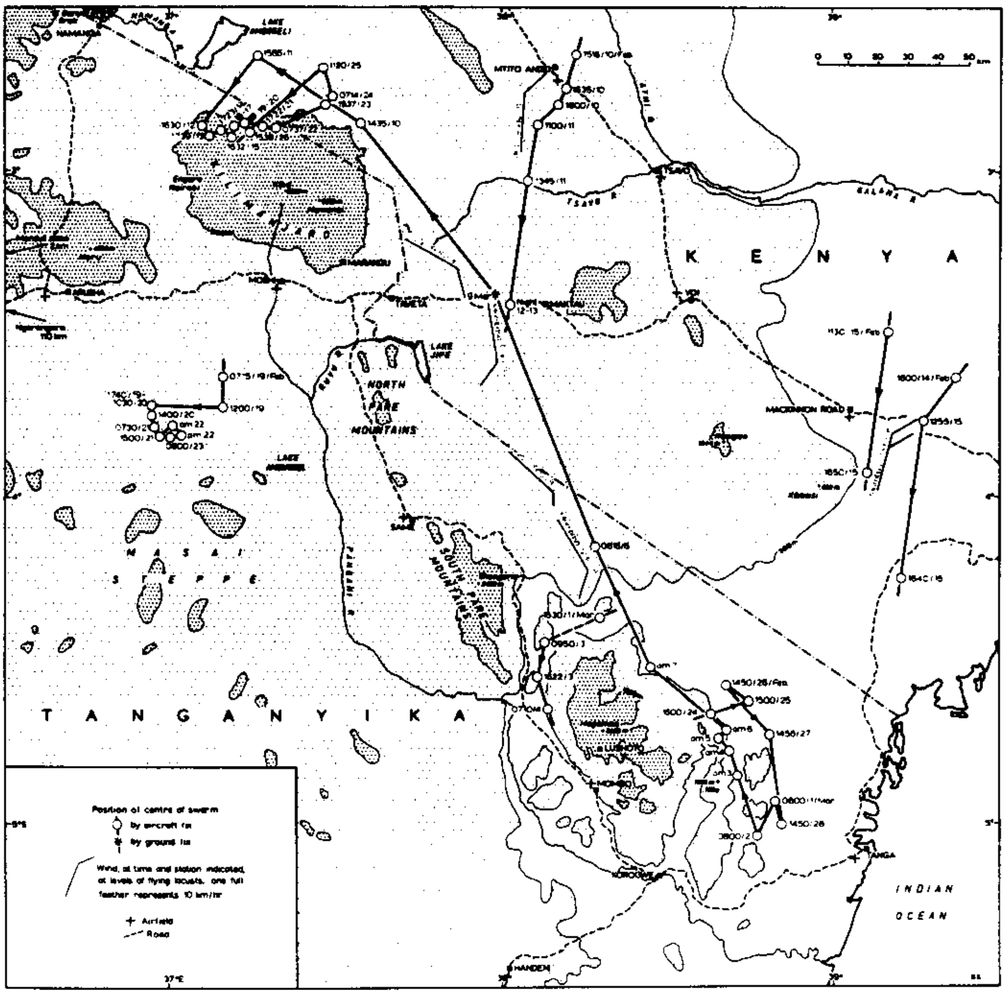


Figure 10 — Effects of topography and of the seasonal movement of the Inter-Tropical Convergence Zone on swarm movements in southern Kenya and northern Tanganyika.

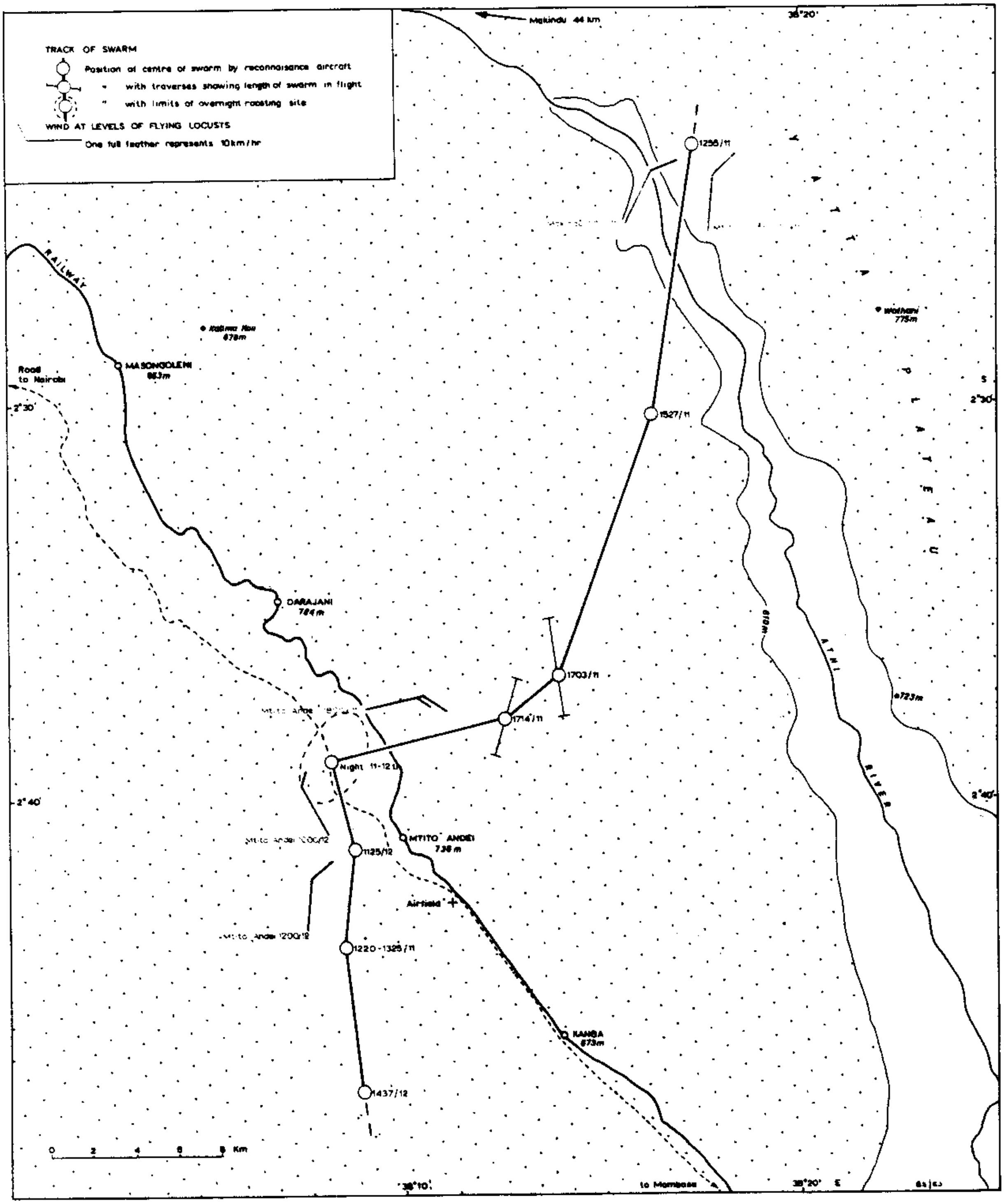


Figure 11 — Effects of hour-to-hour changes in wind-direction on the movements of a swarm.

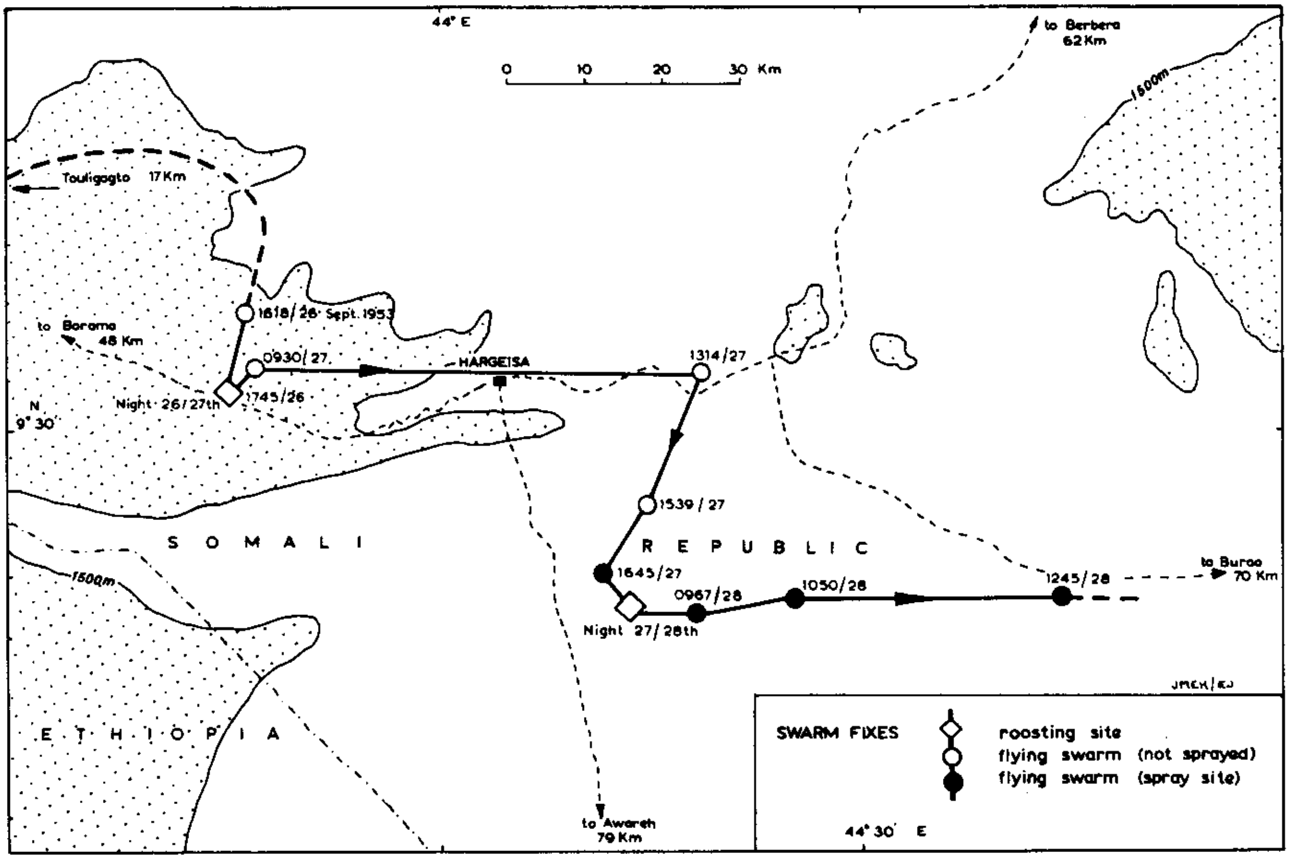


Figure 12 — Movements of a swarm in alternating wind-directions in the vicinity of the Inter-Tropical Convergence Zone in the Somali Republic (1, 123).

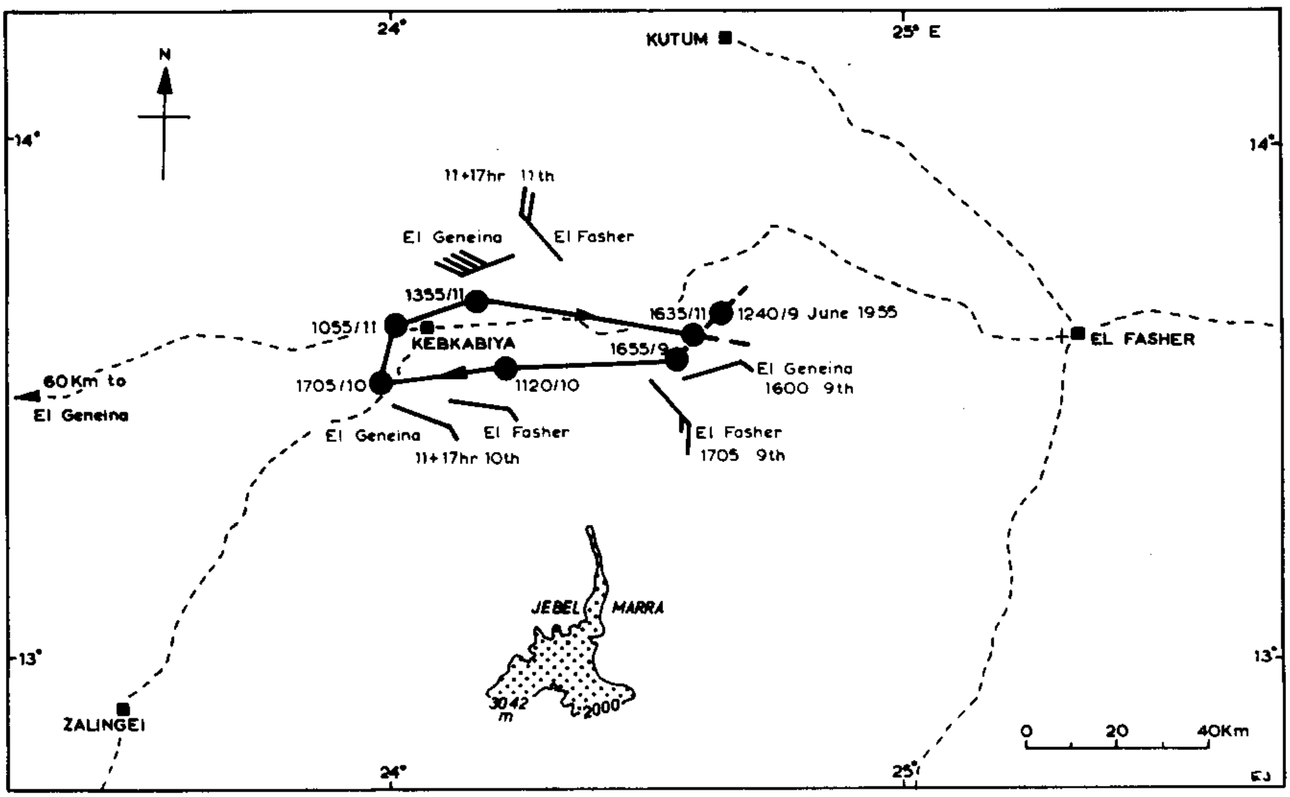


Figure 13 — Movements of a swarm with a reversal of wind-direction in the vicinity of the Inter-Tropical Convergence Zone in the Sudan (163).

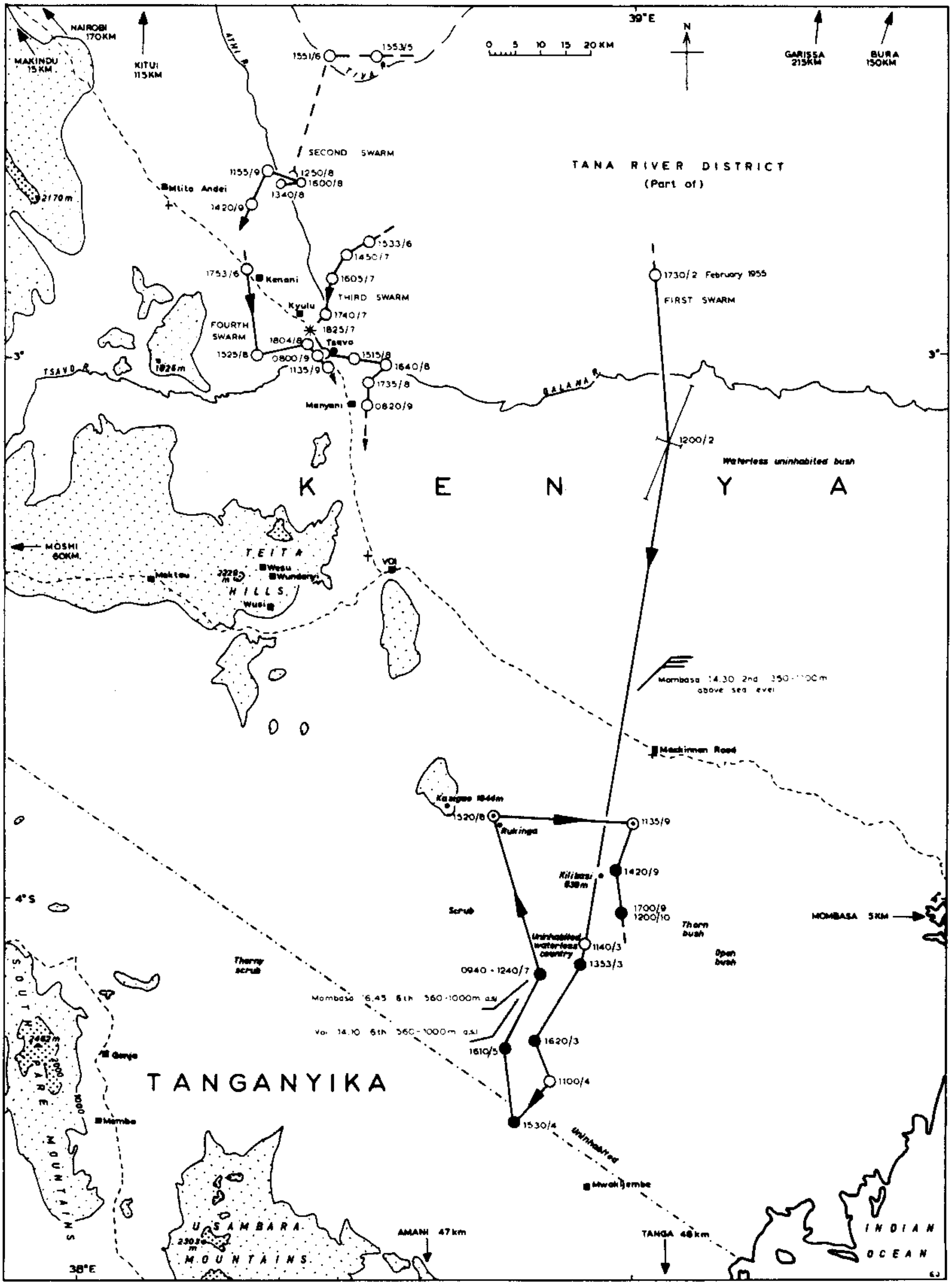


Figure 14 — Swarm movements in disturbed weather in the Coast Province of Kenya.

simplest and best-documented of these cases was the complete reversal of track, again in the vicinity of the Inter-Tropical Convergence Zone, shown by an immature swarm, about 20 km² in extent, sprayed in June 1955 in Darfur province, Sudan, near Kebkabiya, which is 140 km west of the nearest upper-wind station, at El Fasher, and 180 km east of that at El Geneina (Figure 13). Between 1655 on the 9th, when the swarm was flying up to 900 m above the ground, and 1120 on the 10th, when it was reported "just rising", with the topmost locusts at only 150 m, and probably not far from its overnight roosting site, the swarm made good a displacement of some 35 km to the west, reasonably consistent with the direction of the corresponding winds of 140° 15 km/hr up to 600 m at 17 hr at El Fasher and of 075° 2 km/hr at 16 hr at El Geneina. Between 1120 and 1705 on the 10th, the swarm, flying up to 300 m above the ground, travelled a further 25 km to the west, and, after morning westerlies, the corresponding winds at both meteorological stations were again predominantly easterly; pilot-balloon ascents at 11 and 17 hours at both stations gave winds up to 300 m which averaged 7 km/hr from 100° at El Fasher and 5 km/hr from 110° at El Geneina. Such a diurnal variation of wind-direction is common at this season in the Sudan [160, etc.]. The next day, between 1055 and 1635, the swarm, flying up to 600 m above the ground, moved some 65 km back to the east, in winds which had changed, representing a northward movement of the Inter-Tropical Convergence Zone (p. 31), to fresher westerlies, with the 11 and 17–18 hr ascents averaging 18 km/hr from 320° up to 600 m at El Fasher and 41 km/hr from 250° at El Geneina. At 1630 on the 11th the swarm was only about 5 km from its position at 1650 on the 9th, despite a total displacement of 150 km during the intervening period, corresponding to a constancy of 3 per cent. While all three mornings were fine to fair, Cumulonimbus developed each afternoon, with 3 mm of rain recorded at El Geneina on the afternoon of the 10th and 10 mm overnight on the 11/12 at El Fasher.

A series of marked changes of track, including a complete loop, was shown by swarm movements in the Southern and Coast provinces of Kenya during early February 1955 (Figure 14), during a spell of unsettled weather, with periods of widespread and heavy rain, in marked contrast with the persistent direction of displacement and fair weather recorded in the same general area during January 1954 (Figure 8). The positions of the four swarms concerned were not always determined sufficiently frequently to show all the details of every change of track, and the corresponding wind-field, moreover, was at times too complex to be fully established by the meteorological data available, but these observations are of particular interest as the best-documented record so far available of the movements of a number of swarms in disturbed weather, with heavy rains, in contrast with the fair-weather conditions which were particularly characteristic of the data presented in section 2.2.1.

The first of the swarms was initially sighted at a distance of 38 km, flying in cumuliform formation and 14 km long, during a reconnaissance flight from Garissa to Voi on 1 February, and was located at 1730 at a position to the north of the Galana river. The origin of these swarms was an extensive hopper infestation, resulting from egg-laying in November 1954, over an area which extended for some 500 km south-westwards from the vicinity of Afmadu in Somalia, across the neighbouring Garissa district of Kenya, where the first small swarms of young adults had begun to appear in numbers from mid-January onwards, and into Tana River district, where numerous bands of fifth-instar hoppers had been reported between 14 and 28 January within 60 km to the north and north-east of the position at which the swarm was seen on 1 February. For the two preceding days (30 and 31 January) surface winds at Garissa had been between north and east, and, at the time of the sighting, surface winds at Makindu, Voi and Mombasa (the nearest synoptic stations), and, noted from the air, at Bura, were all between north and north-east, as were the corresponding morning pilot-balloon observations (no afternoon ascents were made on this date). It is suggested that the swarm is accordingly likely to have comprised locusts which had fledged in the course of the previous week or so within less than a hundred kilometres of the position at which it was first seen, together with somewhat older locusts from further to the north-east (see p. 35). Weather at the swarm (and over most of southern Kenya) was fine, with only traces of Cumulus and Cirrus.

The following day (2 February) the swarm was sighted again, at a distance of 17 km in noticeably poorer visibility, and located at noon across the Galana and 35 km to the south of its previous position, 25 km in length from NNE to SSW and 5 km wide (as shown), and in plan concave towards the ESE. The weather had become cloudy, with $^6/_8$ Cumulus based at about 900 m above the ground at the swarm ; the height of the topmost locusts was 750 m above ground-level and 1,100 m above sea-level. That afternoon westerly winds and thunderstorms were recorded some 200 km away to the west and south, at Moshi and at Amani (the nearest synoptic station in that direction), with 3 mm of rain at the former, 24 mm at the latter and 51 mm at Mamba in the Pare Mountains, but surface winds at Makindu, Voi and Mombasa remained between north and east, and the only pilot-balloon ascent made in the area that afternoon, at 1430 at Mombasa on the coast, gave as shown a north-east wind of 30 km/hr at the levels of the flying locusts.

On the 3rd, after an overcast morning, the swarm was sighted at a distance of 35 km, and reached at 1140, mostly densely settled and probably still on its overnight roost, to the south of Kilibasi hill, indicating a southerly displacement of some 105 km during the previous afternoon. By 1620 on the 3rd, the swarm, flying up to 600 m above the ground and sighted from a distance of some 45 km, had moved a further 20 km to the south-south-west, with the corresponding surface winds at Voi, Mombasa, Amani and in the vicinity of the swarm all from between north and east. There were, however, further thunderstorms away to the west during the afternoon, with north-westerly winds and 28 mm of rain at Moshi, and, associated with a brief spell of south-westerlies and 74 mm of rain, at Makindu, following early-morning westerlies up to 700 m above the ground, while in the Usambara mountains also falls of as much as 60 mm of rain were recorded.

Spraying was begun on the 3rd, and in the course of the following week a total of 15,985 litres of 20 per cent DNC was applied to the swarm, at first from Voi and later from Mombasa, and on most occasions with the locusts flying up to 100-1,000 m above the ground at the time of spraying. However, from a consideration of assessments of the results of similar operations against other swarms (showing kills under comparable conditions of the order of 10^4 locusts per litre of this insecticide — [65, 75, 95]), in relation to the area of the target-swarm and to estimates of the area-density of such swarms (likely to have been in the region of 50 locusts/m^2 — see p. 4) the total kill achieved during this particular series of operations is only likely to have been of the order of 5 per cent of the original swarm. On the other hand, the size of this swarm simplified the problem of maintaining contact with it ; and, from this point of view, it was also convenient that no other swarm was found between the Voi-Mombasa road and the Usambaras during this period.

On the morning of the 4th an extensive belt of low cloud and continuous rain was encountered at 0720 to the south of Kilibasi, running east-west and preventing the aircraft from reaching the vicinity of the swarm ; and between 0915 and 1000 west-south-westerly surface winds and 11 mm of rain were recorded at Mombasa. At 1100 cloud was still down on Kilibasi, some 400 m above the surrounding plain, but the weather had improved sufficiently to make it possible to locate the swarm, near the Tanganyika border, still densely settled and accordingly unlikely to have flown in these westerly winds — if indeed they reached this area ; although westerlies were reported at Amani, both at 09 and 15 hr, with rain, Tanga on the coast recorded a light shower at 0655 but no westerly winds. At 1530 the swarm was found again, after a 1½ hr square search [39] in weather which remained overcast with occasional rain at first, with locusts flying up to 30 m or so, and at a position 10 km further to the south-west ; a pilot-balloon ascent at 1600 at Mombasa gave a wind from the north-east at the level of the swarm (c. 300 m above sea-level). At 1610, however, a light south-south-easterly wind was noted near Kasigao ; and the next satisfactory determination of the position of the swarm, at 1610 on the following day (5th), was 15 km back towards the north, with the locusts flying up to 800 m above the ground.

At midday on the 5th smoke in the vicinity of the swarm showed a northerly wind, as did pilot-balloon observations at Voi and Mombasa at the levels of the flying locusts (with westerlies above), but in the course of the afternoon of the 5th surface winds were recorded from the east-south-east at Mackinnon Road, from the east at Mombasa and Tanga, from north-west at Amani, and from north and north-west (with a further thunderstorm) at Moshi. The corresponding wind at the swarm during the afternoon is accordingly uncertain, but the wind directions recorded around the area show obvious confluence. Moreover, there were at the same time implications of air-mass differences within the area, with the 1500 synoptic observations demonstrating dry-bulb potential temperatures between 39° and 41° with dew points between 15° and 17° at Kitui (1,180 m above sea-level), Makindu (1,000 m), Moshi (810 m), and Voi (560 m), in contrast with potential temperatures between 30° and 32° and dew points between 23° and 24° at Amani (860 m), Mombasa (60 m), and Tanga (50 m). While such differences between the first two stations, on the plateau, and the last two, on the coast, are usual, the other three — Moshi, Voi and Amani — commonly show intermediate values, suggesting varying degrees of mixing of air of continental and maritime history.

There was widespread heavy rain that night (5/6th), giving overnight totals of 42 mm at Voi (560 m above sea-level), where the airstrip was in consequence unserviceable for most of the next day ; 49 mm at Wesu (1,680 m), 29 mm at Wundanyi (1,460 m) and 40 mm at Wusi (1,220 m), all in the nearby Teita hills ; 56 mm at Maktau

(1,100 m) to the west of the hills; 25 mm at 610 m at the foot of Kasigao, 37 mm at Mombasa on the coast, 39 mm at Mwakijembe (140 m) within 35 km of the swarm, 70 mm at Gonja (550 m) at the foot of the South Pare mountains, 19 mm at Amani (860 m), and up to 126 mm at other stations in the Usambaras. The relative uniformity of many of these figures, with little of the usual association with altitude (illustrated by the contrasting mean annual rainfall totals of 540 mm at Voi and 1,440 at Wesu), suggest general convergence over a wide area.

On the 6th, surface winds between south-west and north-west were recorded at Voi at every hour from 0600 to 1700, at Mombasa from 0600 to 0930 and from 1100 to 1130, and at Amani both at 0900 and 1500, while afternoon pilot-balloon ascents showed south-westerlies up to 450 m above the ground at 1410 at Voi, and at corresponding heights above sea-level at 1645 at Mombasa, veering to north of west at greater heights at both stations. The swarm was not reached again until 0940 on the 7th, when it was located, very largely settled apart from a few locusts flying up to 15 m or so, and probably still on its overnight roost-site, some 17 km to the north-north-east of its position of the late afternoon of the 5th, a movement consistent with the general south-westerly winds of the 6th. Three hours later, at 1240 on the 7th, the swarm was still in the same position, with the locusts mainly settled or flying very low. A subsequent spray-sortie late that afternoon failed to find the swarm again, but at 1730 reported heavy rain, suspected of concealing the swarm, from very heavy Cumulonimbus to the south-west of Kasigao — in which direction a rainfall of 159 mm was recorded on this date at Gonja (with falls of 37 to 152 mm at eight other stations along a line running north-westwards from Gonja for 180 km to Engare Nairobi). At the time of this sortie, thunderstorms were also reported at Moshi, from 1705 until after 1830, and at 1720 Cumulonimbus in the distant south-west was noted from an aircraft over Mtito Andei. The wind at the swarm, in the immediate vicinity of these storms, is unknown but is likely to have been substantially affected by them.

In the meantime, from 3 February, smaller swarms, of similar origin, had been encountered daily by air reconnaissance to the north, in the area of the lower Athi river; and, from the afternoon of the 6th, repeated fixes were made on a number of these swarms in order to plan their interception by mobile research parties operating along the Nairobi-Mombasa road, for detailed studies of the behaviour of the locusts [44, 107, 143]. Between 1450 and 1825 on the 7th, one of these swarms, 2 km in length and 1.3 km in width, moved 17 km to the south-south-west, from the Yatta plateau across the Athi river, following midday observations of north-easterlies at this level at Voi and of a northerly surface wind (and shower) at Manyani (though at Makindu winds had been between south-west and north-west throughout the morning and until 1330). Twenty kilometres or so to the south-west two more small swarms, which had been located just north-west of Kenani at 1753 the previous afternoon, 1 km and 0.5 km in width and within two or three kilometres of one another, were both seen to the west of Kenani at 1248 on the 7th, and, in the distance, to the south-west of the road between Kenani and Kyulu (without being separately distinguished) at 1608 the same afternoon, suggesting a similar though possibly shorter displacement.

At 1250 on the 8th, a further swarm, 1.2 km long and 1 km wide, was located over the western edge of the Yatta plateau, in company with another, 1 km long, within a kilometre or two to the north-east; what were probably the same swarms had been seen near the Tiva watercourse on the afternoons of the 5th and 6th. At 1340 on the 8th the first swarm of this pair, with its leading edge to the west of the Athi river, had moved 3 km on a track of 235° since 1200, closely followed by the other swarm, in fair weather with only $^1/_8$ Cumulus at the swarms. Surface winds at the time at both Voi and Makindu were between north and east, but the early-morning pilot-balloon at Voi had shown westerlies, veering with height to north-westerly at 500 m and northerly at 800 m above the ground; and at 1350, on landing at Mtito Andei after this second fix, a fresh SW surface wind was noted — by reason of the unusual landing-direction involved — together with scattered showers moving from the west. The scale of such local features of the wind-field, in relation to the network of synoptic stations, is illustrated by the absence of any record of south-westerlies from the corresponding hourly observations of surface wind at Voi and Makindu. The swarms were re-visited at 1540, and were found to have retreated, by some 4 km, to a position entirely east of the Athi river again, mainly over the escarpment, and apparently to have joined up into a single swarm, the "second swarm" in Figure 11, which was found to be 3.7 km long and 2 km wide at 1420 the next day.

Meanwhile, the third swarm had been located at 1140 on the 8th, 1 km west of Tsavo bridge and still over part of its overnight roost-site, but had moved 5 km to the east by 1515 (when it was recorded as 1.6 km long, from WNW to ESE, and 1.9 km wide from SW to NE), and a further 7 km in the same direction by 1640. At 1525 the same afternoon, the fourth swarm, 3 km across from east to west (and in all probability representing the pair seen at 1248 the previous day and at 1753 on the 6th) was located 14 km west of Tsavo, was seen in the distance west-north-west of Tsavo at 1804, and roosted overnight 3 km west of Tsavo. It had made good a displacement of 12 km to the east since 1525, and covered, when settled, an area 3 km from NW to SE and 1.2 km from SSW to NNE. Finally, the first large swarm, which was being sprayed from Mombasa, was found again at

1520 this same afternoon, around Rukinga, in heavy showers and still 9 km across ; and re-located at 1135 the following morning (9th), between Kilibasi and Mackinnon Road, which represented a displacement of 28 km to the east, crossing the swarm's own southward track of a week previously. There were 13 mm of rain on the 8th at Wusi, in the Teita hills, and 19 mm at Moshi, though only a trace at Voi.

All four swarms thus exhibited well-marked and exceptional eastward displacements, at some time between midday on the 8th and the morning of the 9th, and at points 150 km apart. Although only in one case, near Tsavo, were there sufficiently frequent fixes to establish the full extent of this easterly movement (12 km between 1140 and 1640 on the 8th for this swarm), the other three cases demonstrated easterly displacements of at least 4, 12 and 28 km respectively.

The corresponding wind-data are tantalizingly incomplete : while the observation of the swarm-movement back across the Athi, immediately after the onset of a south-west wind had first been noted at Mtito Andei, was sufficiently striking, it was unfortunate that no upper-wind observation was made that afternoon nearer than Mombasa, where at 1330 surface easterlies backed to north-west at 1,000 m above sea-level, approaching the level of the topmost locusts over the Yatta plateau that afternoon — and the observation terminated at this height, probably as the balloon entered the $^6/_8$ Cumulus recorded.

One of the effects of these swarm-movements, in the unsettled weather of the 7th and 8th, was to bring the swarms closer together, providing quantitative evidence, over a limited period, of the process of concentration of initially more widely-separated locust populations under the influence of the convergent wind-flow associated with rain. Evidence (including that of swarm-size) has already been presented suggesting, in two cases, the amalgamation of a pair of neighbouring swarms. In addition, relative to the best-documented swarm of this period (that followed from the Yatta plateau to Manyani), the distance of the other swarm in the Tsavo area decreased from about 23 km on the evening of the 6th to 14 km on the night of the 8/9th, and the distance of the large target-swarm decreased from 150 km in the early afternoon of the 7th to 100 km on the morning of the 9th. This reduction in the spacing between these swarms, by a factor of roughly two-thirds on both N-S and E-W axes, resulted from swarm-movements which took place within periods of displacement amounting to about six hours on each of the two successive afternoons, of the 7th and 8th. Had the swarms travelled during these periods with the velocity of the corresponding wind, these changes in the spacing of the swarms would have implied convergence of the order of 3×10^{-5} sec^{-1}, averaged over the two days and the 10^4 km^2 concerned, or a correspondingly somewhat higher value had the swarms travelled at rather less than the speed of the wind. Such a value, falling within the range classed by Palmer [81] as "strong", would be consistent with the heavy precipitation recorded during this period.

All four swarms subsequently resumed displacement in a southerly or westerly direction ; this was already in progress between 1640 and 1735 on the 8th in the case of the only swarm (that south-east of Tsavo) for which fixes were obtained that evening. At Mtito Andei, following the south-westerlies and showers, conditions at 1550 were noted as calm, with "showers finished", but still with $^6/_8$ large Cumulus, which had cleared to $^4/_8$ Cumulus and Stratocumulus by 1630, and to $^2/_8$ Cumulus and Altocumulus at Tsavo by 1650. At this latter time an east-north-easterly surface wind was noted from the air at Manyani, where a further shower was encountered at 1730.

During the following day (9 February), after morning westerlies again at Tsavo (light WSW noted from the air at 0830), Makindu (after fog), Voi, Moshi and Amani, winds between north and east, with fair weather, became re-established over the whole area (already NNE 15 km/hr at 1055 at Tsavo) ; and by midday both swarms with which contact had still been maintained were again moving to the south-south-west. The large target-swarm was flying up to 900 m above the ground at 1420, and when last traversed, at 1700, was still 13 km long from north to south and 9 km wide from east to west.

