A Sea-Breeze Front Moves Seaward

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The progress inland on 5 June 1973 of a 50 km section of a sea-breeze front from the South coast of England was investigated with the aid of an instrumented motor-glider, a high power radar, and ground-based autographic records. In the western section steady progress was made, but further east after reaching 20 km inland the front retreated back to the coast.
The area of lift at the front was investigated, and the maximum depth of the sea-air was found to be just under 1 km. Lines of diffuse radar echoes appear to correspond to the areas of maximum humidity fluctuations measured from the aircraft. Comparison is made with analogous water-tank flows incorporating both advancing and retreating fronts.
The divided behaviour of the front is thought to be due to a local pressure gradient due to the delayed influence of the East Coast; in other cases synoptic scale pressure gradients appear to have been responsible for somewhat similar features.

1. Introduction
Throughout the first week of June 1973 detailed measurements were made of sea-breeze fronts between Lasham Gliding Centre and the South Coast of England. Surface data was obtained from seven stations maintained by voluntary observers, each station being equipped with a thermo-hygrograph in a Stevenson screen, with a clockwork wind-direction recorder mounted on top of the screen. The locations of the stations, and other places mentioned below are shown in fig. 1.
During this period the Appleton Laboratory also carried out searches for sea-breeze fronts using a powerful radar. On three separate days a line of echoes was recorded, and these coincided with the frontal positions deduced from the ground stations, and from aircraft measurements. On each day more detailed studies of the phenomenon were made, using tailed balloons tracked with a single theodolite to give wind measurements, and an instrumented Slingsby T 61C Falke motor glider to give data along horizontal sections. The instrumentation, described by Milford and Whitfield (1970), records height, airspeed, rate of climb, air temperature and wet-bulb depression every 1.6 seconds, or about every 50 m along the flight path. In 1973 a Lyman-alpha humidiometer was added; this instrument, manufactured by the Electromagnetic Research Corporation, measures the water vapour density with a response time considerably shorter than the time interval between logged data points. The calibration of the humidiometer was checked against the temperature and wet-bulb values recorded on the same flight.
This paper describes the events on one day of the series, 5th June.

2. Synoptic Conditions
During the previous 24 hours an anticyclone cell developed over Wales in the ridge of high pressure extending northwest from the Azores. Fig. 2 shows the surface synoptic situation at 1200 GMT. Troughs of low pressure moved towards Western coasts of Scotland on 5th June, but the ridge of high pressure over Southern Britain was maintained. There was a light north-east gradient wind across Southern England with less than 3/8 cumulus during the period of the experiment.

3. Radar Tracking of the Front
The radar used for this study is sited at Chilbolton, 40 km from the South coast, and is installed on a 25 m diameter steerable paraboloid antenna. (Meadows, 1967.) The radar operates at 2700 MHz with a pulse length of 0.5 microseconds (= 150 metres), a peak power of 400 kW, a pulse repetition rate of 1200 Hz and beamwidth (half power – two way) of 15′. The minimum detectable echoing area at 25 km is 130 cm². On 5th June, 43 radar photographs were taken between 1055 GMT and

