

A solitary wave disturbance of the marine boundary layer over Spencer Gulf revealed by radar observations of migrating insects

V. A. Drake, CSIRO, Division of Entomology, Canberra, Australia
(Manuscript received May 1984)

During radar observations of a migration of insects across Spencer Gulf, two steadily propagating linear regions of intense radar reflectivity were detected. The passage of these regions, which were moving in a direction almost perpendicular to the general direction of the insect migration, and to the direction of the prevailing wind, was accompanied by a series of large-amplitude wind oscillations. An analysis of the radar and meteorological records indicates that the observed phenomena were manifestations of a solitary buoyancy wave disturbance of the marine boundary layer, and of the interaction of migrating insects with this disturbance. This interpretation suggests that the disturbance was of the same type as those that produce 'Morning Glory' roll clouds and wind gusts in the Gulf of Carpentaria; a similar disturbance is likely to have produced a roll cloud reported previously from Spencer Gulf.

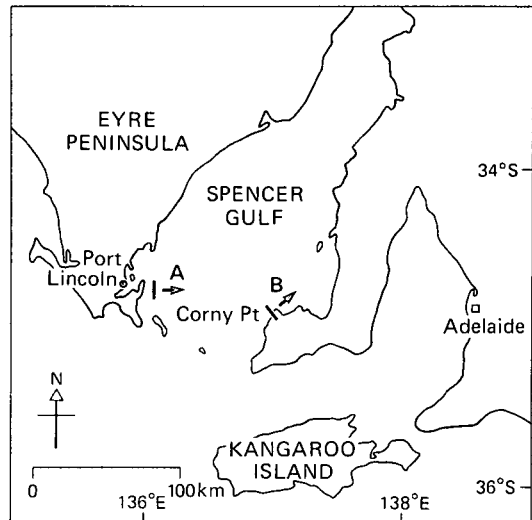
Introduction

Robin (1978) has reported a spectacular low-level roll cloud that was observed near Port Lincoln, on the western shore of Spencer Gulf, South Australia, during the early afternoon of 27 November 1977 (Fig. 1). Christie et al. (1981) have suggested that this cloud may have been caused by solitary buoyancy waves propagating on the marine inversion. Smith et al. (1982) have proposed that the cloud is a manifestation of the phenomenon known in the Gulf of Carpentaria region of northern Australia as the 'Morning Glory'; this phenomenon has been interpreted as an internal bore propagating on the nocturnal boundary layer and frequently evolving into a train of solitary buoyancy waves (Clarke 1983; Clarke et al. 1981).

As part of a continuing study of the early spring migrations of moths (Lepidoptera) in temperate Australia (Drake et al. 1981; Drake and R. A. Farrow, unpublished data) the CSIRO Entomological Radar (Drake 1982) was operated at Corny Point (34° 54' S, 137° 01' E) (Fig. 1), on the eastern shore of Spencer Gulf, between 15 and 26 September 1981. The radar is of the scanning pencil-beam type and operates at a wavelength of 3.2 cm; it is very effective at detecting individuals of the larger species of insects at ranges of a few kilometres. The radar observations were accompanied by autographic surface (2 m) temperature, humidity, and wind measurements and by single-theodolite, pilot-balloon observations of upper winds. During the night of 16-17 September 1981, the autographic instruments recorded a series of large-amplitude wind oscillations that persisted for about an hour. Radar observations made at the beginning of this series of oscillations detected two linear regions of intense

radar reflectivity that propagated steadily across the radar site in a direction almost perpendicular to that of the prevailing wind. These phenomena may be interpreted as manifestations of a train of solitary buoyancy waves propagating on the marine inversion, and of the interaction of migrating insects with these waves. The observations are presented here as further evidence that solitary wave disturbances occur from time to time over Spencer Gulf.

Fig. 1 The Spencer Gulf region of South Australia, showing the position and orientation of the roll cloud (A) reported by Robin (1978) and the radar line echoes (B) described here.