The loop exhibited by the track of this swarm had been entirely executed over the coastal lowlands, well clear of any potentially complicating effects of mountains, either on the air-flow or more directly

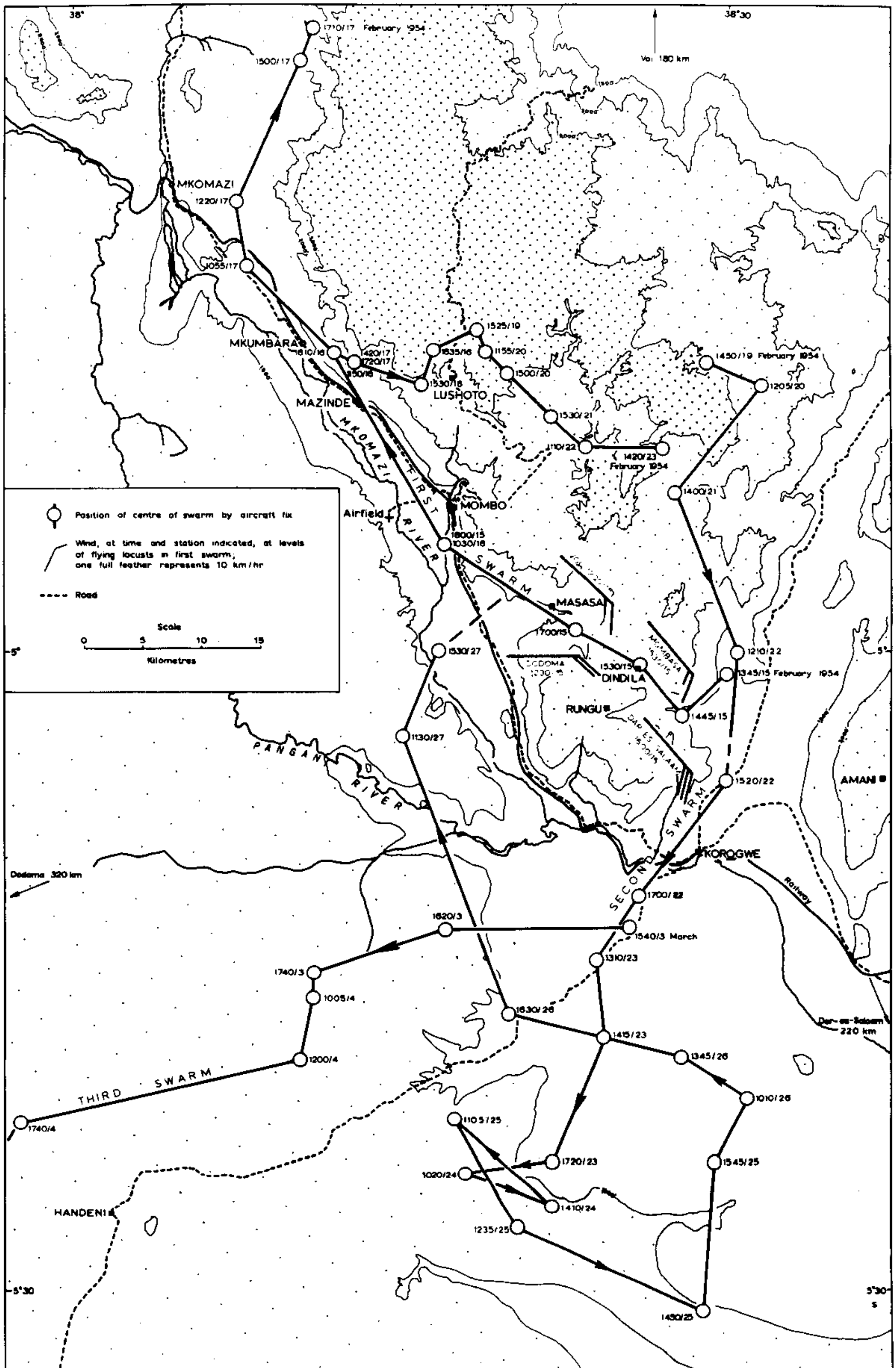


Figure 15 — Swarm movements in the vicinity of the Usambara mountains in Tanganyika.

On 17 February part of the first swarm remained settled on the mountainside above Mkumbara and Mazinde while the other part, which had apparently roosted at lower altitudes, moved off north-westwards on the morning of the 17th.

A swarm was also located on 28 February, 1 and 2 March in the area 0452 to 0454 S, 3820 to 3828 E; this may well have been the one with which contact had been lost in heavy rain after it had re-entered the mountains between Mombo and Masasa on the afternoon of the 27th; and it may also have been the same one which appeared near Korogwe on 3 March.

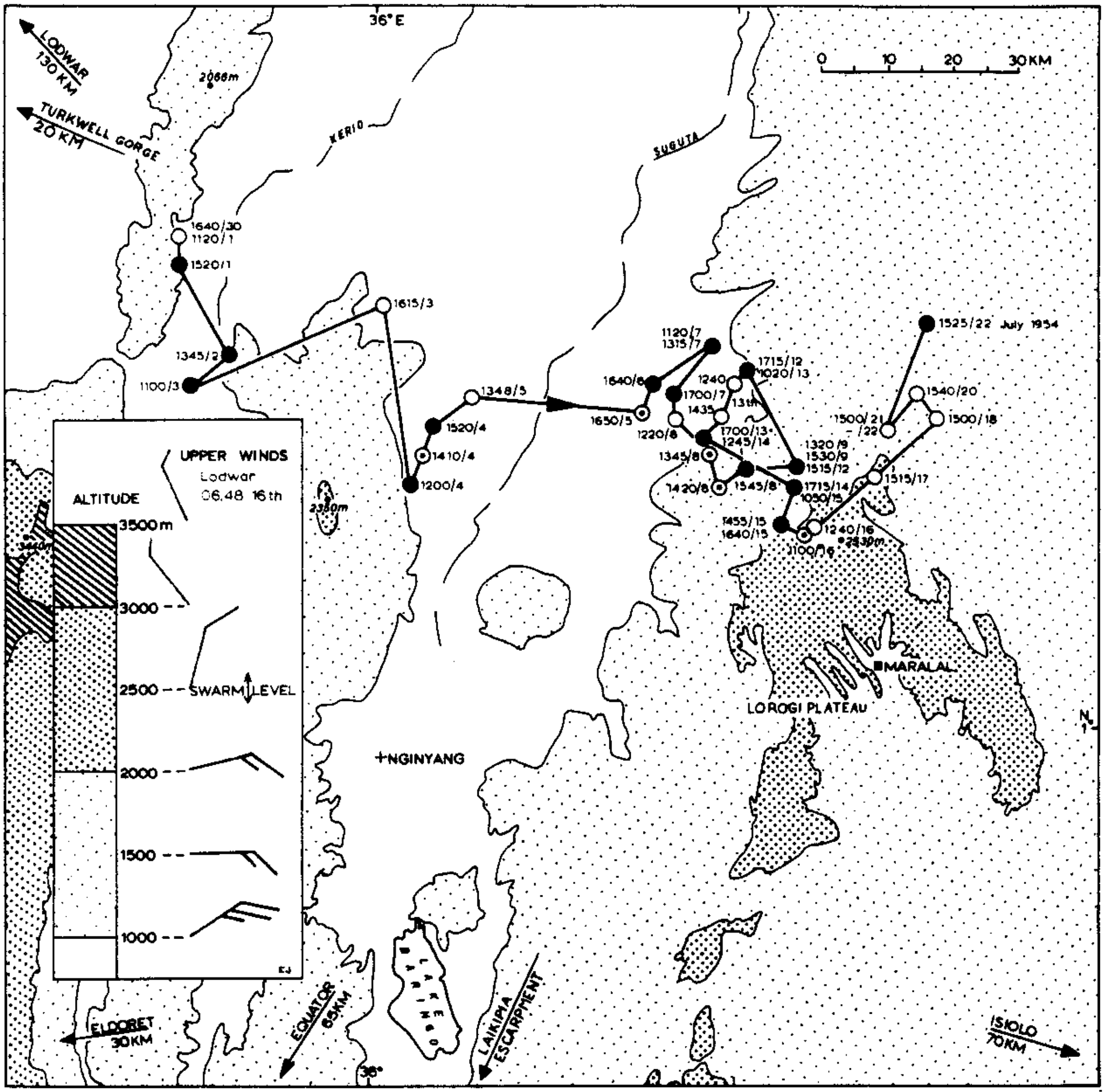


Figure 16 — Swarm movements in disturbed weather over rugged topography in central Kenya.

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on the locusts themselves, though sea-breeze front effects (p. 90) may well have been involved. A somewhat similar case of swarm-movement in a complete loop, meteorologically less-documented but also associated with considerable rains over the coastal lowlands at the same time of year, had been exhibited in Handeni district of Tanganyika between 23 and 26 February of the previous year (1954) (Figure 15). This swarm had previously moved out of the southern Usambara mountains, on 22 February, and subsequently re-entered these mountains on 27 February.

Swarm movements in "a vast circuit forming a series of loops" were similarly and independently established by air reconnaissance over the coastal plain of Senegal, in west Africa, during the winter of 1957–58 [68], when it was concluded that ". . . during the whole period of their stay in Senegal, the insects were held at the confluence of the winds, and their movements were determined by the displacement of this point of encounter in accordance with the changing season ; winds from eastern and western sectors predominated alternately, giving place progressively to the trade winds. This alternation explains the curious loops effected by the swarm in the course of their movements".

Three other East African records of loops shown by swarm-tracks involved complex movements over mountain slopes and the neighbouring lowlands. The first two relate to a single swarm (Figure 10), which spent at least ten days over the eastern Usambaras, followed by 14 days in association with the northern slopes of Kilimanjaro, including a three-day temporary sortie over the neighbouring lowlands. The third case related to another large swarm (Figure 16) which had been followed eastwards from southern Turkana across the Kerio and Suguta valleys in Samburu district in early July 1954 [1, 54] making good a displacement of 75 km in five days with a constancy of 57 per cent, and then remained for 17 days among the Samburu mountains, within an area of only 35×50 km, despite 21 successive recorded displacements during the period, totalling arithmetically some 165 km. The corresponding net displacement during this latter period was 45 km, giving a constancy of 27 per cent. While in such circumstances the actual value found for constancy will depend upon how frequently the position of the swarm has been determined (as well as upon the accuracy of these fixes), such swarm-behaviour may be regarded, on a geographical scale, as effectively almost static. Nevertheless, vigorous daily flight activity had continued among the mountains, and the locusts were noted to be flying up to 120 m above the ground even over terrain 2,400 m above sea-level. The available wind-observations are inadequate to establish in any detail, over this rugged terrain, a wind-field which may well have been of corresponding complexity ; but the data do provide evidence of easterlies over the lowlands with westerlies above, separated by a discontinuity which, on the occasion just mentioned, was at a level (c. 2,500 m) approximating to that of the swarm on the flank of the mountain.

2.2.4 *Quasi-stationary flying swarms*

What may be regarded as an extreme form of effectively static behaviour of a flying swarm has been observed on a number of occasions on which, despite conspicuous flight activity, the displacement of a particular swarm over a period of one or more days has been less than the corresponding linear dimensions of the swarm, so that the ground positions occupied by the swarm on successive days have overlapped, and the swarm as a whole has remained almost stationary. A striking example was provided by a fully-mature swarm observed between 1240 and 1315 on 20 June 1953, extending over an area of 8×6 km just south-east of Adi Ugri at an altitude of 2,000 m on the Eritrean plateau, with the locusts flying in cumuliform formation up to 450 m above ground-level, and extending over the escarpment which falls away to the upper Mareb valley in the east. At 1350 on the 21st, the swarm, with locusts flying up to 350 m above the ground, was still centred within the north-eastern part of the area occupied 25 hours previously and only 16 km north of the position over the escarpment at which it had first been located two days previously, near Adi Tafa at 1700 on the 19th [120]. In addition to its clear association with this 500 m N-S escarpment, maintained on all three days of observation, the swarm was also in the immediate vicinity of a marked wind-shift at the Inter-Tropical Front [123,158].

Thus on the 19th a surface wind of 280° was shown by smoke within a few kilometres south-west of the swarm, with 270° 3 kt recorded at 1500 at Adi Ugri, while at Asmara, 47 km further to the north, the afternoon pilot-balloon ascent showed NNE-NE at all levels, having been NW in the lowest 300 m in the morning. On the 20th a ground-party recorded a surface wind of 240° 4-8 kt at the south-western edge of the swarm at 1300, and Adi Ugri reported 270° 4 kt at 1200 and 290° 2 kt at 1500, while Asmara recorded surface winds of 360°-020°, increasing from 8-16 kt in the early afternoon to 18 kt between 1500 and 1630 (too strong for cross-wind take-off from the main runway by spray aircraft), and giving 049° 29 kt at 180 m above the ground (i.e. 2,500 m A.S.L.) at 1600. Finally, on the 21st, while Adi Ugri still reported 270° 4 kt at 1500, Asmara recorded a surface wind of 020° 9-12 kt between 1330 and 1600, following 010° 15-20 kt up to 2,800 m A.S.L. at 1000 (no afternoon ascent available) ; and the ground-speeds made good by the spray aircraft, on both outward and homeward runs, demonstrated a northerly wind of about 30 kt between 1340 and 1415 at 2,800 m within 20 km to the north of Adi Ugri, associated with Cumulonimbus and showers in the vicinity of the swarm, clearing to $^3/_8$ high Stratocumulus at 20 km to the north. At Keren, 70 km north-west of Asmara, winds remained westerly, reported as 270° 6-9 kt at 1200 and 1500 both on the 20th and 21st.

A second example was furnished by the immature swarm, already mentioned, on which observations were made from the ground (with ZW and PTH) on three successive days (21–23 February 1955) at the same site in Tanganyika, near Marangu at an altitude of about 1,500 m on the lower slopes of Kilimanjaro. The swarm was said, by local Wachagga, to have arrived on the 18th, and a swarm, probably the same one, was seen from the air within a few kilometres of this position on the 18th, 19th and 20th. Flight activity, recorded photographically (Plate II) on the afternoon of the 22nd, and observed visually on the 21st and 23rd as well, was at times apparently fully comparable with that recorded on other occasions in low-flying swarms exhibiting progressive displacements (such as one travelling at 4 km/hr, on which photographic observations were made near Mtito Andei, Kenya, between 1700 and 1725 on 9th February 1955), but, although some displacement of the southern edge of the Marangu swarm was noted between the 21st and 22nd, the areas occupied by the swarms on all three days showed a substantial overlap.

A third case was that of the larger swarm which moved into the Kilimanjaro area from the Usambaras at the beginning of March (Figure 10), was noted as having been carried up on to the mountains by northerly up-slope winds on the 12th [62], and remained for the next nine days along the northern slopes of the mountains at altitudes between about 1,800 and 2,400 m, occupying areas of 40–50 km² which overlapped throughout this period — again despite daily flight activity.

Of six further cases, less well-documented but all likewise associated with mountains or escarpments, three related to observations made from Moshi in February 1954, when a swarm was seen on three successive days in the same area at 1,900 to 2,100 m on the slopes of Monduli, west of Arusha ; a second swarm was observed flying and densely-settled on trees over an area of 8×5 km at an altitude of 2,400 m on the western Rift escarpment near Sabatia (on the same afternoon as the last Monduli sighting) and seen again the next afternoon within a mile of its previous position ; and there were three successive sightings, within a five-day period, of a large flying swarm, 40 km² in extent, at 1,500 to 2,600 m over the eastern slopes of Ngorongoro. A further swarm was seen to remain effectively static for three days in late June 1954 over the escarpment just north of the Turkwell gorge in Turkana, with locusts at times flying up to 2,100 m above sea level ; another remained for five days at the beginning of July 1954 at 1,500–1,800 m over the western slopes of the Lorogi plateau near Maralal, again with considerable flight activity, and yet another was seen on two successive days in June 1955 at 1,800 to 2,900 m over the north-eastern slopes of Jebel Marra in Darfur province of the Sudan [1, 163].

It is clear that the effective immobilization of these swarms, though associated with mountains or escarpments in all cases, was not attributable to any general inhibition of flight activity, associated for example with low temperatures, as may occur in Morocco and Iran during the winter months (pp. 90–91), or with egg-laying, which may have been concerned in the partial immobilization and loss of cohesion in other (mature) swarms observed in Kordofan in the Sudan in July 1954 [162]. Swarm tracks such as those shown in Figures 10, 15 and 16 indicate in fact a number of cases of swarms having been apparently directly deflected towards, and up, mountain slopes, sometimes (e.g. 27 February 1954) during a storm over the slopes. It is conceivable that locust orientation might be involved, since locusts can at times show a marked visual attraction towards conspicuous objects in their field of view [50]. Considering, however, the direct observation of movement with up-slope winds on to Kilimanjaro [62], and the well-marked anabatic circulation which has been found to develop regularly by day over mountain features in these regions, such as the Ufipa escarpment of the Rukwa rift valley in south-western Tanganyika [106], it is suggested that once again it is the details of the corresponding wind-field which are likely to be particularly involved in these cases also.

The conditions under which such quasi-stationary swarms can begin to move again, often with spectacular abruptness after weeks of apparent inaction (sometimes interrupted by brief and temporary sorties over the adjoining lowlands), are of considerable practical interest ; and attention may be directed to the establishment of a particularly uniform wind-field, over the whole area concerned, which immediately preceded three of these movements (Figures 10 and 15).

Such quasi-stationary swarms, together with those effectively static by reason of complex changes of track, are likely to be relatively under-represented in these aircraft records, not only because of the difficulties of terrain and associated weather, in initially locating swarms from the air under these conditions, as well as in being satisfied that successive sightings related to the same swarm, but also because at this period the main operational research effort of the Desert Locust Survey was concerned with the development of operations against the swarms in areas and periods in which no control measures from the ground were practicable. This meant in practice concentration on immature swarms, particularly difficult from the ground by reason of their mobility, and particularly accessible from the air because of the fair weather with which they tend to be associated.

Conversely, as already indicated, the early field studies on swarms, made from the ground with little or no assistance from aircraft, necessarily tended to be over-representative of relatively static swarms, at the expense of those showing higher mobility. This difficulty of the unavoidably unrepresentative distribution of these field observations, both ground and air, has been met, with the help of WMO, by a comprehensive study of the whole of the available records, both of locusts and of weather, for the entire area invaded by the Desert Locust during a complete year of widespread infestation, as described in the following chapter.

CHAPTER 3

THE GEOGRAPHICAL DISTRIBUTION AND MOVEMENTS OF DESERT LOCUSTS DURING 1954-55 IN RELATION TO THE CORRESPONDING SYNOPTIC METEOROLOGY

by

R. C. Rainey and C. I. H. Aspliden

The findings of the WMO Technical Assistance Mission for Desert Locust Control, on the history of locusts and weather over the whole invasion area during 1954–55, require consideration from two alternative points of view. The first is for occasions and circumstances when (as with the aircraft observations already considered) the locust data alone provide direct and unambiguous evidence of the nature (particularly the general direction) of the movements and distribution of the swarms concerned ; such cases will be examined in relation to the corresponding weather data, particularly the wind-fields, in order to test the hypotheses already indicated as to the mechanism of the swarm movements involved. The second approach, for circumstances in which the locust data are incomplete and ambiguous, will be to attempt to utilize these hypotheses, with the corresponding weather data, to throw further light on the locust situation. Logically, the evidence provided by the first approach should be assembled and considered before the second is undertaken ; but, to facilitate presentation, both approaches will initially be combined to provide a consecutive account of locust and weather during 1954–55, and the findings of the two approaches will subsequently be separated in considering what conclusions are to be drawn.

3.1 Nature and treatment of data

With the active co-operation of all the meteorological services concerned, the original synoptic observations which had been made during the study-period were transferred to microfilm, in a series of visits to the headquarters of these services. The synoptic data were assembled and analysed in Nairobi, Kenya, where accommodation and close co-operation were provided by the East African Meteorological Department and the Desert Locust Survey. Daily surface synoptic charts were plotted, on a Mercator's projection with a scale of 1 : 20 million at latitude 15°, for the time 1200 GMT, chosen to represent a time of day at which locust flight activity might be expected to be near its maximum over the area as a whole. Daily streamline analyses [81] of the corresponding wind observations were prepared, on the same scale, for a level of 600 m above the ground, again chosen as likely to be reasonably representative of the winds encountered by flying locusts in migrating swarms. Daily streamline analyses were also prepared for a height of 3 km above sea-level, together with cross-sections (both space and time) to assist in characterizing the synoptic features under consideration [2].

For the presentation and comparison of the corresponding locust records, it was necessary to give further consideration to the nature of the basic locust data, outside the very limited periods and areas (confined to eastern Africa) for which aircraft observations were available. For the thirteen months from May 1954 to May 1955, a total of more than 1,400 separate reports, some of them comprising up to 580 individual records of swarms, egg-fields and hopper-bands, had been received at the Anti-Locust Research Centre, from 46 different countries, mainly through governmental channels, but also from ships, travellers, press and other sources.

While such records provide a picture of the changing overall distribution of the Desert Locust which is probably better established than that available for any other species of animal, the locust data (apart from a few limited areas) are nevertheless characteristically and inevitably less complete and less representative than the corresponding routine observations of synoptic meteorology, and have accordingly required a treatment somewhat different from that of the daily synoptic charts. Following the standard practice developed at the Anti-Locust Research Centre over the past thirty years [141], the locust reports had initially been plotted, as they had been received, from mid-1954 onwards, on series of monthly maps on scales of 1 : 2 million or 1 : 4 million, and subsequently transferred (with some consolidation) to 1 : 11 million maps of the complete invasion area. Such maps have been found of the greatest value in the study of season-by-season and year-by-year changes in the distribution of swarms and of breeding ; but, with each map incorporating every swarm report received over a period of a whole month, evidence of day-to-day changes in the overall distribution of swarms, to which the corresponding daily synoptic charts would be most relevant, is inevitably largely obscured. On the other hand, apart from the very limited areas and periods of intensive air reconnaissance, the evidence provided by the swarm reports received for any single day is too incomplete and fragmentary (see p. 65) to be adequately representative even of the general overall distribution of swarms — and still less useful as evidence of any particular swarm movements which may be in progress. Clearly some combination of the locust data for successive days is necessary in order to delimit the areas infested at any one time ; and, equally clearly, any such combination is liable to obscure the evidence on day-to-day movements. Finally, it was considered to be of the first importance to avoid any subjective element in the routine treatment of the data.

It has long been recognized [83] that the general direction of a locust invasion can only be reliably established by mapping the regions successively reached, and it was therefore decided, in the present work, not to rely on any routine report of direction of swarm movement, in view of the evidence now available both on the considerable difficulty of establishing the real direction of displacement of any swarm as a whole (section 2.1.3.1), and on the manner in which this actual direction of swarm displacement can change even from hour to hour (Figures 11, 12, etc.). At the same time, it may be mentioned that the geographical patterns of migration found in the course of the present work have in fact proved to be remarkably consistent with those inferred from earlier work [17, 19, 33, 141] in which recorded directions of swarm movement were taken into account.

In seeking a compromise on the problem of how to present the locust data in order to facilitate both the visualization of the overall distribution of swarms and the recognition of day-to-day changes in this distribution, consideration was also given to earlier experience of the striking contrast between spectacular long-range swarm movements and periods of quasi-static swarm distribution, and to the indications, provided both by the earlier synoptic studies and by the aircraft observations, that differences in wind-field might be involved in this contrast, which is of the greatest practical significance (pp. 76–77, etc.). Particular attention has accordingly been paid, in this connexion, to demonstrating the presence or absence of any progressive swarm displacement, on a scale of hundreds or thousands of kilometres ; and the degree of simplification and consolidation of reports necessary for adequate visualization of the locust situation for this purpose has been achieved by omitting, on the main working charts of locust data, any presentation of potential evidence of swarm movements on a scale smaller than the limit of resolution of the densest part of the available synoptic network of meteorological stations. Only in one of the larger countries invaded by locusts during 1954–55 (India) does the number of synoptic stations approach an average coverage of one per degree-square ; and the degree-square, representing an area which ranges from 1.23×10^4 km^2 at the Equator to 1.01×10^4 km^2 at a latitude of 35°, has accordingly been used as a convenient unit in the presentation of the locust records.

The working charts of locust data used for this purpose were prepared as transparent overlays, on the same scale as the main meteorological working charts (1 : 20 million at latitude 15°, on a Mercator's projection), and with each overlay relating to one pentade of five consecutive days. Within each degree-square any and every swarm report for each day was combined into a single figure (that of the date), showing by colour(s) the state(s) of sexual maturity of the swarm(s), recorded as either immature, partly mature, mature, egg-laying, or of unknown maturity (section 1.1). These pentade locust charts provided, individually or in combination, a satisfactory presentation of the overall distribution of swarms, together with evidence of any day-to-day change in the recorded extent of the infested area by more than an average figure of 100 km, in a form showing clearly and objectively not only the onset and development of any progressive changes in swarm distribution on a scale greater than this, but also, equally clearly, the areas and periods characterized by the absence of such systematic displacement, i.e. by quasi-static swarm distribution.

In order to study the transfer processes, biological as well as meteorological, operating on these airborne populations, it is necessary to specify the sources and sinks of the locusts concerned. Records of egg-laying, of course, represent the first stage in the development of a potential new source of swarms (as well as being the nearest available approach to evidence of a sink, since swarms commonly die off not long after laying), the subsequent stages being represented successively by corresponding records of hatching, of hoppers of the five successive instars, of fledglings, and finally of the new swarms. Only very rarely, however, are all these stages reported ; thus for example only for 57 per cent of the hopper infestations recorded during the study period was there a corresponding report of egg-laying even anywhere in the same degree-square ; and the reporting of fledglings is probably still more incomplete. Every record of locust eggs or hoppers was accordingly treated as evidence of a potential source of new swarms ; and the procedure followed was to estimate, for each degree-square and for every available record of eggs or of hoppers, the dates on which new swarms could be expected to appear in the square concerned, in the absence of sufficient mortality from control measures or natural causes, utilizing in this estimation the best available evidence of the probable duration of egg and hopper development for the area and time of year concerned on each particular occasion (see p. 105). The degree of accuracy to be expected, for these estimated dates of production of new swarms, varied enormously, depending not only on how recently and completely had the current breeding been reported, but also on the scope and nature of the evidence available on the rates of development in the same area and season in other years. Each estimate made was accordingly graded into one of five classes of reliability, ranging from the most reliable estimates (based on a dated report of fledglings and used as evidence of probable appearance of new swarms during the current or following pentade (i.e. within a period of ten days) to the most vague (provided e.g. by a report of hoppers, of unspecified instar, and on an unspecified date of a particular month, in an area with little evidence on rates of development in other years, resulting in an uncertainty of 40–80 days in the estimated date when new swarms might be expected). Each reliability class was indicated by a particular background colour which was used, on the locust working charts, for each degree-square and pentade so indicated as a potential source of new swarms. A similar procedure was used to infer probable dates of egg-laying for occasions on which egg-fields or hopper bands were recorded without any corresponding report of egg-laying swarms in the same degree-square.

During the study-year there were two separate periods (August 1954 — see section 3.2.2, and March 1955 — see section 3.2.4) showing little or no systematic overall displacement of swarms ; and counts of the number of degree-squares in which swarms were reported over varying intervals of time, during these periods, provide evidence of the characteristically incomplete nature of the routine reporting of locust swarms, to which reference has already been made.

Thus during August 1954 swarms were reported from a daily total number of degree-squares which ranged from 32 to 62, as compared with corresponding totals of 74 to 125 degree-squares for successive

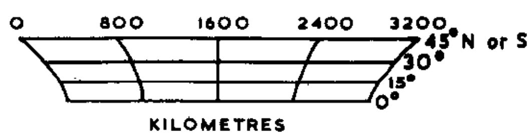
(continued on p. 65)

FIGURE 17

Seasonal changes in the Desert Locust situation
April 1954 - May 1955

(see pages 57-64)

SWARMING LOCUSTS		LOCUSTS NOT IN SWARMS
	Adults – immature	
	Adults – maturing & mature (including inferred presence of laying swarms)	
	Adults – maturity not reported	
	Hoppers	



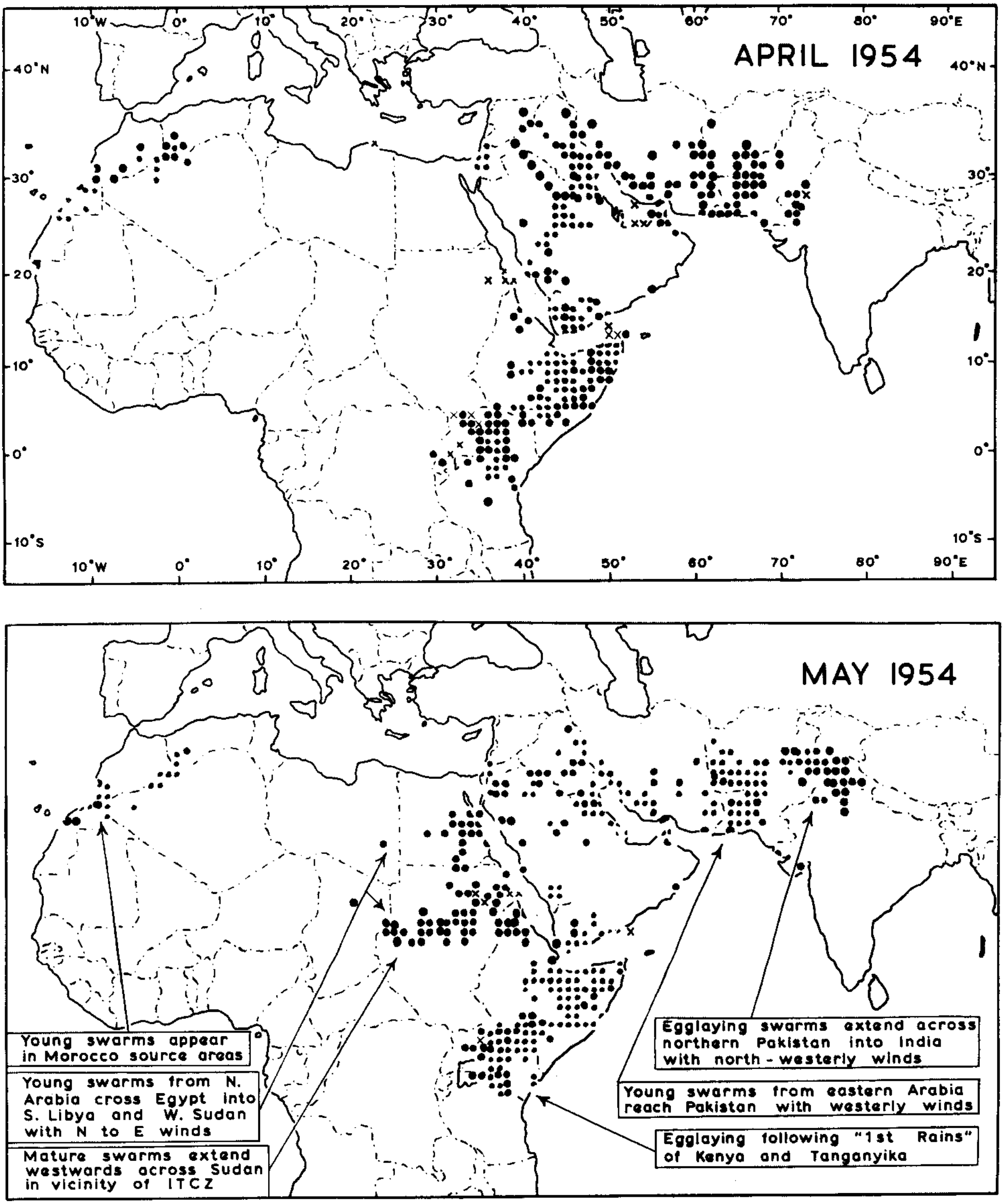
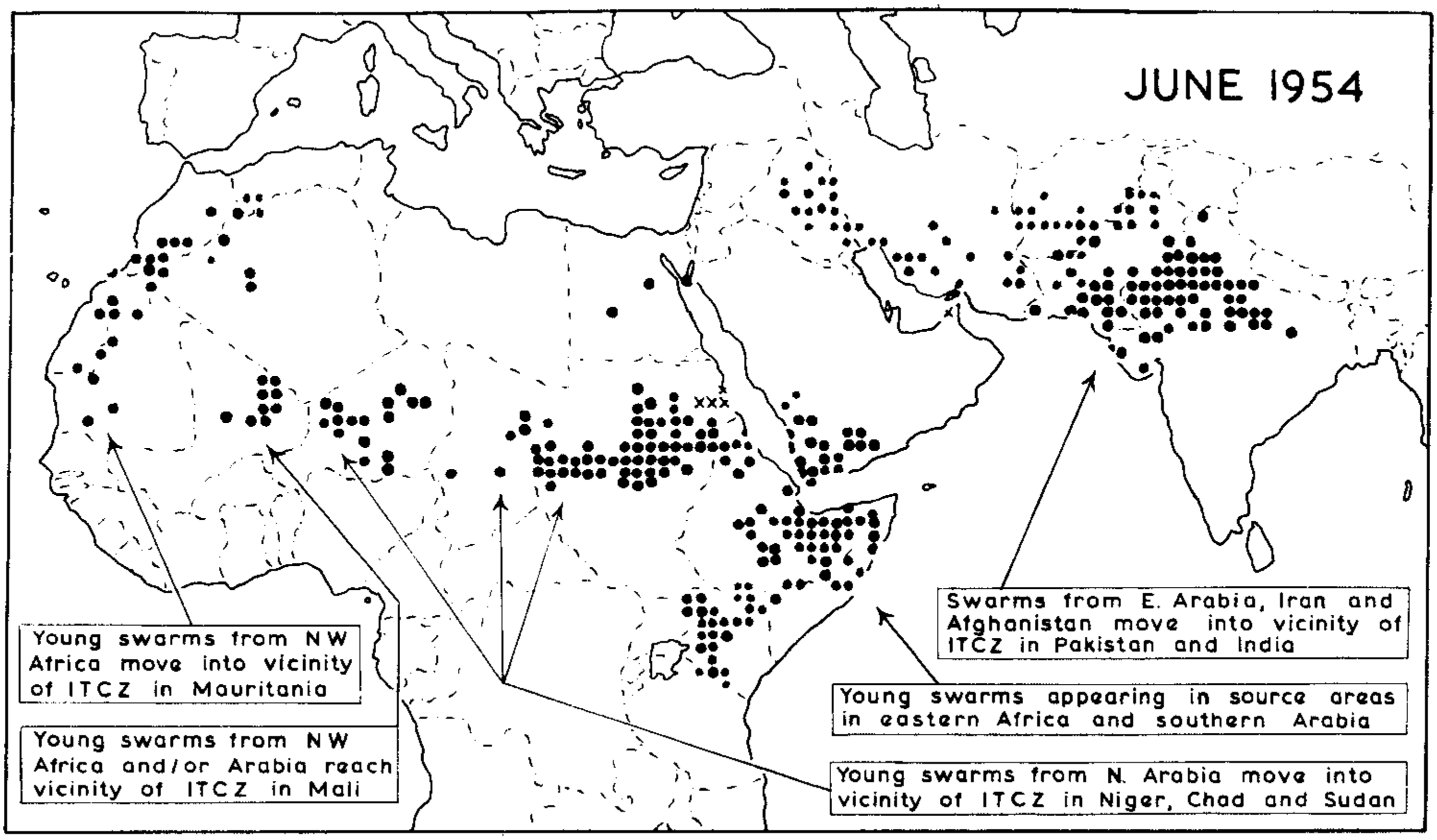


Figure 17 — Seasonal changes in the Desert Locust situation April 1954 – May 1955.



