Fig. 4 Cumulonimbus mamma over Annapurna Himal, 1015 local time, 28 February 1981

the characteristics of a warm sector. Over the mountains cumulonimbus cloud with mamma formed in a very stormy looking sky (Fig. 4).

This could only have been a disturbance in the upper westerlies, deep enough to affect the weather right down to the low levels. This inclement weather lasted for about one day before the pattern reverted once again to its fineness.

SUMMARY

The trek was a splendid way of getting into the mountains to see the great peaks at close range and to observe the weather changes over them. It gave us the opportunity to see the weather in action with the dramatic cloud developments that occurred, and to experience at first hand some of the marked variations in climate that exist across Nepal.

INSECTS IN THE SEA-BREEZE FRONT AT CANBERRA: A RADAR STUDY

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THE arrival of the sea-breeze during the late afternoon or early evening of a hot summer's day is a frequent event at Canberra, Australian Capital Territory. The phenomenon is well known to the city's inhabitants, the cooler easterly airflow often bringing welcome relief from temperatures which may have fallen only slightly from an afternoon maximum of perhaps 35°C. The penetration of the sea-breeze as far inland as Canberra is perhaps surprising, not so much because the city lies at a distance of 120 km from the sea as because it stands on an extensive tableland at an elevation of about 600 m. Hilly terrain is generally believed to present a considerable barrier to the advance of the sea-breeze, and it is possible that the easterly airflow arriving in Canberra should be classified as a pseudo-sea-breeze which is induced by the temperature differential between the air immediately above the plateau and the air at the same height above the adjacent lowland (Wallington 1977); in this instance the low ground is situated next to the sea, and a true sea-breeze blowing over the coastal plain is likely to strengthen the temperature differential caused by the plateau.

On 22 December 1980 the CSIRO entomological radar, which was being operated on agricultural land just outside Canberra, detected the arrival of this 'sea-breeze' airflow. The passage of the front, which appeared as a strong line-echo on the radar plan-position-indicator (PPI), was observed for just over an hour, during which time a number of measurements were made. Radar echoes from sea-breeze fronts have been detected previously, and have been attributed variously to reflections from refractive index discontinuities (Atlas 1960), insects (Geotis 1964) and, at least in part, birds (Eastwood and Rider 1961). Glider pilots have actually seen birds flying in the sea-breeze front that moves northwards from the coast of southern England (Simpson 1964), but a study at Melbourne, Victoria, (Berson and Simpson 1971) indicated that birds were probably not a significant cause of the radar line-echoes observed in that part of Australia. The Canberra sea-breeze echo was undoubtedly caused almost entirely by insects, which the CSIRO radar is known to be very effective at detecting. Very large numbers of flying insects (especially grasshoppers (Acrididae)) were present in the Canberra region at the time, and as the day was hot the aerial insect population would have been high; moreover, radar observations both immediately before and after the passage of the front showed widespread echoes of the types that have come to be associated with insect activity (Schaefer 1976).

THE RADAR

The CSIRO entomological radar is an incoherent pulse radar which operates on a wavelength of 3·2 cm. The radar is equipped with a parabolic reflector which concentrates the transmitted energy into a 1½ deg wide pencil beam. This beam, which can be directed at any elevation angle, is scanned about the zenith at 20 revolutions per minute. Observations are made on a PPI display which is photographed with a cine camera to produce a time-lapse movie film; the maximum range displayed on the PPI can be adjusted, and in the present study varied between 1500 m and 45 km. The maximum range at which an individual grasshopper can be detected by the CSIRO radar is about 2 km, but concentrations of insects are detectable at much greater ranges.

When the radar antenna is scanned the space swept out by the pencil beam is located on the surface of a cone, the angle of which depends on the elevation angle of the antenna. The range at which a target appears on the PPI therefore also indicates the target's height. Thus by making a series of observations at different elevation angles, it is possible to investigate the vertical extent of the front, and to determine its profile. However, when a conical scan of this type is used, the PPI image of the front may appear distorted: for example, a front that has the form of a simple wedge, with a straight leading edge and a constant slope, will appear bowed on the PPI, as the more distant portions of the front will be detected at a greater height than, and therefore at some distance behind, the portions closest to the radar. At very low elevation angles the PPI picture is further complicated by the undulating terrain of the Canberra area, as the radar beam is then intercepted by areas of high ground, and the image of the front becomes confused by 'clutter' echoes and regions of 'shadow'; these effects make observations at long range relatively difficult.