Meteorological observations

A northerly airflow, which was moving under the influence of a weak trough over the Great Australian Bight and an anticyclone centred over the Tasman Sea, prevailed over Spencer Gulf throughout the night of 16-17 September 1981. The nearest synoptic-scale fronts were located about 1000 km away, towards the west and southwest. A pilot balloon ascent at 0010 Australian Central Standard Time (CST — 9 h 30 min ahead of Greenwich Mean Time) showed that the wind at 1000 m was from the north-northwest, but that there was considerable shear in both direction and speed near the surface, the wind being northerly at 150 m and from east of north at lower altitudes. For most of the night the sky was covered by stratus cloud.

The anemograph record shows that the surface wind became steady soon after 2100 CST, i.e. about two hours after sunset. Between 2100 and 2330 CST the surface wind was from the northeast, but during the next hour it became lighter and gradually veered to east-southeast. It then started to pick up speed again and to back, and for the hour from 0100 CST it was blowing steadily from slightly east of north. The anemograph trace for the period 0100 to 0400 CST is reproduced in Fig. 2. It can be seen that at 0200 CST the wind suddenly backed to west-southwesterly, and that after about five minutes it veered again to return to its original direction. The wind-run chart shows a clear change of slope, indicating a sudden increase in wind speed, at the time the wind direction was from the west-southwest. This initial temporary windshift was followed by a succession of similar oscillations at nearly regular intervals of about 7 min. In each case the wind backed to westerly or west-southwesterly, and then veered to northerly or north-northwesterly; a careful examination of the wind-run trace indicates that an increase in wind speed occurred during all but one

of the periods of westerly flow. Towards the end of this series of oscillations the surface wind became lighter, and the variations recorded on the direction trace after 0245 CST are of doubtful significance, and certainly difficult to interpret. After 0305 CST the surface wind became very light and an approximately southerly direction was recorded. This was maintained until about first light (0554 CST), when the wind speed increased again and the direction backed, first to northeasterly and later to northerly, where it remained throughout the following day.

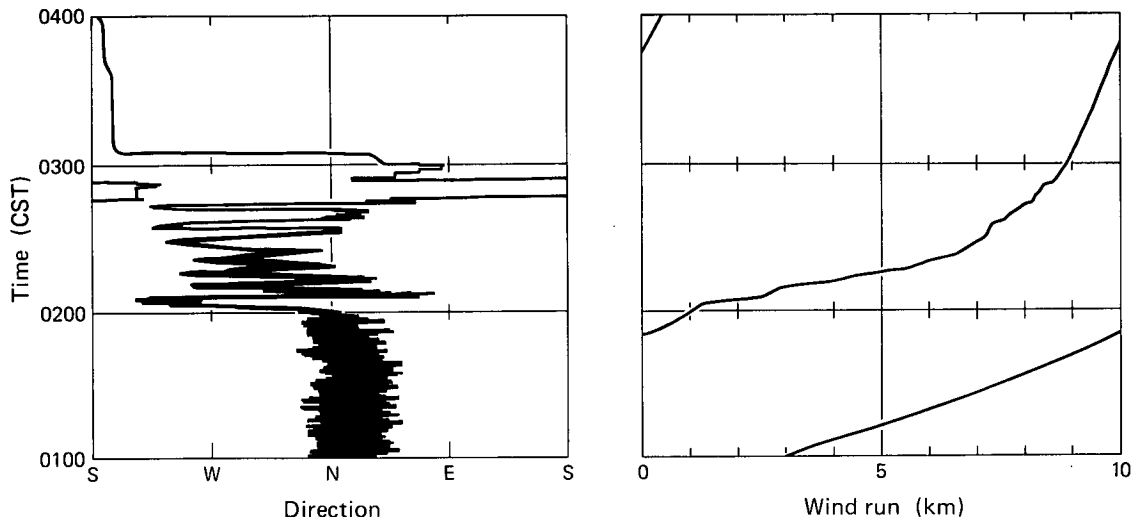
The thermohygrograph record shows a sudden increase in temperature, by about 2.5°C, and a simultaneous decrease in humidity, over a period of about 7 min starting approximately at 0200 CST. These rapid changes were followed by a more gradual decline in temperature, and an accompanying increase in humidity, over the following hour. These changes stood out clearly against the background of the gradual diurnal variation and a number of much smaller sudden changes. The traces indicate that these temperature and humidity variations were not significantly oscillatory.