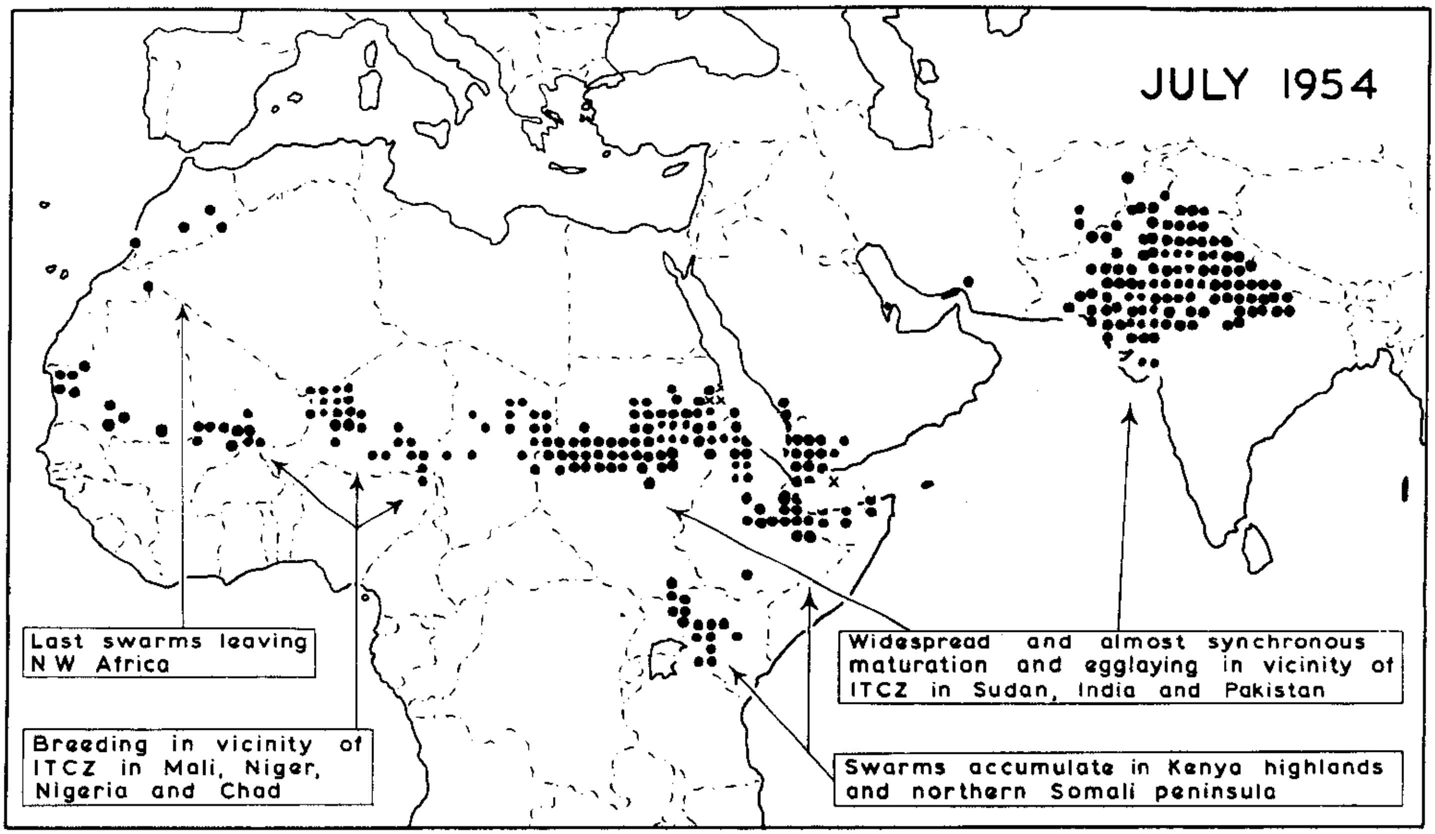
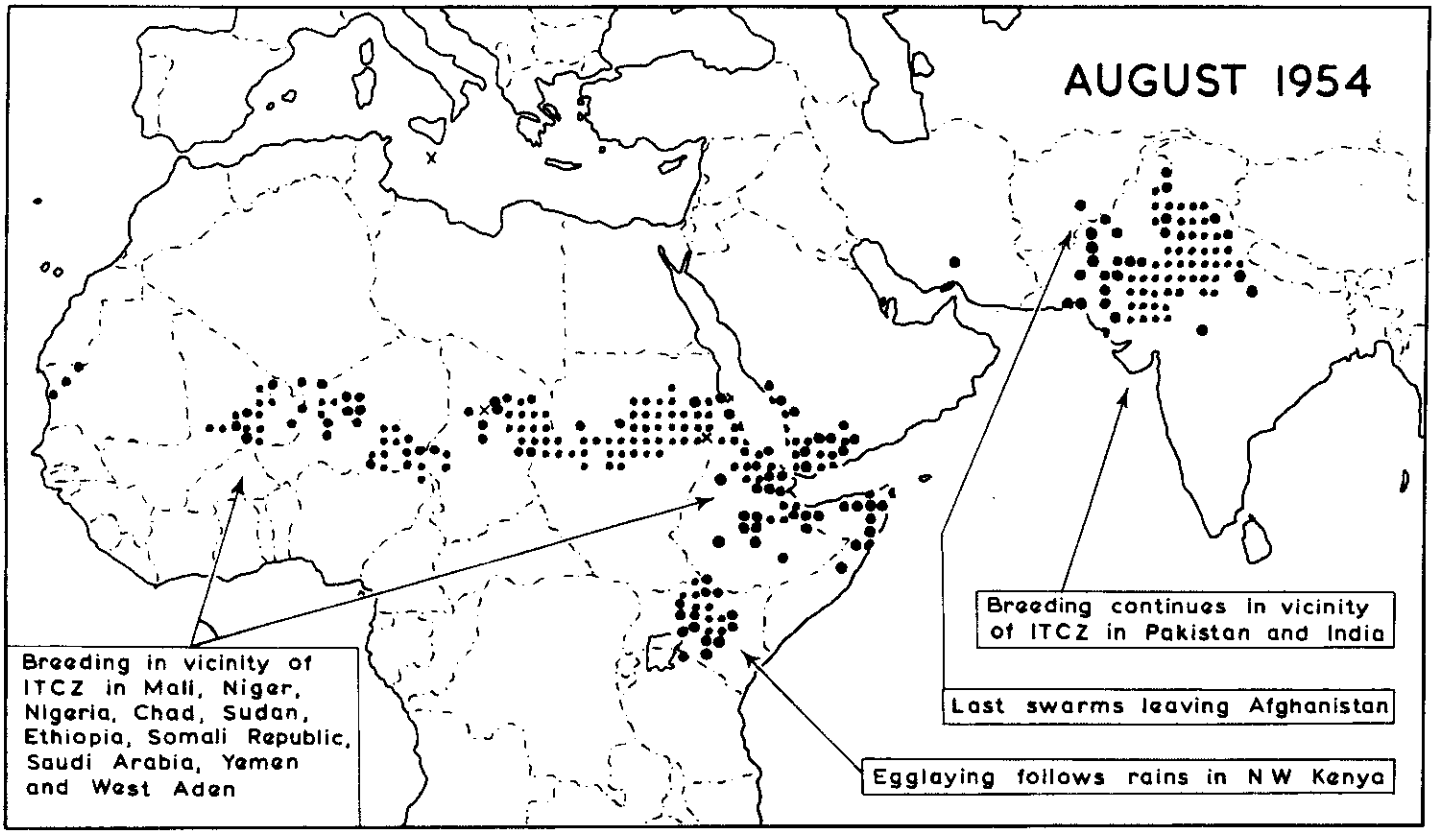
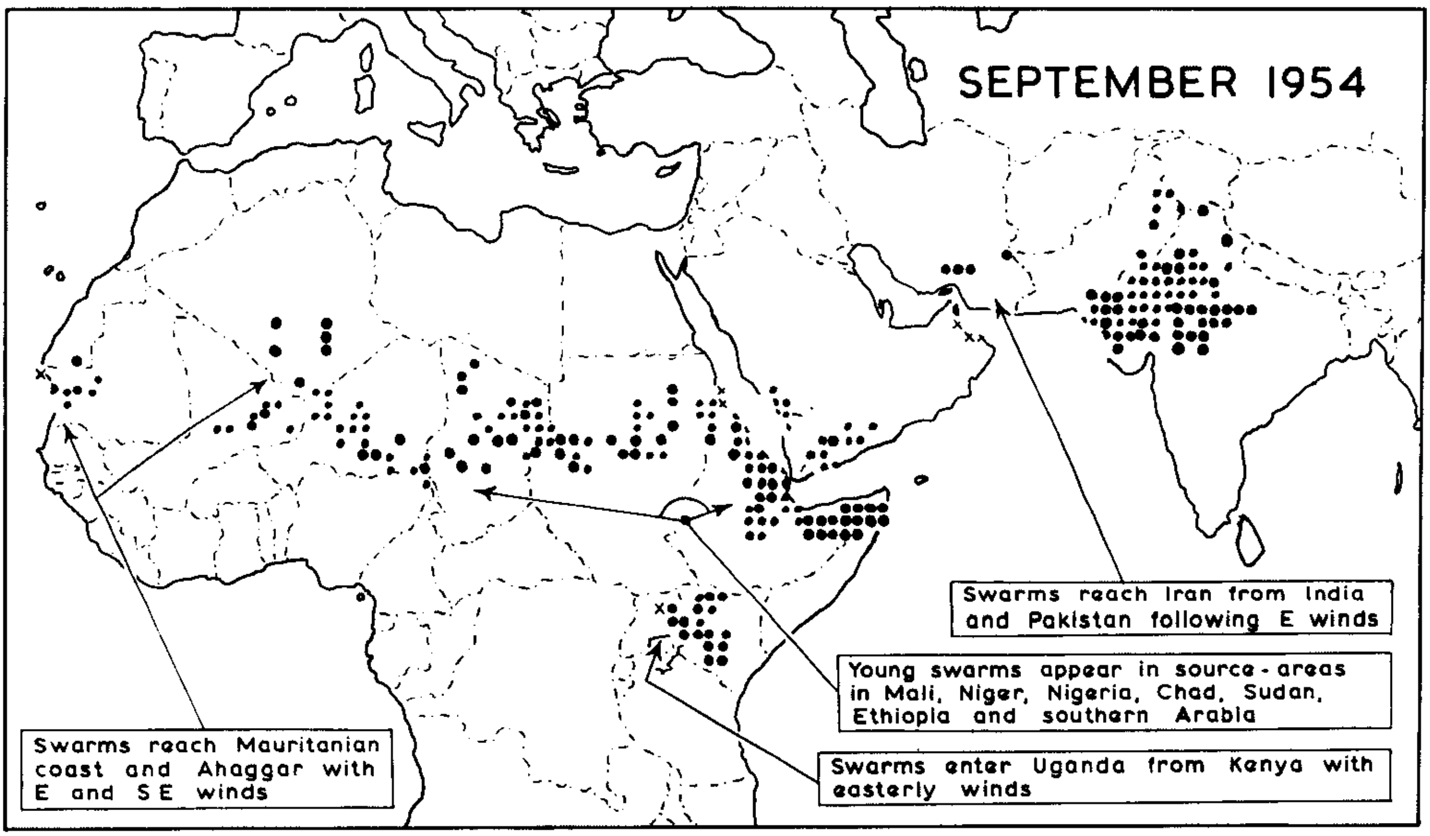


Figure 17 — Seasonal changes in the Desert Locust situation April 1954 – May 1955.





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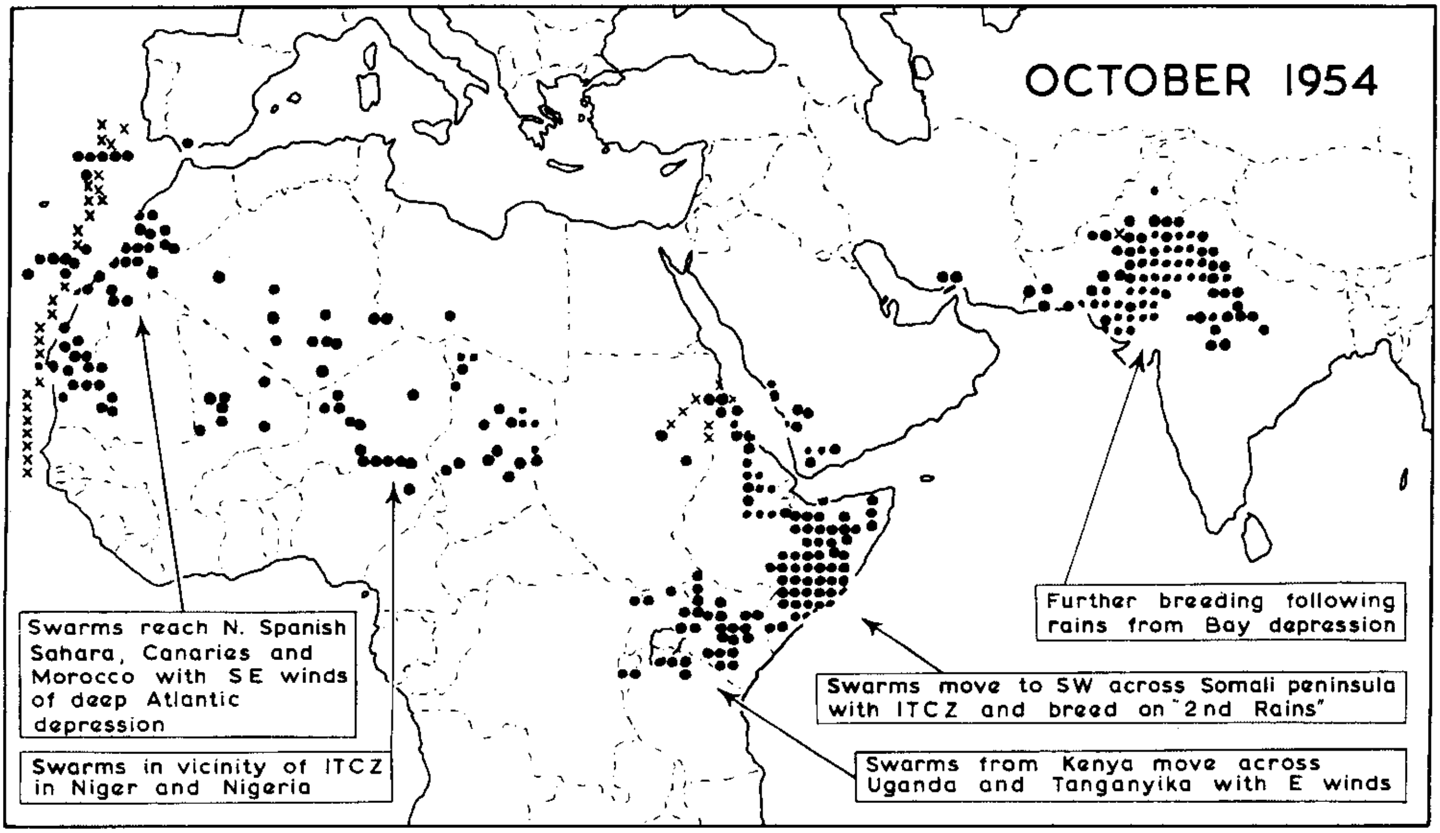


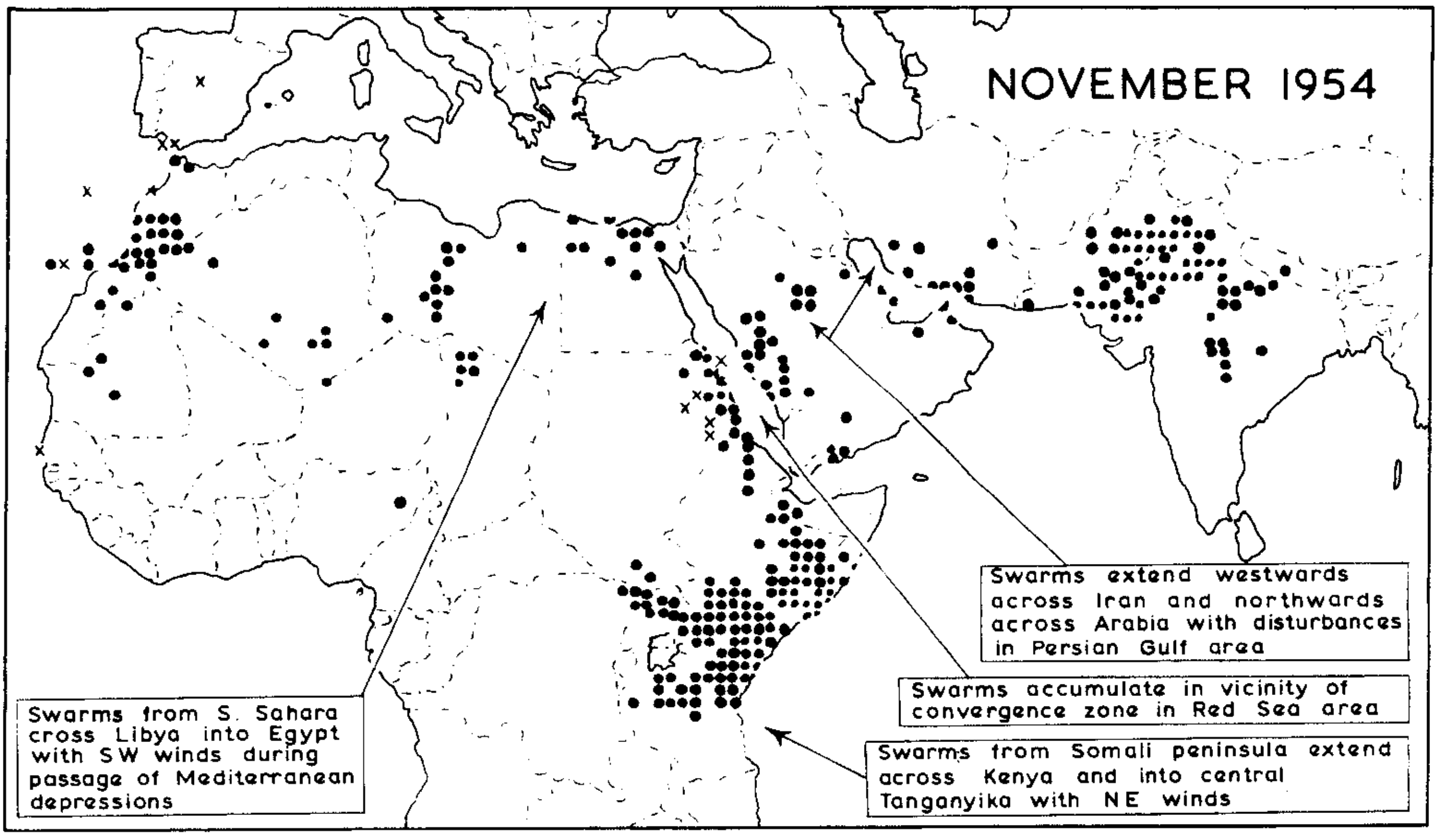
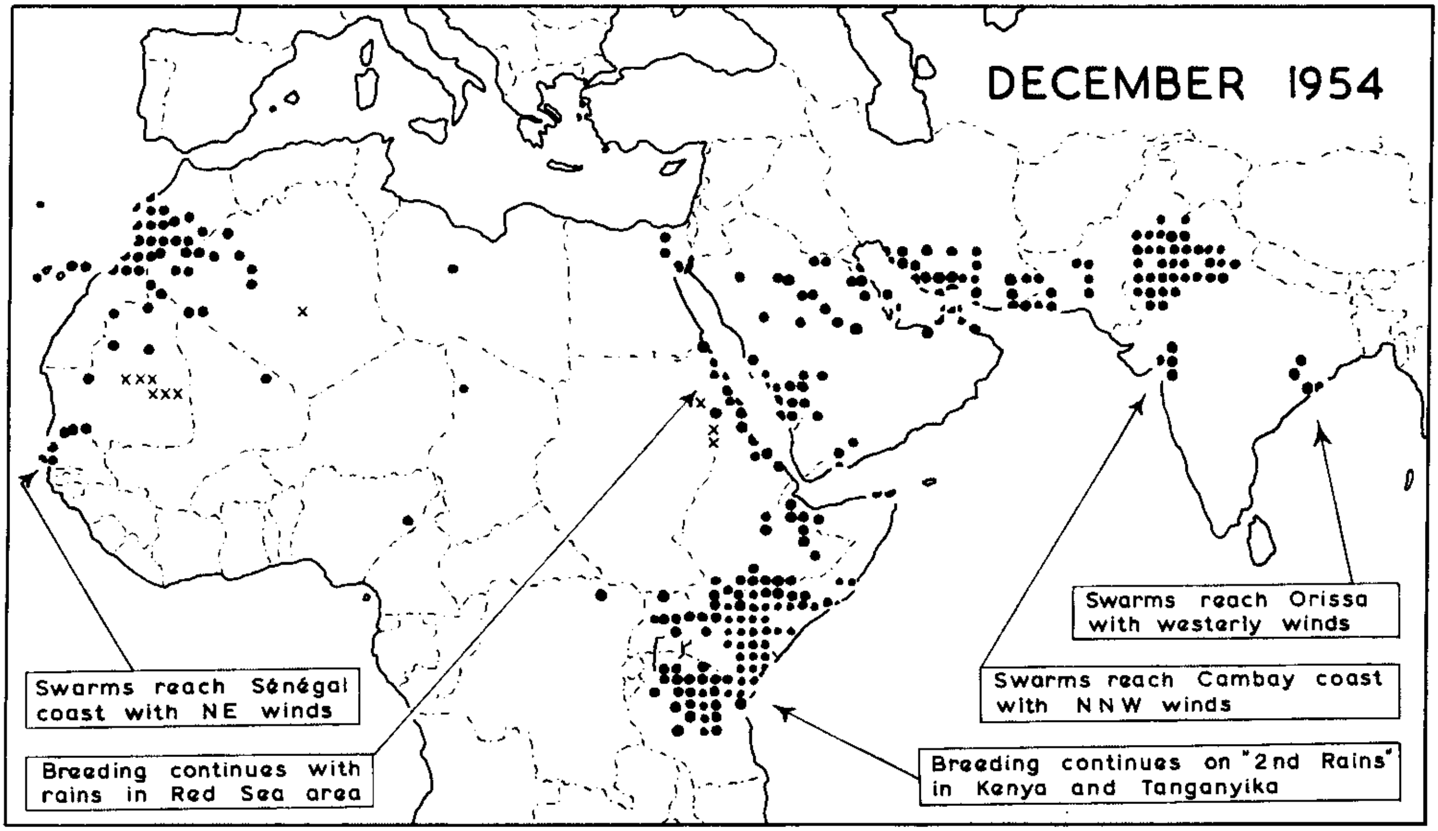


Figure 17 — Seasonal changes in the Desert Locust situation April 1954 – May 1955.



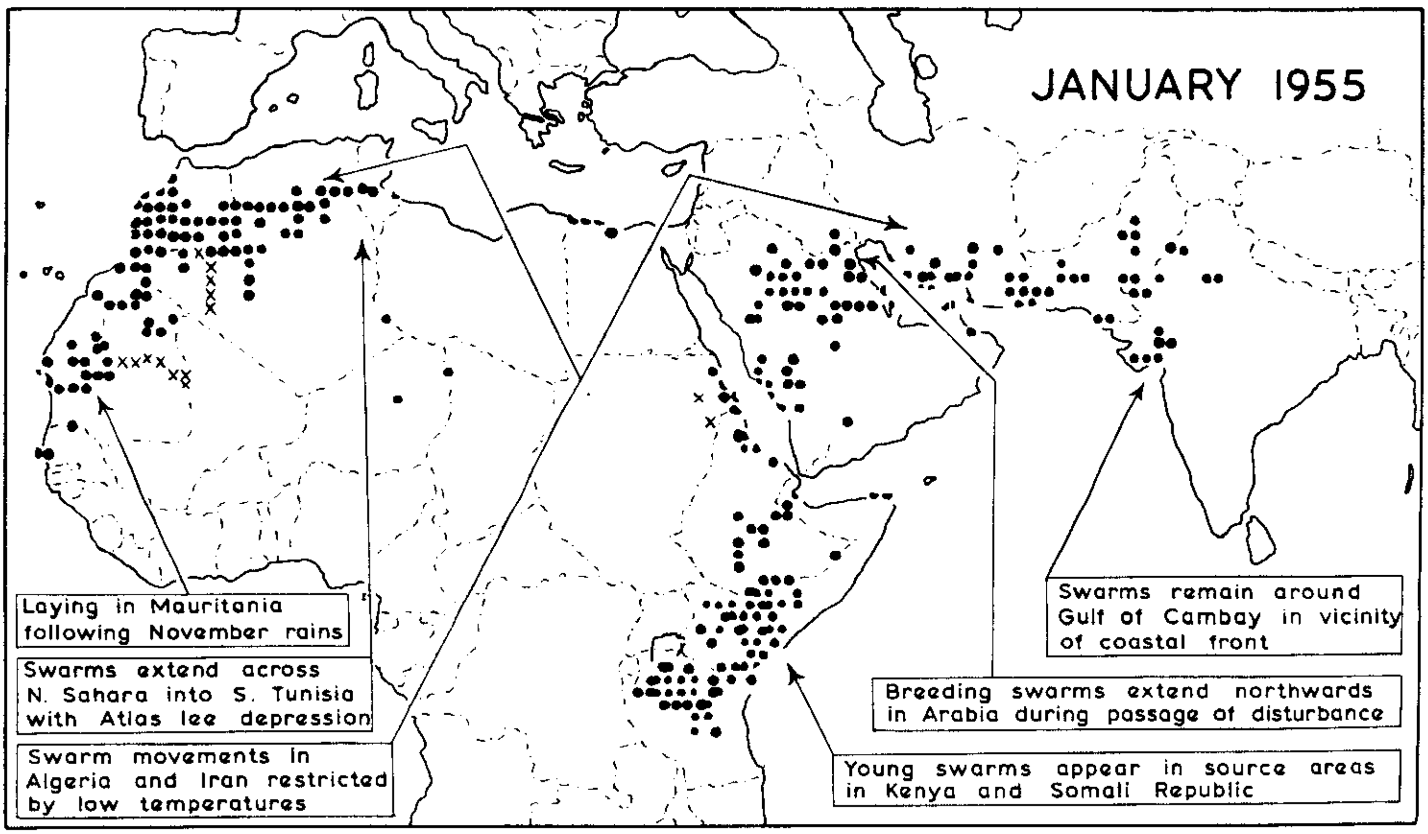
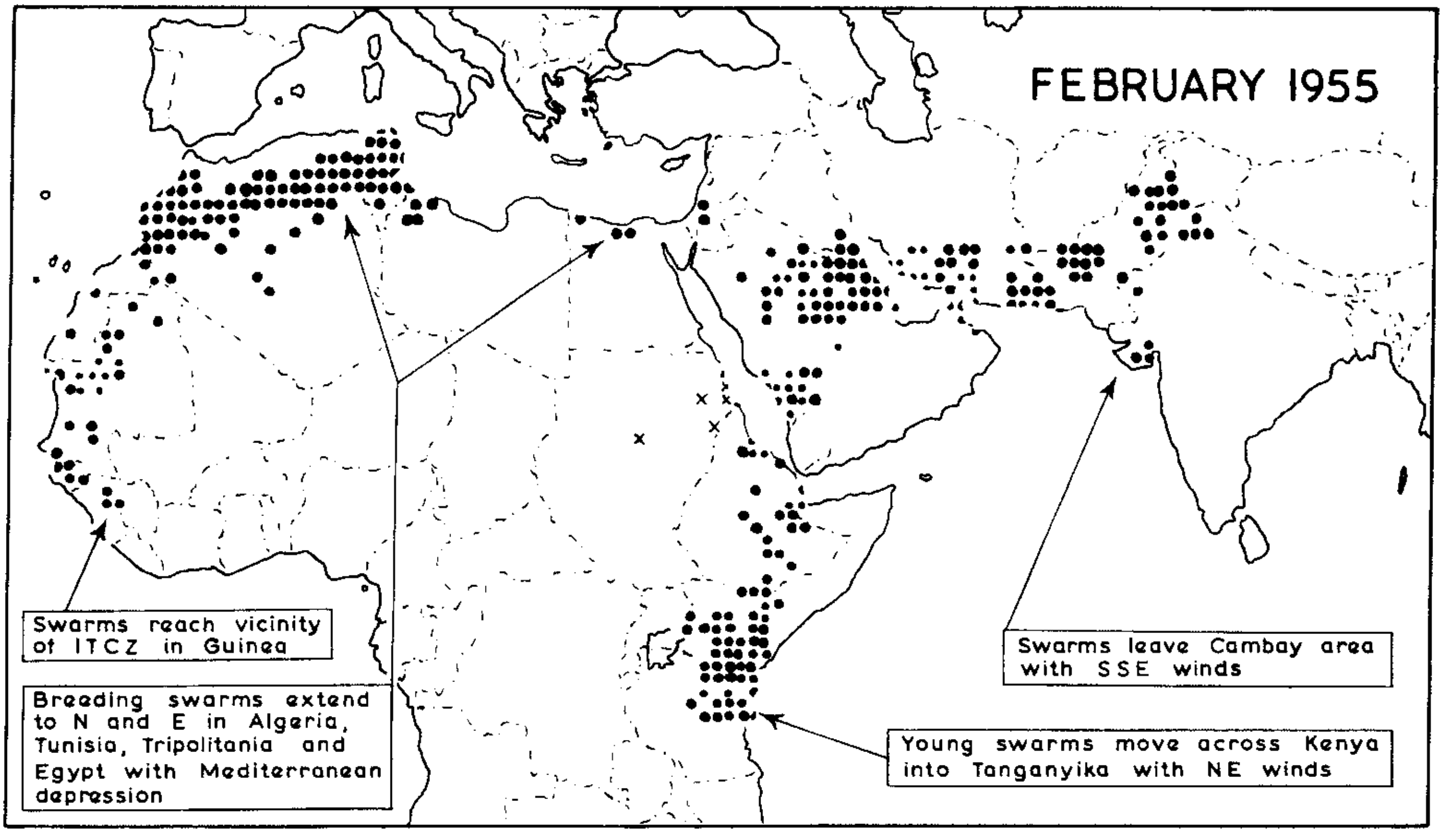


Figure 17 — Seasonal changes in the Desert Locust situation April 1954 – May 1955.



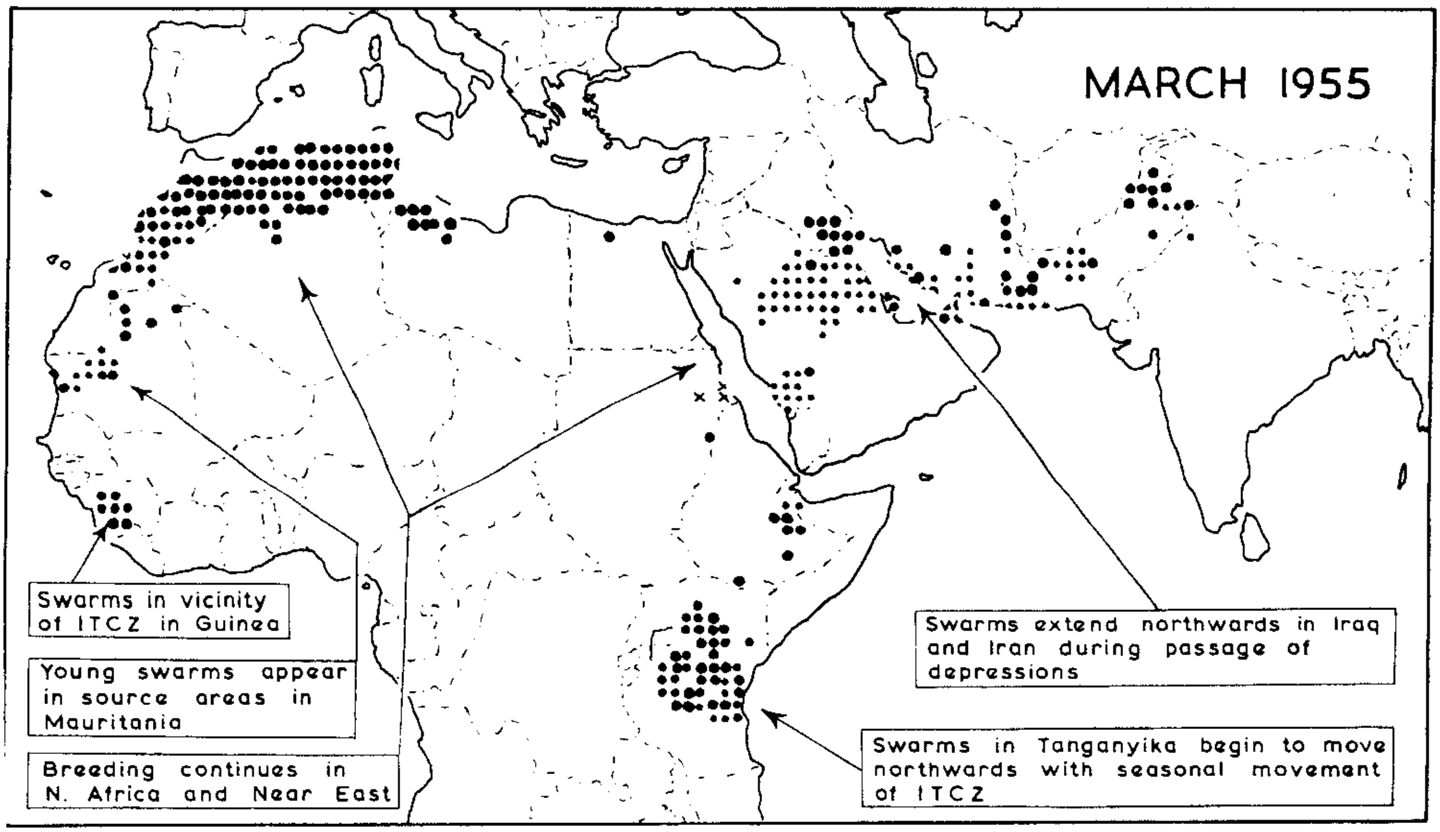


Figure 17 — Seasonal changes in the Desert Locust situation April 1954 – May 1955.

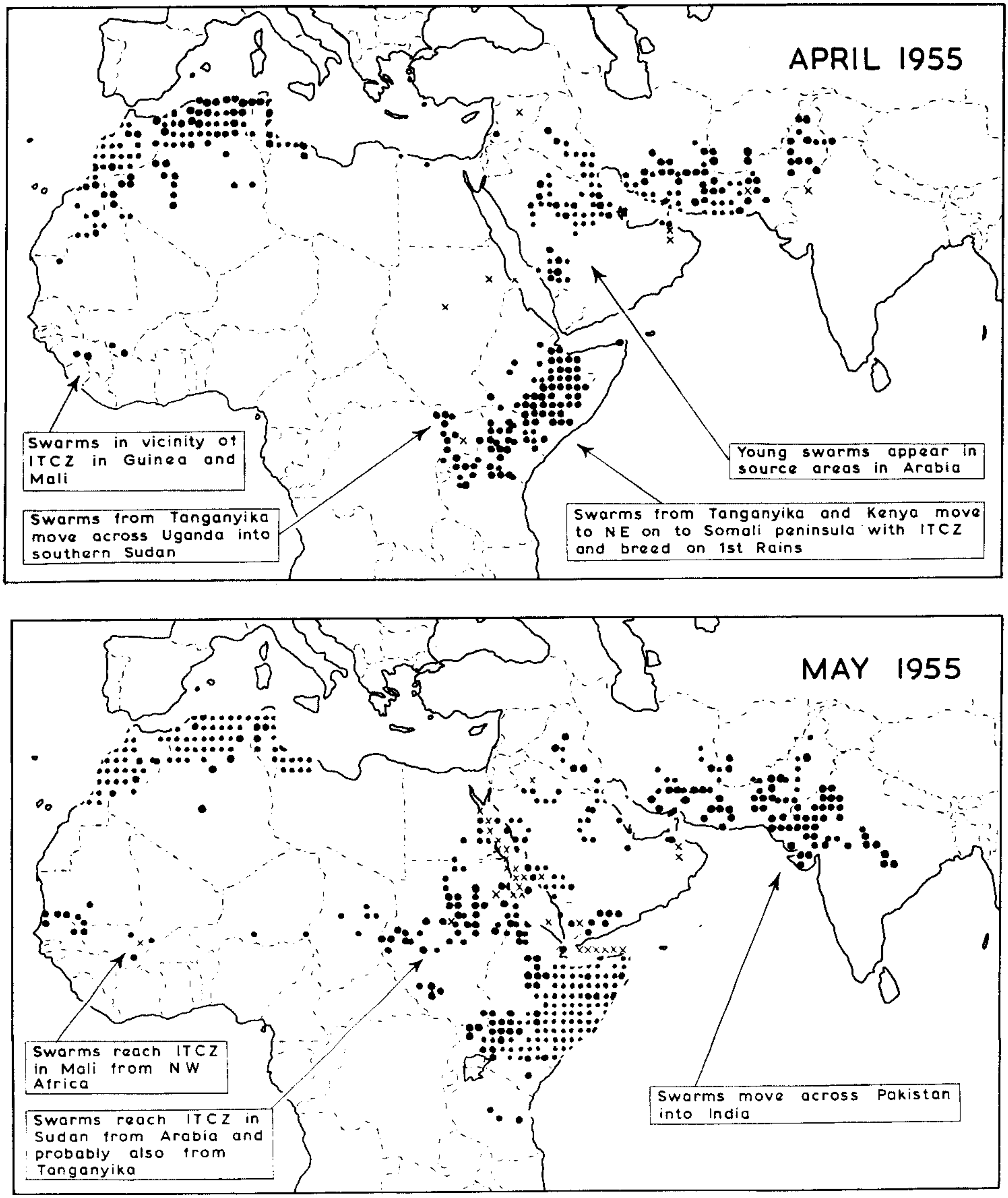


Figure 17 — Seasonal changes in the Desert Locust situation April 1954 – May 1955.

five-day periods during this month, and of 107 to 155 degree-squares for the corresponding ten-day-periods. Likewise during March 1955 — when different regions and countries were involved — the reported daily totals ranged from 23 to 53 infested degree-squares, with corresponding totals of 71 to 104 over five-day periods during this month, and of 119 to 127 degree-squares during ten-day periods.

It may therefore be reasonably inferred that even during such periods, when little or no systematic long-range swarm-movement was in progress, no single day provided swarm-reports from more than 50 per cent of the number of degree-squares in which there was good reason to believe swarms to have been present ; and on some days less than 20 per cent of these infested squares provided swarm reports (despite the fact that a single infested degree-square commonly contains a number of swarms). No single day's locust reports could therefore be adequately representative even of the general overall distribution of swarms. Moreover, these percentages are averaged over all countries concerned ; and in some of the more thinly-populated areas reporting is much less complete than these figures would indicate. Thus the large swarm which was followed by aircraft over largely uninhabited areas of the Coast Province of Kenya for nine days in February 1955 (Figure 14) was not reported from the ground at all throughout this period. Most of the large day-to-day variation in the recorded number of infested squares must be attributed to the random vagaries of reporting ; and, to a smaller extent, this same effect probably also accounts for some of the irregular variations in recorded infested area still shown between successive five-day periods.

Finally, it should be made clear that, while the number of infested degree-squares provides a convenient rough index of total infested area, the strikingly discontinuous spatial distribution of locusts means that no rigorously quantitative significance can be claimed for such figures. Even during a heavy invasion, the total area of the individual swarms concerned — the "net infested area" — is small (of the order of 1 per cent) compared with that of the empty areas between and around the swarms ; and the extent of any corresponding "gross infested area" must obviously vary with the size of the unit-area considered.

3.2 **Desert Locusts and weather May 1954 - May 1955 : a consecutive account**

3.2.1 *Swarm movements into the Inter-Tropical Convergence Zone : May-June 1954*

May 1954 began (Figure 17) with widespread Desert Locust infestations, both of swarms and of hoppers, extending across the Middle East from southern Israel to Pakistan, and from Iran in the north to Tanganyika in the south. North-western Africa was also infested, but India and the countries to the south of the Sahara desert, from Senegal to the Sudan, were clear, as is commonly the case at this time of year. During May and June, developments in the locust situation took place in ways which were initially very different in different areas. Thus in eastern Africa there was continued widespread breeding, with relatively little change in the overall infested area ; in much of south-west Asia, there were progressive extensions of the infestation, northwards in Iraq, and eastwards from Iran and Afghanistan, further across Pakistan, and into India ; while other countries of the Middle East, and of north-west Africa, were completely evacuated by the locusts between May and mid-July, with a corresponding widespread invasion of all the countries along the southern borders of the Sahara.