METEOROLOGICAL OBSERVATIONS

The synoptic chart for south-eastern Australia for 1700 on 22 December 1980 is shown in Fig. 1. Inland stations showed high temperatures and a light northerly airflow circulating around an anticyclone in the Tasman sea; the cold front to the west did not reach Canberra until the following afternoon. Stations along the east coast were all affected by a well-developed on-shore breeze, and coastal temperatures were much

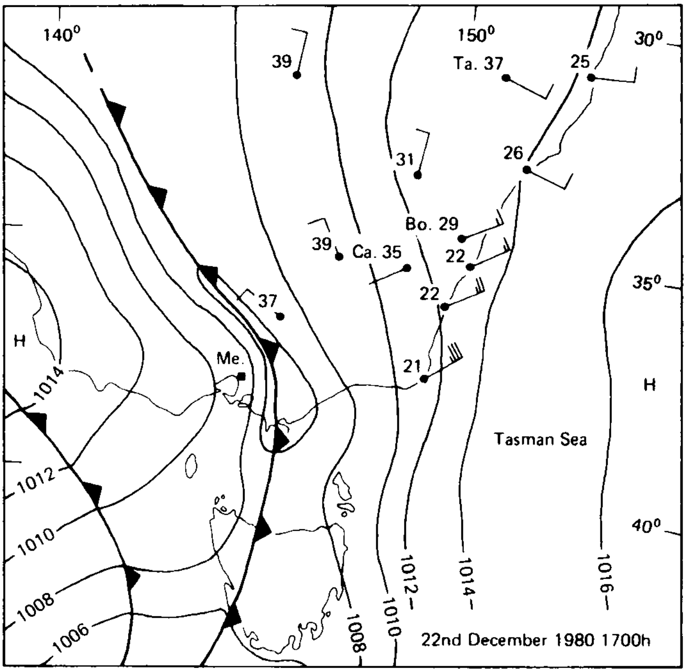

Fig. 1 Synoptic chart for south-eastern Australia for 1700 AEST, 22 December 1980. Surface winds and temperatures (°C) are shown for a number of stations. Key: Bo. – Bowral, Ca. – Canberra, Me. – Melbourne, Ta. – Tamworth.

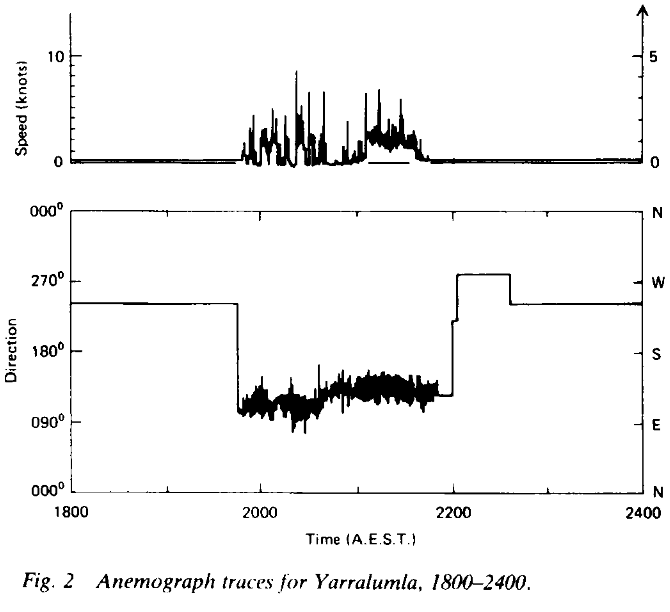

Fig. 2 Anemograph traces for Yarralumla, 1800–2400.

lower than those inland; the on-shore airflow had already moved inland as far as Bowral and, probably, Tamworth. At Canberra, the surface wind was light and – somewhat anomalously – from the south-west; upper winds, measured at 1400, were also light but from the north-north-west. According to the local forecasting staff of the Commonwealth Bureau of Meteorology, the sea-breeze would be expected to extend as far as Canberra when the situation is as shown in Fig. 1.