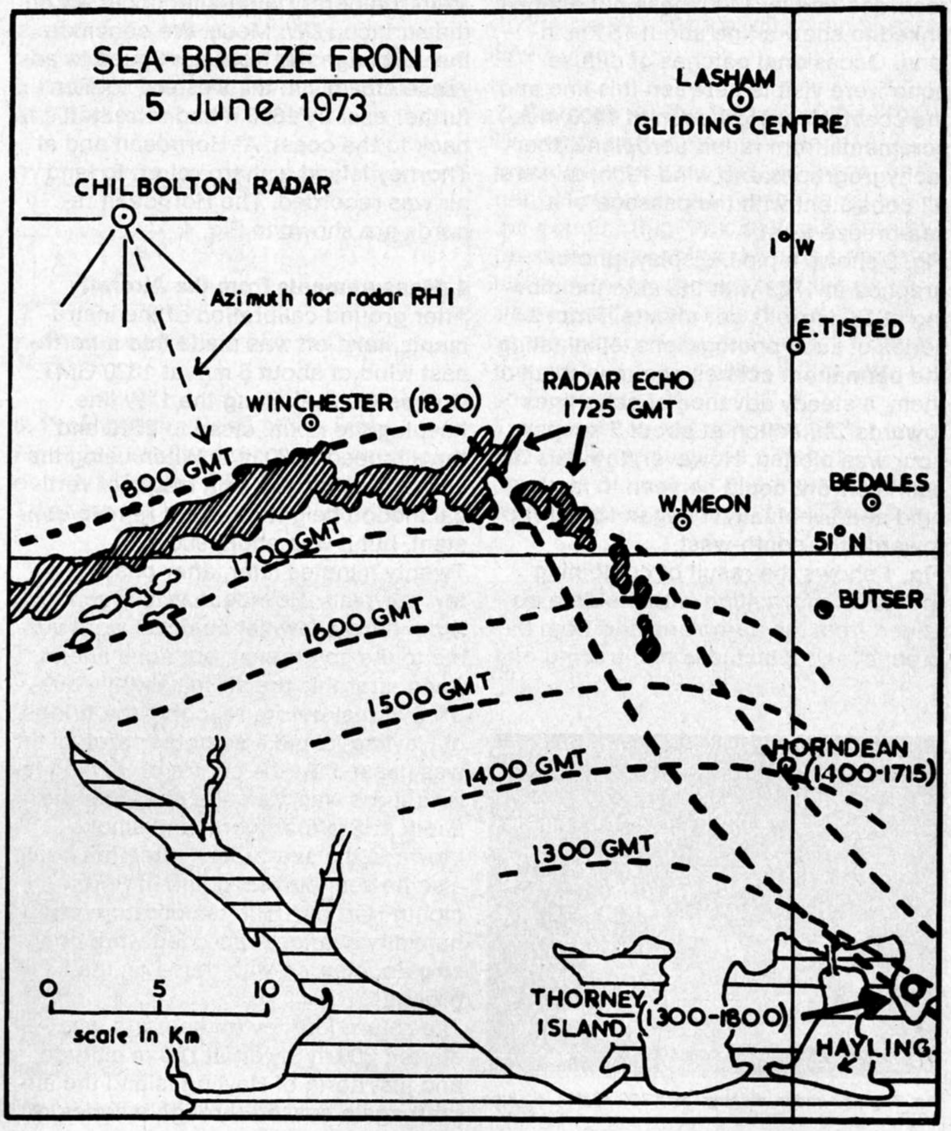

Fig. 1. Map of the sea-breeze area. ⊙ indicates ground stations. Dashed lines show hourly position of sea-breeze front, shading indicates radar echo at 1725 GMT.

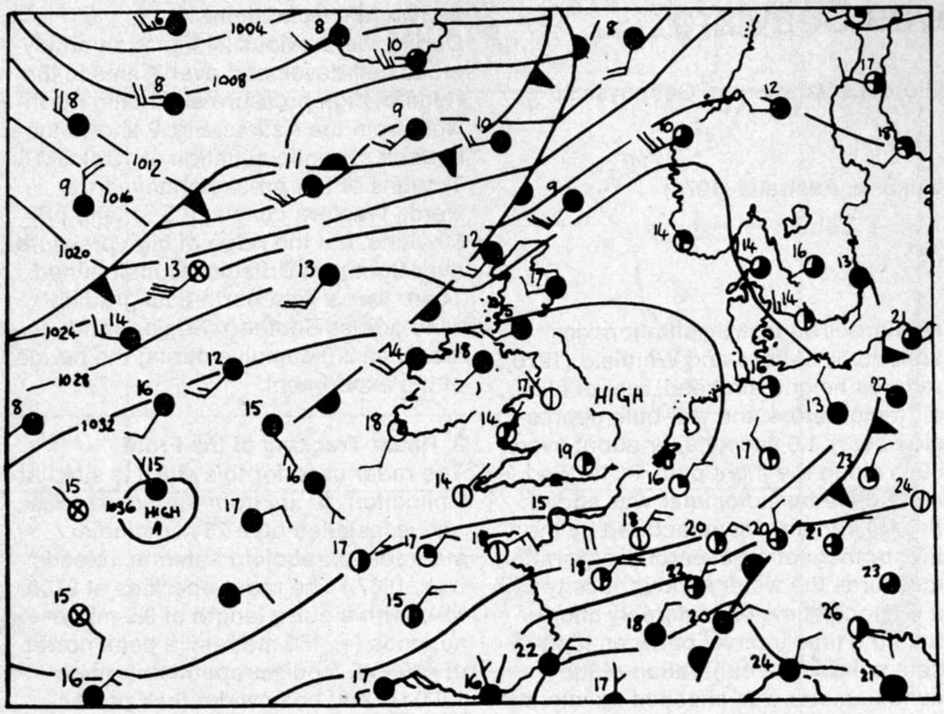

Fig. 2. Surface synoptic situation, 1200 GMT, 5 June 1973.