3.2.1.1 *From northern Arabia and the Red Sea area, and across Egypt and Libya, to the Sudan, Chad, Niger and probably Mali*

The first of a series of major source-areas to give rise to new swarms, in early May, was northern Arabia, where the last egg-laying of the season was recorded near Jauf on the 3rd and 5th, while on the 4th the first young swarms of the next generation were reported in source-areas in Qasim and Kuwait (for most place names see Figure 1). Between the 5th and 9th young swarms appeared at a number of other sources in northern Saudi Arabia, the Neutral Zone, and Kuwait; and on the 10th, from three points in Badanah district near the Saudi/Iraq border, there were the first reports of young swarms well outside these source-areas, to the north-west of them, during the second day of a spell of easterly and southerly winds associated with one of the last of the Mediterranean/Persian Gulf depressions of the season. This initial move of young swarms to the north-west appears to have been important in ultimately diverting many of the northern Arabian swarms of 1954 towards Africa, rather than towards India; the exact position of the anticyclonic cell concerned at this stage appears to be critical in determining in which of these two alternative directions the main weight of locust invasions from northern Arabia will fall in a particular year.

Mature swarms may also have moved northwards, across Iraq, at about the same time (as they did across adjoining areas of Syria, Turkey and Iran during the passage of an active depression in early May 1962 [100]). Thus egg-laying was reported near Kirkuk on 11 May 1954, following heavy rain (up to 32 mm) in this area on the 9th; this same disturbance also gave precipitation in Iran and Baluchistan, where there was further egg-laying at about this time; and, during 9–12th, there was the only appreciable rainfall of the month in northern West Pakistan, followed by laying a week or so later (p. 69).

During 12–16 May there were further reports of young swarms in the Jauf area of northern Arabia, and on 17 May a swarm was observed near Rutba in western Iraq; during 14–17th winds became northerly to north-easterly over this area. On the 18th, with north-erlies over the northern Red Sea and north-north-easterlies at Hurghada, the first immature swarms were recorded in Egypt, not only on the coast, near Hamata (and at about the same date at a number of other points further northwards along the west coast of the Red Sea), but also reported on the same day (18th) near Aswan on the Nile, already over 1,000 km from their probable sources in northern Arabia. The following day (19th), mature swarms were reported in the northern Sudan Republic near Wadi Halfa, in north-easterlies which had persisted for at least three days, and accordingly perhaps also derived from north-western Arabia, where they may already have laid eggs earlier in the month.

Meanwhile, other mature swarms had appeared some 700 km further south in the Sudan; the first to be reported, on the 15th, was a very small one (0.06 km^2) seen at Wad Medani, in Blue Nile Province, following easterly winds, and probably derived from Eritrea, where there had been laying swarms near the coast earlier in the month, and indications of a movement inland with north-east winds from the 6th onwards. This Medani swarm was the first to be reported west of 35° in a belt, between about 13° and 21°N, in which swarms appeared right across Africa within the following three weeks, and which remained infested throughout the next four months. This is a belt characteristically dominated by the Inter-Tropical Convergence Zone at this season; and these swarms characteristically moved into and remained in the vicinity of this Zone. Thus the swarms reported on 18 May in Blue Nile province (as well as others on the same day in western Eritrea) were all within less than 150 km of the 1200z position of the ITCZ, between N-NNE winds with dew points of 2° to 7°, and SE-SW winds with dew points of 11° to 22°. On the early morning of the 19th, the ITCZ moved northwards over the Sudan, with fresh southerlies at Khartoum after at least four days of consistently northerly to easterly winds; and the mature swarms, which by the 19th had been reported along an E-W belt to the south of Khartoum, across Kassala and Blue Nile provinces and into Kordofan, were reported along a belt some 2° further to the north during the 21st and 22nd. On the 24th scattered mature adults were reported reaching Chad.

In Egypt, the immature swarms from Arabia reached Kharga oasis with easterly and northerly winds on the 21st, by which date they had also been reported along some 480 km of the Nile in Girga, Qena and Aswan provinces, while other immature swarms, still in Arabia, had reached as far south as Jeddah on the coast by the 19th. On the 22nd, young swarms also began to appear, with north-north-westerly winds, at a number of points in southern Jordan, to the south and south-east of further source-areas in the Negev area of southern Israel and the Jordan valley. There were more reports of young swarms in southern Jordan during the next two days ; winds, recorded at Akaba, were then easterly, and it is accordingly suggested that these swarms may subsequently have added to the infestation in Egypt, where young swarms continued to be reported on the coast until the 27th and in the Qena province on the Nile until 30 May. The first young swarms to reach the Sudan were reported from the 23rd to the 27th, along the coast near Port Sudan, and from the 24th further inland, with north-easterly winds, and accordingly may well correspond with some of the young swarms which were reported almost daily between the 19th and 25th in the Jeddah area on the other side of the Red Sea. Further Sudan evidence of the passage of incoming swarms was provided by counts of scattered locusts which were being made, as part of an ecological study [77], during regular camel traverses planned to sample appropriate Red Sea coastal habitats (e.g. *Pennisetum* cultivations and wild *Heliotropium*) along the watercourses of Khor Arbaat and Tokar (some 170 km apart, to the north and south of Port Sudan) as well as at Tohamiyam in the Red Sea hills 130 km west of Tokar. At all three points the numbers of scattered locusts seen increased sharply on 24/25 May.

On about 29 May swarms were again recorded near the north-west Arabian coast, in the neighbourhood of Wejh and Al Ula, with northerly winds — the last swarms to be reported for five months anywhere in Arabia north of 20°N, and again probably from the Negev and Jordan areas. Northern Arabia was thus clear of reported swarms within three weeks of the first recorded movement of young swarms out of their source-areas. On the same day (29th), the first immature swarm appeared in Darfur, westernmost province of the Sudan, and the first swarms were reported in the Chad Republic, with a well-developed north-north-easterly wind-flow from central Egypt and southern Cirenaica — where extensive damage by a large immature swarm was recorded at Kufra oasis on five unfortunately unspecified days during May. Mature swarms, spreading westwards along the Inter-Tropical Convergence Zone (the surface wind-shift, from light N to moderate S-SW, was again recorded at Khartoum on the late evening of the 29th, with a report of a mature swarm within 40 km of Khartoum on the same day), and apparently oscillating meridionally with it, e.g. northwards to beyond 18°N on the 26th, had already reached the eastern border of Darfur by the 24th.

No immature swarms had yet been reported in any other province of the Sudan west of 35°E. It is suggested that this may have been related to a spell of south-westerly winds recorded over the northern Sudan on the 29th, well to the north of the surface change in humidity associated with the ITCZ, as is known to occur from time to time in this area and season [128]. This south-westerly spell appears temporarily to have excluded the young swarms from more direct access from Egypt into the Sudan. On 30 May the north-easterlies were becoming re-established over Upper Egypt and the northern Sudan, and on 1 June the first young swarm was recorded in Khartoum province. On 2 June further swarms were reported in Chad, in north-easterlies, and in the Northern province of the Sudan, in northerlies, followed next day (3rd) by swarms further to the south in Chad and Darfur, in the immediate vicinity of the ITCZ. By the 4th the first immature swarms had been reported in Blue Nile and Kordofan provinces, in northerlies following a southward movement of the ITCZ ; and, away to the west, swarms had been reported in the Niger Republic, in south-easterlies following north-easterlies, representing a displacement of some 3,500 km from their probable source in northern Arabia in a period of just a month. During 5–8 June there were further reports of swarms in the Sudan, some of them in the vicinity of the ITCZ, with others still to the north of it, including reports of immature locusts invading and damaging young cotton on the Zeidab pump-scheme from the 5th onwards [78].

Meanwhile, young swarms had begun to appear in many other source-areas, in eastern and north-western Africa as well as in south-west Asia, involving during the second week of June an area of the order of 10^6 km^2 (107 degree-squares), the highest figure so recorded in the whole study period, and reflecting a telescoping of the periods of egg and hopper development by the general rise in temperature [85], with the later layings in the spring breeding areas developing more rapidly than the earlier ones.

The further history of the young northern Arabian swarms, particularly in the west, is no longer distinguishable from that of young swarms derived from north-west Africa.

In 1950 young swarms produced by heavy breeding on the Red Sea coast of Saudi Arabia between February and April reached the Nile valley, near Atbara in the Sudan, from 17 May onwards, and were reported in Darfur province, some 1,100 km away to the west-south-west, fifteen days later. Some of these swarms reached the Ouaddai area of Chad in mid-June ; and it was concluded, from a detailed examination of the evidence, that certainly the greater part, and probably the whole, of this movement across the Sudan had taken place down the north-east monsoon [92].

South-westward movements of swarms from Arabia, across the Red Sea, Egypt and the Sudan, are in fact of very frequent occurrence at this season. Thus swarms have begun to appear in Egypt, on the west coast of the Red Sea, at some date between 3 April and 16 June in 16 of the 22 years 1941–1962, and in half of these years between 10 and 26 May (with 18 May, as recorded in 1954, representing the median date of this series). During 15 of these years these records appeared clearly to relate to a movement of swarms from central and northern Arabia, and sometimes from countries further to the north, across Egypt and into the Sudan, and in six of these years extending into Chad [147] ; during three of these latter years (as well as during 1950, when the Sudan was crossed but not Egypt) swarms of Arabian origin appeared to extend westwards at least as far as Niger.

3.2.1.2 *From north-western Africa to Mauritania and probably Mali*

In north-western Africa the last recorded egg-laying by the previous generation was on 18 and 19 May, in western Algeria, and young swarms of the new generation were first reported on 24 May, within a source-area along the Wadi Dra in southern Morocco. Young locusts of north-west African origin also probably provided the immature component of a partly mature swarm reported in southern Spanish Sahara with north-north-easterly winds on 5 June, with source-areas to the north and north-east. On 9 June (when swarms were reported further northwards again in the Sudan, with strengthening southerly and south-westerly winds), swarms, both immature and mature, were first reported in Mali, in southern Adrar des Iforas though with predominantly south-westerly winds. No Desert Locusts had however been reported anywhere to the south-west of this area since December 1953, and it is accordingly most likely that the swarms in Adrar des Iforas on 9 June had in fact reached Mali a few days previously, either from the direction of Morocco and Spanish Sahara, perhaps across the "Empty Quarter" of Majabat al-Koubra, with a well-developed northerly and north-westerly flow on the 6th, or, equally possibly, from Niger with the easterlies and north-easterlies of the 4th and 5th.

On 10 June the first young swarms, of unambiguously north-west African origin, to be reported well outside these source-areas were recorded near Fort Trinquet, in northern Mauritania, in northerly winds, and to the south and south-west of source-areas in southern Morocco and western Sahara. From 11 June onwards, swarms in Mali, as well as in Chad, Sudan and Niger, continued to be reported in the vicinity of the ITCZ. In Niger the locust invasion of 1954 was one of the heaviest on record [6]. On the 21st, young swarms were reported in north-western Mauritania, in easterlies and north-easterlies, and probably represented a further movement out of source-areas in Morocco. Two days later, on 23 June, a number of young swarms, which may well have been of similar origin, had reached a surface wind-change between north-easterly and south-westerly winds near Atar, in central Mauritania ; and on the 27th were reported still further to the south in Mauritania, at Tidjikja and near Aleg, again close to the wind-change. Swarms have similarly reached southern Mauritania during May or June in eleven of the past twenty years, and during July/August in a further four [147].

At about the same time, roughly on 25 June 1954, there was egg-laying on a limited scale in the plain of Tamesna, in west Niger. There was no general maturation of the young swarms along the ITCZ until mid-July, and this initial breeding in late June in Tamesna may perhaps be attributed to swarms arriving already mature, possibly from Ethiopia or the southern Red Sea area ; evidence that such swarms had already reached the western Sudan by late May, with scattered mature locusts as far as Chad at the same time, has already been indicated.

3.2.1.3 *From northern and eastern Arabia to Pakistan and India*

Returning to the consideration of further events in the east : following the evidence of an initial move to the north-west out of the source-areas of Kuwait and the adjoining territories in early May, further young swarms continued to appear in these source-areas until 18 May, with northerly winds. At about the same time (16 May), young swarms began to appear in new source-areas in Oman ; and on the 21st young swarms were reported at Ras Duqam, on the coast of south-eastern Arabia, with westerly winds following several days of north-westerlies, and accordingly likely to have been derived from the source-areas of Oman and/or of north-eastern Arabia. Young swarms continued to be reported in the Oman until 28 May ; and on 25 May the first young swarm appeared in Pakistan, at Turbat in southern Baluchistan, following surface westerlies, and again likely to have originated from eastern Arabia. By 30 May, when swarms were also appearing in source-areas in southern Iran, young swarms in Pakistan had penetrated as far east as Hyderabad, still in the westerlies ; an association of a general trend of locust flights to the east with winds from the west at this season was noted in India in 1930 [111] and 1959 [6a]. By 3 June 1954 swarms had entered India, where they were reported west of Bikaner, in Rajasthan, close to the north-eastern limit of south-westerlies ; on the 5th swarms were reported at a number of points from the vicinity of Karachi to northern Rajasthan, again along the northern limit of the south-westerlies. Following indications of a movement of swarms to the south-east with a displacement of this limit on 6 and 7 June, swarms were reported on the 8th at a number of points within a well-marked area of convergence over Rajasthan. On this date (8th), young swarms also began to appear in new source-areas near the Afghanistan/Baluchistan border, and cannot subsequently be distinguished from those which had originated around the Persian Gulf. A similar eastward movement, towards and into India, by swarms resulting from spring breeding in and around Arabia, Iran and Pakistan, has been recorded during May/June in 15 of the past 20 years [147].

Within the area of northern Rajasthan which was reached by young swarms about 4 June, mature swarms had already been present for about a fortnight. Following egg-laying in Baluchistan, Afghanistan, and Dera Ismail Khan at the beginning of May, mature swarms spread and laid across Peshawar, Rawalpindi and Lahore, extending progressively to the south-east with north-west winds, reaching Punjab, in India, on the 15th, Uttar Pradesh by the 17th, and northern Rajasthan on 18 May ; there was laying in Punjab and in northern Rajasthan shortly afterwards. The Rajasthan area, which was thus invaded by mature swarms in mid-May and by young swarms in early June, was to remain continuously infested throughout the following seven months. There was, however, no further laying recorded in this area during the first half of June, and no indications of any general maturation of the invading young swarms during this period.

On the 9th June the swarms moved into southern Rajasthan, following northerlies ; on the 10th the surface wind-change was back to north of the swarms ; and on the 12th there were swarms, with locally SE and NW surface winds among the general south-westerlies in Hyderabad and Rajasthan, and 71 mm rain at Ajmer, while young swarms were continuing to appear in Baluchistan and others in new source-areas near Kandahar in Afghanistan. On the 13th, 14th and 15th all swarms were still well within the south-westerlies, but on the 16th (when 33 mm rain fell at Bikaner) they were again in the vicinity of the limit of the south-westerlies, as in June 1959 [6a]. During 17–22 June swarms moved south-eastwards and eastwards, with north-westerly and westerly winds, from Punjab and Rajasthan with the leading young swarms reaching northern Madhya Pradesh on 22 June, and with egg-laying taking place between the 19th and 24th over a relatively limited area of the adjoining parts of Punjab (where 15 mm had been recorded in the course of the preceding 12 days at Hissar), northern Rajasthan, and eastern Uttar Pradesh. During 25, 26 and 27 June, with a marked advance of south-easterlies and easterlies associated with the movement of a shallow depression across Orissa from the Bay of Bengal, swarms disappeared again from northern Madhya Pradesh and eastern Uttar Pradesh. During 27/28th isolated young locusts were seen in flight at sea, some 500 km west-south-west of Bombay, in a WNW wind ; within the previous three days young swarms had been reported to the north and north-west of this position, not far inland from the coasts of Baluchistan and Kathiawar.

In late June 1956, when India was free of locust swarms, locally heavy rain in Sri Ganganagar district of Rajasthan was found to have been associated with a concentration of previously solitary-living locusts from a considerable area, attributable to the markedly convergent wind-field associated with a deep trough of low pressure, and followed by breeding and by gregarisation of the resulting hoppers [7]. A similar concentration had taken place in Eritrea in November 1950 [92, 99, 132], and may also have occurred in Rajasthan in mid-1949 [41].

Young swarms continued to appear in the neighbourhood of source-areas in Baluchistan and Afghanistan throughout June 1954, and from 20–27th were reported damaging orchards in the Quetta area, while damage to cotton by the young swarms was reported in Sind, particularly in Nawabshah and Mirpur Khas districts. At the end of June, swarms were still immature over the greater part of the infested areas of India and Pakistan.

3.2.1.4 *Breeding in eastern Africa and southern Arabia*

In marked contrast with the striking swarm movements which affected so many countries during May and June, there was relatively little change in the overall distribution of infestation in eastern Africa and southern Arabia during this period, though from evidence of other years southern Arabia is likely to have been receiving further young swarms from the north. During May, egg-laying, following the First (or "Long") Rains, was widespread in Kenya, extending also into northern Tanganyika, and occurring also in a few areas of the Somali Republic (where a relatively isolated recurrence of laying on 9 May, near El Dere, followed three reports of "precipitation seen in distance" from stations in the area). Young swarms appeared in early May in source-areas on the Ethiopian coast and in northern Tanganyika, and on 26 May in northern Turkana, with ENE winds, consistent with arrival from a corresponding source-area in southern Ethiopia. At the end of May young swarms began to appear in new source-areas in southern Saudi Arabia, the Yemen, West Aden, eastern Ethiopia and the Somali Republic, and during the greater part of June continued to appear in these areas as well as in others in Kenya, northern Tanganyika, and, at times, in the East Aden Protectorate. From 25 June onwards these swarms began to accumulate across the northern Somali peninsula and in the Kenya highlands bordering the Rift Valley — areas in which swarms remained throughout the next three months (section 3.2.2.3).

3.2.2 *Swarms and breeding in the vicinity of the Inter-Tropical Convergence Zone : July-September 1954*

3.2.2.1 *India and Pakistan*

Reference has already been made to egg-laying on a limited scale in India in May, following the rains of one of the last westerly depressions of the spring, and to further egg-laying over a relatively limited area during 19–24 June, following rains in easterlies. There were indications of further movements of young swarms into Rajasthan and Hyderabad from the spring breeding areas to the west and north-west, where young swarms continued to appear in source-areas in western Pakistan until 6 July, and in Afghanistan until 14 August ; in addition, young swarms began to appear on 20 July in the source-areas provided by the initial May layings in India. On 9–11 July widespread laying began in Rajasthan ; and

FIGURE 18

The Inter-Tropical Convergence Zone and the distribution
of locust swarms in July 1954

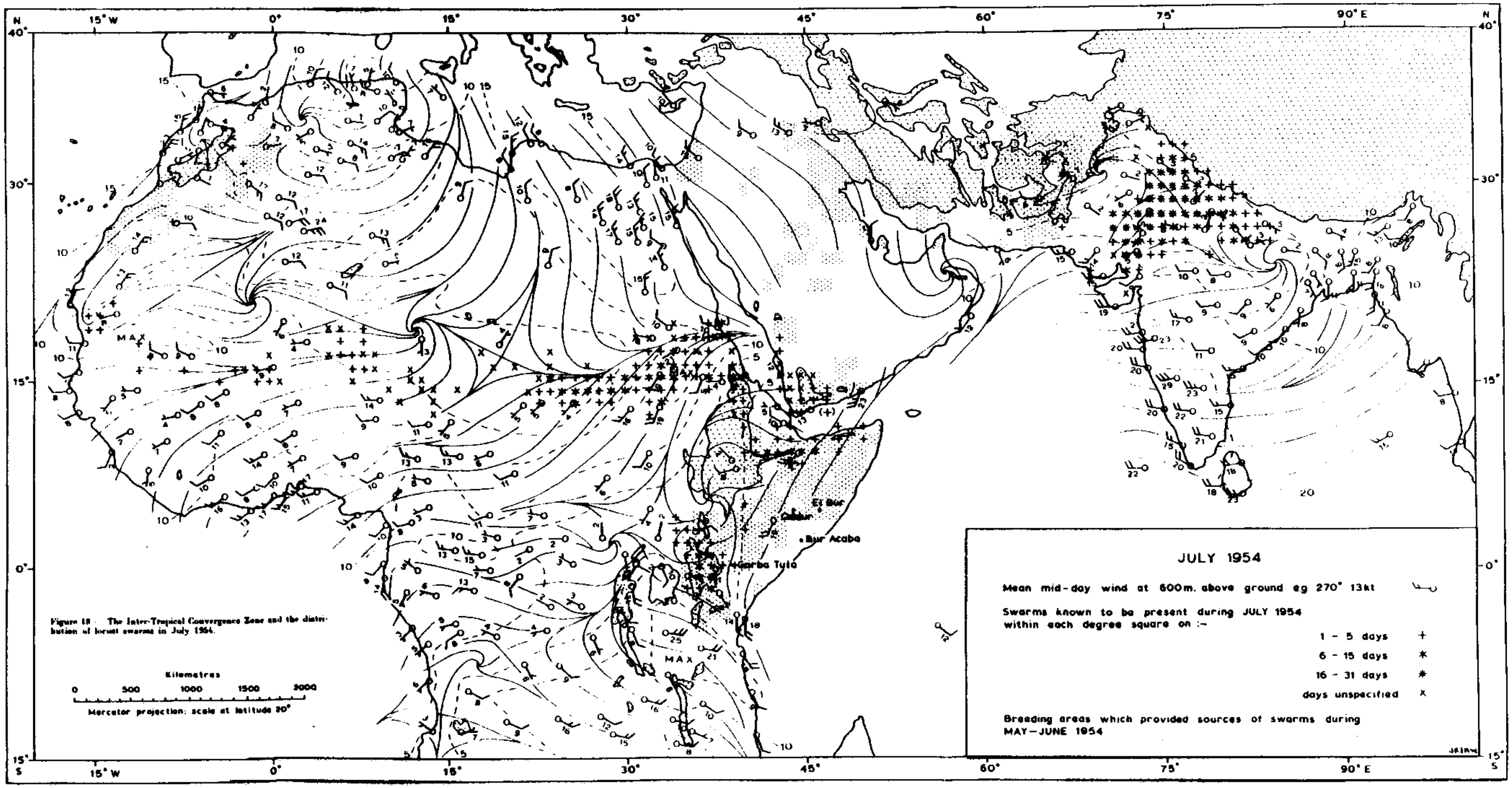


Figure 18 · The Inter-Tropical Convergence Zone and the distribution of locust swarms in July 1954.

within ten days reports of mature swarms increased from a minority to a large majority of the swarm reports from the entire infested area, covering the whole of Rajasthan and extending into East Punjab, Uttar Pradesh [129a] and northern Gujerat. For each of ten rainfall stations in different parts of the desert area of Rajasthan, the first laying in the same *tehsil* (minor administrative unit, of the order of 10^4 km^2), between 9 and 19 July, followed rainfall totalling 23–99 mm within the previous nine days [67].

Swarms continued to lay in Rajasthan and the neighbouring Indian states together with the adjacent parts of Pakistan (Hyderabad, Khairpur, Bahawalpur, Multan and Lahore), until early November, without any indication of significant movement out of the area before late September, a degree of relative immobilization which was of major practical importance. Thus 1954 was a year of heavy locust damage both in India and Pakistan ; crop-losses to a value officially estimated at more than a million dollars were recorded in each of the two countries [27]. During most of July the area was just within the northern fringe of the SW monsoon (Figure 18). The vectorial mean winds for the month at 600 m above the ground over Rajasthan were from 220° to 290°, but only of 2–7 kt, as compared with corresponding values of 220°–270° 14–21 kt further up-wind, along the coast from Karachi to Bombay, demonstrating marked low-level convergence of the mean speed field. Moreover, the corresponding mean winds over Punjab and Uttar Pradesh were all light easterlies (020°–140° 2–5 kt), representing the fringe of the "Bay Monsoon", with particularly marked low-level convergence at the meeting of easterlies and westerlies along the "Ganges trough". The daily charts show oscillations of the boundary between easterlies and westerlies across much of the area occupied by the swarms. Thus the wind-field was such as could be expected to result in the observed accumulation and relative immobilization of the swarms.

During August, the mean low-level wind-field continued to show speed convergence within the south-westerly and westerly monsoon flow over the Rajasthan area, but confluence was less striking than in July, with the corresponding mean winds over Punjab now from the north-west, though still from the east in parts of Uttar Pradesh, and the "Bay Monsoon" was still active at times, as on 6 August, when easterlies and south-easterlies extended over much of Rajasthan. Moreover, throughout August swarms were almost entirely mature, with widespread and almost continuous laying, so that a corresponding reduction of flight activity may also have contributed to the relative immobilization of the swarms.

Until late September, there was little change in the overall area of infestation in India and Pakistan, apart from a clearance of most of Punjab and Uttar Pradesh associated with a re-establishment of easterlies in this area.

An association between the Inter-Tropical Convergence Zone and the distribution of locusts in Pakistan and India was noted in September 1952 [123a].

3.2.2.2 *Southern borders of the Sahara*

In west Africa, as in India and Pakistan, swarms continued to move during early July from the spring breeding-areas towards the Inter-Tropical Convergence Zone. Thus at the beginning of July young swarms were again reported in southern Mauritania, on the 1st at Tamchakett, close to a wind-change between north-north-easterly and south-south-westerly winds, and on the 2nd at Kiffa, with surface north-westerlies. Evidence of a very close association of swarms with the ITCZ in this area and season was provided by the field observations of the FAO/UNESCO Desert Locust Ecological Survey five years later [30]. In particular, the first swarm to be encountered, at Tamchakett, after more than two months in the field in Mauritania and Senegal, was seen on the day (18 July 1959) in which the party reached the ITCZ, indicated by the wind veering from westerly 15 kt to easterly 5 kt during the afternoon, with a corresponding fall in dew point from 15° to 10°, a rise in air temperature from 38° to 43°, and deterioration in visibility due to haze, noted as accompanying change of wind at 1400. The swarm was recorded at 1700 in easterlies, and left the area in southerlies which set in abruptly at 1840 and continued into the night.

Young swarms continued to be reported in source-areas in Morocco in July 1954 on the 3rd, 5th, and, for the last time, on the 6th, on which date a young swarm was also reported in southern Spanish Sahara, in north-easterlies, with other swarms further to the south-west, near the Mauritanian coast, in south-westerlies but close to the previous day's position of the ITCZ, as shown by differences of winds, temperature and humidity between Atar and Akjoujt. Two days later, with a southward movement of the ITCZ, north-easterly winds were established at both stations (with temperatures of 40° and dew points of 9° to 10°), and a young swarm appeared near the latter station. Next day (9 July), a number of young swarms were reported in the Nema area, in south-eastern Mauritania, with westerly and north-westerly winds. On 11 July a further young swarm was reported at Lahouetat, in central Mauritania, close to an indraught vortex, and following a north-westerly and northerly wind-flow from the direction of Morocco. The last locust report of the season from north-west Africa was of a young swarm on 15 July near Tindouf, in western Sahara, with easterly winds.

While the 5,000 km stretch of the Inter-Tropical Convergence Zone, from Mauritania to the Sudan/Ethiopia border, which had first been reached by swarms in mid-May, remained largely occupied from early June onwards, individual swarms could still show considerable movement within this belt, e.g. at 100 km per day eastwards across northern Kordofan in early July (p. 23) ; and other years have provided evidence that swarms from western Africa could extend at this season as far eastwards as the Sudan and occasionally Eritrea [19, 147]. In 1954 reports of young swarms continued to predominate until early July along the ITCZ in Africa, as in India, without evidence of their beginning to mature ; but from 9 July onwards, and following the onset of relatively widespread and heavy rains, there was an increasing predominance of reports of mature swarms. Thus there were no further reports of young swarms in the west after 19 July, in Mauritania, nor in the Sudan, between 23 and 31 July. Egg-laying began in the Western Province of Eritrea following heavy rains, on 8/9 July, and at about the same time near the massif of Termet in Niger. Laying extended rapidly westwards across the Sudan, where it was first reported on 11 July, near the Eritrean border north of Kassala, and then in Northern Province from the 14th, Blue Nile from the 17th, Kordofan from the 19th and Darfur from the 24th. The swarms were within predominantly south-westerly winds throughout this period, so that this staggered onset of egg-laying in the Sudan is probably to be interpreted in terms of a corresponding staggering of maturation, rather than as evidence of any westward movement of the laying swarms. At Shendi in Northern Province, the first egg-laying, on 17 July, followed rainfall totalling 38–66 mm over the preceding nine days at two neighbouring rainfall stations ; and the first laying near Khartoum, on 26 July, followed rainfall totalling 17–65 mm over the previous 22 days at three stations in the same degree-square. The period of most widespread egg-laying, like that of the onset of maturation, showed remarkable synchronization between the Sudan and India ; in both countries the four days 24–27 July showed a very marked peak in the number of degree-squares reporting egg-laying — perhaps attributable to a corresponding synchronization in the onset of the rain and in associated ecological factors, as yet unknown, concerned in the onset of maturation. For the invasion area as a whole, egg-laying during pentade 25–29 July, in 80 degree-squares (say 9×10^5 km^2), was much more widespread than during any other part of the study-period (the next highest peak, in early May 1955, reaching only 52 degree-squares).

In contrast e.g. with 20 July, when the surface ITCZ was further south than it had been for some time, with northerlies down to south of 13°N, the Zone moved well to the north towards the end of the month. Thus on 30 July there were south-westerly winds up to 20°N right across Africa, southerlies at Wadi Halfa, and (with a corresponding northward movement of the rain-belt) 37 mm rain at Atbara, with laying in the vicinity on 1 August. On 31 July the south-westerly flow was maintained up to Wadi Halfa, with south-south-easterlies at Kassala and SE-E winds over northern Ethiopia, where further young swarms had been reported in late July ; and from 1 to 14 August there was a temporary reappearance of young swarms in Northern and Kassala Provinces. With continuing egg-laying in these provinces, these swarms also may perhaps be presumed to have matured and laid in their turn. During 5–8 August widespread laying was recorded in Mali, in western Adrar des Iforas, following 4–95 mm rain at five stations in this area on the 4th. On the 8th, there was an extensive re-establishment of northerlies, and laying occurred at about this time in many other areas of Mali and Niger, extending also into northern Nigeria. In Chad, laying was recorded on 24 August in Ennedi, following rain in this area on the 18th.

The association between the overall distribution of swarms and the Inter-Tropical Convergence Zone across Africa is illustrated by Figure 18, showing swarm distribution and the mean low-level wind-field for July. From Mauritania across Mali, Niger and Chad to the Sudan, the northern limit of recorded swarms corresponds very closely with that of south-westerly mean winds ; and the N-S width of the belt within which swarms were recorded during the month, ranging from 2 to 6 degrees of latitude in different territories, is consistently less than the corresponding range of daily positions of the surface ITCZ. This general wind-field, and the corresponding swarm-distribution, were maintained throughout August into early September.

The association between the distribution of swarms and the Inter-Tropical Convergence Zone had first been noted in July 1950, when it was shown that between the 12th and 31st (while the ITCZ remained relatively stationary) "practically all recorded swarms ... from Chad in the west, through the Sudan, Ethiopia, Yemen, the Somalilands, the Aden Protectorates and Pakistan to northern India ... were between the position of the air mass boundary at the surface (the Inter-Tropical Front) and the southern limit of the over-running upper northerlies (the 'limit of deep monsoon air' or 'nose of the Inter-Tropical Front'), which at this season is usually closer to the main zone of precipitation than is the surface Inter-Tropical Front [118, 119, 129]. During this particular season (1950), both the Inter-Tropical Convergence Zone and locust breeding were incidentally recorded as extending considerably farther north than usual in the Sudan, and the ITCZ was probably also farther north than usual over Arabia" [92].

3.2.2.3 *Eastern Africa*

In eastern Africa, following breeding on the First ("Long" or "Gu") Rains, young swarms continued to appear in source-areas in Tanganyika and in the Southern Region of the Somali Republic until late June, in other source-areas in the Ogaden (Ethiopia) and in the Northern Region of the Somali Republic until mid-July, and in others in Kenya until the beginning of August. Throughout July, August and September, swarms continued to accumulate and to remain grouped in two areas, in the highlands bordering the Rift Valley in Kenya (and at times in the adjoining areas of Uganda and Tanganyika), and across the northern Somali peninsula. The erratic movements of such swarms, with little effective displacement despite considerable flight activity, have already been illustrated (Figure 16, showing the erratic movements of a swarm in Samburu in July 1954), with an indication of the manner in which complexities of the corresponding wind-field, as well as the rugged terrain, are likely to have been involved.

In neither of these areas, around the East African Rift and across the Somali peninsula, are the data sufficient to establish in any detail either the movements of an adequate sample of all the swarms involved, or the corresponding wind-field. In East Africa, however, the area concerned is one in which easterly and westerly wind-currents, probably respectively of southern Indian Ocean and southern Atlantic origin, often meet at this season (References [13, 34, 69] and Figures 16 and 18). Across the northern Somali peninsula, while the few upper-wind observations available may suggest a uniformly south-westerly flow over much of the area, mean winds were north-westerly at Djibouti in July and at Assab in August. Furthermore, fuller meteorological observations available for this season in earlier years have established the regular development of an afternoon sea-breeze from a northerly quarter both at Berbera and Bosaso (Bender Cassim) though apparently not at Djibouti ; and detailed studies of locust records and meteorological data for 1943–47 have shown that swarms landing on the coasts of the Somali peninsula during the summer are probably mainly of local origin, swept out to sea by the SW monsoon and subsequently brought in again by the sea-breeze [9, 104]. Field-studies of swarms in the interior of the Somali peninsula during August and September in 1952 [142], and in the course of control work during 1953 [120, 123], 1955 [64], 1957 [61], and 1960 [49, 123] have not only shown how locusts remained settled throughout the part of the day during which the south-westerlies were strongest, i.e. during the morning, but have also recorded northerly wind components well inland, particularly in the afternoons, and probably associated with an anabatic flow over the abrupt north-facing escarpment, along whose crest the swarms were repeatedly to be found.

It may accordingly be suggested that the quasi-static swarm distribution observed during July, August and September in these two areas of eastern Africa may at least in part have been attributable, as elsewhere, to the corresponding wind-fields, with local anabatic circulations associated with the rugged topography of these areas (p. 52, etc.) superimposed upon, and often significantly modifying, the general wind-fields exhibited on the scale of normal synoptic analysis.

Thus, from mid-July until late September, there was, throughout the infested area, a complete absence of long-range swarm displacements, i.e. of movements on a scale of more than a few hundred kilometres ; the only appreciable displacements during this period appear to have been the inferred movement of the last Afghanistan swarms into Pakistan, the southerly surge into Bornu province of Nigeria, and the northerly movements at the end of July and the beginning of August, into the Northern Province of the Sudan and, at almost the same time, into Turkana from north-central Kenya. This last movement appears to have begun with southerlies and rain in southern Turkana on the 1st, followed by 36 mm of rain at Lodwar on the 3rd ; and widespread laying began during 4–6 August, almost simultaneously in Lodwar, Maralal (where the swarm of Figure 16 probably bred) and Isiolo districts.

The relatively limited scale of the swarm displacements during this period (in contrast with those recorded during May and June and again in October and November) was illustrated by an almost identical overall distribution of swarms in mid-July and in mid-September, differing by little more than a slight south-westerly shift of the centre of gravity of the infestations in India and Pakistan, with East Punjab and Uttar Pradesh having become largely clear, while swarms had spread into Kutch and Sind.

This period of quasi-static swarm distribution, exhibited in one or more of these areas during nineteen of the past twenty years, is of considerable significance in relation both to the incidence of damage and to the strategy of control operations. Concerning damage, brief reference has already been made to India and Pakistan. In eastern Africa, damage was officially reported during late June and July to wheat and other crops at a number of points in Nakuru and Laikipia districts of Kenya [53], to maize and millets in Karamoja districts in north-eastern Uganda [74], to lucerne near Mara in northern Tanganyika, and at about this time in the northern Somali peninsula, near Au Barre on the Ethiopian/Somali border. In August further damage was recorded in Kenya in Fort Hall district during the passage of swarms probably resulting from the last of the "Long Rains" breeding in the Isiolo area.

Concerning control strategy [28, 29] : in addition to ground control operations against the hoppers at this season, which in India and Sudan, for example, have long represented the main control effort, the quasi-static distribution of the swarms was beginning to be utilized, in 1954, to facilitate sustained spraying operations by aircraft from appropriately located bases, from which contact could be maintained with the swarms for extended periods. Such operations are illustrated by those in central Kenya between June and October 1954 (e.g. Figure 16, at times restricted by associated weather), in Darfur during June 1955 (e.g. Figure 13 ; References [76, 163]), and in the Northern Region of the Somali Republic during July-September in 1953–60 (p. 75; Plate I).

In the course of these operations in the northern Somali Republic in June–August 1960 [123], swarms were repeatedly found to be within a marked wind-discontinuity, with opposing winds shown by smoke-generators dropped by aircraft at points less than 16 km apart. It was also found that larger swarms were often broken up by the associated high winds and storms, into numbers of smaller swarms connected by thinly scattered locusts, and subsequently re-concentrated into larger swarms again at the wind-discontinuity. These opposing meteorological processes, causing both disintegration and re-concentration of the swarms, could sometimes alternate within a single day; and, under such conditions, individual swarms no longer retained their identity from day to day.

Unlike practically all swarms elsewhere at this season, which mature and breed during July and August, the swarms in the interior of the northern Somali peninsula regularly remain sexually immature until October (p. 78), for reasons which are not understood. Thus air temperatures, though lower in some of these areas of the Somali peninsula than those experienced by the swarms maturing at the same time in the Sudan or India, appear to be fully comparable with those at which maturation is known to occur in other areas and seasons; and although rain is not general at this season, showers and thunderstorms are frequent in the vicinity of the northern Somali watershed, where the swarms are usually to be found. During August and early September 1957, for example, swarms with which contact was being maintained in the Borama-Hargeisa area were repeatedly seen engulfed by the heavy afternoon showers experienced almost daily in this area, with temperatures at Hargeisa giving mean maxima of 31° and mean minima of 17°; but egg-laying by these swarms did not begin until 20 October. The mechanism of the commonly-observed association between rainfall and the sexual maturation of locusts remains an unsolved problem.