Anemograph records from three locations in Canberra show that shortly after 1700 the wind dropped further, and all three instruments recorded calm for more than an hour prior to the arrival of the front. The anemograph trace obtained at Yarralumla is illustrated in Fig. 2; it shows the sea-breeze arriving at about 1945 and continuing for a period of almost exactly two hours. The wind was from the east-south-east and light, with maximum (gust) speeds of 3–4 ms^{-1}. The trace at the other two locations was very similar, except that at Canberra Airport (arrival time 1925) the wind was from the east, and at Canberra City (arrival time 1941) it was from the north-east. Temperature and humidity traces also recorded the easterly airflow which manifested itself, unexpectedly, as a temporary halt to the usual evening fall in temperature and rise in humidity; this apparently anomalous effect is presumed to be due to disruption of the low-level nocturnal inversion by the turbulence of the sea-breeze airflow. Observations at the radar site showed that the wind changed from very light westerly to light easterly with the passage of the front. Apart from some slight veil cloud at high level, the sky was completely clear at all times. Sunset was at 1918.

RADAR OBSERVATIONS

The appearance of the PPI screen immediately prior to the arrival of the front is shown in Fig. 3. This photograph was taken at 1927, with the beam directed upwards at an angle of 5 deg and the PPI set to display ranges out to 11 km. The picture shows an intense line-echo to the east-north-east of the radar (which is located at the centre of the screen). The line was moving towards the west-south-west and reached the radar at 1934, ie about seven mins after the photograph was taken. It can be seen that the leading edge of the line is sharp, but the rear edge appears to be rather less well

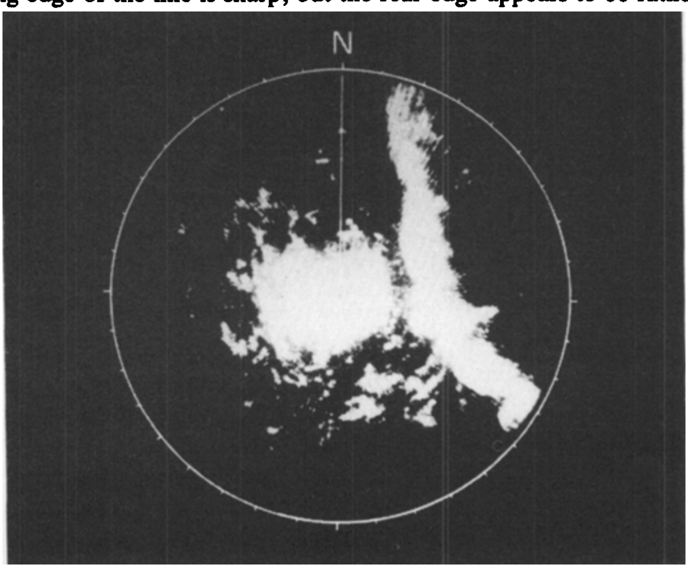

Fig. 3 Photograph of the PPI screen at 1926; antenna elevation angle 5 deg, maximum range displayed 11 km. The intense band of echo to the north-east marks the position of the sea-breeze front

defined. The bowed appearance of the line is at least in part due to the distortion effects described earlier, but a series of undulations or bulges, with lengths along the line of 3–4 km and depths of up to about 750 m, are real; the width of the line varies between 1·5 and 3·0 km. The blotchy echoes to the west of the radar are due to insects concentrated in convection cells. These echoes had been of greater intensity when observations commenced half an hour previously, and their weakening can no doubt be attributed to the cessation of convection towards evening. The echoes had also originally been present in all parts of the screen, and their absence from the region behind the line indicates that the front was sweeping the air clear of flying insects as it advanced. The insects in the front were therefore probably mainly day-flying species which had been carried aloft by convection before being caught up in the sea-breeze airflow.