2028 GMT. As the sea-breeze front developed, faint diffuse radar echoes were first seen. Random dots were also recorded and by 1400 these dot echoes linked to show a line about 15 km inland. Occasional patches of diffuse echo were visible between this line and the coast. Near Horndean at 1400 measurements from radar, aeroplane, thermohygrographs and wind-records were all consistent with the passage of a sea-breeze front.
Fig. 3 shows a p.p.i. display, photographed at 1702 with the antenna moving at 18 degrees per minute. From a series of such photographs, eliminating the permanent echoes common to all of them, a steady advance of echo-lines towards Chilbolton at about 5 km per hour was plotted. However, towards the east the front could be seen to lag behind and eventually it began to retreat towards the south-west.
Fig. 1 shows the result of combining the radar information with the data obtained from the aeroplane and from the ground, and it includes one tracing of a typical radar echo-line with the permanent echoes deleted. No sea-breeze reached Butser or Bedales, and only a short temporary wind-shift occurred on the surface at W. Meon. We conclude that although the front continued to advance steadily in the western section, further east by 1800 it had retreated back to the coast. At Horndean and at Thorney Island a sharp return to land air was recorded. The Horndean records are shown in Fig. 4.

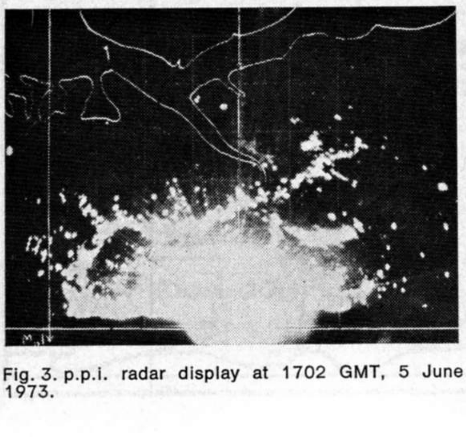

Fig. 3. p.p.i. radar display at 1702 GMT, 5 June 1973.

4. Measurements from the Aircraft

After ground calibration of the instruments, take-off was made into a north-east wind of about 5 m/s at 1320 GMT. Course was set along the 1°W line, keeping the r.p.m. close to 2500 and the airspeed at 30 m/s. When using the aircraft in this way as a tracer of vertical motion height does not remain constant, but it was about 900 m.
Twenty minutes later, after passing a few thermals, Horndean was reached. From here a few flat cumulus were visible to the south-east, but none ahead. Soon after this the air felt slightly bubbly and just before reaching the bridge ot Hayling Island a smoother area of lift was passed. At the centre of Hayling Island there was a smoke trail from the south at 5 m/s or more, and smoke blown in the sea-breeze direction could also be seen further south in Portsmouth Harbour. The temperature and humidity changes recorded were only small compared with those on the ground.
The return journey to the north was started 300 m lower, at 600 m altitude, and just north of Hayling Island the aircraft again passed through a series of disturbances. The first area was recorded as «Smooth, steady lift», nex about 3 km further north «gliding air, bubbly». This felt like the choppy expectant air one often flies through on the outskirts of a thermal. Lastly, nearly 5 km from the start of the lift, a kilometre of «rough air» was traversed, still behind the surface front because at this point another smoke trail was blowing from the south.
Records of vertical speed, humidity mixing ratio and potential temperature throughout this passage at 600 m are shown in Fig. 5. The final «rough» kilometre before reaching the land-air is of expecial interest. A strong periodiity appears, with a wavelength of roughly 150 metres, and patches of unmixed dry air can still be found over half a kilometre from the leading edge of the front. At the point «A» the value of humidity is close to that of sea-air as recorded simultaneously on the ground beneath at Horndean, whereas the next point «B», logged 1.6 seconds later, has the humidity value typical of the dry land air. It is in this region that tank models show mixing taking place through breaking waves.

5. Causes of Radar Echoes

The radar dot echoes were probably due to birds, while the fainter more diffuse echoes seen behind the front and in the r. h. i. are due either to insects or back-scattering from humidity gradients.
Swifts have been established as the cause of some radar echoes at thunderstorm outflows (Harper, 1958) and at sea-breeze fronts (Simpson, 1967. Al-) though on this particular day no observations of swifts were made, early June is a peak time for collecting airborne food for the growing young. On