3.2.2.4 *Appearance of the next generation*

Young swarms resulting from this widespread breeding in the Inter-Tropical Convergence Zone first appeared in west Niger on 10 August, and in Rajasthan (mixed with mature locusts of the previous generation) on 23 August, and by early September were being reported in numbers. In mid-September new swarms were appearing almost simultaneously along some 4,900 km of the breeding-belt, from Mali, through Niger, Chad, Sudan and Ethiopia, to Yemen and the adjoining areas of Saudi Arabia and of East and West Aden, as well as in north-western Kenya, from source-areas of a total extent which had increased from a minimum in late July and early August (11 to 12 degree-squares, the lowest values so recorded for the entire study period), to a second major maximum in late September (103 degree-squares, exceeded only by that of early June, and almost twice as high as any peak recorded during the remainder of the study-period).

On 14–15 September swarms were reported in the Oman, on the Batina coast, in the vicinity of the ITCZ (with south-westerlies at Masira and on the Makran coast, northerlies at Sharjah, and northerlies and north-easterlies inland in Baluchistan), with alternative and equally possible sources represented by reports of young swarms both in eastern Baluchistan on 13 September, and in a West Aden source-area on 13–15th.

3.2.3 *Autumn re-distribution of swarms: effects of movements of the Inter-Tropical Convergence Zone and of extra-tropical depressions during late September-November 1954*

In late September there were signs of the beginning of the seasonal displacement of the Inter-Tropical Convergence Zone, in the retreat of monsoon westerlies followed by corresponding extensions of easterlies and, at times, of south-easterlies under the influence of extra-tropical depressions. The first corresponding locust movements were recorded on 24 September when swarms began to appear well outside the source-areas of the ITCZ both in Iran and in Uganda. Thus it was reported that in Iran "locust attacks began" on this date, probably representing a first movement out of northern India and West Pakistan, where easterlies had become widespread during the past few days, ahead of a disturbance with which a rainfall of 415 mm was recorded in 17½ hours at Lahore on the 24/25th. On the same day, swarms arrived in north-eastern Uganda, during a relatively dry spell of easterly winds which had persisted since the first reported appearance of young swarms in Turkana, away to the east in Kenya, six days previously ; and further reports of swarms followed in eastern Uganda, with crop-damage by locusts in Teso district recorded on the 29th. A roughly comparable movement had been shown in 1945 by a swarm followed with the help of aircraft in a neighbouring area of Kenya [40] ; between late August and mid-September this swarm had made good a gradual north-westward displacement of some 90 km across northern Laikipia district, in predominantly south-easterly winds.

On 25 September 1954 (the day after the first Iran and Uganda reports) the first young swarm was recorded just into southern Sahara, with south-easterly winds from the extensive source-areas of western Niger, together with reports of mature swarms (probably remnants of the parent generation) further into Sahara, in the Ahaggar area. The same day (25th) the first young swarm was reported in southern Spanish Sahara, following a two to three day spell of easterly winds further to the east, from the direction of the source-areas of Mali ; and, with continuing easterlies, swarms reached the adjoining coastal areas of Mauritania from the 27th, when a young swarm was in fact seen in flight 4 km off shore. A mature swarm was seen next day in the same region ; mature locusts were also recorded at Boa Vista in the Cape Verde Islands during September, possibly derived from swarms which had laid in Mauretania during August.

There were more reports of mature swarms with south-easterly winds in Sahara on 28–30 September, around the Ahaggar, and again on 2 October, reaching Tidikelt. On 3 October further swarms were reported in southern Spanish Sahara, again with south-easterlies, as well as in adjoining parts of Mauritania, where local source-areas may also have been coming into production and where several swarms were reported by aircraft at a height of 2,000 m between Port Etienne, Atar and Akjoujt ; scattered locusts were recorded in the Canary Islands on the same day.

3.2.3.1 *Swarm movements associated with seasonal movements of the Inter-Tropical Convergence Zone in Africa and western Arabia*

Between 26 September and 3 October, the appearance of young swarms was reported to the south and south-west of source-areas in Niger, Chad and the Sudan, accompanying and following spells of northerly and north-easterly winds, representing southward surges of the ITCZ and presaging its seasonal displacement. Between 7 and 13 October there were reports, from four widely separated areas in Africa (as well as one in India — p. 86), of swarm movements associated with the major seasonal displacements of the ITCZ and of associated semi-permanent synoptic features. Thus on 7 October there were the first reports since August of swarms in Tanganyika, with the establishment of east-north-easterlies from the infested areas of the Kenya highlands. All swarms in the Somali peninsula were still north of 8°N — their southern limit in this area since the end of August — but next day (8th), with northerlies at Hargeisa and the first north-easterly of the month at Gardo, there was evidence of a general move to the south, with swarms entering the neighbouring Ogaden province of Ethiopia south of 8° along a front of 200 km, and reaching the Danot and Marcanuein areas. On the 9th a swarm was reported further into Tanganyika, to the south of Lake Victoria, with east-south-easterlies ; and on the same day swarms were reported reaching north-eastern Nigeria, with a temporary incursion of northerly and north-westerly winds, from the adjoining infested area of Niger, associated with the development in the ITCZ of an indraught vortex centred over southern Chad. West of 10°E, the ITCZ temporarily disappeared under the influence of particularly vigorous extra-tropical depressions, considered in the following section. Beyond the influence of these Atlantic and Mediterranean disturbances, the ITCZ, between drier north-easterlies and humid south-westerlies, remained recognizable east of about 10°E throughout this period, and a swarm was again reported in its vicinity near Zinder in southern Niger on 17 October.

On the Somali peninsula, meanwhile, young swarms were reported to the south-west of a Danakil source with north-east and north-north-east winds at Hargeisa on the 10th and 11th. The southward movement continued, with swarms reported on the 12th as far south as the vicinity of Belet Uen, where a NNW surface wind was recorded, with the beginning of the Second or "Der" Rains represented by considerable precipitation ahead of the surface ITCZ (63 mm at Oddur and 28 mm at Bur Acaba), in a position to provide soil conditions suitable for egg-laying by the advancing swarms. The fourth area in Africa involved in these developing seasonal movements of the ITCZ and associated semi-permanent synoptic features was western Uganda, where swarms appeared in West Nile district on the 13th, in and following an incursion of easterly winds with corresponding retreat of the "Congo westerlies".

On 14 October the further southward advance of the ITCZ across the Somali peninsula was marked by wind-shifts from SW to E at Mandera in Kenya, and to N at Bulo Burti in Somalia with 56 mm rain, and there was the first of numerous reports of mature swarms in the Somali peninsula, while next day (15th), a swarm reached the El Carre area of southern Ethiopia, some 200 km north of Mandera. Away to the south-west, swarms reached Burundi on the 16th ; these swarms, which were in all probability the ones which had begun to move into Tanganyika from Kenya a week or so previously, continued to be reported in Burundi, in the vicinity of the "Congo air boundary" between drier easterlies and more humid westerlies, until 22 October. In Somalia, Bulo Burti was reached on the 18th by a partly-mature swarm, while on the 20th north-easterly winds were first established at Belet Uen and El Bur, and a mature swarm reached the Oddur area, which had had heavy rain eight days previously ; next day (21st) the first swarm was reported in Bardera district, with weather recorded as calm.

The onset of this southward movement of swarms across the Somali peninsula, with the seasonal displacement of the ITCZ, coincided with a temporary disappearance of young swarms from the northern side of the Danakil source-area in north-eastern Ethiopia, where no swarm was reported in the immediately adjoining Red Sea coastal areas between 9 and 24 October (though fledglings and young swarms were appearing in Yemen and northern Ethiopia sources). The Danakil source therefore may well have provided the young swarms recorded on the western flank of the southward movement across the Ogaden, while the probably older swarms in the centre and on the eastern flank of this movement (in all probability including those which had remained in the northern Somali peninsula for up to four months previously) were showing rapid maturation. On 23 and 24 October marked divergence in the Danakil area was indicated by north-easterlies at Hargeisa with south-easterlies at Djibouti, and, over the Red Sea, no longer to be regarded as under the influence of the ITCZ, south-easterlies extended on the 23rd up to the latitude of Qunfida, where young swarms appeared on the 24th, with corresponding potential sources on both sides of the southern Red Sea. The beginning of laying was recorded in the Ogaden on the same day (24th), and occurred at about the same time in adjoining regions of the Somali Republic ; and on the 26th mature swarms reached Mandera and Wajir districts of north-east Kenya. In 1950, when Kenya, then otherwise clear, had been similarly invaded by swarms from the Somali peninsula (also at Mandera, and on the same date, 26 October), it was first noted [92] that the beginning of this movement of swarms across the Somali peninsula, in September, and the arrival of the first swarm in Kenya, 800 km away and a month later, had both taken place within a day of the passage of the Inter-Tropical Front across the area concerned, defined as the date after which northerly to easterly winds were established at the surface for the greater part of each day. Swarms have similarly appeared in Mandera district between 6 October and 11 November in fourteen of the past twenty years (in half of these years between 20 October and 1 November, with 27 October as the median date) ; in five of these years (including 1950) Kenya, Uganda and Tanganyika had previously been clear.

On 26 October 1954, the date on which mature swarms reached Kenya, the first mature swarms to be recorded on the eastern side of the Red Sea basin for nearly a month were reported at a number of points near the Saudi-Yemen border, and on the 30th there was the first report of a mature swarm on the African side for three weeks, at Tokar, with south-easterlies and east-south-easterlies at sea up to this latitude, and inferred egg-laying. This area around the central Red Sea remained continuously infested by swarms throughout the next three months, and exhibited characteristically opposing north-westerly and south-easterly low-level wind-currents, with precipitation under the additional influence of extra-tropical depressions passing further to the north (pp. 30, 89).

On 1 November south-easterlies were recorded over the Red Sea up to 20°N, and young swarms, in all probability from sources in eastern Ethiopia, reached the extreme north-eastern Sudan; on the 3rd some south-easterlies were recorded as far as 25°N, with scattered mature locusts seen at sea at 21°, about the latitude of Jeddah. The next day (4th), with south-easterlies up to 23°N at sea, further young swarms were reported on the Sudan coast between 20° and 22°; and on the 5th, with south-easterlies still up to at least 23° at sea, young swarms reached 21° on the Arabian side, at Mecca, on the third day of a spell of southerly winds recorded in the Jeddah area. Meanwhile, somewhat further eastwards, young swarms had been appearing around new source-areas in southern Arabia, in West Aden since 28 October and in the Hadhramaut since 1 November, and further young swarms continued to be reported in both these areas until 6 November. Throughout this nine-day period a marked predominance of southerly winds was also recorded over northern Arabia, at times reaching Bahrein on the Persian Gulf, and associated with the passage of disturbances across Iraq, with precipitation; and on 8 November the first swarm to be recorded anywhere in north-central Arabia since May was reported at Buraida. Next day (9th), south-westerlies were again recorded at Bahrein, as well as south-south-westerlies at Kameran; and on the 10th there was a further report of a swarm near Buraida. While observations of weather and of locusts were both lacking from much of central Arabia, it is considered that the meteorological observations around the perimeter of this area in early November were such as to establish, with reasonable probability, the existence of a general southerly flow across Arabia over this period, and accordingly to suggest that the Buraida reports are most probably to be attributed to swarms from the southern Arabian source-areas.

Thus the older swarms, which had remained in the northern Somali peninsula during the summer months, had moved southwards with the ITCZ towards Kenya and Tanganyika, together with the earlier of the young swarms bred on the rains of the ITCZ in north-eastern Ethiopia. The later swarms produced in this latter area, however, together with young swarms from corresponding sources in southern Arabia, appear to have been formed only after these areas were no longer under the influence of the ITCZ, and by early November had accordingly become distributed between the newly-established seasonal convergence zone in the central Red Sea area, and northern Arabia, reached under the influence of disturbances passing over Iraq and the Persian Gulf.

In Kenya, meanwhile, swarms produced in Samburu in early October (and probably including the progeny of the swarm of Figure 16) moved southwards from Isiolo and across Meru (where damage to African smallholdings was reported) and Machakos districts of south-central Kenya during a spell of northerly winds in mid-October. These swarms were usually reported as "partly mature", probably representing some admixture of mature locusts surviving from the parent generation, of which swarms had still been present in the breeding-area up to 29 September; and, in the absence of reports of laying in Kenya or Tanganyika (implying in turn absence of conditions for maturation), such swarms may conveniently be distinguished both from the fully-mature swarms which began to reach Kenya later in the month, after having matured from mid-October onwards in central Somalia and the adjoining parts of the Ogaden; and, with rather less certainty, from completely immature swarms such as appear to have begun to reach Kenya by the end of October from the Danakil source. Following a spell of south-easterly winds across southern and central Kenya around 25 October, the ex-Samburu swarms appear to have moved out of this area, and may well have accounted for those which began to be recorded away to the north-west, around Kitale, particularly from 25 October onwards, with reports of considerable damage to wheat in Uasin Gishu and of damage to maize in Trans-Nzoia [53], at the same time as the mature swarms from the Somali peninsula were reaching the eastern border of Kenya.

Following a report of a partly-mature swarm in northern Uganda on 24 October, further young swarms were recorded in south-eastern Uganda, not far from Kitale, from the 29th onward, and during November again under notably dry conditions, Uganda experienced its biggest influx of swarms for some years [74]; some were immature and some partly-mature. On 5 November, with the establishment of a particularly uniform easterly wind-flow, swarms extended into central Uganda, where on 6–9th heavy damage to food-crops and damage to cotton were reported in Lango district. During 12–14 November swarms extended north-westwards, to reach the Uganda-Congo and Uganda-Sudan borders, with an extension of south-easterly winds, and followed by reports of considerable damage to finger-millet, pigeon-peas and simsim in this area (West Nile district) on the 14th and 15th. Swarms were recorded further to the west in the Congo on 17 November, and crop-damage, described as slight, was reported in Bunyoro district of Uganda on the 18th. With a return of wetter conditions, at the end of November, the locusts were subsequently reported to have disappeared abruptly from Uganda in early December [74].

Meanwhile, as already mentioned, mature swarms, from central Somalia and the Ogaden, had arrived in the Mandera and Wajir districts of the north-eastern Kenya lowlands on 26 October; and, with generally easterly to northerly winds in northern and central Kenya, mature swarms were also reported on the 29th and 30th reaching several widely separated areas of the highlands of Kenya (near Nanyuki and Eldoret) and northern Tanganyika (Ol Moloc). Swarms, mature or of unrecorded maturity, were subsequently reported reaching the Taveta area of northern Tanganyika on 2 November, and then, following a disturbance marked by north-westerlies at Voi on the 3rd, and rain at Amani on the 4th, and the subsequent establishment of a well-marked north-easterly flow across the highlands of Kenya and Tanganyika, reached Gonja in the Pare mountains on the 5th, with damage to maize, and finally Handeni district, to the south of the Pare and Usambara mountains, on 7 November. This was a penetration unusually far south into Tanganyika for this time of year, apparently attributable to the disturbance mentioned, and followed by a westward movement of the mature swarms, with the usual easterlies of the area, into central Tanganyika. The subsequent breeding by these swarms, in central Tanganyika from early December onwards (instead of in central Somalia/Ogaden during October-November, as in most other years), was an unusual development, last paralleled in 1945, which provided a series of major problems in the organization of control measures in this particular season [18].

The initial invasion of Kenya and Tanganyika from the Somali peninsula in late October was thus of swarms which had already matured. In addition, young swarms were reported, initially in Garissa district on 27 October, with east-north-east winds after at least a week of winds from between east and south-east, and accordingly most unlikely to have come from Samburu or Turkana. Young swarms had previously been reported in south-eastern Ethiopia, at Danan on 23 October and at Dolo near the Somalia-Kenya border on the 25th, and had in all probability originated from the Danakil source, which is accordingly suggested as the most likely origin for this Garissa swarm and for other similar swarms in the same district until the 30th (on 2 November a mature swarm was reported as damaging riverine cultivations along the Tana). There were subsequent reports of immature swarms on 31 October, near Kitui; on 12 November near Arusha, following north-easterlies, and on 15, 19, and finally 23 November in the Kondoa-Singida area of central Tanganyika, where they may well have matured and participated in the subsequent heavy breeding in early December. In Kenya heavy rains in late November and early December caused flooding and closed roads in parts of the Northern Frontier province, where the first recorded egg-laying in the Garba Tula area, for example, on 27 November, followed a total of 110 mm of rain over the preceding 13 days.

Meanwhile, away to the west, young swarms were recorded on 4 November in Chad, to the south-west of a new source-area near Tibesti and in north-easterly winds; and, on 5 November, swarms were reported in Bauchi province of eastern Nigeria, still in the vicinity of the ITCZ, between east-north-easterly winds characterized by dew points of 5° to 12° and west-south-westerlies with dew points of

14° to 23°. Swarms were again reported in late November in this area, apparently beyond the range of the Atlantic and Mediterranean disturbances considered in the following section, and the only part of western Africa to provide such evidence of a continuing association between swarm-distribution and the ITCZ throughout the autumn and early winter.

3.2.3.2 *Swarm movements from the southern Sahara to the Atlantic and the Mediterranean under the influence of extra-tropical disturbances*

In western and north-western Africa during this period, there had been a major movement of swarms, out of the region previously dominated by the ITCZ, under the influence of extra-tropical depressions and associated barometric disturbances. Thus on 10–11 October young swarms appeared at several points well into Sahara, around the Ahaggar, during a spell of southerly to south-westerly winds from the infested areas of Mali and Niger, associated with the passage of an active depression across Tunisia and Tripolitania. Also on the 11th, swarms were reported in Spanish Sahara as far north as the Tropic, with east-south-easterly winds. For the next six days (12–17 October), associated with a very active depression over the Atlantic, centred near the Azores on the 16th with a pressure of 975 mb and winds of force 8–9 (much the most vigorous depression of the entire study-period in this area), south-easterly winds were established over Spanish Sahara, northern Mauritania, western Sahara, and, during the first two days much of Mali and Niger as well, with a temporary disappearance of the usual ITCZ structure in this region. With these south-easterlies the first swarms reached northern Spanish Sahara on 13 October, at Cape Bojador, and the Canary Islands on the 14th, with an invasion in strength on the 15th, when locusts were seen at sea, still with winds from between east and south, between a position 100 km off the coast of southern Spanish Sahara, near the Tropic and 500 km south of the Canaries, up to the latitude of Tangier, some 700 km to the north of the islands ; this invasion of the Canaries was described as the heaviest since 1932, and damage to tomato, banana and other crops was recorded. Next day (16th) there was the first report of a swarm in Morocco, on the coast at Essaouira with a locally west wind ; and, with a southerly airstream extending from the area of the Canaries right up to the quasi-stationary and very active Polar Front over the British Isles (where the London "Times" recorded the "worst rainstorm within living memory" in southern Scotland), scattered locusts reached the Isles of Scilly and the south coast of Ireland on the 17th.

These were the first Desert Locusts to reach the British Isles since 1869, and, while of course of no practical significance, the mechanism of such an exceptional move is of considerable theoretical interest. We are accordingly greatly indebted to Mr. G. A. Corby, of the Meteorological Office, Dunstable, for trajectories of the air in which they are likely to have arrived (Figure 19). The first such trajectory, drawn for geostrophic winds at 300–600 m, led back out into the Atlantic ; but the second, drawn by backing the geostrophic winds given by the M.S.L. isobars through 10° and reducing their speed by 10 per cent and therefore appropriate to a height of the order of 100 m, passed at the appropriate time within 130 km of a position at which flying locusts were seen at sea in the latitude of Gibraltar, and led back to the vicinity of the Canaries on the night of 14/15th, i.e. at the time of the main invasion of the islands. This quite exceptional locust movement, resulting in an enormous destruction of locusts at sea — such as has been familiar elsewhere since the beginnings of history [11] — would therefore appear to have been produced by down-wind displacement towards a zone of active convergence — essentially the same mechanism as that postulated for the more usual swarm movements (p. 29) with their positive value for the continued existence of the species. Floating locusts were seen at sea on the 17th as far north as a position some 300 km west of Cape St. Vincent, but no locusts were reported reaching Portugal at the time, as they had done in somewhat similar circumstances in October 1945 [140] ; on this 1954 occasion, there were offshore winds along the Portuguese coast.

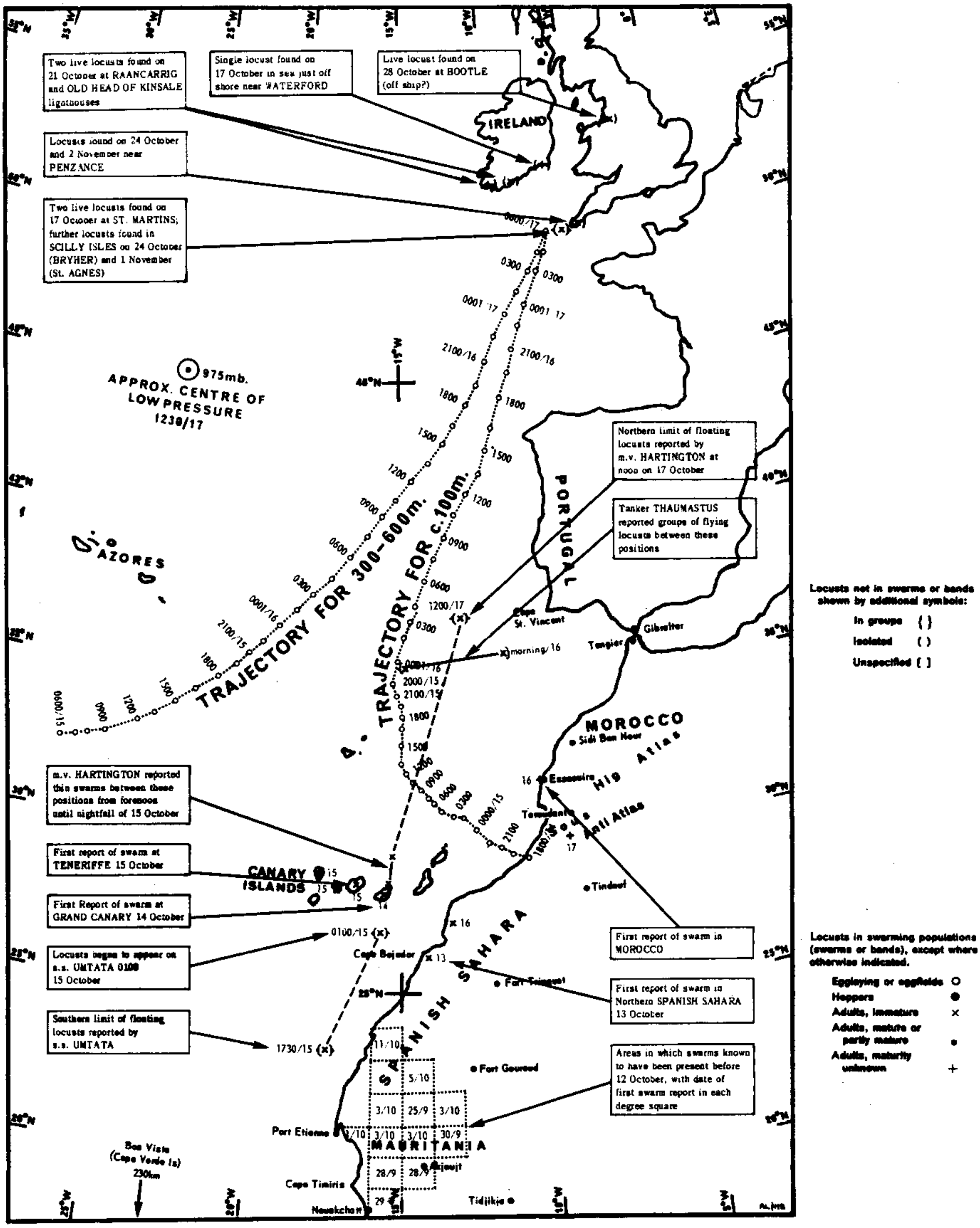


Figure 19 — Desert Locusts over the Atlantic : October 1954.

Despite this massive emigration, further young swarms continued to be reported during this period in the vicinity of source-areas in Mauritania, Mali, Niger and Chad, as well as in Fezzan (with easterlies and probably from Sudan and/or Chad sources), and in the major "transit area" of southern Sahara, where young swarms were recorded almost continuously in the Ahaggar until the second week of November.

By 18 October winds over Spanish Sahara and southern Morocco had backed to east-north-east, after the south-easterly spell, and on the 19th an offshore east-north-easterly was well established over this coast. The next day (20th), a swarm was reported at Gibraltar, with westerlies further seawards, while winds over southern Sahara veered to easterly and south-easterly. On 21 October swarms were reported at Tindouf and Fort Trinquet ; on the 22nd the western half of the Sous valley was reported as virtually carpeted by invading locusts, while others were seen at sea 600 km off Cape Timiris. On 23 October, further swarms appeared in Spanish Sahara, after six days' easterlies from southern Sahara, where young swarms were continuing to be reported. Next day (24th), with southerlies at Tindouf, in western Sahara, there were further reports of swarms in this area and in the adjoining parts of southern Morocco, as well as in Spanish Sahara and northern Mauritania (reported as "destroying all vegetation for more than 100 km") ; and on the 25th the invasion of Morocco continued with further southerlies and south-easterlies over western Sahara. A possibly associated disturbance in the western Mediterranean on 25/26 October gave a rainfall of 500 mm in 15 hours over an area of 100 km^2 near Salerno, the heaviest rainfall on record in Italy, with much damage and loss of life [149]. There were offshore winds over northern Spanish Sahara on the 25th ; and next day (26th), a mature swarm was recorded at Gibraltar, with westerlies.

During 23–28th there were still young swarms in Sudan and Chad, and during 26–28th south-easterlies again at Tamanrasset, in southern Sahara, with more reports of young swarms from 28th onwards, indicating that Sahara was continuing to receive further young swarms, probably of Chad and Sudan origin, at the same time as the main invasion of Morocco was already in progress. Young swarms continued to be reported in Mauritania almost daily until 5 November, including appearance in a new source-area east of Nouakchott as well as others reported in the north, around Fort Trinquet, with winds from between south and east, and in all probability also in transit to Morocco. Thus on 31 October there were still southerly winds into Morocco, while on 1 and 2 November further young swarms were reported around Tamanrasset, with easterlies, and again on the 3rd, with north-easterlies, at the same time as swarms were reported to the north-west of Tamanrasset in south-easterlies. Meanwhile on the 3rd, swarms extended northwards within Morocco, in further southerlies ; next day (4th) a swarm was reported near Tangier, with generally south-easterly winds associated with a deep depression centred near Madeira ; and, with south-westerly winds in Mauritania the following day (5th) further swarms were reported, to the north-east of the source-area. On the 6th, swarms were reported in easterly to north-easterly winds near Bidon Cinq, in Sahara west of Tamanrasset, where further young swarms were continuing to be reported daily.

During 6, 7 and 8 November the infested area recorded in Morocco was at a minimum, probably representing the end of the main invasion, though this area remained continuously infested by swarms throughout the following five months, and locust damage on an unprecedented scale was recorded, particularly to crops and orchards in the recently developed irrigated cultivations of the Sous valley. Losses of the order of three million dollars were stated to have occurred here within the first two weeks of the invasion [138], while for the whole season crop-damage in Morocco was officially estimated at thirteen million dollars [*in* 79]. While damage on this scale is exceptional, mention has already been made of the degree of regularity with which Morocco is invaded at this time of year (p. 3). Thus invading swarms have reached Morocco between 28 September and 1 November, with a median date of 16 October, in 16 of the past 22 years. This was, in fact, in every year in which swarms are known to have bred during the preceding summer months in western or equatorial Africa [147].

West-north-westerly winds were recorded in Morocco on 9 November, with a corresponding eastward and southward extension of the relatively restricted area within which swarms had been recorded during the three preceding days. Next day (10th), with a deep depression (< 998 mb) centred near Sicily, west-north-westerly winds were also recorded in southern Sahara, at Tamanrasset, with further reports of young swarms, while others were recorded south of Sebha in the central Fezzan, with strong south-westerly winds, rain at Sebha, and drizzle at Hon. On the 11th, with a north-west wind at Tamanrasset, there was the last swarm to be recorded until the 29th in this area, where young swarms had been reported in this single degree-square (22°N 05°E) on fourteen of the previous twenty-three days. In Libya, winds between south-west and south-east were reported at Kufra during 11–13th and at Hon during 14–15th ; on the 16th further young swarms, recorded as large, were reported at Gatrun in the Fezzan, on the fourth day of a spell of winds from between SSE and SW at Sebha, with south-westerly winds over Cirenaica ; and next day (17th) young swarms were reported in central Cirenaica, at Gialo, and in north-western Egypt at Qara oasis and at Sidi Barrani on the coast, with further south-westerly winds and temperatures of 26° to 29°, and in the vicinity, moreover, of the lowest barometric pressure (1,010 mb at El Adem) recorded at the time anywhere on the southern and eastern coasts of the Mediterranean. This was associated with one of the four most vigorous depressions of the year in the central Mediterranean, with south-south-west winds and temperatures of 22° to 24° at sea to the south and south-east of Crete, contrasting with values of 13° to 19° further to the west, with a westerly gale, showers and a pressure of 1,004 mb to the south-east of Malta.

On 19 November, young swarms had reached Bahariya oasis in central Egypt, following westerly winds the previous day, and others were reported at four points in Fezzan and southern Tripolitania, still in southerly winds. Next day (20th), a further young swarm was reported near Gialo in Cirenaica, now in north-westerlies ; and on the 21st young swarms in Egypt reached the Cairo area with west-north-west winds and as far as Asyut with north-north-westerlies. On the same day (21st), in southern Tripolitania, a young swarm was still reported in the vicinity of Hon, which now had a pressure of 1,024 mb (the highest value anywhere in northern Africa at the time), and an anticyclone, centred just south of Hon, had built up in the rear of the depression, giving easterly winds further to the south, as at Sebha in the Fezzan. On the 22nd, with north-west winds but with temperatures still above 20°, young swarms in Egypt reached the Gulf of Suez, while in the Fezzan, where swarms were again reported in the Sebha area, the wind-field was now markedly divergent, with corresponding 600 m winds at 0900–1000b from 080° at Sebha and from 250° at Hon. On the 23rd a young swarm was reported at Bardia, on the Cirenaican coast near the Egyptian border, with NW wind and rain following the south-westerlies of the previous afternoon, and another at Hon in Tripolitania, while on the opposite side of the anticyclonic cell young swarms were reported near Ghat, on the Fezzan/Sahara border, on the third day of easterlies at Sebha. On the 24th, a swarm appeared at Siwa oasis, near the western border of Egypt, with further north-westerly winds, which veered to north-easterly for the next three days ; and the swarm may accordingly be expected to have returned into Libya.

With the development of the main depression, winds from between south-west and south-east had thus become temporarily established over much of Libya during 11–17th November, and swarms from a wide sector of southern Sahara, perhaps also including northern Niger and Chad (and some probably initially of Sudan origin), had moved northwards and north-eastwards, becoming distributed on 19–20th along some 1,800 km across Fezzan, southern Tripolitania, northern Cirenaica, and into western Egypt. With the subsequent re-establishment of the anticyclonic cell over central Libya in the rear of the cold front, the invasion appears to have become divided into three sections. The advance-guard, experiencing conditions still warm enough for continued flight activity, even behind the cold front, moved through Egypt between the 17th and 23rd and, with the subsequent extension of surface northerlies and north-westerlies over the northern Red Sea down to the latitude of Port Sudan (with thunderstorms and rain both at sea and ashore), may reasonably be expected to have joined the concentration of swarms of eastern Ethiopian and perhaps also southern Arabian origin, which had been established in the central Red Sea convergence zone since late October ; immature swarms (probably newly arrived) were in fact reported on the coast north of Port Sudan on the 24th, two days after further laying in this area. The original rear-guard of the invasion appears to have been cut off by the resumption of easterly winds to the south of the re-established anticyclonic cell, and to have moved back again from Fezzan, perhaps accompanied by further young swarms from a source in north-western Chad, into southern Sahara, where swarms reappeared near In Guezzam on the Sahara/Niger border on 27 November, following northerlies and easterlies. These swarms were perhaps followed back into the Sahara, around the eastern and southern flanks of the anticyclone, by the last of the swarms reported in Tripolitania, near Hon and Braak on the 24th and still in southerlies. The last of the swarms to be recorded in Egypt, at Siwa on 27 November, Bahariya on the 28th and Fayoum on the 30th, were reported during the approach of a further disturbance which gave widespread south-westerlies and precipitation along the Cirenaican and Egyptian coast on 30 November.

An association between the arrival of flying swarms in Egypt and the passage of barometric depressions was first noted during February – June 1915, when seventeen successive depressions recorded by the Physical Service were each attended by a fresh influx of locusts [66]. From further studies during the later locust invasions of Egypt in 1928–30, it was concluded that the approach of a depression was more dangerous in this respect than when it was actually over or north of Egypt [4].

3.2.3.3 *Swarm movements from monsoon breeding areas in India and Pakistan*

In India a cyclonic storm from the Bay of Bengal moved inland on 27 September and travelled north-westwards, as a typical deep monsoon depression [82] centred successively over Hyderabad on the 28th, western Madhya Pradesh on the 29th, and eastern Rajasthan on the 30th (Figure 20), finally weakening and recurving north-eastwards over Uttar Pradesh on 1 and 2 October. Associated with the passage of the depression, swarms moved southwards in Kutch on the 29th, with northerly winds, and other swarms subsequently extended northwards into northern Rajasthan and Punjab again on 1 and 2 October. The associated heavy rains included a record October rainfall of 220 mm in 24 hours in Delhi on the 1st, with floods and loss of life ; and the rains were followed by further widespread egg-laying by the locusts, representing a second generation of monsoon breeding, and a further development of practical significance. An association between the development of such a second generation (which has occurred in 13 of the past 23 years) and heavy rains in August or September has long been recognized [111].

The monsoon was reported to have withdrawn from the Punjab, Rajasthan and Gujarat by 3 October, and there was evidence of some south-eastward movement of swarms, following the retreat of the monsoon, during the same week in which swarm-movements associated with the seasonal displacements of the ITCZ and other semi-permanent synoptic features were reported from Nigeria, Uganda, Tanganyika and the Somali peninsula (p. 78). Thus on 10 October swarms appeared in southern Uttar Pradesh, following north-westerly winds from the direction of Punjab source-areas ; and on the 11th a young swarm was reported further to the south, in Bhopal, with northerlies. At the same time, widespread egg-laying continued in Rajasthan and Punjab.

Following the first south-eastward movement of young swarms into Uttar Pradesh and north-western Madhya Pradesh [129a] swarms reached northern Madhya Pradesh on 16 October, and remained in this and the neighbouring states, widely separated from the main Indian infestations, for a further two months. On 1 November winds over the main infested areas, still centred on Rajasthan, were conspicuously divergent, with north-westerlies extending across Uttar Pradesh (where young swarms appeared to the east of the source-areas of northern Rajasthan, and the last laying of the year in India was recorded

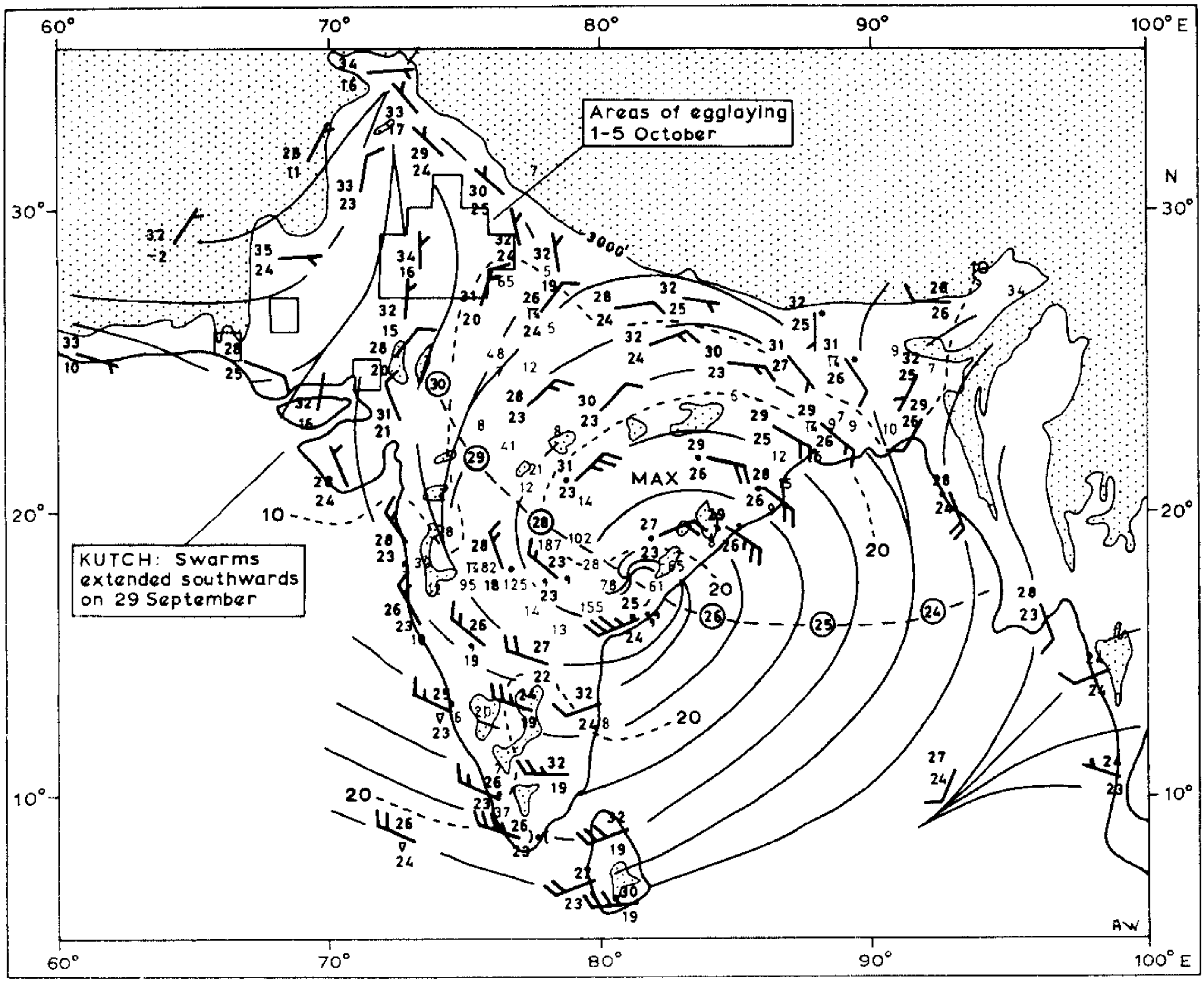


Figure 20 — Effects of a monsoon depression.