Barographs were operating at a number of Bureau of Meteorology stations in the Spencer Gulf-Kangaroo Island region during the night of 16-17 September 1981, but the traces do not give any indication of the disturbance detected at Corny Point; nor could this disturbance be identified in barograph, thermograph, and anemograph traces recorded in Adelaide, 150 km to the east.

Radar observations

Radar observations made during the afternoon of 16 September 1981 detected only small numbers of migrating insects. At around dusk (1839 CST), however, the radar showed that a take-off flight was in progress, with insects moving towards the

Fig. 2 Trace (redrawn) from the Corny Point anemograph for the period 0100-0400 CST, 17 September 1981.



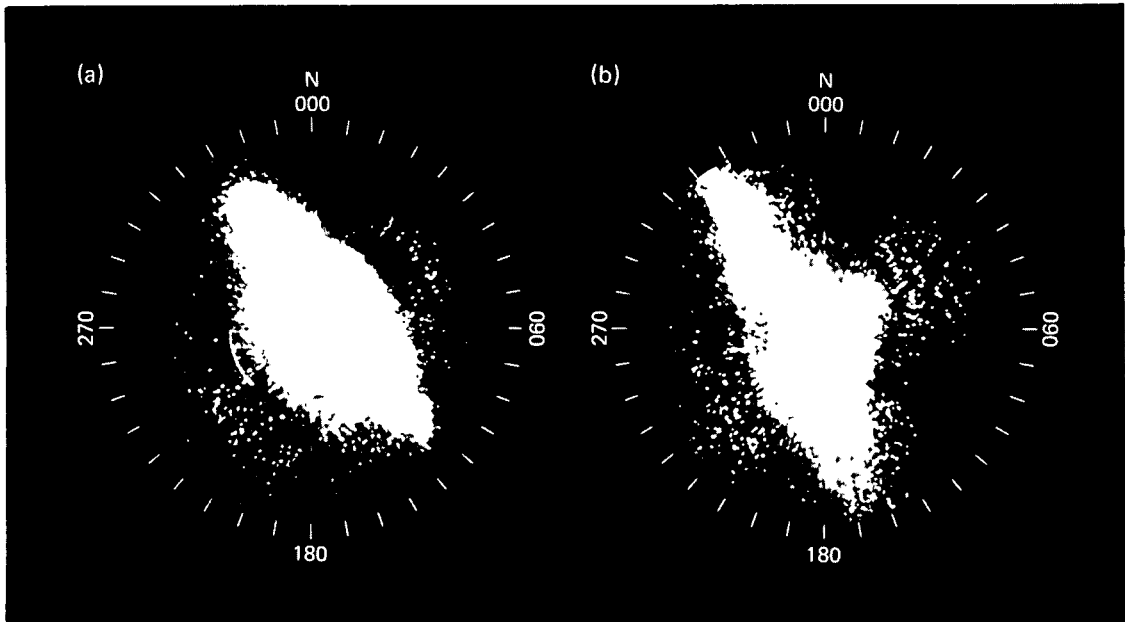
southwest below about 100 m and towards the south-southeast or southeast at higher altitudes. At this stage no insects were detected over the sea to the north of the radar, indicating that the migrants were of local origin. The radar echoes were of the strong and distinct (or 'coherent') type that are characteristic of the reflections from individual large insects. Moths of a number of species were very numerous at Corny Point at the time, and were regularly observed in flight at dusk (R. A. Farrow, unpublished data); as moths are known to undertake long-distance migrations at this time of year (Drake et al. 1981), it is considered certain that these insects were the cause of the radar echoes.