A more detailed view of the line-echo as it passed overhead is shown in Fig. 4. In this photograph, which was taken at 1936, the antenna elevation angle is 18 deg and the distance from the centre to the edge of the screen is approximately 3 km; the height of the beam at the maximum displayed range is about 900 m. Close to the radar the line appears as a concentration of dot echoes, each representing the position of an individual insect; at longer range (and greater height) the echo is continuous and individual targets cannot be discerned. The intensity of the echo appears to increase with height, and to be greatest at about 700 m above ground level.

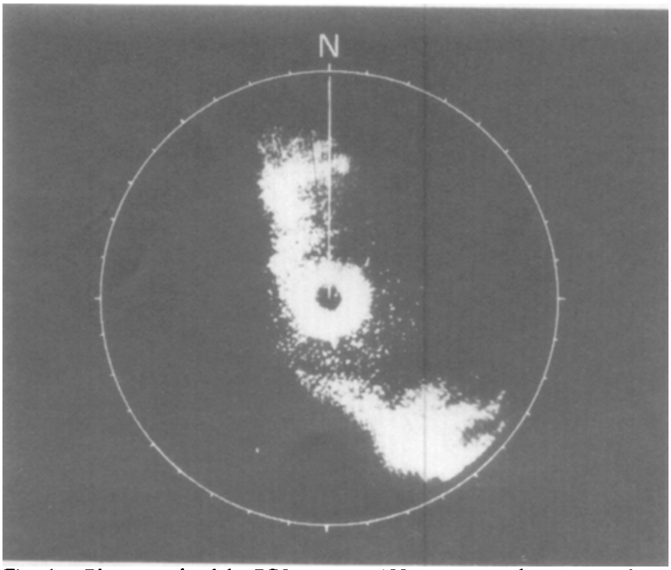

Fig. 4. Photograph of the PPI screen at 1936; antenna elevation angle 18 deg, maximum range displayed 3 km. The sea-breeze echo band is exactly overhead. The diffuse ring echo near the picture centre is an artifact of the radar receiver and should be ignored

The advance of the line-echo during the hour of radar observations is illustrated in Fig. 5. The lines in this figure mark the position of the leading edge of the echo, as determined from a series of photographs of the PPI screen. The figure also shows the position of the three autographic stations and the 700 m contour, which serves to indicate the higher ground. It is evident that the arrival of the line-echo at each of the autographic stations coincides to within a few minutes with the onset there of the easterly airflow; the small discrepancies can probably be accounted for by timing differences between the various autographic instruments and the radar. The line-echo can therefore quite clearly be identified with the sea-breeze front.

Although the varying and uneven nature of the leading edge of the line-echo makes it impossible to determine the front's rate of advance precisely, it is straightforward to obtain an approximate value from Fig. 5. The rate appears to slow somewhat, from about 7·3 ms^{-1} during the first half hour of observations to about 5·9 ms^{-1} during the second half hour; the speed calculated for the full 65 min is 6·6 ms^{-1}. There also appears to be some indication in Fig. 5 that the direction of the front altered somewhat during the hour of observations, but again the irregularity of the leading edge of the echo makes this difficult to confirm; the change, if real, is in the anticlockwise direction and has a magnitude of about 15 deg.