0900z 27 September 1954; winds at 600 m above ground, with streamlines and isotachs, surface air temperature (black), dew point (red), daily rainfall (green), and daily positions of centre of vortex from 24 to 30 September.

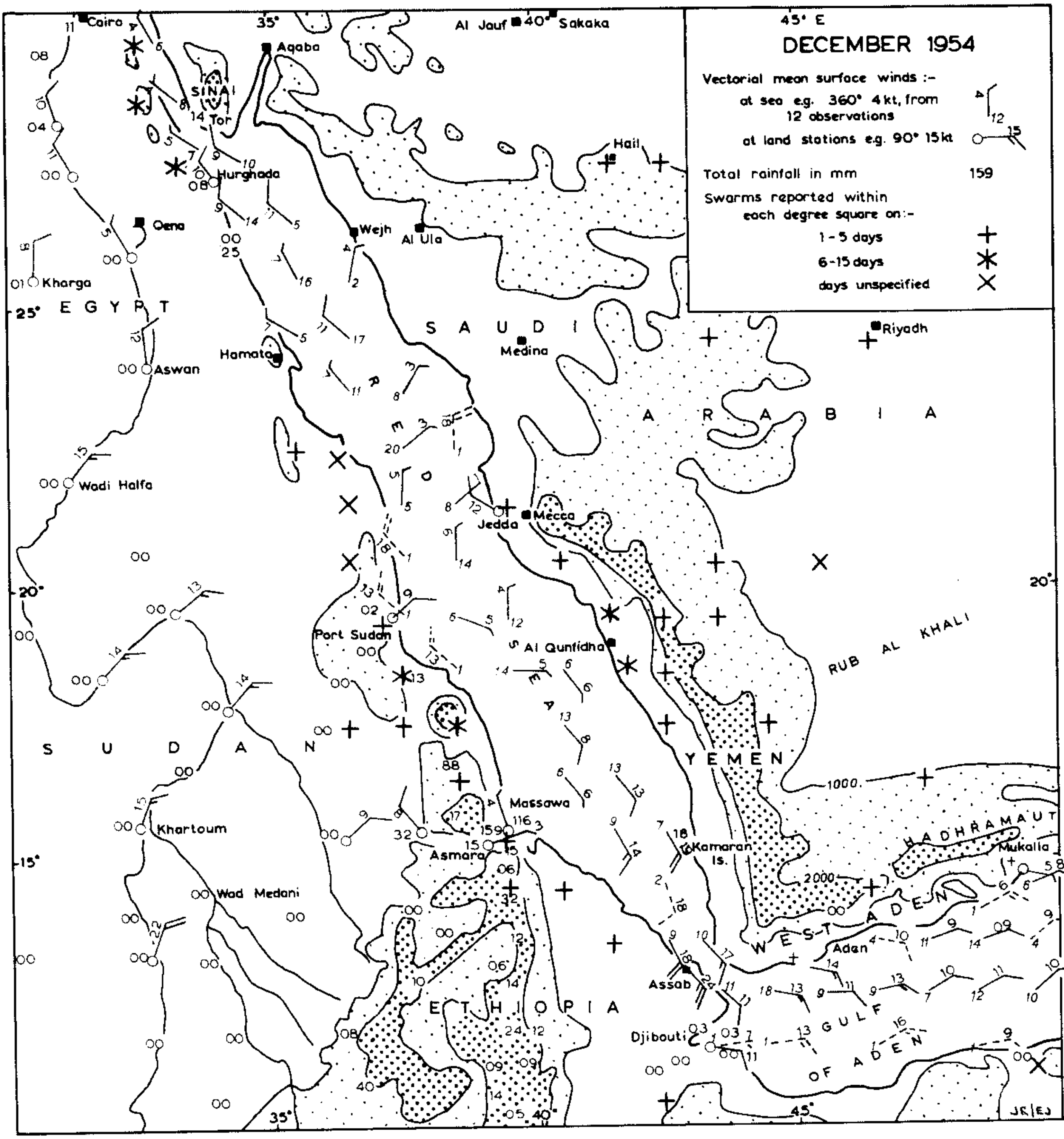


Figure 21 — Winds, rain and the winter distribution of swarms in the Red Sea area.

during the following week), while at the same time easterly and south-easterly winds extended from the more extensive source-areas of south-western Rajasthan and Kutch across Baluchistan. Young swarms were reported between 1 and 15 November at Jask, on the coast of Iranian Baluchistan, though it is not possible to decide whether they had in fact just moved out of India/Pakistan, at the beginning of November, or had done so during the previous move in late September. A mature swarm was reported further to the west, in the Bandar Abbas area, on 7 November, an occasion for which yet a third possibility, of a southern Arabian origin, cannot be entirely excluded (p. 79).

On 3 November there were further reports of swarms in Uttar Pradesh [129a] and Madhya Pradesh with north-westerlies, down-wind from Rajasthan sources, and continuing during 4–7th and 10th. This was a second series of movements of young swarms out of the summer breeding-areas of Rajasthan/Punjab in a generally south-easterly direction (i.e. in a direction away from all potential breeding areas), and contrasting with the biologically-significant movements to the west towards the winter breeding-areas. On 11 November there was a definitely-dated report of a young swarm at Jask, following generally easterly winds over Baluchistan, and the first laying of the season in Iran was recorded on the same day near Bandar Abbas. Two days later (13th), easterlies were well established as far as the south of the Persian Gulf, and the first rains of the season were reported in Trucial Oman, together with rain over the northern Persian Gulf and at Bahrein, where a swarm was reported with north-east winds. As described above (p. 79), swarms had already reached Buraida, in north-central Arabia, a few days previously, in all probability from southern Arabian sources; and from this point onwards it is accordingly not possible to distinguish, in the northern Arabia/Persian Gulf area, between swarms originating from southern Arabia and those from India/Pakistan.

On 15 November young swarms were reported reaching Trucial Oman, Qatar and the Iranian coast west of Bandar Abbas, with south-easterlies over the Gulf of Oman, north-westerlies over the upper Persian Gulf, and showers over the lower Persian Gulf, while other swarms were reported at a number of points in central and north-eastern Arabia. By 30 November egg-laying had begun in Oman, and occurred at roughly about this time in the Medina and Hail areas of northern Arabia ; the leading swarms had thus completed their biologically highly significant migration from the summer breeding areas of southern Arabia, India and Pakistan to the winter breeding areas of northern and eastern Arabia and southern Iran. Swarm movements from the Indo-Pakistani summer breeding areas into Iran have been recorded at this season in 13 of the past 23 years, and into eastern Arabia also in ten or eleven of these years [147]. These autumn locust migrations have long been associated with the Gorich or north-east wind of Makran [111], which reaches the Oman coast as the Nashi.

3.2.4 *Locusts in winter quarters — December 1954 to March 1955 ; effects of wind-fields, temperature and topography*

In marked contrast with the radical re-distribution of swarms effected by the long-range movements recorded during September-November, the overall distribution of Desert Locusts showed few significant changes in the course of the following four months (December-March). During this period, interest accordingly centres primarily on the factors responsible for maintaining this relatively static overall distribution ; and, before describing such significant swarm displacements as did occur during this period, consideration will be given to the meteorological characteristics of the various areas in which the swarms remained effectively static.

3.2.4.1 *Meteorological factors involved in maintaining effectively static distribution of swarms*

3.2.4.1.1 *Convergent surface winds in the central Red Sea area*

One of these areas, which has long been regarded as important in relation to the Desert Locust [48, 146] is that bordering the central Red Sea, which was continuously infested by swarms from late

October 1954 until February 1955. While the number of synoptic stations in the area is limited, it is traversed by major shipping routes, and the characteristic wind-field is well illustrated by the ship-observations available for December 1954 (Figure 21), plotted in the form of the vectorial mean of all wind-observations made during the month in each degree-square. In addition to the conspicuous confluence of the resultant wind-directions, it will be noted that the south-easterlies, in particular, show a marked down-stream decrease in speeds, demonstrating true convergence. The area is in fact characterized, at this time of year, by almost continuous low-level convergence between north-westerly and south-easterly wind-streams. However, while such low-level convergence was also shown on a very large proportion of the individual daily charts, significant precipitation did not occur as frequently as this, but appears to have been associated with the additional effects of extra-tropical depressions passing further to the north. The semi-permanent low-level convergence zone over the Red Sea appeared in fact to represent a favoured area for the occurrence of such precipitation — sometimes apparently separated by a largely rainless belt from the track of the centre of the depression away to the north. Associated with these winter rains and with the air-temperatures which, under maritime influence, remain relatively high for the latitude and season, the central Red Sea area is an important breeding area for locusts at this season, and in 1954 egg-laying was recorded from October onwards.

3.2.4.1.2 *Coastal front in western India and elsewhere*

A second area, of less regular and general importance in relation to locusts than that bordering the Red Sea, but in which the study period provided almost equally striking evidence of the significance of the corresponding wind-field, was that around the Gulf of Cambay on the north-west coast of India. Broach and Surat, in this area, were reached by swarms on 17 December 1954, in north-north-westerlies from western Rajasthan (extensively infested with young swarms at the time), and swarms continued to be reported in the area almost daily until 21 February. Throughout these two months this infestation remained clearly isolated from the main infested area (Punjab — West Pakistan — Rajasthan), with the last-named state in fact becoming clear by mid-February.

Winds around this area at the height usually studied (600 m above the ground), at Veraval, Ahmedabad, and Bhuj, though generally light, were almost invariably offshore, very predominantly from between northerly and north-easterly, thus providing no explanation of the continued presence of the swarms. The corresponding coastal surface winds, on the other hand, at Veraval, showed a marked and regular sea-breeze, commonly from between west and south, i.e. in directions opposing that of the general wind at higher levels. The swarms are likely to have done most of their flying in the afternoon [111], when temperatures were usually between 25° and 30°, and may accordingly have been expected to be retained in the vicinity of the "coastal front" by the convergence between the sea-breeze and the offshore general wind. The convergence was clearly a very shallow feature ; there was little or no rain, and no signs of maturation or breeding of the locusts concerned. The locusts finally left the Cambay area on 21 February with a spell of south-south-easterly winds, the first such spell since their arrival, and the area remained free of swarms throughout the next three months. Swarms were retained in the neighbouring Kutch area in similar circumstances from 23 November to 13 December 1962 [31].

A similar effect may have been involved in the case of the young swarms which appeared in western Senegal on 15 December, with east-north-easterlies and following winds from between north-east and north, and in all probability from Mauritania, which was still infested by young swarms. In Senegal swarms continued to be reported intermittently near the coast during late December, January and early February with persistently offshore easterly to northerly winds at 600 m. The corresponding Dakar surface winds at 1200z were predominantly northerly, occasionally north-westerly, though this time of observation (1100 local time) may perhaps be too early for the full development of a sea-breeze. Further to the south, scattered mature locusts appeared on board ship some 170 km off Sierra Leone on 27 February, in a northerly wind but with offshore surface winds (at 1200z) at coastal stations in southern Senegal (Ziguinchor) and Guinea (Boke), and may perhaps be interpreted as an effect of a possible temporary weakening of the sea-breeze. Swarms approaching Dakar from the landward side have on occasion been noted as being blocked by the sea-breeze "as by a wall" [114].

The significance of the sea-breeze circulation in relation to swarm-movements near the coasts of the Gulf of Aden has already been indicated (p. 75). There is evidence of a semi-permanent coastal front elsewhere, in northern and southern Africa [86, 91]; and attention has been drawn to the general significance of sea-breeze effects in retaining swarms over land [123].

3.2.4.1.3 *Temperature and topography in southern Morocco and elsewhere*

A third area, of outstandingly regular and persistent infestation by swarms, but of very different physical characteristics, is that of the Sous valley in southern Morocco, reached in late October 1954 by swarms some of which appear to have remained continuously within this area until they matured and bred from the end of January 1955 onwards. While the interaction of westerly sea-breezes and of offshore general winds are often important in relation to the local movements of swarms in this area also, the main "locust trapping" effect, for which the Sous is notorious, is clearly a topographical one: the valley is bounded on the north by the High Atlas, rising to over 4,000 m and snow-capped throughout the winter, and to the south-east by the Anti-Atlas, up to 2,500 m. Even at Taroudant, on the valley floor 70 km from the sea and at an altitude of only 250 m, and accordingly likely to be one of the warmest parts of the area by day, daily maximum temperatures were at times as low as 12°, with overcast skies, when flight activity is likely to have been completely inhibited.

Low temperatures are also likely to have limited the mobility, and hence the spread, of swarms at this season in a number of areas along their northern limit of distribution. Thus in Iran during spring, as in the Sous, swarms at the northern limit of their current distribution are commonly to be found in valleys among snow-capped mountains, with the locusts at times encountering and surviving direct exposure to snow; and during January 1955 temperatures below 5° at 1200z were recorded on a number of occasions in the infested areas of the interior of Iran as well as in the Algerian Atlas mountains. As already indicated, however (p. 52), an association of swarms with mountains may also result from anabatic winds; the association of swarms with the Atlas mountains during February and March was noted as more persistent than appeared to be attributable to the air temperatures recorded at the synoptic stations in the area, and was apparently broken only intermittently, for example, during the passage of major depressions such as that of 17 February (p. 93).

3.2.4.1.4 *Breeding, wind-fields and topography in Kenya and Tanganyika*

A further area in which the overall distribution of infestations showed little change between late November and early March was Kenya and Tanganyika, despite some of the striking day-to-day movements of individual swarms already mentioned (p. 39). One factor contributing to this degree of immobilization was the onset of breeding. Egg-laying, which had already extended from the Somali Republic and eastern Ethiopia south-westwards into Kenya with the seasonal passage of the ITCZ in October and November, continued to follow the seasonal movement of the rains southwards and westwards from Kenya across Tanganyika during December. Thus laying in the Dodoma area of central Tanganyika began on 8 December, following records of 10–74 mm of rain at six stations in the same degree-square within six days prior to laying; and the beginning of laying in the Shinyanga area of western Tanganyika, on 23 December, followed rains totalling 52–156 mm at eleven stations in the corresponding degree-square during 20 days prior to laying.

While many of the young swarms of the following generation appeared in Kenya during January in well-established north-easterly wind-fields, and accordingly showed initially progressive south-westward displacements of up to a hundred kilometres per day, these movements took place within areas already infested by the swarms of the preceding generation. Moreover, such progressive displacements were characteristically terminated within a few days either by features of the general wind-field, with the swarms encountering southerlies or westerlies (as in Figure 14), or by mountain features such as Kilimanjaro or the Usambaras (as in Figure 10), probably as a result of anabatic effects on the local wind-fields concerned.

3.2.4.2 *Abortive south-eastward movement in India*

In eastern India, swarms appeared in Orissa on 5 and 7 December, in west-north-west and westerly winds, and to the east of the areas of Madhya Pradesh and Andhra Pradesh in which swarms had been reported up to 23 November. On 8 December swarms were recorded further to the south in Orissa, with northerly winds, and the swarms continued to be reported in this state until 12 December. There were, however, no further reports of swarms within 800 km of this area for the next six months, and the swarms — probably the survivors of those which had originally moved into Madhya Pradesh from Punjab and possibly Rajasthan sources in October — must be presumed to have died off without issue.

Similar swarm movements southwards or eastwards from the summer breeding areas of Indo-Pakistan have been recorded in six of the past 23 years [147]. The abortive nature of the movement of swarms to Orissa in 1954, like that of the locusts which reached the British Isles, emphasizes that, while downwind displacements in general appear to have a very marked survival value for the species as a whole, particular movements can still be completely abortive as far as particular swarms or individuals are concerned. This was probably true of a number of other swarm-movements during the study period, such as some at least of the invasions of Burundi, the Congo, Nigeria, the southern Sudan and Uganda. All are relatively high rainfall areas, providing conditions under which locusts are likely to be more vulnerable to a number of natural enemies, including pathogenic fungi, and perhaps also to various insect parasites and predators. In October 1952 swarms appeared on the west coast of southern India, and wind-trajectories provided evidence of a movement over the sea from the Kathiawar-Kutch area [110]; locusts were seen at sea in the vicinity of the inferred track.

3.2.4.3 *Swarm movements and breeding associated with extra-tropical disturbances*

3.2.4.3.1 *In northern Africa*

Movements of swarms across Libya and Egypt in association with vigorous Mediterranean depressions during November 1954 have already been described. During the next two months there were two further locust invasions of Egypt, less well-documented in respect of the antecedents of the swarms concerned, but in circumstances which the corresponding synoptic situations assist in interpreting.

Thus on 23 December 1954, after Egypt had been clear of reported swarms for some 23 days, young swarms appeared at a number of points around the Gulf of Suez. Within the previous eleven days young swarms had been recorded not only in the Ahaggar in southern Sahara (the area from which the previous invasion of Egypt had begun, in November), but also along the coasts of the Sudan and Eritrea, and in both southern and north-central Saudi Arabia ; in the last area swarms of unrecorded maturity continued to be reported until the 16th. During 18–20th there was a three-day spell of south-easterlies from north-central Arabia, with air temperatures up to 24°, and on the day of the arrival of the swarms around the Gulf of Suez further south-easters were recorded at Tor, as well as at sea at the entrance to the Gulf ; it would therefore appear most likely that these swarms had in fact come from north-central Arabia.

The last report of these swarms in Egypt was on 29 December, still near the Gulf of Suez. On 30 December, following the passage of a cold front, consistent north-westerlies were established throughout Egypt for the first time since the arrival of these swarms. The locusts may accordingly be expected to have returned to north-western Arabia or perhaps to the African side of the central Red Sea ; immature swarms were reported in both these areas during the first half of January.

After another 19 days without further reports of swarms in Egypt, mature swarms appeared on 17 January 1955 near Mersa Matrouh, and continued to be recorded at a number of points along the western coast of Egypt until the end of February. One of the alternative possibilities for the origin of these swarms was western Tibesti, some 1,700 km away to the south-west near the Niger/Chad border, where young swarms had been reported on 12 January. While these were immature (unlike the swarms which reached Egypt), and there was no indication of any intermediate rainfall which might have suggested subsequent maturation, it is also known that egg-laying occurred at about this time in Niger, so that mature swarms must also have been present in this area. However, consistently north-easterly to easterly winds were recorded at Kufra during 13–16 January, and, even making allowance for the gaps in the synoptic network over the Sahara, it appears unlikely that swarms could have approached Egypt from this direction during this period.

Mature swarms were repeatedly recorded in early January in the coastal areas of the north-eastern Sudan, some 1,600 km to the south-east from Mersa Matrouh, and were also reported in northern Saudi Arabia, reaching the Sakaka area on 10 January (p. 94). During 31 December to 9 January there was a persistent anticyclonic circulation capable of giving a wind-track from the north-eastern Sudan to western Egypt. A similar synoptic situation was re-established on 15 January, with south-westerlies into western Egypt, followed by north-westerlies next day ; on the 17th, when the swarms were reported at Matrouh, winds were easterly, with east-south-easterlies further inland. While there were no corresponding swarm reports from intermediate points (such as the Nile valley), it is suggested that, on balance, the north-eastern Sudan was the most probable origin of these swarms, with north-western Arabia as a second alternative, and long-distance movement from the south-west considerably less likely.

Probably the most significant of the swarm-movements which did occur during these winter months were the first invasion of Tunisia on 30 January and of Algeria on 1 February, by swarms spreading eastwards from southern Morocco (where at least some of them had probably remained since early October), under the influence of an active depression which had deepened under the lee of the Atlas (Figure 22), and was subsequently associated with rains along the coast of Cirenaica and western Egypt, with 15 mm recorded at Alexandria on the 6th. There was a further spread northwards and eastwards during 15–19 February into north-eastern Algeria, northern Tunisia, Tripolitania, and almost to the Nile delta in Egypt, under the influence of a further extensive depression centred in the central Mediterranean (Figure 23), with the beginning of laying in eastern Algeria at the same time, apparently on the rains which had fallen during the passage of the earlier disturbance at the end of January and the beginning of February (see below). A study of an earlier locust invasion of Tripolitania, in 1951, had shown that the main wave of swarms arrived during 29–30 January, with the warm south-westerly winds which developed ahead of the primary cold front of one of the deepest and most active depressions of the whole winter [92].

In addition to the effects of the wind-fields of such depressions on the movements and distribution of swarms, the commonly associated rains and rise of temperature are of considerable potential importance in relation to maturation and egg-laying by the swarms. As yet, however, it has only been found possible to conclude that the data of the study-period are consistent with other evidence of minimum values, both for soil-moisture [67], equivalent to about 20 mm of rain, and for air temperature [87, 88], with spells of 21° or more at synoptic stations within the same degree-square, as representing conditions which are necessary but, even in combination, not sufficient for egg-laying to occur.

Furthermore, in northern Africa during the winter half of the year there was very little indication of the clear-cut association between the onset of the rains and the beginning of egg-laying which was often shown within the ITCZ, as for example in the Sudan and India during July 1954 ; and there were a number of occasions on which egg-laying appeared to be associated with rains which had fallen a month or more previously. Thus for example the first egg-laying in Mauritania was recorded during January, from the 10th onwards in the Atar and neighbouring areas which had received exceptional rains in late November, amounting between the 22nd and 24th to 36 mm at Atar and 55 mm at Akjoujt. Immature swarms had been repeatedly reported in this general area of Mauritania during November and December, but without any indication of the beginning of maturation until 2 January, and the first report of a fully mature swarm on 5 January. At about the same time (10–17 January) a proportion of mature locusts began to appear, between Habar-ou-Gdour in northern Mali and the Ijafen dunes in Mauritania, among the scattered locusts encountered during a crossing of Majabat al-Koubra [74a].

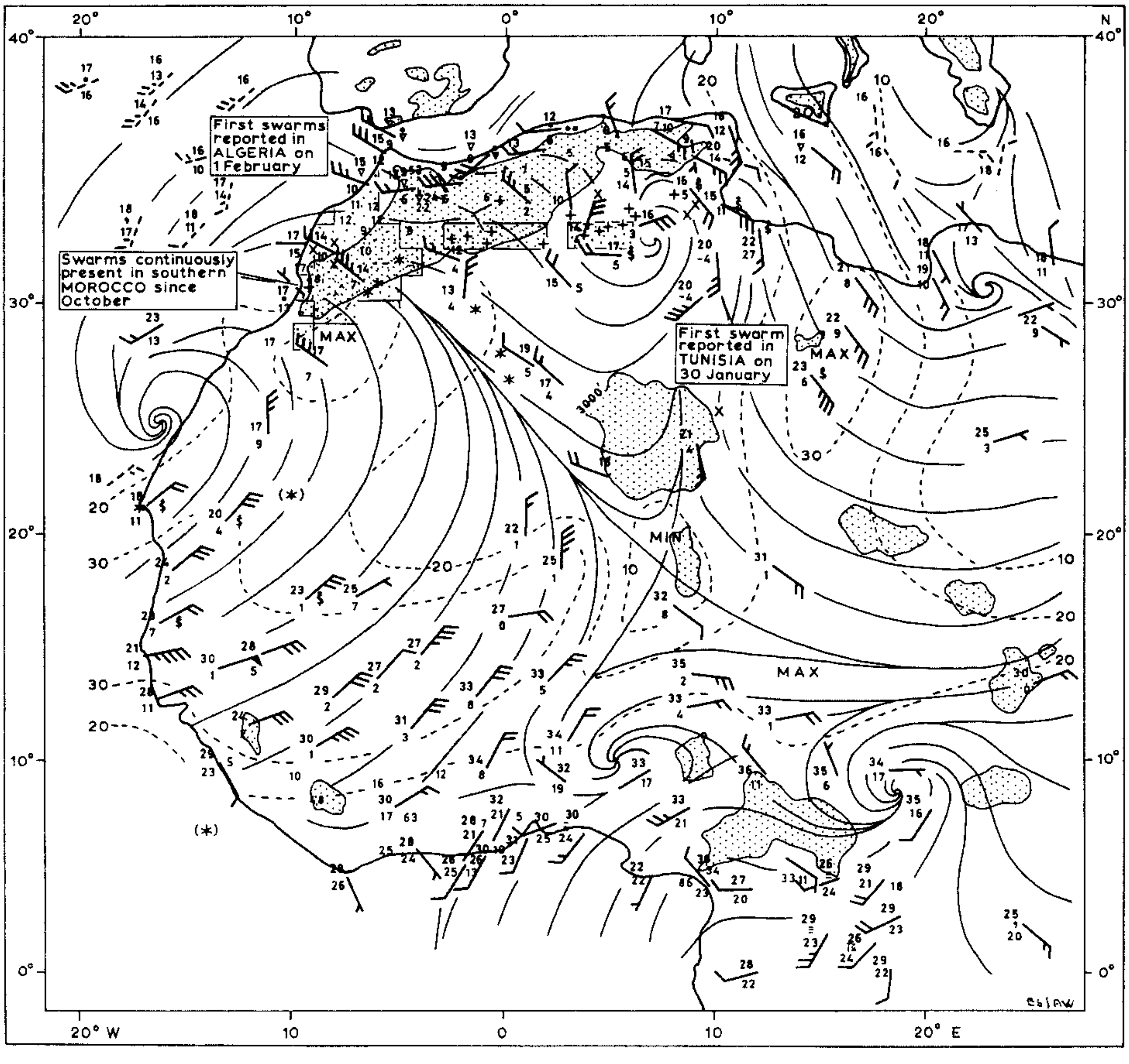
Mention has already been made of the beginning of laying in eastern Algeria also, in the Biskra area on 19 February 1955. Three of the four stations available in this degree-square had received rains, totalling 14 to 23 mm, between 18 and 25 days before the beginning of this laying, while no subsequent fall had been reported. In Morocco, near Sidi Ben Nour, on the other hand, where laying began at about the same time, on 22 February, a total of 47 mm of rain had been recorded at this station within the previous five days. However, in the Zuara area of north-western Libya, where laying began on 21 March, no rainfall in excess of 2 mm had been recorded since early February, when six of the eleven stations in this degree-square had recorded falls totalling 10 to 56 mm on the 41st and 42nd days before laying. Finally, near Medjez el Bab in northern Tunisia, where egg-laying began on 30 March, rainfall totalling 28 mm had been recorded at this station between 14 and 16 days prior to laying.

3.2.4.3.2 *In the Somali peninsula and Arabia*

Young swarms appeared near Borama in the western Somali Republic and north of Harrar in the neighbouring part of Ethiopia on 5 December, on the second day of south-south-easterlies intermittently interrupting the more usual northerlies at Hargeisa, and in all probability representing the first of the young swarms moving out of the source areas provided by the October layings in the Ogaden province of eastern Ethiopia and in adjoining areas of the Somali Republic — a reversal of the direction of movement of the parent swarms in October. These south-south-easterly winds developed during the passage of a disturbance over the Persian Gulf, with showers at sea on the 4th and at Bahrein on the 5th, and the lowest barometric pressure for nearly two months at Bahrein on the 6th.

In January 1952 a northerly movement of young swarms produced in the Somali peninsula had similarly begun during a temporary spell of southerlies, with the highest temperature of the month at Hargeisa, found to be associated with a particularly active depression centred over the Persian Gulf at the time. In 1952 this was the beginning of a massive movement of swarms right across Arabia (previously clear) to Jordan, Iraq and Iran, over a distance of some 3,000 km in a month, which was found to have occurred as a succession of down-wind displacements during periods of warmer southerly and westerly winds, associated with depressions passing further to the north, and interrupting the cooler north-easterlies characteristic of much of the area at this season [93]. A similar northward movement of young swarms produced on the Somali peninsula had likewise begun in early January 1958, again with warm southerlies recorded at Hargeisa in association with a vigorous depression over the Persian Gulf.

Evidence of a northerly swarm-movement in Saudi Arabia during the passage of a disturbance was provided by the arrival of mating swarms in the Sakaka area in the far north on 10 January 1955 (with the beginning of egg-laying in the area at about the same time) when southerly to south-easterly winds were recorded right across northern Arabia and along the whole length of the Red Sea, with showers over the northern part of the Sea.



Locusts not in swarms or bands shown by additional symbols:

In groups { } Isolated ( ) Unspecified [ ]

Locusts in swarming populations (swarms or bands), except where otherwise indicated.

Egglaying or eggfields O   Adults, mature or partly mature •

Hoppers ●   Adults, maturity unknown +

Adults, immature ×

Figure 22 — Effects of an Atlas lee depression.

Streamline analysis for 600 m above ground at 1200z 31 January 1955 ; broken arrows show surface winds ; areas where swarms reported 25–29 January shown by violet stippling ; locust reports of 30–31 January and 1 February shown in violet by symbols as in Key ; otherwise as Figure 20.

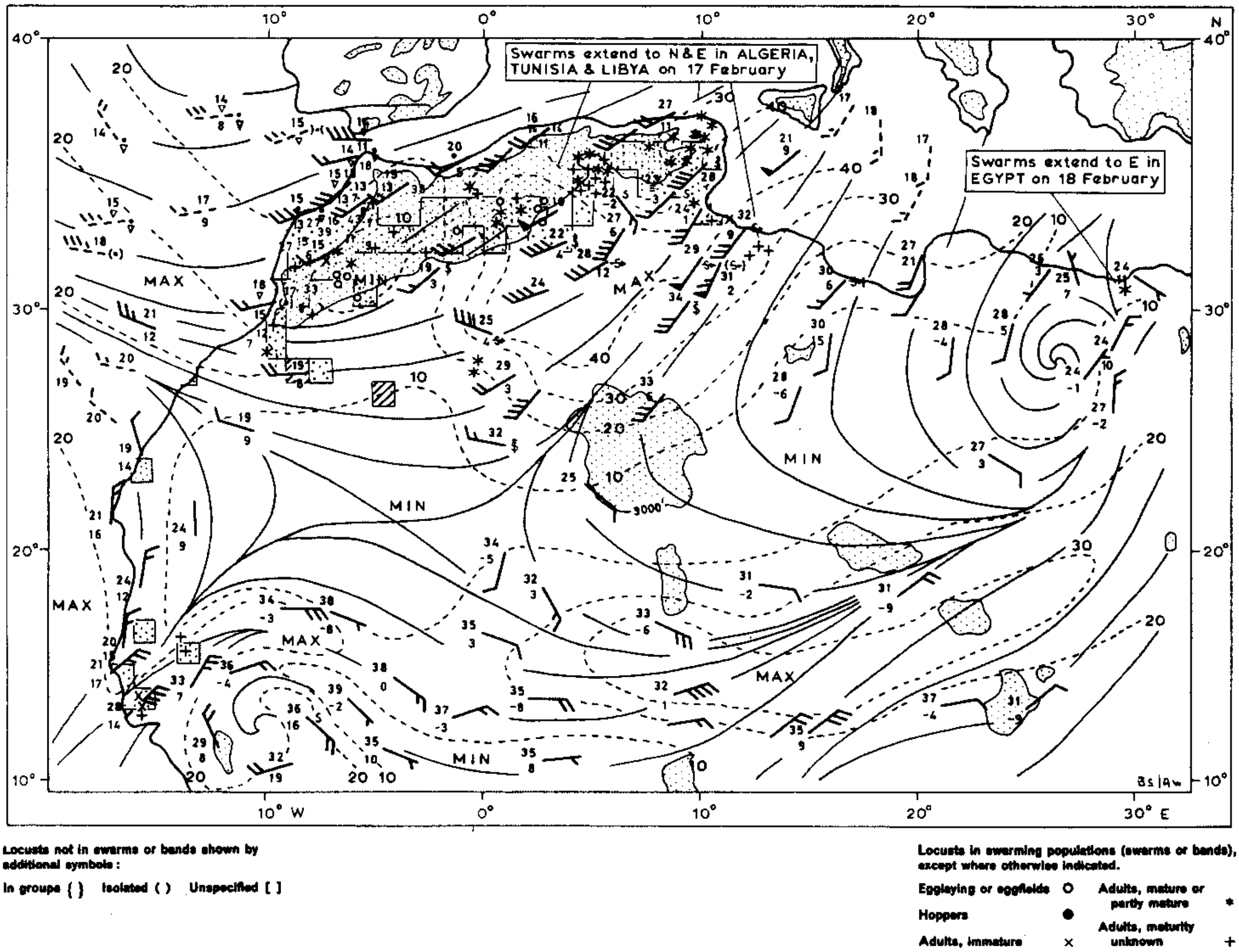


Figure 23 — Effects of a central Mediterranean depression.

Streamline analysis for 600 m above ground at 1200z 17 February 1955; areas where swarms reported 11–15 February shown by violet stippling; area of earlier breeding providing potential source of swarms during 10–19 February shown by violet line-shading; locust reports of 16–18 February shown in violet by symbols as in Key; otherwise as Figure 22.

3.2.4.3.3 *In Iran and Iraq*

On 29 December 1954 there was evidence of northward swarm movements associated with the passage of a disturbance in Iran, with a laying swarm recorded east of Shiraz and immature swarms in Kerman reaching Saidabad and the Bam area, on the third day of a spell of southerly and south-westerly winds over the Iraq/Persian Gulf area, particularly marked at 3,000 m.

On 12 March swarms reached southern Iraq, in all probability from the infested areas of northern Arabia, in association with a closed cyclonic circulation and thunderstorms over central Iraq, with southerlies and south-easterlies of up to 35 kt and temperatures up to 27° over the upper Persian Gulf and into Iraq. On the 23rd there were indications of a northward move of swarms in Iran, and of the passage of a corresponding disturbance, and on the 25th swarm(s) were reported further to the north-west in Iraq, in southerlies with temperatures up to 28° ahead of an active cold front.

In March 1962, during the eastward movement of a depression centred successively over the Black and Caspian Seas, there was evidence of a flow of warm air from the south and south-west, from the vicinity of eastern Ethiopia and across Arabia and Iran, ahead of a trough of low pressure accompanying the depression, and associated with a series of important northward swarm movements, in Jordan and Israel on 9 and 10 March, in the Jiggiga area of eastern Ethiopia on 10 March, and in Iran on 10–11th, both in Lorestan in the west and Khorasan in the east [100]. The widespread corresponding fall in barometric pressure was illustrated by the fact that the 850 mb levels at Aswan, Aden and Bahrein all fell, for more than a week, to minima on 11–12 March.

3.2.4.4 *Swarm movements associated with the Inter-Tropical Convergence Zone*

The ITCZ during the northern winter, representing the southern limit of surface air-currents of recognizably northern-hemisphere origin, corresponds very closely with the southern limit of distribution of the Desert Locust (Figure 1, References [123, 127]).

3.2.4.4.1 *In western Africa*

Following the November reports of swarms in Nigeria (p. 81) a swarm was recorded on 8 December 1954 in the Yola area, near the eastern border, in easterly winds some three hundred kilometres short of the previous day's position of the ITCZ between drier north-easterlies and more humid southerlies over central Nigeria. The locusts appear subsequently to have died off without issue (see p. 92), since no further swarms were recorded within 1,000 km of Yola for a further six months ; and no swarm was reported anywhere in the vicinity of the ITCZ over western Africa, west of 25°E, for more than two months, until well after the beginning of its seasonal northward movement.

Away to the north of the ITCZ, swarms remained during late December, January and early February in the neighbourhood of the coasts of Senegal, near Dakar, and, during early February, of Mauritania, in the region of Nouakchott. On 12 February, in association with a temporary northward surge of the ITCZ, a shallow cyclonic vortex appeared, centred near the Guinea/Mali border, with only a single record (1 mm) of rain in the area, but with widespread airborne dust recorded at Bamako. With the associated northerlies and north-easterlies, swarms, mature (possibly from Mauritania) as well as immature, extended southwards in Senegal, appearing near the coast in the region of Kolda from the 13th onwards, while others (possibly resulting from early egg-laying in western Sahara at the end of December) were reported in the interior of Senegal, in the region of Matam on the 14th and 17th with winds between north-east and north-north-east. On the 19th the last swarms to be recorded in Senegal until late May were reported near Kolda, close to the southern border. On 22 February the first swarm appeared in Guinea, at Labé in northerlies approaching the re-established position of the ITCZ. From this time onwards, until 22 March, immature swarms were repeatedly recorded in Guinea between 10° and 12°N, in the vicinity of the ITCZ — on 23 February just south of Labé, at the limit of the previous day's northerlies ; on the 24th in the same area but now in westerlies following a northward movement of the ITCZ ; on the 25th still in the same area, again in westerlies now just south of the ITCZ ; and on the 27th close to the ITCZ near Mamou. On 1 March swarms were again reported just south of Labé as well as in the neighbouring Kabala area of Sierra Leone, both close to a well-marked southern limit of north-easterlies, at about 10°N, corresponding also with a difference of 15° to 20° in dew point and of up to 5° in dry-bulb temperature. In Guinea, swarms near Labé on the 4th were just in the northerlies, but following a northward extension of the southerlies to beyond 10°N ; on the 12th a swarm west of Kouroussa was in north-easterlies, but following a disturbance on the 11th associated with rains and a development of south-westerly and west-south-westerly winds into southern Sahara ; a swarm on the 19th south-south-west of Kouroussa was in southerlies and south-westerlies which had extended northwards since the previous day ; and swarms in Kouroussa on the 22nd, to the east of earlier positions, were still in southerlies, with some rain.