By 1915 CST the take-off flight had given way to a steady migration, with insects arriving continuously from the west-northwest and insect numbers over land and sea areas being approximately equal. These insects must have migrated across Spencer Gulf from Eyre Peninsula. By 1930 CST insects were present in significant numbers at altitudes of over 1 km, and the migration had started to become stratified, i.e. the insects were tending to become concentrated into layers at particular heights (Drake 1984a). The migration continued in this manner throughout the evening, the insects arriving from the north or even from slightly east of north in the bottom few hundred metres of the atmosphere, and from west-northwest or northwest at higher altitudes. Radar observations at the time of the 0010 CST pilot balloon ascent showed that the insects were moving approximately downwind at all heights, and that the marked

variation of the migration direction with height could be accounted for by the strong directional shear found to be present in the low-altitude wind.

After 0030 CST the radar was operated in an unattended mode in which the plan-position-indicator (PPI) display is photographed with a time-lapse cine camera for about 5 min every half hour. The radar beam was directed upwards at an angle of 12°, and the display set to show a maximum range of about 3 km, so that the echoes at the edge of the PPI screen were produced by insects flying at altitudes of about 600 m; echoes near the centre of the screen were usually obscured by ground clutter, and little information could be obtained about insects flying below about 200 m. The time-lapse film records made at 0030, 0100 and 0130 CST all show a uniform and steady migration of insects from the northwest, with no marked stratification features in the 200 to 600 m height band. The following film sequence, which started at 0159 CST and continued until 0204 CST, also shows this steady migration from the northwest, but in addition it shows two successive bands of intense radar echo moving steadily across the screen from southwest to northeast. PPI photographs taken when each band was approximately overhead are reproduced in Fig. 3. The time-lapse film shows very clearly that the echoes ahead of, between, and behind these two bands were moving towards the southeast, i.e. approximately at right angles to the direction in which the bands were advancing. Unfortunately this film sequence was the last obtained on this night,

Fig. 3 The PPI display at (a) 0159 and (b) 0204 CST, 17 September 1981. Maximum range displayed 1.6 n. mi (2.9 km), antenna elevation angle 12°, pulse duration 0.25 μ s. Projection of the entire time-lapse sequence showed that the diagonal bands of intense echo were moving steadily towards the northeast, while the individual point echoes ahead of and behind the bands were moving steadily towards the southeast.



as an equipment failure occurred shortly after it was taken.

As atmospheric radar echoes detected during the rest of this night were caused by migrating insects, it seems reasonable to suppose that the band echoes were also caused by this type of target, the insects presumably having become concentrated into a narrow linear region by some small-scale atmospheric process. Some properties of the linear concentrations can be determined from measurements of the PPI photographs. From the rate at which the bands moved across the screen, for example, the speed of both concentrations can be estimated to have been about 12 m s^{-1} . Because individual insects were detectable to the edge of the screen, it seems likely that the shapes of the bands were determined by the shapes of the concentrations; in particular, the maximum range of about 2.2 km at which the initial band could be detected, when combined with the beam elevation angle of 12° , indicates that the first concentration extended only up to about 500 m. Similar measurements indicate that this concentration was 1500 to 2000 m wide, and that the second concentration was about 600 m high and 1000 to 1500 m wide. The period between the times at which the two concentrations were overhead was about 5.5 min, and the peak-to-peak separation of the concentrations was about 4 km. The intensity of echo, and thus presumably the concentration of targets, was somewhat greater in the first band than in the second.