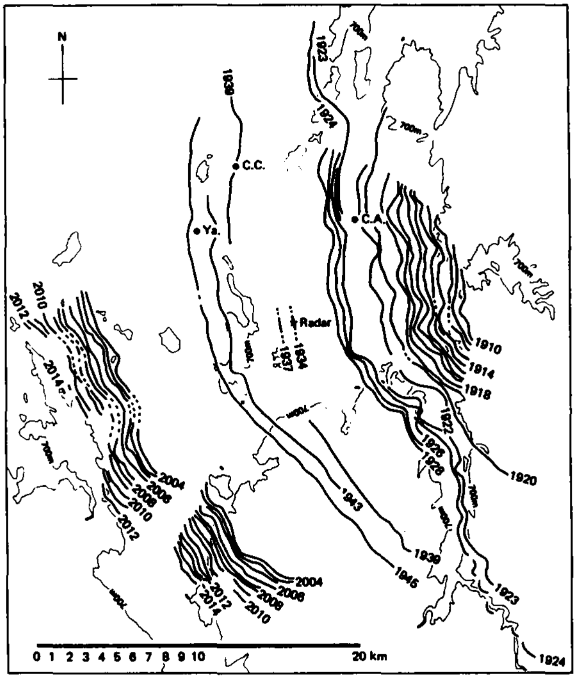

Fig. 5 Successive positions of the leading edge of the line-echo, 1910–2015. The 700 m contour and the position of the radar and the three meteorological stations are also shown. Key: C.A. – Canberra Airport (arrival time of the front as determined from the autographic record 1924), C.C. – Canberra city (1941), Ya. – Yarralumla (1945)

It is evident from Fig. 5 that, in addition to the 3–4 km long bulges already noted, the line has a number of irregularities which are on a rather larger scale. Two of these, which took the form of bulges, were visible, far to the north and the south, only in the observations made at 1923 and 1924; a third, which took the form of a lag in the southern end of the line, was visible between 2008 and 2015. It was thought that these irregularities might be associated with large-scale terrain features, the front presumably slowing down as it moves across rising ground and surging forward where the ground falls away. However, interpretation of the observation in terms of these effects must take account not only of the terrain, but also of the pre-existing shape of the line. In the present instance the terrain is fairly complex, and there is no convincing evidence to relate the lags and surges with upland areas. It may be noted, however, that the front has evidently had no difficulty in surmounting ranges that rise up to 200 m above the surrounding plain.

Measurements of the profile of the frontal echo were made both as the front approached the radar and as it moved away. The measurements were made with a scanning beam which was directed at a series of elevation angles, the position of the echo being recorded photographically. Profiles were obtained at a number of points along the front's length by measuring the position of the leading edge at each of the elevation angles, and making a correction for the front's rate of advance. During the time taken to complete a set of profile measurements (about 3 min) the front would have advanced about 1000 m, so this correction is unfortunately very significant, and the shape obtained for the profile will depend somewhat on the value assumed for the rate of advance; the general form of the profile should, however, be correct. Attempts to confirm these forms by determining the slope directly from measurements of the conical scan distortion effects were usually unsuccessful, presumably because the shape of the line-echo on the screen was affected as much by the bulges and undulations along the front as by the distortions.

Several of the profiles obtained from these measurements are illustrated in Fig. 6, and it is evident that their form is quite variable; however a nose, or at least a markedly steeper slope near the ground, is a feature of most of them. In all cases the front extends up to a height of at least 1 km, the highest point occurring between 1 and 2 km behind the nose. Profiles of the rear of the front could not be obtained because the trailing edge of the echo was too diffuse; however it is evident from the width of the line-echo that the rear must usually have been no less steeply sloping than the front. The profiles in Fig. 6 appear generally similar to those obtained by Simpson *et al.* (1977) from a radar range-height indicator display, and by direct exploration of a front with a meteorologically-instrumented glider.

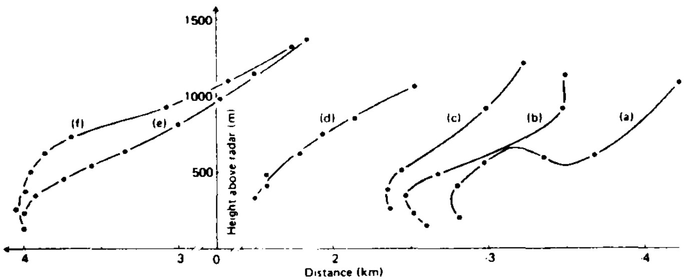

Fig. 6 Profiles of the leading edge of the sea-breeze front at a number of times and places. The horizontal axis lies along the direction of the front's advance, and has an arbitrary origin at the radar. (a), (b), (c) 1921, at positions 3 km apart along the front; (d) 1930; (e), (f) 1942, at positions 11 km apart