Meanwhile, infestations very much heavier than those in the vicinity of the ITCZ in western Africa still remained in Morocco and along the Mediterranean littoral.

3.2.4.4.2 *In eastern Africa*

Reference has already been made (see e.g. Figures 10, 11 and 14) to the westward and south-westward movements shown between late January and late February 1955 by young swarms produced by breeding on the 1954 Second ("Short" or "Der") Rains in the lowlands of Kenya and the adjoining areas of southern Somalia. These movements, with easterly and north-easterly winds and towards the ITCZ over Tanganyika, at times exceeded 100 kilometres per day, but, as already indicated, did not in general extend beyond the area already infested by swarms of the preceding generation, and were commonly terminated within a few days by encountering southerly or westerly winds or mountains.

There was still a general predominance of north-easterlies in East Africa at the beginning of March, but on the 7th the seasonal northward movement of the ITCZ was indicated by a very marked windshift to the south-easterly sector throughout Kenya and adjoining areas of Ethiopia and parts of Tanganyika, and a swarm, probably from a Kenya source, appeared in southern Ethiopia. On the two following days (8th and 9th), the large swarm which had remained for the best part of a month in the Usambaras area of northern Tanganyika moved rapidly north-westwards, covering 160 km in just over two days (Figure 10), with consistently south-easterly winds at Mombasa, Voi and Makindu, before becoming static again on the north-western slopes of Kilimanjaro. On 15 March young swarms were continuing to appear around the source-areas of central Tanganyika, in easterly winds, later becoming south-easterlies, with which swarms reached Mwanza district, to the south of Lake Victoria, on the 21st.

During March the overall area of swarm-production was at a minimum, restricted to central Tanganyika and to relatively limited areas around the Persian Gulf and Red Sea and in Mauritania. Swarms remained throughout the month in these and neighbouring areas (including most of north-western Africa), but the total area infested by swarms was at its lowest since August. The distribution of swarms was however less static than in August, and, as has been indicated, there was evidence of systematic swarm-movements in a generally northward direction in a number of areas, in eastern Africa in association with the seasonal northward movement of the ITCZ, as well as in Iraq and Iran, associated with the passage of extra-tropical depressions.

3.2.5 *Main spring breeding and the beginning of re-assembly in the Inter-Tropical Convergence Zone : April–May 1955*

3.2.5.1 *From Mauritania into the Inter-Tropical Convergence Zone in western Africa*

At the beginning of April the early breeding in Mauritania was coming to an end ; the first fledglings in the Atar source-area had been observed on 8 March, with young swarms in the same area later in the month ; and on 1 April a further young swarm was reported near Atar, in a spell of northerly winds which persisted, from directions between north-east and north-west, for at least a week. Swarms reappeared on 6–9 April in the immediate vicinity of the ITCZ, both near the areas previously infested in Guinea, and also further to the east in southern Mali, close to the Ivory Coast border — with no evidence of any alternative destination of the swarms from Mauritania. There were occasional subsequent swarm reports from Mali in early May, with evidence of a major movement of young swarms from north-western African sources across Mauritania and reaching the ITCZ in Mali in late May.

3.2.5.2 *Northwards across eastern Africa with the Inter-Tropical Convergence Zone*

The most striking series of swarm-movements during April were those associated with the seasonal northward movement of the ITCZ in eastern Africa, with swarms produced in Tanganyika and Kenya moving north-eastwards into the Somali peninsula (and joined by others moving southwards from Danakil), followed by widespread breeding on the associated First ("Gu" or "Long") Rains of the Ogaden and the Somali Republic. At the same time, other swarms from Tanganyika moved westwards and then northwards, to the west of Lake Victoria, successively into Burundi, Uganda, Congo and the southern Sudan.

Thus in Tanganyika on 6 April swarms appeared to the south-west of Lake Victoria, with winds which were generally from between east and south-east, and on the 8th were in an almost pure indraught centred near the Burundi and Uganda borders. On the 9th swarms had extended northwards, into south-western Uganda near Kabale, with southerly winds, while, away to the other side of Lake Victoria, other swarms reached Marsabit in northern Kenya, with southerly to south-easterly winds ; and on the 11th, a partly-mature swarm was reported at El Wak in north-eastern Kenya, with southerlies over the Kenya coast and lowlands. On the 16th a northward movement was resumed in Uganda, with swarms reported near Mbarara, and the establishment of winds from the south-south-east after a previous predominance of northerlies ; and on 18 April Fort Portal was reached by swarms, with south-easterly and south-south-easterly winds meeting westerlies in this area. Over north-eastern Kenya, there were wind-shifts between the 18th and 20th at Mandera, from north-east to south-west, and at Moyale, from east and south-east to south-south-west ; and egg-laying began in south-eastern Ethiopia on the 19th. By 21 April winds (at 600 m) were south-south-easterly at Kismayu, Mogadiscio and Hargeisa, with surface southerlies at Mandera and Diredawa and south-westerlies at Adola, and rain at Mandera, Adola and Belet Uen, with widespread reports of swarms between 2° and 10°N and 41° to 43°E, including a young swarm in northerlies, down-wind from a Danakil source, suggesting movement into the ITCZ from its northern side as well as from the south. On the 22nd swarms reached 45°E in Somalia, as well as extending into the Congo to the north of Fort Portal, and were reported just over the southern border of the Sudan on the 23rd, while on the same day south-westerly winds were recorded at Galkayu in Somalia. Next day swarms reached 46°E in this area, with winds from between southerly and south-westerly at Hargeisa, Mogadiscio and Djibouti. In 1961 the comparable initial establishment of the SW monsoon across the Ogaden and adjoining areas of the Somali Republic was shown by the midday observations of 5 May ; and within ten days laying swarms had extended across the area for some 500 km eastwards from their previous limits [31].

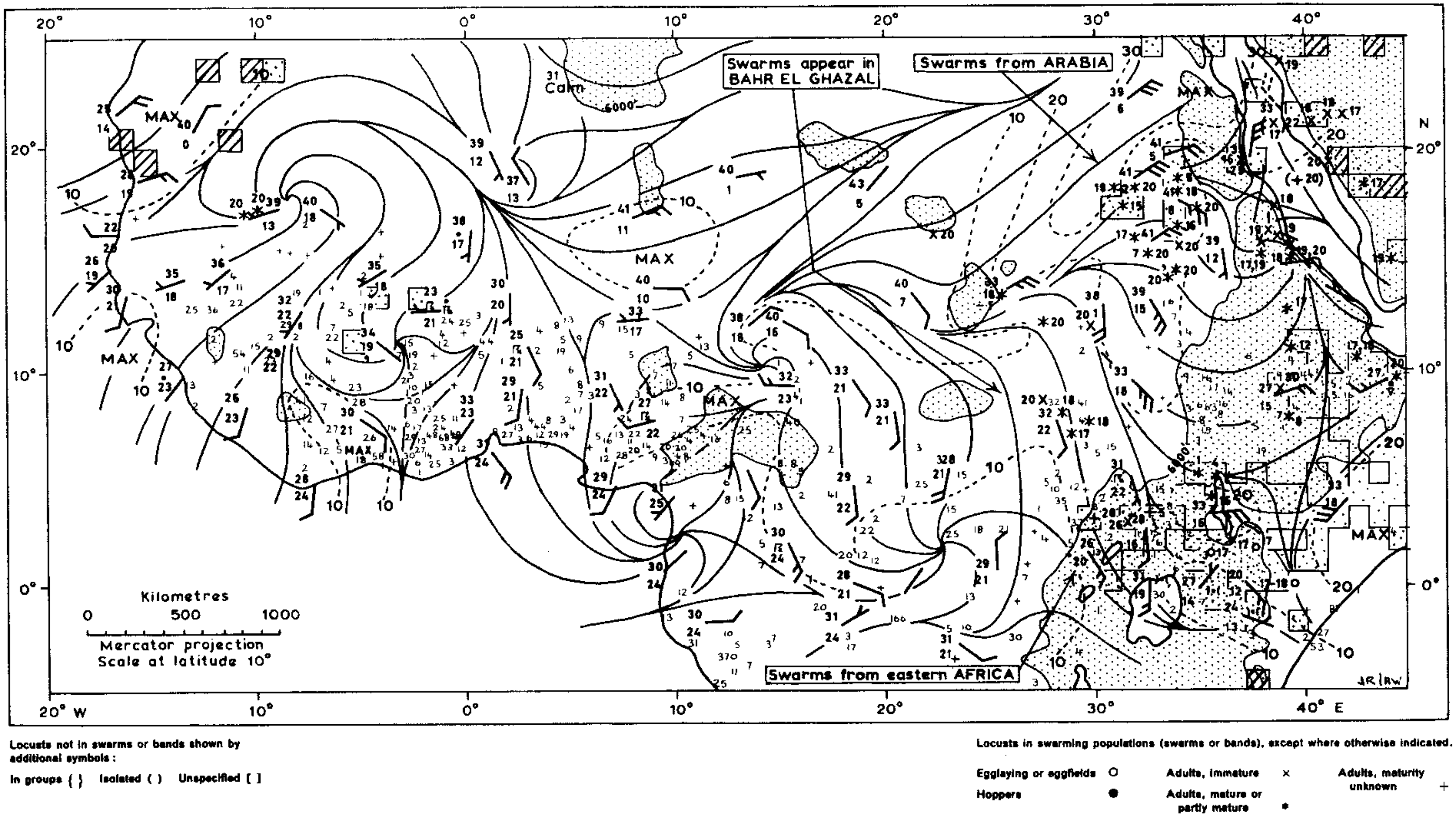


Figure 24 — Swarms in Bahr el Ghazal, May 1955; current situation and potential sources.

Streamline analysis for 600 m above ground at 1200z 17 May 1955; all areas where swarms reported between 26 April and 15 May shown by violet stippling, with dates of significant individual reports; all areas of known earlier breeding providing potential sources of swarms between 26 April and 20 May shown by violet line-shading; all reports of adult locusts during 17–20 May shown, with dates, in violet by symbols as in Key; otherwise as Figure 22.

In late April and early May 1945 a swarm, already mentioned (p. 27), made good a net northward displacement of some 250 km across the highlands of western Kenya, from the vicinity of Kericho to southern Turkana, in 12 days, after having spent at least the previous ten days in erratic local movements within Kericho district ; the northward displacement was noted to have taken place during the transition from the NE to the SE monsoon season [40].

In 1955 the first egg-laying reported near Galkayu, in Somalia, on 8 May, followed rains totalling 39 mm over the previous 12 days ; and the beginning of laying near Garba Tula, in northern Kenya, on 9 May, followed 80 mm of rain at this station during the previous three days. Following the initial onset of very widespread egg-laying on the First Rains in the Somali peninsula in late April, laying was also in progress by the end of that month in Morocco, Algeria, Tunisia, Libya, Iraq, Saudi Arabia, Iran and India, in areas (most of which had been reached by swarms some months previously) with a total extent at the beginning of May of the order of half a million square kilometres (52 degree-squares) — an extent exceeded within the study-period only during late July and early August.

3.2.5.3 *Swarms in the central Sudan : re-assessment of an apparent exception to down-wind displacement*

During May 1955, there was a series of major swarm-movements, towards the ITCZ, paralleling those of the beginning of the study-period in May 1954 — from Saudi Arabia across the Red Sea and Egypt to Sudan and Chad, between 4 and 20 May 1955 ; from north-western Africa to Mauritania and Mali ; and eastwards into Pakistan. In addition to these developments, May 1955 is of particular importance in the study of effects of weather on swarm-movements in having provided the nearest approach so far recorded to an exception to the general hypothesis of the down-wind displacement of swarms, towards and with zones of convergent surface wind-flow. Thus, following the preliminary survey of this subject undertaken by the Mission, it was initially concluded that :

"Although the convergence hypothesis is attractive it may not provide a complete explanation of the phenomenon ... In May 1955, for example, swarms moved south from the Hedjaz region of Arabia into the wet southern half of the Sudan, where they began to breed. In order to do this, they had to cross the main Equatorial convergence zone, which, at the same time, was travelling northwards. Had the locusts behaved completely like inanimate airborne particles, they could not have done so [55]."

Since this conclusion is at variance with that indicated by the remainder of the work of the Mission, the evidence on which it was based clearly merits the closest study. The swarms in question were those reported in Bahr El Ghazal province of the Sudan, on 17 May at Tonu, south-east of Wau, and next day (18th) at Gogrial (north of Wau) and at Wuncwe, all mature swarms, together with a young swarm at Aweil, north-west of Wau, on the 20th (Figure 24).

It is true that, as already mentioned, the Sudan was at this time in the course of being invaded by locusts from the Hedjaz and other parts of Arabia, including both immature swarms, first reported in the Sudan on 6 May, on the Red Sea coast near Port Sudan with north-north-easterlies, and also mature swarms, first reported near Karima on the 11th, in north-easterlies, and following a record of egg-laying to the north of Jeddah on the 8th. It is also true that throughout this period the Inter-Tropical Convergence Zone remained well to the north of Bahr El Ghazal, with winds at Wau, for example, observed at 600 m above the ground at 11 hrs local time, remaining continuously between 130° and 270° from at least 6 to 20 May, with corresponding dew points between 17° and 22°, values typical of the southerly monsoon air. Moreover, on the date of the first swarm report in Bahr El Ghazal (17 May), the nearest north-easterlies recorded in the Sudan were nearly a thousand kilometres away, at El Fasher, with the typically associated low humidity (dew point −1°).

However, on locust evidence alone Arabia was not the only nor even the most likely origin of the Bahr El Ghazal swarms ; these reports had been preceded by records of swarms, within the previous three weeks and within distances of 450 to 800 km, from the adjoining parts of four different neighbouring countries (Congo and Uganda, as already mentioned, together with Kenya and Ethiopia), extending along the whole sector between south and east-south-east from the area of the Bahr El Ghazal reports, as well as with swarms already reported at several points in Equatoria province, inside the southern border of the Sudan itself. Moreover, at the time of the first Bahr El Ghazal record, none of the neighbouring Sudan provinces to the north (Darfur, Kordofan and Blue Nile) had yet been reached by the incoming swarms from Arabia ; and the nearest reports of this invasion were still 1,000 km away.

On the locust evidence of 1955 alone, there was thus the alternative possibility, of movement from the south or south-east, and over a shorter unreported distance ; and further evidence is provided by the locust records of earlier years. Bahr El Ghazal had previously been free of locusts for more than a decade ; and its last previous comparable invasion, in 1930, had also been preceded by the unusual presence of swarms in Congo, Uganda and Kenya. Purely on the locust evidence, it is therefore considered much more likely that the swarms which reached Bahr El Ghazal had come from eastern Africa rather than from Arabia. It is therefore concluded that they were probably moving down-wind, from the south or south-east, towards the Inter-Tropical Convergence Zone ; and that the suggestion that they had traversed the ITCZ from the north and subsequently made good an up-wind displacement of the order of a thousand kilometres may reasonably be rejected. The author of this suggestion has very kindly indicated his willingness to state that, on the fuller evidence now available, the case for these swarms to have come from the south, and not to have crossed the convergence zone, now appears convincing to him [56].

3.3 Conclusions of the WMO Technical Assistance Mission

3.3.1 The study period has provided twelve cases of long-range progressive displacement of Desert Locust swarms, over distances ranging from 600 to 3,500 kilometres within periods ranging from five days to two months, in circumstances in which the locust data alone were sufficient to establish, by progressive day-to-day changes in the area occupied, at least the general direction of displacement made good, within a degree of certainty ranging from about 40° to about 90°.

Five of these twelve casespp. 78–79, 92, 98–99, 101took place within relatively uniform wind-fields, and with winds over the area concerned either exclusively (three cases) or very predominantly (two cases) from within the quarter corresponding with the overall direction of the displacement throughout the period of the move.

The remaining seven cases (pp. 65–68, 77–85, 93) related to less settled wind-fields, three of them under the influence of the seasonal displacements of the Inter-Tropical Convergence Zone, with superimposed short-term oscillations of its position, and three of them under the influence of extra-tropical depressions. In all seven of these cases, there is clear evidence that the main, overall displacements were in fact made good during spells of winds from the appropriate sector, but with evidence of temporary interruptions of the move during periods of opposing winds.

3.3.2 The study period has also provided seven cases of quasi-stationary swarms, remaining for periods of two to four months within relatively restricted areas, of a few hundred kilometres across, without indication of any progressive overall displacement.

Two of these cases (Sudan, June-August 1954 and Rajasthan, June-September 1954) were associated with the characteristically convergent low-level wind-fields of the ITCZ (section 3.2.2) ; one (central Red Sea basin, November 1954 to January 1955) was associated with characteristically opposing north-westerly and south-easterly low-level wind-currents (section 3.2.4.1.1) ; and one (Cambay, December 1954 to February 1955) was associated with on-shore coastal surface winds (sea breezes) opposing the light off-shore more general wind-flow (section 3.2.4.1.2). One case (southern Morocco, November 1954 to January 1955) was associated with temperatures low enough to be expected to lead to a direct reduction of flight activity (p. 91); and the two remaining cases (Algerian Atlas, January-March 1955, p. 91, and Kilimanjaro, February-March 1955, p. 52, Fig. 10) were both associated with mountainous areas, where low temperatures may to some extent have been similarly involved, but where local anabatic circulations, superimposed on the general wind-field, are also likely to have been important.

3.3.3 Taking also into account the results now available from studies, on the scale of meso-meteorology, of the hour-to-hour and day-to-day movements of individual swarms (chapter 2) together with the corresponding studies of the behaviour of individual locusts in these swarms (section 1.4), it is therefore concluded that the movements and distribution of Desert Locusts, on scales from a hundred to thousands of kilometres, are not merely correlated with, but are to a very large extent determined by, the corresponding low-level wind-fields.

3.3.4 Conversely, if it is accepted that the movements and distribution of locusts are in fact very largely determined by the corresponding wind-fields, then evidence of wind-fields can be used to assist in interpreting the distribution and movements of locusts, in situations for which the data on locusts alone are inadequate and ambiguous. Such situations include for example cases of the arrival of swarms in a new area, such as the invasions of Egypt in December 1954 and January 1955 (pp. 92–93) with two or more potential sources of these swarms; and other cases of disappearance of swarms from a particular area, as from the Ahaggar in mid-November 1954 (p. 85), with a corresponding ambiguity as to which of two or more subsequent infestations in different neighbouring areas may have represented a reappearance of these same swarms.

3.3.5 The study period has provided numerous examples of the association between egg-laying and the onset of rains, which has long been recognized. On 14 occasions, swarms were observed egg-laying in the neighbourhood of rainfall stations, in areas free of major topographical complications. In each of these cases, egg-laying was preceded by rainfall, recorded within the same degree-square, and ranging from at least 20 mm within 25 days prior to egg laying to at least 40 mm within 50 days prior to laying. These figures are in general agreement with those previously found in other studies [67] of rainfall and egg-laying records in India and elsewhere. Rainfall amounts of this order may accordingly be indicated as a necessary though not sufficient condition for oviposition; and such rainfall records can be of corresponding value in assessing the probability of locust breeding a month or more ahead.

CHAPTER 4

RECOMMENDATIONS ON THE USE OF METEOROLOGY IN LOCUST CONTROL

The most important characteristics of the basic problem presented by the control of the Desert Locust are, on the one hand, the near-overwhelming scale of the infestations experienced from time to time by many of the countries liable to invasion, together with the intercontinental degree of mobility shown by the invading swarms, while on the other hand only a relatively small proportion of the total area liable to invasion is ever heavily infested at any one time. This means that forecasts of swarm movements and of breeding are essential for the effective direction of control operations ; and it is in relation to such forecasts that meteorological guidance has already been found of direct value in locust control.

Two types of forecast of swarm movements are necessary : long-term, strategic forecasts, in general terms, for planning the procurement and distribution of stores and heavy equipment for the coming season or the coming year ; and short-period, detailed tactical forecasts, to guide the movements of personnel and mobile control units, particularly aircraft, necessitated by the continuously changing locust situation. Such tactical forecasts may be subdivided further into those relating to periods of weeks or days ahead, needed for the effective deployment of each control detachment to the appropriate province or district, and those needed for day-to-day and hour-to-hour guidance in establishing and maintaining contact with particular swarms.

Sections 2 and 3 have illustrated the manner in which meteorological data and analyses can contribute to the interpretation of the current locust situation and to forecasting its future development. It will also be clear that the preparation of such forecasts demands the fullest possible utilization of all available locust data, not only for the present, inevitably incomplete, but also for the past, as well as making the fullest use of meteorological data of many different types. In outlining techniques and procedures which have so far been found useful in this respect, it will be noted that in general meteorological guidance assumes progressively more importance as progressively shorter time-scales are considered. Attention has, however, recently been drawn [127] to a notably successful long-range forecast [125] of the general rise and fall of locust infestations in India and south-western Asia for a period of nine years ahead, published in 1952 from a consideration of sun-spot cycles. Earlier experience of the sun-spot cycle as a guide to the fluctuations of locust infestations in this region [108] had not been encouraging [83, 111], and the evidence now available on fluctuations in the overall extent of the area infested by swarms [145] does not suggest an 11-year cycle, but the subject merits re-examination.

At present, long-term strategic forecasts are necessarily based almost entirely on the very considerable regularity of seasonal swarm movements and breeding shown by past records. Compared with weather forecasting, the provision of such forecasts of swarm movements is facilitated by a more limited range of possibilities, a much greater constraint imposed by continuity, and a correspondingly much greater value of seasonal analogues, with many of the major seasonal swarm movements occurring at dates showing a regularity comparable with (and often directly associated with) that of the onset and change of the monsoons. An outstanding example of such a forecast, based entirely on the degree of regularity of seasonal breeding and swarm movements in the eastern African region, was issued in June 1949, when swarms had just appeared in the interior of south-western Arabia, while the whole African continent was free of them. The Director of the Desert Locust Survey then warned the East African governments that, if this new outbreak could not be suppressed, swarms could reach the Kenya border by November or December 1950, i.e. some 17–18 months ahead. The first such swarm was in fact reported in Kenya on 26 October 1950.

The longest period ahead for which a routine study of meteorological data has so far been found useful is of the order of a month. Since locust movements with a necessarily highly convergent wind-flow in all probability account for the frequently-recorded association of exceptional rains with the arrival of locusts, a causal connexion is thus indicated for what had previously been only an empirical association, and rainfall may be regarded with correspondingly more confidence as a useful index, in appropriate circumstances, of the risk of locust invasion. Thus reports of precipitation, both in synoptic observations and in the rainfall totals for the past month as reported in the regular CLIMAT signals exchanged by most meteorological services, have on a number of occasions assisted in assessing the chances of breeding in a particular area, by modifying the long-term probability as indicated by the number of years in which breeding had occurred in the area and season under consideration as a proportion of the total number of years on record — most recently in forecasting the further generation of breeding which occurred in India and Pakistan in September and October 1962.

By recommendation of the WMO Commission for Climatology, the meteorological services of nine of the countries concerned are already adding to their CLIMAT broadcasts reports from additional stations in locust breeding areas, included specially for the use of the Desert Locust Information Service and of other interested locust organizations.

For forecasts of swarm movements over periods of as much as a month ahead, however, it remains necessary to rely very largely on past locust history. Thus, for example, in early December 1953, it was found possible, by considering the distribution and timing of the egg-laying reported in the Somali peninsula during October-November 1953 in relation to comparable locust maps for earlier years and to the subsequent history of these years, to plan an aircraft reconnaissance programme some weeks ahead, to intercept with minimum aircraft hours the escaping swarms on their way towards the crop-areas of Kenya and Tanganyika [94]. The leading locusts were in fact met as planned as they approached the Juba river in Somalia, on the day after the reconnaissance programme was begun.

This involved forecasting the rate of development of the eggs and hoppers which had been reported in late 1953, to provide estimates of their dates of fledging, and then applying to the postulated new swarms the corresponding expected winds. Such forecasts of rate of development have a wider range of application, for planning control operations against egg-fields and hoppers as well as against adults, and are now prepared on a routine basis by the Desert Locust Information Service in respect of all current reports of locust eggs or hoppers, to provide estimates of possible dates of fledging in all potential sources of new swarms. So far, the most useful guidance on such rates of development has been that provided by the corresponding developmental periods recorded in the same area and season in earlier years. From the evidence so far available, for a range of different breeding areas (p. 56), variation between years has been small compared with variations with time of year and from area to area, though there remains the possibility, particularly for the cooler areas of correspondingly protracted egg-development, that evidence of a particular season being warmer or cooler than normal may make it possible to improve upon such purely historical forecasts.

Coming down from a time-scale of months to one of weeks, the forecasting value of current meteorological data begins to approach that of past locust history ; and it is convenient to distinguish, on this and smaller time-scales, between locust movements which are initiated by a change in the locusts themselves, particularly by their reaching the fledging stage and beginning to fly, and other locust movements which are initiated by changes in meteorological factors, such as in the corresponding wind-field. Sometimes both effects may be involved, as for example when locusts grounded by a cool wind from one direction begin to fly in a warmer wind from a different direction.

Forecasting the first of these types of locust movement requires first the estimation of the corresponding rate of development, as just discussed, and then forecasting the wind-field to be expected over the area at that time. In tropical and subtropical regions, where seasonal changes in surface winds may be large compared with day-to-day changes, such forecasts of a future wind-field may not be difficult; and the changes in overall distribution of the young swarms produced at the end of a breeding season may often be regarded as coming into equilibrium with the effects of progressive changes in wind-fields which have been in progress since the egg-laying by the parent generation.

In considering changes in locust distribution initiated by changes in meteorological factors, interest shifts predominantly into the field of synoptic meteorology. The problem is first that of recognizing particular synoptic features which are important in this connexion, and then of recognizing signs of the type of change in these features which can be expected to be significant in relation to locust distribution. In chapter 3, mention has been made of all synoptic features so far found to be associated with the distribution and movement of Desert Locusts, and it will have been immediately obvious that these features include a number which are already familiar to the synoptic analysts of these regions by reason of their importance in weather forecasting.

Thus the feature or features variously known as the Equatorial Trough, Inter-Tropical Front or Discontinuity, or Inter-Tropical Convergence Zone clearly dominate the movements and distribution of locusts throughout almost the whole area infested between May and September, and in parts of the area, such as eastern Africa, may be regarded as doing so for most of the year. Here major swarm movements are regularly and directly associated with corresponding seasonal movements of the ITCZ, which are sometimes so well marked as to have been long recognized by the local peoples. Thus for at least a millenium Arab navigators have likewise utilized the regularity of the seasonal changes of the monsoons of the western Indian Ocean; and the Swahili term "tanganbili" ("two sails"), for the weather of the change of the monsoon, correspondingly and considerably antedates its technical equivalents such as the ITCZ. By reason of the degree of diversity of meteorological opinion, usage and terminology in this connexion, however, it has been found essential to utilize objective criteria for the phenomena under consideration, and to look for particular wind-shifts at particular stations to establish the onset of the seasonal movements of the ITCZ, for example northwards and southwards across the Somali peninsula. This made it possible in 1950 and again in 1951 to provide, from Desert Locust Survey headquarters in Nairobi, five days' immediate warning, to the administration and locust control units in the Northern Frontier Province of Kenya, of the arrival of invading swarms from the north, while the nearest reported swarms were still some 500 km away. Since March 1961, current daily synoptic observations from the whole invasion area of the Desert Locust have been available to the Desert Locust Information Service in London, and in October 1961 DLIS was accordingly enabled to provide two days' warning of the onset of a 500 km south-westward extension of breeding swarms across the Somali peninsula with the seasonal movement of the ITCZ. Two days' warning had been similarly given of the onset of another 500 km extension of breeding, this time eastward across the northern Somali Republic, in association with the establishment of the SW Monsoon across this area in early May 1961. Clearly, any progress in synoptic research, enabling such developments to be recognized at an earlier stage, would enable correspondingly longer warning to be given.

In addition to these regular seasonal movements of the ITCZ, it is necessary to be alert for departures from normal in this respect, which can also be of major significance in relation to locusts. Thus in mid-1950 a French airline pilot, with considerable experience on trans-Saharan routes, commented, during debriefing in Nairobi, on having encountered rain further north into the Sahara than he had ever previously seen; and it was discovered, long afterwards, that these rains had been associated with heavy locust breeding in uninhabited and normally arid areas of the north-western Sudan.

An even more important effect of a single disturbance associated with the ITCZ was shown by an exceptional tropical cyclone which moved into south-eastern Arabia in October 1948, and of which the probable importance, in relation to the overall dynamics of the Desert Locust, was established long afterwards [26, 99]. Detailed analysis has shown that the air which was brought into the circulation of the cyclone from the surrounding countries must be expected to have collected from wide areas locusts from any scattered solitary-living populations as well as survivors from several swarming populations. The associated widespread and heavy rains provided conditions particularly suitable for the rapid multiplication of all such immigrants ; and new swarms, which subsequently played a vital part in the resurgence of the plague (otherwise in almost complete recession) were in fact produced on a substantial scale. This illustrates the manner in which current synoptic analysis, even for areas where no regular observations are available, might occasionally provide indications of weather of vital importance to subsequent locust control operations.

The second major class of synoptic features which have been found significant in relation to locust movements are those associated with extra-tropical disturbances — depressions and troughs of low pressure, often with corresponding frontal systems, travelling in a generally eastward direction along the Mediterranean and Persian Gulf and across north-western Indo-Pakistan, and often associated with eastward-moving disturbances of higher latitudes. The importance of these synoptic features (in relation to effects upon locusts as well as to the meteorological mechanisms involved) arises from the corresponding changes not only in wind-field but in air temperature. More than twenty years ago it was noted that northward and north-eastward swarm movements in spring in Baluchistan were attributable to downwind displacement in the warm sectors of passing depressions [111]. Such effects were later shown to be the probable explanation of the apparent paradox of the characteristically northward spread of swarms in spring across the countries of northern Africa and the Near East, against the general direction of the corresponding prevailing northerly winds [92, 93], with the higher temperatures associated with the southerly winds in the warm sector of a depression operating as a "rectifying factor" [50], favouring displacement in a northerly direction by increasing flight activity.

The operation of such a "rectifying effect" would of course be dependent on the actual conditions being such as to stimulate flight activity in the warm sector and to depress it in the cold sector. Evidence of a reversal of this effect at substantially higher temperatures later in the season was provided by field experience in western Tripolitania in June 1957. Widespread fledging was in progress in a heavy hopper infestation less than 20 km to the south of the coastal cultivations around Zuara, when the prevailing north-westerly winds, with air temperatures up to 30° or so, were interrupted on the 9th and 10th by the passage of a depression, with southerly "Ghibli" winds in which temperatures of up to 42° were recorded. Air temperatures as high as this, however, could be expected to restrict flight activity (pp. 8-9), not to promote it ; only isolated adult locusts were in fact seen in Zuara on the 10th, and no serious invasion of the cultivations was recorded.

In forecasting the more usual type of northerly swarm movement in association with the passage of disturbances in the spring, the type of movement to be expected is commonly known, in general terms, from the records of earlier years, and interest centres primarily on the timing and extent of the movement. The problem is therefore that of recognizing, as early as possible, the development of a disturbance sufficiently vigorous to re-distribute the locusts in this manner — or, sometimes, recognizing an early member of a family of such disturbances, such as made possible the provision by DLIS of five days' warning of the invasion of Iraq by swarms in April 1961, and six days' warning of the main invasion of the same country in March 1962.

In recognizing the onset of such disturbances, and in distinguishing them from the larger number of less significant features often shown by analyses of surface observations, it has been found useful to follow the practice of a number of the services in the area [47, etc.] by concentrating particular attention on the 850 mb contour chart, together with isotherms for the same level. Here, again, any advances in synoptic research enabling the development of such disturbances to be recognized at an earlier stage would enable correspondingly earlier warning of the associated locust developments to be given. Preliminary studies of the data available for March-May of 1961 and 1962 have shown that out of a dozen disturbances passing through the eastern Mediterranean area which affected locusts in this manner, only a single disturbance could be traced back for as much as 14 days, across the Atlantic, while half of the number could only be clearly followed back for four days or less [124].

Perhaps one of the most important findings of the work associated with the WMO Mission, and one well substantiated by subsequent experience, has been the repeated occurrence of situations in which swarms have shown no significant displacement for extended periods, attributable in a number of cases to features of the wind-field not shown by routine synoptic analyses of the area — sometimes by reason of scale, involving meso-scale features such as anabatic circulations, and sometimes because the feature concerned, such as a coastal front, may occur so regularly as to be of little value in forecasting day-to-day changes in weather.

Such features become of still greater importance in relation to forecasts on the shortest of the time-scales under consideration, for the day-to-day and hour-by-hour displacements of swarms on the meso-scale. It is on this scale, and particularly in assisting in the establishment and maintenance of contact with swarms by aircraft, that meteorological guidance has so far been found of the most immediate value in locust control, directly increasing the effectiveness of air reconnaissance and of subsequent control with corresponding saving in flying time.

Air reconnaissance has been found capable of providing basic locust information available in no other way, not only on the tracks of individual swarms, as presented in chapter 2, but also on the number and size of swarms involved in a complete invasion [95, 101]. The effectiveness of such air reconnaissance, however, has been found to be highly dependent on appropriate flight planning, briefing and aircrew experience. In appropriate flight-planning, meteorological guidance plays a part which is always important and at times predominant, both for the initial location of swarms and for the subsequent maintenance of contact with them. For the initial location of swarms, it is convenient to distinguish, in the first place, problems of interception, particularly relating to periods of long-range movement and re-distribution of swarms, when interest centres on wind-fields which may be quasi-uniform (e.g. p. 105) or showing a degree of day-to-day variation in which early-morning pilot-balloon ascents have been found to make it possible to plan the interception of swarms approaching from different quarters on different days (e.g. Figure 2), from, secondly, problems of the location of swarms at times when their overall distribution is showing little change, when interest centres on meteorological factors, especially features of the local wind-field, likely to be involved in maintaining this static distribution. Particular attention must of course be paid in this connexion to any localized and semi-permanent zones of low-level convergence such as may be associated with the Inter-Tropical Front, coastal fronts and anabatic wind systems. The recognition and location of such zones may be of the greatest value in narrowing down the areas which are to be intensively searched for swarms.

The efficient maintenance of subsequent contact with a particular swarm involves taking full account of all available information on the wind-field concerned (even of very light winds, down to 1 m/sec) if the swarm is likely to have been in flight since the last sighting, and planning to put into immediate effect a pre-arranged systematic search procedure [39], such as "square search" or "creeping line ahead", if the swarm is not immediately sighted in the vicinity of its forecast position. Experience, from a considerable number of areas and seasons, including very light infestations as well as heavy ones, has also shown that locating a swarm, however small, must be regarded as evidence of the probable presence of others within a few tens of kilometres. In utilizing upper-wind observations for forecasting the direction of displacement of high-flying swarms (extending up to heights of the order of 1,000 m above the ground), it is possible that, given further observations on such swarms (p. 19), some improvement might be envisaged from the use of a modified vectorial mean wind, analogous to the "equivalent constant wind" used to meet artillery requirements, weighted in favour of the winds at the lower levels of the swarm to correspond with the greater numbers of flying locusts at these levels.

Information from national meteorological services which has been found of direct value in the course of such operations has ranged from detailed synoptic analyses (as provided by the East African Meteorological Department to Desert Locust Survey headquarters Nairobi from late 1949 onwards) and observations specially made by the Meteorological Department for locust control (such as the pilot-balloon ascents made during periods of aircraft operations at Wajir from 1952 onwards), to telegraphic collectives of upper-wind observations at neighbouring stations (still useful in circumstances of minimal telecommunications facilities). In addition, locust control facilities and staff have provided supplementary local meteorological data, of which pilot-balloon observations at a number of the airstrips concerned, such as Borama and Mtito Andei, have been found of particular value. Such ascents should either be by the tail method, for which a second, air-filled balloon, containing also a few grammes of water, represents a considerable improvement on the usual paper tail [117]), or by twin theodolites (for which a measured length of field-telephone cable has been found a convenient and portable field baseline [96]). The problem of a portable hydrogen supply, in circumstances in which cylinders have not been practicable, has been found to be conveniently met by a low-pressure generator using caustic soda and scrap aluminium, as used in the early days of a number of the meteorological services in eastern Africa.

Moreover, locust control aircraft have provided not only vital visual reports of winds and weather but also relevant instrumental observations [96] on vertical profiles of temperature and humidity (by strut psychrometer and sensitive altimeter), wind (by drift-sights), vertical air movements (by sailplane variometer) and turbulence (by counting accelerometer). In addition, surface observations (even purely visual ones) by anti-locust detachments in areas remote from established synoptic stations have at times (e.g. pp. 73–94) been of the greatest value in helping to locate synoptic and meso-scale features of importance in relation to locusts. While, in this Note, emphasis has been laid on the immediate possibilities of the fuller utilization of existing meteorological data and facilities in providing guidance to locust control organizations, future improvements in synoptic coverage, particularly additional upper-air observations from a number of areas such as Arabia and the Somali peninsula, would of course also be of direct value in relation to locust control as well as to synoptic services in general.