Discussion

The passage of the two band echoes coincided, to within a few minutes, with the times of the first two wind oscillations recorded on the anemograph, and there can be no doubt that the phenomena were associated. Unfortunately, uncertainty about the precise timing of the anemograph trace makes it impossible to determine the relative phase of the two phenomena. However, as the direction of migration between the bands appeared to be very similar to that observed in the steady northwesterly airflow ahead of the disturbance, it seems very likely that the passage of the bands occurred during the periods of stronger, westerly or southwesterly surface winds (Fig. 2). The 5.5 min interval between the two bands agrees well with the 6 min interval between the peaks of the first two periods of surface westerlies. It is possible further band echoes would have been detected, in association with the later wind oscillations, if the radar observations had continued after 0204 CST.

A train of propagating band echoes with speeds, peak-to-peak separations, and individual dimensions very similar to those of the present event has been detected during radar observations of insects migrating over inland New South Wales (Drake 1984b). These band echoes were tentatively identified as manifestations of a train of solitary buoyancy waves propagating on the surface inversion, the

waves evidently being of such large relative amplitude that they contained regions of closed circulation (Davis and Acrivos 1967; Tung et al. 1982) in which large numbers of the migrating insects had become entrained. A similar explanation appears to be appropriate for the propagating band echoes observed at Corny Point, as insects were migrating throughout the boundary layer at the time of the disturbance, and as the passage of a warm northwesterly airflow over the relatively cool waters of Spencer Gulf would be expected to produce a strong marine inversion. The stability of the boundary layer on this occasion is in fact indicated by the horizontal uniformity and vertical stratification of the migration ahead of the disturbance, and by the amount of shear in the low-level wind profile; the temperature and humidity variations associated with the disturbance can also be interpreted as being due to the disruption of a stable surface layer. Low-level temperature inversions, and often also regions of closed circulation, were present in the Morning Glory disturbances investigated by Clarke (1983) and Clarke et al. (1981). Surface wind shifts, and often wind oscillations, occur during the passage of Morning Glory disturbances and, as in the Corny Point event, the direction to which the wind shifts is close to the direction in which the disturbance is propagating, and the initial wind shift, and often also any subsequent shifts, are accompanied by wind gusts (Neal et al. 1977; Smith et al. 1982). It therefore seems likely that the Corny Point band echoes and the Morning Glory roll clouds are both manifestations of a solitary wave-dominated disturbance propagating on a stable boundary layer. In the case of the Corny Point event, the origin of this disturbance remains unknown.

The airflow at the time of the Port Lincoln roll cloud appears to have been suitable for the formation of a marine inversion, so the interpretation of this event in terms of a disturbance of the Morning Glory type is plausible. Smith et al. (1982) have listed a number of reports of wind oscillations and propagating disturbances that appear to be of a similar type; in the present context, the wind oscillations that have frequently been observed at Malta (Lamb 1954; Kirk 1961) are of particular interest, because they occur in a marine environment. Wind oscillations also accompanied a train of large-amplitude waves detected with a vertical-pointing radar at a coastal locality in California (Gossard et al. 1970, event of 13 November 1969). It is worth noting, however, that observations in inland Australia have shown that there are often no major perturbations of the surface wind during the passage of boundary layer solitary wave disturbances (Christie et al. 1979; Drake 1984b); this suggests that the extent to which the solitary wave circulation penetrates to the surface may depend critically on the degree of stability of the air very near the ground.

The formation of insect concentrations within the waves indicates that the passage of the wave train must have had an effect on the flight trajectories of at least some of the migrants. Nevertheless, the absence of any sustained change in the intensity and general direction of the migration following the passage of at least the first two wave components, and the comparatively short duration of the wave disturbance at any particular point, suggests that most trajectories would have been governed primarily by the synoptic-scale wind, and that the passage of the wave is likely to have caused only minor perturbations, probably of the form of small lateral displacements, to these trajectories. Major deviations from the direction of the synoptic wind would have occurred only for those insects that became entrained within the waves, and then only if they remained entrained for extended periods. Radar observations of the effect of solitary wave disturbances on insect migrations over inland Australia also suggest that these waves usually have only a minor effect on the migration trajectories (Drake 1984b).

Acknowledgments

I am grateful to Dr D. R. Christie and Dr R. K. Smith for their comments on a draft.

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