As mentioned previously, radar observation made prior to the arrival of the front showed that the airborne insect population was distributed in a highly non-uniform fashion, with the insects strongly concentrated into regions of convectionally-rising air. At 1955, ie about 20 minutes after the passage of the front and 40 min after sunset, the insects were distributed much more evenly, and were moving steadily towards the west-south-west. It is likely that these insects, unlike those seen earlier, were nocturnal migrants which had taken off at dusk. The density of insects at a series of heights was measured at this time by counting the number of dot echoes in a standard area of the PPI screen (Drake 1981). The results, shown in Fig. 7, indicate an approximately logarithmic decrease of insect density with height. Observations an hour later showed that the insects were still distributed uniformly and that they were continuing to move towards the west-south-west. The vertical profile of density had changed, however, a clear layer of insects about 80 m thick having formed at a height of about 400 m (Fig. 7). A photograph of the PPI screen, taken with the antenna directed upwards at 26 deg

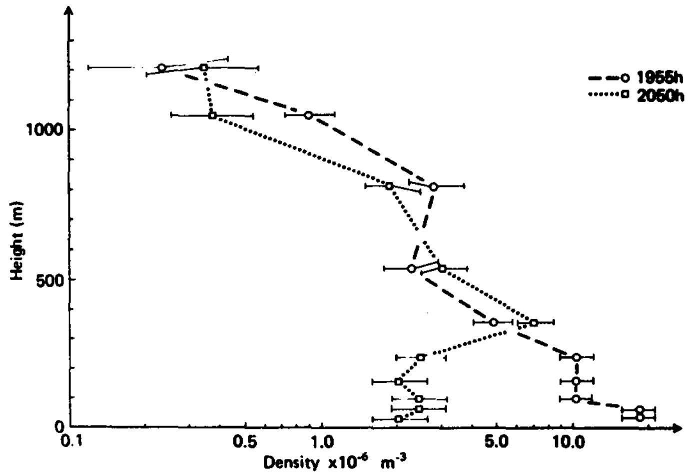

Fig. 7 Insect density as a function of height, 1955 and 2050

and a maximum range of 1400 m displayed, is reproduced in Fig. 8; the layer manifests itself as a concentration of dot echoes at a range of 900–1000 m. The layer actually slopes somewhat, and is about 80 m higher to the west, where the ground rises, than to the east. The uneven distribution of the insects around the screen indicates that they are preferentially aligned, in this instance in an approximately north–south direction: the insects to the east and west are sideways-on to the radar beam and present a larger target, and are therefore detected in greater numbers, than the head-on or tail-on insects to the north and south. It is possible that this layer marks the upper boundary of the undercutting cooler air, as Schaefer (1976) has found that insect layers frequently form at shear interfaces of this kind; however, in the absence of high-resolution upper wind data, this hypothesis cannot be confirmed. Nevertheless it is interesting to note that, if the layer does mark this boundary, the vertical dimensions of both the front and the airflow behind it would seem to be very similar to those observed by Simpson *et al.* (1977) from their instrumented glider.

DISCUSSION

The observations described here demonstrate that a radar capable of detecting flying insects is a potentially valuable tool for the study of the sea-breeze front. The narrow pencil beam, scanning variable-elevation antenna, and short working range of the CSIRO entomological radar have enabled observations to be made with much finer resolution than would have been possible with a large surveillance radar, so that information about both the vertical profile of the front and the shape of its leading edge could be obtained. It appears that insects act very satisfactorily as tracers of the advancing stream of cool air.

Despite the precision of the measurements, however, some fundamental properties of the front, such as its profile and its rate of advance, have proved to be difficult to estimate accurately. These difficulties arise as much from the nature of the front itself as from inadequacies in the observation procedures: on a scale in which the uneven and rapidly changing nature of the front's leading edge is apparent, quantities such as the rate of advance become poorly defined. Similarly, the vertical profile is only well defined at a particular point along the front and at a particular instant in time; profile observations can therefore most effectively be made with a vertically-scanning beam and a range-height indicator display, a mode of operation not currently available on the CSIRO radar. In the present instance the interpretation of the observations was made additionally difficult by the presence of an undulating terrain, and there can be little doubt that studies of the dynamics of sea-breeze fronts can most effectively be made in areas where the terrain is relatively simple.