Finally, in planning air reconnaissance for locust swarms, as in considering other problems of the distribution of airborne organisms, from bacteria to birds, it is necessary, while making the fullest use of all relevant information on the physical aspects of systems such as flying swarms, to take also comparable cognizance of the biological aspects of these systems. Thus, for example, the effective rate of search achieved for swarms has been shown, under particular conditions, to vary with time of day by two orders of magnitude, as a result of regular diurnal changes in relevant aspects of locust behaviour, with the locusts at one time of day (mid-morning) invisible from the air except from immediately above the swarm, and with the same swarm at another time of day (mid-late afternoon) flying high and visible from distances of as much as 100 km [101].

References

1. Allen, J. E., 1953–55 — Records of aircraft spraying operations in eastern Africa. Unpublished.

2. Aspliden, C. I. H., 1960 — The work of the WMO Technical Assistance Mission for Desert Locust control. *In* Tropical Meteorology in Africa. Proceedings of the Symposium. Nairobi, Munitalp Foundation, pp. 420–426.

3. Aspliden, C. I. H. and Rainey, R. C., 1961 — Desert Locust control. Findings of the WMO Technical Assistance Mission. WMO Bull., **10**, pp. 155–161.

4. Ballard, E., Mistikawy, A. M. and El Zoheiry, M. S., 1932 — The Desert Locust (*Schistocerca gregaria* Forsk.) in Egypt. Bull. Minist. Agric. Egypt, **110**, 149 pp.

5. Bellamy, J. C., 1954 — Objective calculations of divergence, vertical velocity and vorticity. Bull. Amer. Met. Soc., **30**, pp. 45–49.

6. Besnault, C., Roy, J. and Rossetti, C., 1962 — Distribution des pontes et des pullulations larvaires de *Schistocerca gregaria* Forsk. signalées entre 1950 et 1961 en Afrique occidentale. FAO Report No. UNSF/DL/ES/1. 86 pp.

6 a. Bhatia, D. R. and Mital, V. P., 1962 — Displacement of invading Desert Locust swarms during 1959 in India in relation to wind movements. Indian J. Ent., New Delhi, **23** (1961), pp. 225–229, 1 map.

7. Bhatia, G. N., 1961 — Observations on concentrated solitary breeding of Desert Locust (*Schistocerca gregaria* Forsk.) in Rajasthan (India) during 1956. Indian J. Ent. **21** (1959), pp. 77–81.

8. Brooks, C. E. P. and Carruthers, N., 1953 — Handbook of Statistical Methods in Meteorology. London H.M.S.O.

9. Brooks, C. E. P. and Durst, C. S., 1935 — The circulation of air by day and night during the south-west monsoon near Berbera, Somaliland. Quart. J.R. Met. Soc., pp. 167–177.

10. Burtt, E. T. and Catton, W. T., 1956 — Electrical responses to visual stimulation in the optic lobes of the locust and certain other insects. J. Physiol., **133**, pp. 68–88.

11. Buxton, P. A., 1955 — Animal Life in Deserts. A study of the fauna in relation to the environment. London, Edward Arnold Ltd.

12. Byers, H. R. and Braham, R. R., 1949 — The Thunderstorm. Report of the Thunderstorm Project. Washington, United States Department of Commerce.

13. Clackson, J. R., 1947 — Notes on forecasting in East Africa. Nairobi, Meteorological Service Press. 6 pp.

14. Cochemé, J. A. M., 1960 — Some streamlines and contours over the Equator. *In* Tropical Meteorology in Africa. Proceedings of the Symposium. Nairobi, Munitalp Foundation, pp. 181–211.

15. Cochemé, J. A. M., 1960 a — Interim report on divergence computations for locust met. comparisons. Nairobi, UN/WMO Technical Assistance Mission for Desert Locust Control. 9 pp. Typescript. Unpublished.

16. Davey, P. M., 1954 — Quantities of food eaten by the Desert Locust (*Schistocerca gregaria* Forsk.), in relation to growth. Bull. ent. Res., **45**, pp. 539–551.

17. Davies, D. E., 1952 — Seasonal breeding and migrations of the Desert Locust (*Schistocerca gregaria* Forsk.) in north-eastern Africa and the Middle East. Anti-Locust Mem., **4**. 56 pp.

18. Desert Locust Survey, 1956 — Report of the Desert Locust Survey and Control. 1st January 1953 - 30th June 1955. Nairobi, East Africa High Commission. 70 pp.

19. Donnelly, U., 1947 — Seasonal breeding and migrations of the Desert Locust (*Schistocerca gregaria* Forsk.) in western and north-western Africa. Anti-Locust Mem., **3**. 42 pp.

20. Durst, C. S., 1946 — Radio climatology. *In* Meteorological Factors in Radio-wave Propagation. Report of a Conference held on 8 April 1946, London, Physical Society, pp. 193–212.

21. Durst, C. S., 1961 — Unpublished report.

22. Eldridge, R. H., 1957 — A synoptic study of west African disturbance lines. Quart. J.R. Met. Soc., **83**, pp. 303–314.

23. El Fandy, M. G., 1940 — The formation of depressions of the Khamsin type. Quart. J.R. Met. Soc., **66**, pp. 323–336.

24. Ellis, P. E., 1959 — Learning and social aggregation in locust hoppers. Anim. Behav., **7**, pp. 91–106.

25. Ellis, P. E. and Ashall, C., 1957 — Field studies on diurnal behaviour, movement and aggregation in the Desert Locust (*Schistocerca gregaria* Forsk.). Anti-Locust Bull., **25**. 94 pp.

26. FAO, 1956 — Report of the FAO panel of experts on the long-term policy of Desert Locust control, London, April 1956. No. 1956/11. 27 pp.

27. FAO, 1958 — Report of the Fifth Session of the FAO Desert Locust Control Committee, Rome, June 1958. No. 1958/11. 44 pp.

28. FAO, 1959 — Report of the FAO panel of experts on the use of aircraft for Desert Locust control, Rome, April 1959. No. 1959/4. 26 pp.

29. FAO, 1959 a — Report of the FAO panel of experts on the strategy of Desert Locust plague control, Rome, April-May 1959. No. 1959/5. 26 pp.

30. FAO, 1959 b — Desert Locust Ecological Survey —Field records. Unpublished.

31. FAO, 1961–63 — Desert Locust Information Service. Unpublished studies.

32. Flohn, H., 1960 — The structure of the Inter-Tropical Convergence Zone. *In* Tropical Meteorology in Africa. Proceedings of the Symposium. Nairobi, Munitalp Foundation, pp. 244–252.

33. Fortescue-Foulkes, J., 1953 — Seasonal breeding and migrations of the Desert Locust (*Schistocerca gregaria* Forsk.) in south-western Asia. Anti-Locust Mem., **5**. 35 pp.

34. Glover, J., Robinson, P. and Henderson, J. P., 1954 — Provisional maps of the reliability of annual rainfall in East Africa. Quart. J.R. Met. Soc., **80**, pp. 602–609.

35. Grinsted, W. A., 1963 — Private communication.

36. Gunn, D. L., 1960 — The biological background of locust control. Annu. Rev. Ent., **5**, pp. 279–300.

37. Gunn, D. L., 1960 a — Nomad encompassed. The development of preventive control of the Red Locust, *Nomadacris septemfasciata* Serville, by the International Red Locust Control Service. J. ent. Soc. S. Afr. **23**, pp. 65–125.

38. Gunn, D. L., 1963 — Private communication.

39. Gunn, D. L., Graham, J. F. *et al.*, 1948 — Aircraft spraying against the Desert Locust (*Schistocerca gregaria* Forsk.) in Kenya, 1945. Anti-Locust Bull., **4**. 121 pp.

40. Gunn, D. L., Perry, F. C. *et al.*, 1948 — Behaviour of the Desert Locust (*Schistocerca gregaria* Forsk.) in Kenya in relation to aircraft spraying. Anti-Locust Bull., **3**. 70 pp.

41. Gurdas Singh, 1952 — Formation of incipient swarms of the Desert Locust in India in 1949. Indian J. Ent., **13**, pp. 109–116.

42. Gurdas Singh and Bhatia, K. R., 1952 — Population density of hopper bands of the Desert Locust (*Schistocerca gregaria* Forsk.) in different instars. Indian J. Ent., **14**, pp. 161–164.

43. Hamilton, R. A. and Archbold, J. W., 1945 — Meteorology of Nigeria and adjacent territory. Quart. J.R. met. Soc., **71**, pp. 231–265.

44. Haskell, P. T., 1957 — The influence of flight noise on behaviour in the Desert Locust (*Schistocerca gregaria* Forsk.). J. Insect Physiol., **1**, pp. 52–75.

45. Hurst, H. E. and Black, R. P., 1943 — The Nile Basin. Volume VI. Monthly and annual rainfall totals and number of rainy days at stations in and near the Nile Basin for the period ending 1937. Cairo, Government Press.

46. Jensen, M., 1956 — Biology and physics of locust flight. III. The aerodynamics of locust flight. Phil. Trans., (B) **239**, pp. 511–552.

47. Johnson, D. H. and Mörth, H. T., 1960 — Forecasting research in East Africa. *In* Tropical Meteorology in Africa. Proceedings of the Symposium. Nairobi, Munitalp Foundation, pp. 56–137.

48. Johnston, H. B., 1926 — A further contribution to our knowledge of the bionomics and control of the Migratory Locust (*Schistocerca gregaria* Forsk.) (*peregrina* Oliv.) in the Sudan. Bull. Wellcome trop. Res. Lab. (Ent.), **22**. 14 pp.

49. Joyce, R. J. V., 1962 — Report of the Desert Locust Survey 1st June 1955 to 31st May 1961. Nairobi, East African Common Services Organization. 112 pp.

50. Kennedy, J. S., 1951 — The migration of the Desert Locust (*Schistocerca gregaria* Forsk.). I. The behaviour of swarms. II. A theory of long-range migrations. Phil. Trans, (B) **235**, pp. 163–290.

51. Kennedy, J. S., 1956 — Phase transformation in locust biology. Biol. Rev., **31**, pp. 349–370.

52. Kennedy, J. S., 1961 — Continuous polymorphism in locusts. 1st Symp. R. ent. Soc. Lond., London 1961, pp. 80–90.

53. Kenya, 1954–55 — Reports from provincial and district administrative and agricultural officers. Unpublished.

54. Kingsley, G., 1954 — Aircraft spraying reports. Unpublished.

55. Kraus, E. B., 1958 — Meteorological aspects of Desert Locust control. *In* Arid Zone Research: XI. Climatology and Microclimatology. Proceedings of the Canberra Symposium. Paris, UNESCO, pp. 211–216.

56. Kraus, E. B., 1961 — Private communication.

57. Krogh, A. and Weis-Fogh, T., 1952 — A roundabout for studying sustained flight of locusts. J. exp. Biol., **29**, pp. 211–219.

58. Kruger, E., 1960 — Forecasting divergence as a tool to forecast thunderstorms in the Sudan. *In* Tropical Meteorology in Africa. Proceedings of the Symposium, pp. 156–167.

59. Kruger, E., 1961 — The structure of the Inter-Tropical Convergence Zone in the Sudan. Sudan met. service, 12 pp. Typescript. Unpublished.

60. Lean, O. B., 1960 — Annual and monthly frequencies of Desert Locust infestations. FAO Pl. Prot. Bull., **8**, pp. 82–85.

61. MacCuaig, R., Rainey, R. C. *et al.*, 1958 — Desert Locust Survey. Research using aircraft in British Somaliland, 1957. A.L.R.U. Porton. Report No. 2/58. 20 pp. Mimeograph. Unpublished.

62. McDonald, D., 1955 — Report on target swarms 21 and 22, and the change from air-to-air to air-to-ground spraying. 24 February - 26 March 1955. 23 pp. Typescript. Unpublished.

63. McDonald, D., 1955 a — The East African airspray campaign. January-May 1955. 20 pp. Typescript. Unpublished.

64. McDonald, D., 1955 b — Airspray campaign against swarms in the Somaliland Protectorate, June-September 1955. 58 pp. Typescript. Unpublished.

65. McDonald, D., 1956 — Methods for calculating the pick-up of spray droplets by locusts under most conditions of behaviour, with their applications to field observations and practical control. 3 + 89 + 6 pp. Typescript. Unpublished.

66. McKillop, A. T. and Gough, L. H., 1916 — Report on the great invasion of locusts in Egypt in 1915 and the measures adopted to deal with it. Cairo, Government Press. 72 pp.

67. Magor, J. I., 1962 — Rainfall as a factor in the geographical distribution of the Desert Locust breeding areas, with particular reference to the summer breeding area of India and Pakistan. Ph.D. thesis, Edinburgh.

68. Mallamaire, A. and Roy, J., 1959 — La lutte contre le criquet pèlerin (*Schistocerca gregaria* Forsk.) en Afrique Occidentale Française. Bull. Prot. Vég., 1958, pp. 1–113.

69. Manning, H. L., 1956 — The statistical assessment of rainfall probability and its application in Uganda agriculture. Proc. roy. Soc., (B) **144**, pp. 460–480.

70. Mason, B. J., 1959 — *In* Rainey, R. C., 1959. Quart. J.R. met. Soc., **85**, p. 171.

71. Maxwell-Darling, R. C., 1936 — The outbreak centres of *Schistocerca gregaria* Forsk. on the Red Sea coast of the Sudan. Bull. ent. Res., **27**, pp. 37–66.

72. Maxwell-Darling, R. C., 1937 — The outbreak areas of the Desert Locust (*Schistocerca gregaria* Forsk.) in Arabia. Bull. ent. Res., **28**, pp. 605–618.

73. Maxwell-Darling, R. C., 1948 — Locusts in the Sudan. *In* Tothill, J. D. (Ed.) Agriculture in the Sudan. Oxford University Press, pp. 404–415.

74. Michelmore, A. P. G., 1954 — Locust report for period July to mid-December 1954 in the Uganda Protectorate. 6 pp. Typescript. Unpublished.

74 a. Monod, T., 1958 — Majâbat âl-Koubrâ. Contribution à l'étude de l'« Empty Quarter » ouest-saharien. Mém. Inst. franç. Afr. noire, nº 52. 406 pp. (see pp. 257-259).

75. Morris, H. J., 1954 — Aerial spraying of swarms : July 1954. Sudan, Wadi Medani. 5 pp. Mimeograph. Unpublished.

76. Morris, H. J., 1955 — Aerial spraying of swarms : June 1955. Sudan, Wadi Medani. 2 pp. Mimeograph. Unpublished.

77. Morris, H. J., 1955 a — Unpublished data of the Sudan Desert Locust Survey.

78. Morris, H. J., 1959 — Report on behaviour of locusts in irrigated crops. Typescript. Unpublished.

79. Mudie, F., 1955 — Report of the Commission on the Desert Locust Control Organisation. Nairobi, East Africa High Commission. 87 pp.

80. Needham, J., 1942 — Biochemistry and Morphogenesis. Cambridge University Press.

81. Palmer, C. E., Wise, C. W., Stempson, L. J. and Duncan, G. H., 1955 — The practical aspect of tropical meteorology. Air Force Surveys in Geophysics No. 76. Bedford, Mass., Air Force Cambridge Research Center. 195 pp.

82. Parthasarathy, K., 1958 — Some aspects of the rainfall in India during the south-west monsoon season. Symposium on Monsoons of the World, New Delhi 1958, pp. 185–194.

83. Pasquier, R., 1942 — Prévision et périodicité des invasions de la sauterelle pèlerine en Afrique du Nord. Bull. Soc. Agric. Algér., **85**, pp. 51–70.

84. Pasquier, R., 1942 a — Les sauterelles pèlerines. L'invasion actuelle, les recherches, la lutte. L'Agria, No. 99. 12 pp.

85. Pasquier, R., 1959 — Quelques propos sur la sauterelle pèlerine. Bull. tech. Ing. Serv. agric., No. 142, pp. 495–505.

86. Pedgley, D. E., 1958 — Summer sea-breeze at Ismailia. London, Meteorological Office Report No. 19 (3rd part of vol. 3). 19 pp.

87. Popov, G. B., 1954 — Notes on the behaviour of swarms of the Desert Locust (*Schistocerca gregaria* Forsk.) during oviposition in Iran. Trans. R. ent. Soc. London, **105**, pp. 65–77.

88. Popov, G. B., 1958 — Ecological studies on oviposition by swarms of the Desert Locust (*Schistocerca gregaria* Forsk.) in eastern Africa. Anti-Locust Bull., **31**. 70 pp.

89. Pramanik, S. K., 1952 — Hydrology of the Rajasthan Desert — rainfall, humidity and evaporation. Bull. Nat. Inst. Sci. India, **1**, pp. 183–197.

90. Predtechenskii, S. A., 1938 — The annual cycle of the Desert Locust (*Schistocerca gregaria* Forsk.), its migrations and periodicity in Persia and adjacent countries of tropical and subtropical Asia. New Delhi, Government India Press. (Translated from the Russian : Bull. Pl. Prot., Leningr. No 12, 1935.)

91. Rainey, R. C., 1948 — "Coastal fronts" in South Africa. Quart. J.R. Met. Soc., **74**, pp. 199–200.

92. Rainey, R. C., 1951 — Weather and the movements of locust swarms : a new hypothesis. Nature, London, **168**, pp. 1057–1060.

93. Rainey, R. C., 1952 — Desert Locust swarm movements and weather. (Abstr.) Proc. R. ent. Soc., London, (C) **17**, pp. 45–46.

94. Rainey, R. C., 1956 — Research. *In* Desert Locust Survey, 1956. Nairobi, East Africa High Commission, pp. 45–58.

95. Rainey, R. C., 1958 — The use of insecticides against the Desert Locust. J. Sci. Fd. Agric., **9**, pp. 677–692.

96. Rainey, R. C., 1958 a — Some observations on flying locusts and atmospheric turbulence in eastern Africa. Quart. J.R. Met. Soc., **84**, pp. 334–354.

97. Rainey, R. C., 1959 — Some observations on flying locusts and atmospheric turbulence in eastern Africa. Discussion. Quart. J.R. Met. Soc., **85**, pp. 171–173.

98. Rainey, R. C., 1960 — Applications of theoretical models to the study of flight-behaviour in locusts and birds. Symp. Soc. exp. Biol., **14**, pp. 122–139.

99. Rainey, R. C., 1962 — Some effects of environmental factors on movements and phase-change of locust populations in the field. Colloq. int. Cent. nat. Rech. sci., Paris, **114**, pp. 175–199.

100. Rainey, R. C., 1962 a — National reporting and forecasting service. Advisory visits to the United Arab Republic, Sudan, Ethiopia, Lebanon and Iran. FAO Report No. UNSF/DL/RFS/I. 23 pp.

101. Rainey, R. C., 1963 — Aircraft reconnaissance and assessment of locust populations. 2nd Int. Agric. Aviat. Congr., Grignon 1962, pp. 228-233.

102. Rainey, R. C. and Sayer, H. J., 1953 — Some recent developments in the use of aircraft against flying locust swarms. Nature, London, **172**, pp. 224–228.

103. Rainey, R. C. and Sayer, H. J., 1957 — Unpublished field observations.

104. Rainey, R. C. and Waloff, Z., 1948 — Desert Locust migrations and synoptic meteorology in the Gulf of Aden area. J. Anim. Ecol., **17**, pp. 101–112.

105. Rainey, R. C. and Waloff, Z., 1951 — Flying locusts and convection currents. Anti-Locust Bull., **9**, pp. 51–70.

106. Rainey, R. C., Waloff, Z. and Burnett, G. F., 1957 — The behaviour of the Red Locust (*Nomadacris septemfasciata* Serville) in relation to the topography, meteorology and vegetation of the Rukwa Rift Valley, Tanganyika. Anti-Locust Bull., **26**. 96 pp.

107. Rainey, R. C., Waloff, Z. and Sayer, H. J. — Observations on the behaviour of flying Desert Locusts in eastern Africa (in preparation).

108. Rao, Y. R., 1938 — A preliminary note on a study of locust infestations in North-West India since 1863 in relation to sunspot cycles. 5th Int. Locust Conf., Brussels 1938, pp. 252–257.

109. Rao, Y. R., 1942 — Some results of studies on the Desert Locust (*Schistocerca gregaria* Forsk.) in India. Bull. ent. Res., **33**, pp. 241–265.

110. Rao, Y. R., 1954 — An unusual appearance of Desert Locust swarms on the Malabar coast in October 1952. Curr. Sci., **23**, pp. 248–251.

111. Rao, Y. R., 1960 — The Desert Locust in India. New Delhi, Indian Council of Agricultural Research.

112. Remaudière, G., 1955 — Le problème acridien. Nature, Paris, **83**, pp. 97–102, 149–154.

113. Roffey, J., 1963 — Observations on night flight in the Desert Locust (*Schistocerca gregaria* Forsk.). Anti-Locust Bull., **39**. 32 pp.

114. Roy, J., 1958 — Private communication.

115. Rungs, C., 1946 — Rapport sur les essais de lutte contre les adultes de *Schistocerca gregaria* Forsk. au Maroc français au printemps de 1945. Bull. sem. Off. nat. anti-acrid., Alger. **2**, pp. 41–87.

116. Rungs, C., 1960 — La physiologie du criquet pèlerin, comportement et méthodes de lutte qui en découlent. *In* Lectures of the First Desert Locust Training Course, Morocco, 1960. FAO Report No. UNSF/DL/TC/2, pp. 61–74.

117. Rushforth, J. M. and Pearce, R. P., 1962 — Preliminary investigations into the air-flow over Bishop Hill, Kinross, using tail balloons. Weather, **17**, pp. 136–141.

118. Sawyer, J. S., 1947 — The structure of the inter-tropical front over N.W. India during the S.W. monsoon. Quart. J.R. Met. Soc., **73**, pp. 346–369.

119. Sawyer, J. S., 1952 — Memorandum on the Inter-Tropical Front. Met. Rep. London, 2 (5) (1951). 14 pp.

120. Sayer, H. J., 1952–57 — Unpublished field observations.

121. Sayer, H. J., 1954 — Private communication.

122. Sayer, H. J., 1956 — A photographic method for the study of insect migration. Nature, London, **177**, p. 226.

123. Sayer, H. J., 1962 — The Desert Locust and tropical convergence. Nature, London, **194**, pp. 330–336.

124. Shaw, B., 1962 — Unpublished studies.

125. Shcherbinovskii, N. S., 1952 — The Desert Locust *Schistocerca*. The problem of the defence of southern territories of the USSR against invasions by *Schistocerca* swarms. [In Russian.] Moscow, State Publishers of Agricultural Literature.

126. Shulov, A., 1952 — The development of eggs of *Schistocerca gregaria* Forsk. in relation to water. Bull. ent. Res., **43**, pp. 469–476.

127. Shumakov, E. M., 1962 — Study of locust ecology in the U.S.S.R. with special reference to the development of opinions on phase variation. Colloq. int. Cent. nat. Rech. sci., Paris, **114**, pp. 217–228.

128. Soliman, K. H., 1951 — Air masses and quasi-stationary fronts in spring and summer over the Middle East. Proc. math. phys. Soc. Egypt, **4**, pp. 15–30.

129. Solot, S. B., 1945 — The Meteorology of Central Africa — Report of Research, Weather Research Center, 19th Weather Region. Accra, Gold Coast, 1943.

129a. Srivastava, A. S., 1958 — Movement and direction of swarms of the Desert Locust (*Schistocerca gregaria* Forsk.) in Uttar Pradesh (India) during 1954. — 10th Int. Congr. Ent., Montreal 1956, vol. 3, pp. 465–467, 10 Figs.

123a. Shabbar, M., 1952 — Relationship between weather and locust swarms over Indo-Pak subcontinent.
Part I – Monthly mean position of Inter-Tropical Convergence Zone and its slope
Part II – Movements of locust swarms and the Inter-Tropical Convergence Zone.
32 pp. Mimeograph. Unpublished.

130. Stephenson, P. R., 1951 — *In* Rainey, R. C., 1951. Nature, London, **168**, p. 1060.

131. Stower, W. J., 1963 — Photographic techniques for the analysis of locust "hopper" behaviour. Anim. Behav., **11**, pp. 198–205.

132. Stower, W. J., Davies, D. E. and Jones, I. B., 1960 — Morphometric studies of the Desert Locust (*Schistocerca gregaria* Forsk.). J. Anim. Ecol., **29**, pp. 309–339.

133. Tanganyika, 1954–55 — Reports from provincial and district administrative and agricultural officers. Unpublished.

134. Trench, J. F., 1951 — Aircraft reconnaissance reports. Unpublished.

135. Uvarov, B. P., 1928 — Locusts and Grasshoppers. A Handbook for their Study and Control. London, Imperial Bureau of Entomology.

136. Uvarov, B. P., 1931 — Insects and climate. Trans. ent. Soc., London, **79**, pp. 1–247.

137. Uvarov, B. P., 1957 — The aridity factor in the ecology of locusts and grasshoppers of the Old World. *In* Arid Zone Research: VIII. Human and Animal Ecology. Reviews of Research. Paris, UNESCO, pp. 164–198.

138. Vayssière, P., 1954 — Le problème acridien sur le continent africain. Rev. Etud. Calam., **14**, pp. 23–36.

139. Walker, H. O., 1958 — The monsoon in West Africa. Symposium on Monsoons of the World, New Delhi, 1958, pp. 35–42.

140. Waloff, Z., 1946 — A long-range migration of the Desert Locust from southern Morocco to Portugal, with an analysis of concurrent weather conditions. Proc. R. ent. Soc., London, (A) **21**, pp. 81–84.

141. Waloff, Z., 1946 a — Seasonal breeding and migrations of the Desert Locust (*Schistocerca gregaria* Forsk.) in eastern Africa. Anti-Locust Mem., **1**. 74 pp.

142. Waloff, Z., 1951–55 — Unpublished field observations.

143. Waloff, Z., 1958 — The behaviour of locusts in migrating swarms. (Abstr.) 10th Int. Congr. Ent., Montreal 1956, vol. 2, pp. 567–569.

144. Waloff, Z., 1960 — Some notes on the Desert Locust and on its occurrence at sea. Mar. Obs., **30**, pp. 40–45.

145. Waloff, Z., 1960 a — The fluctuating distribution of the Desert Locust in relation to the strategy of control. Rep. Commonw. ent. Conf., **7**, pp. 132–140.

146. Waloff, Z., 1963 — Field studies on solitary and *transiens* Desert Locusts in the Red Sea area. Anti-Locust Bull., **40**. 93 pp.

147. Waloff, Z. and Betts, E. — Biogeography of the Desert Locust: Part I (in preparation).

148. Waloff, Z. and Rainey, R. C., 1951 — Field studies on factors affecting the displacements of Desert Locust swarms in eastern Africa. Anti-Locust Bull., **9**, pp. 1–50.

149. Weather, 1954 — The weather of October 1954. Weather, **9**, p. 350.

150. Weis-Fogh, T., 1952 — Fat combustion and metabolic rate of flying locusts (*Schistocerca gregaria* Forsk.). Phil. Trans., (B) **237**, pp. 1–36.

151. Weis-Fogh, T., 1956 — Biology and physics of locust flight. II. Flight performance of the Desert Locust (*Schistocerca gregaria*). Phil. Trans., (B) **239**, pp. 459-510.

152. Williams, C. B., 1933 — Observations on the Desert Locust in East Africa from July 1928 to April 1929. Ann. appl. Biol., **20**, pp. 463–497.

153. Williams, C. B., 1958 — Insect Migration. London, Collins.

154. Wootten, N. W. and Sawyer, K. F., 1954 — The pick-up of spray droplets by flying locusts. Bull. ent. Res., **45**, pp. 177–197.

155. WMO, 1953 — Doc. 36. *In* Final Report on the First Session of the Regional Association for Africa, Tananarive (Madagascar), 19–30th January 1953, pp. 166–172.

156. WMO, 1953 a — Doc. 52. *In* Final Report on the First Session of the Regional Association for Africa, Tananarive (Madagascar), 19–30th January 1953, pp. 173–174.

157. WMO, 1953 b — Doc. 66. *In* Final Report on the First Session of the Regional Association for Africa, Tananarive (Madagascar), 19–30th January 1953, pp. 175–184.

158. WMO, 1953 c — Doc. 67. *In* Final Report on the First Session of the Regional Association for Africa, Tananarive (Madagascar), 19–30th January 1953, pp. 184–190.

159. WMO, 1953 d — Doc. 79. *In* Final Report on the First Session of the Regional Association for Africa, Tananarive (Madagascar), 19–30th January 1953, p. 196.

160. WMO, 1953 e — Doc. 84. *In* Final Report on the First Session of the Regional Association for Africa, Tananarive (Madagascar), 19–30th January 1953, pp. 197–198.

161. WMO, 1959 — Provisional Guide to Synoptic Meteorological Practices. WMO, Geneva. 42 pp.

162. Young, R. F., 1954 — Records of aircraft spraying operations in the Sudan. Unpublished.

163. Young, R. F., 1955 — Records of aircraft spraying operations in the Sudan. Unpublished.

Most of the unpublished material cited is on record at the Anti-Locust Research Centre, London.

APPENDIX

HOUR-TO-HOUR MOVEMENTS OF INDIVIDUAL SWARMS IN RELATION TO WIND

	SWARM										WIND				
DATE	Size km×km or km²	Height of flight (topmost locusts) m. above ground	Initial fix: Lat.	Initial fix: Long. E	Initial fix: Time (local)	Displacement between initial and subsequent fix: At (local time)	Displacement: Direction (towards) °T	Displacement: Distance km	Displacement: Ground-speed km/hr	Time, place and method of observation	Vectorial mean wind between ground & level of topmost locusts: Direction (from) °T	Vectorial mean wind: speed km/hr	DEVIATION of displacement of swarm from wind direction degrees	RATIO of ground-speed to wind-speed %	REMARKS
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1951															
Feb. 6	0.4×0.1	15	0025 N	3736	1205	1515	260	10	3	1435 Isiolo PB (+ surface obs.)	080	11	0	27	Unsprayed
Feb. 13	0.7×0.2	60	0024 N	3726	1100	1240	240	9	5	1145–1147, 1215–1230 Isiolo surface obs.	050	19	+10	26	Unsprayed; Locusts mainly below 15 m
1952															
Feb. 7	5	500	0153 N	4015	1118	1355	251	18	7	1215 Wajir PB	073	28	— 2	25	Fig. 2
Feb. 8	4×1	400	0146 N	3945	0936	1114	273	13	8	1200 Wajir PB	091	27	+ 2	29	Fig. 2
Feb. 11	3	300	0135 N	4030	1100	1320	308	8	3	1200 Wajir PB	120	12	+ 8	25	Fig. 2
Feb. 12	5×2	Say 150	0152 N	4007	Roost	1120	311			1210 Wajir PB	108	19	+23	—	Fig. 2
Feb. 14	1.4	200	0150 N	4029	1250	1607	338	21	6	1300 Wajir PB	152	13	+ 6	46	1429 position (approximate only) 0200 N 4027 E
Feb. 15	0.6	300	0205 N	4021	1056	1319	309	8	3	1210 Wajir PB	130	34	— 1	10	Swarm almost completely destroyed by 1550 l. 20 % DNC applied 13th – 15th
1953															
Jan. 14	1.6	Say 100	0128 N	4036	0730	1000	294	19	8	0715 Wajir PB	107	28	+ 7	29	Unsprayed
Jan. 14	1 ½	250	0141 N	4009	1320	1620	284	15	5	1500 Wajir PB	095	17	+ 9	29	
Jan. 14	1 ½	Say 200	0142 N	4001	1620	1720	313	13	13	1710 Wajir PB	112	17	+21	76	
Jan. 22	2	Say 100	0145 N	3956	1710	1800	282	9	11	1815 Wajir PB	085	17	+17	65	Largely destroyed by 1230 l. 20 % DNC applied during 22nd
1954															
Jan. 5	8	> 900	0134 N	4101	1300	c. 1800	310	30	c. 6	1415 Wajir PB	109	6	+21	100	Fig. 9
Jan. 6	3×3	Say 900	0144 N	4048	Roost	1800	300	60	—	1150 Wajir PB	139	15	—19	—	Fig. 9
Jan. 6	4×?	800	0125 N	4038	1140	1555	309	28	7	1150 Wajir PB	139	15	—10	47	Fig. 9
Jan. 6	5	900	0119 N	4008	1155	1530	303	22	6	1150 Wajir PB	139	15	—16	40	Fig. 9
Jan. 7	14×13	900	0126 N	4055	0915	1625	300	84	12	1140 Wajir PB	114	12	+ 6	100	Fig. 9

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Jan. 8	c. 15×?	> 700	0151 N	4003	Roost	1200	c. 290	c. 20	—	1145 Wajir PB	084	17	+26	—	Wind up to 150 m from 103° *
Jan. 9	8×?	1700	0153 N	4019	1105	1700	265	84	14	1215 Wajir PB	065	13	+20	108	
Jan. 12	24×6	1700	0134 N	4042	1200	1520	235	43	13	1205 Wajir PB	023	14	+32	93	Wind up to 150 m from 055° *
Jan. 13	16×?	> 1200	0120 N	3955	1330	1510	254	27	16	1200 Wajir PB	041	15	+33	107	Wind up to 150 m from 063° *
Jan. 21	60	c. 900	0123 S	3737	1440	1700	253	21	9	1413 Nairobi RS	048	28	+25	32	Fig. 8
Jan. 22	60	800	0131 S	3718	1500	1700	232	23	11	1415 Nairobi RS	048	26	+ 4	42	Fig. 8
Jan. 23	60	500	0136 S	3656	1610	1720	237	16	14	1415 Nairobi RS	075	23	—18	61	Fig. 8
Jan. 25	10	c. 600	0143 S	3735	1225	1630	242	13	3	1408 Nairobi RS	051	20	+11	15	Fig. 8
Jan. 26	4×2	600	0238 S	3836	1340	1740	222	39	10	1450 Makindu PB 1335 Makindu PB 1330 Voi PB	030	22	+12	45	Fig. 8
Jan. 27	3×1 ½	500	0255 S	3819	1150	1315	199	8	6	1155 Makindu 1335 Voi	015	12	+ 4	50	Fig. 8
Jan. 28	5×1	c. 500	0316 S	3753	0940	1315	180	4	—	1200 Voi PB	345	7	—15	—	Fig. 8
Jan. 30	10×3	300	0203 S	3735	1120	1550	256	25	5½	1340 Makindu PB	076	6	0	92	Fig. 8
Jan. 31	4×2	200	0206 S	3707	1315	1720	257	24	6	1330 Makindu PB	058	26	+19	23	Fig. 8
1955															
Jan. 27	7×1	300	0020 S	3946	1108	1425	303	5	1½	1105 Garissa PB	114	7½	+ 9	20	Unsprayed (until later)
Jan. 28	4×1	> 180	0011 S	3925	1630	1725	294	11	12	1755 Garissa PB	095	19	+19	63	
Jan. 29	8	300	0005 S	3918	Roost	1210	246	7	—	1150 Garissa PB	082	6	—16	—	
Jan. 29	2	Say 150	0046 S	3926	1700	Roost	255	9	—	1720 Garissa PB	109	10	—34	—	
Feb. 9	1 ½×1	Say 100	0241 S	3811	1555	1705	184	5	4	Surface and cloud obs.	010	11	— 6	36	Unsprayed
Feb. 10	6×5	700	0238 S	3814	1515	1800	199	17½	6	Surface and cloud obs.	010	12	+ 9	50	Unsprayed Plate III and Fig. 10
Feb. 11	20	600	0251 S	3806	1100	1345	185	20	7	1110 Mtito Andei PB	002	9	+ 3	81	Unsprayed (until later) Fig. 10
Feb. 11	5×?	800	0223 S	3817	1255	1527	191	15	6	1110 Mtito Andei PB 1210 Makindu PB	013	9	— 2	67	Unsprayed Fig. 11
Feb. 11	4×2 ½	> 670	0238 S	3811	1714	Roost	257	8	c. 5	1800 Mtito Andei PB	078	14	— 1	36	Unsprayed Fig. 11
Feb. 12	4×2 ½	Say 450	0240 S	3806	Roost	1125	165	4	—	1000 Mtito Andei PB	333	6	+12	—	Unsprayed Fig. 11
Feb. 12	c. 8	Say 450	0242 S	3807	1125	1250	185	4	3	1200 Mtito Andei PB	009	10	— 4	30	Unsprayed Fig. 11
Feb. 13	3×1	> 150	0231 S	3840	1020	1205	173	3	2	1110 Mtito Andei PB	345	9	+ 8	22	Unsprayed
Feb. 15	2×1	> 50	0233 S	3806	1000	1155	197	7	4	0957 Mtito Andei PB	029	8	—12	50	Unsprayed
Feb. 15	c. 5	Say > 800	0329 S	3910	1130	1650	189	48	9	1330 Mombasa PB	014	21	— 5	43	Unsprayed Fig. 10
Feb. 15	25	> 800	0346 S	3917	1255	1640	186	49	13	1330 Mombasa PB	014	21	— 8	62	10,460 l. 20 % DNC applied 0950-1640 15th ; Fig. 10
Feb. 17	8	150	0239 S	3807	1453	1553	205	7	7	1330 Voi PB 1415 Makindu PB	025	23	0	30	Unsprayed
Feb. 17	8	c. 150	0242 S	3806	1540	1720	215	9	5	1742 Mtito Andei PB	035	34	0	15	Unsprayed
1957															
Aug. 6	15	600	1009 N	4300	1200	1430	103	11	4	1110 Borama PB	254	41	+29	10	Unsprayed
Aug. 15	3×2	> 180	0957 N	4310	1010	1235	085	12	5	1145 Borama PB	267	17	— 2	29	

* The only cases found in which the direction of displacement of the swarm appeared to be significantly closer to the direction of the wind at lower levels than to the direction of the vectorial mean wind between the ground and the level of the topmost locusts.

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