To the entomologist, the observations are of considerable interest. On a synoptic scale the shallow sea-breeze circulation may be of little meteorological significance, but to migratory insects, which fly predominantly in the bottom few hundred metres of the atmosphere, it may be very important. At the heights at which insects usually fly the front is a region of strong horizontal wind convergence, and insects which tend to maintain their height, perhaps by dropping towards the ground in response to the lower temperatures they experience when carried aloft, will become concentrated at the front. Greenbank *et al.* (1980) reported an early evening observation of insects concentrated in a sea-breeze front, and showed that the insect population of the front could be accounted for by the convergence of insects which became airborne at dusk. In the present instance the frontal concentration was already well established before dusk, and it is likely that it formed mainly from insects which were flying in convectionally rising air ahead of the front and which became entrained in the sea-breeze circulation as the front advanced. Entomologically the formation of concentrations is potentially of great importance, because if the insects are all deposited together in a favourable habitat they may rapidly increase their population to plague levels, ie to levels where the damage done by pest species is of economic importance; whether the sea-breeze front has this potential for triggering population outbreaks is doubtful, however, as it seems likely that in most circumstances the frontal concentration would dissipate gradually so that the insects would be deposited over a wide area.

Perhaps no less important than this concentrating effect is the potential of the sea-breeze for transporting insects away from coastal areas. In south-eastern Australia, spectacular insect migrations frequently occur on warm anticyclonic north-westerly winds which carry insects from inland areas towards the coast, and frequently out to

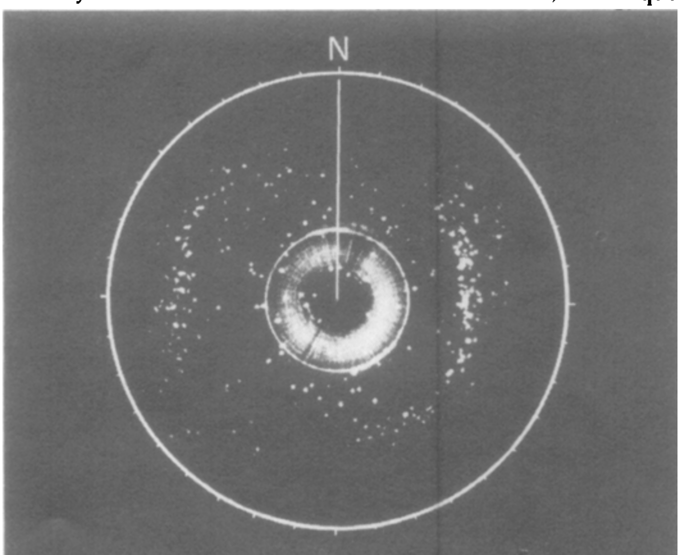

Fig. 8 Photograph of the PPI screen at 2104; antenna elevation 26 deg, maximum range displayed 1400 m, interval between range rings 426 m. Each dot is caused by the echo from a single insect; a layer of aligned insects appears as a concentration of echoes to the east and the west at a range of 900–1000 m. The diffuse ring echo just inside the innermost range ring is an artifact

sea (Farrow 1975, Drake *et al.* 1981). The sea-breeze provides one mechanism for transporting these insects, or their offspring, at least part of the way back into the continental interior. Moreover, many radar investigations have shown that insect migrations frequently commence at dusk, and that migration is usually most intense during the hours immediately after nightfall. It may be noted that this diurnal pattern of migration provides a relatively safe dispersal strategy for insects inhabiting coastal areas, as during the early evening a sea-breeze circulation will often have become established, and this will tend to carry the insects inland rather than out to sea.

ACKNOWLEDGEMENTS

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A NOTE ON THE COLD SPELL OF DECEMBER 1981 IN CENTRAL ENGLAND

By K. B. SHONE

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THE mean temperature in central England for December 1981 was −0·3°C. This is the coldest December there since 1890 and equal third coldest since 1659, the first year of the series of monthly central England temperatures (CET) compiled by Manley (1974). Fig. 1 shows the mean daily CET for December 1890 and 1981 with that for the 150 Decembers from 1826 to 1975. While December 1890 had a lower mean CET, −0·8°C, and remains the coldest since 1659, the lowest daily temperatures then were