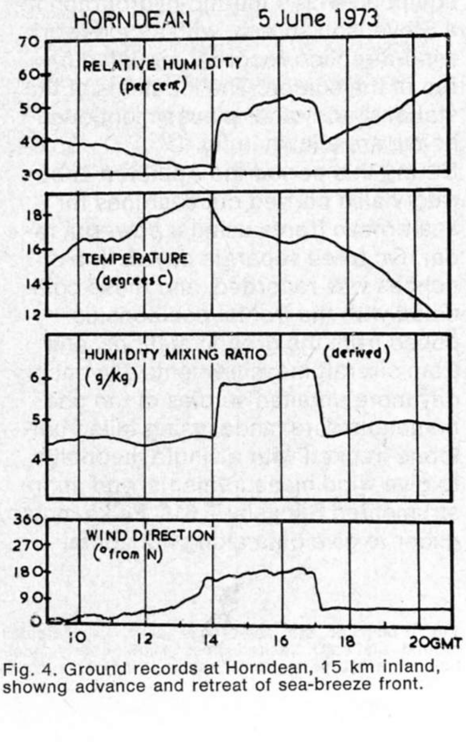

Fig. 4. Ground records at Horndean, 15 km inland, showng advance and retreat of sea-breeze front.

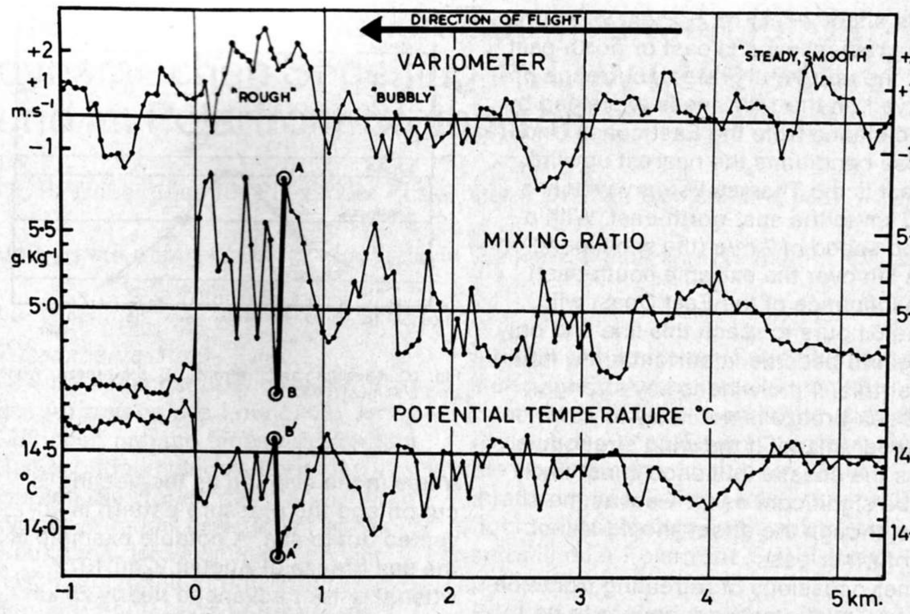

Fig. 5. Aircraft records made through front at 600 m, time approx. 1400 GMT.

two other days during the week swifts were seen from the aeroplane when flying through the area of the radar echo at a height of about 800 m. The amplitude of the dot echoes is consistent with swifts, and as the dot echoes finally linked to show the full line of the front, swifts seeking out insects carried up at the front are likely to be their cause.

In clear air, radar reflectivity is due to fluctuations in refractive index, caused by changes in temperature and humidity. The fall in temperature and rise in vapour pressure which are characteristic of the sea-breeze front both act in the same sense; however, the measured differences across the front show that refractive index changes here are mainly due to changes in humidity. Turbulent elements of size 5 cm are most effective in back-scattering 10 cm radar. It was not possible to measure humidity gradients down to this scale from the aeroplane, but measurements of humidity fluctuations at the 50 m scale give a pointer to the regions in which the finer scale structure is most intense.

As a measure of the humidity fluctuations a structure ufnction has been calculated. This is the mean of the squares of successive changes in humidity mixing ratio across the 50 m interval, averaged over eight readings,

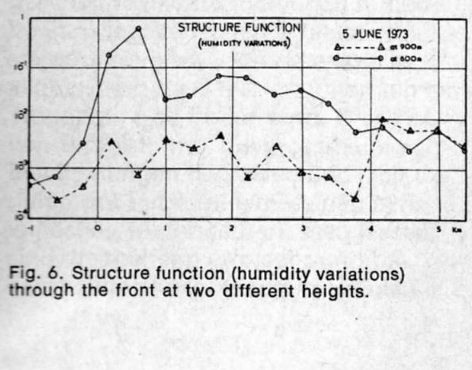

Fig. 6. Structure function (humidity variations) through the front at two different heights.

and it is plotted in Fig. 6 for the flights at 600 m and 900 m through the front. It can be seen that during the 600 m run by far the greatest values of the structure function occur in the kilometre nearest to the front, but continue for several kilometres at a hundred times the value in the land-air. Five kilometre distant from the front at 600 m the values are only ten times land-air values, but at this point they are also attained at 900 m.

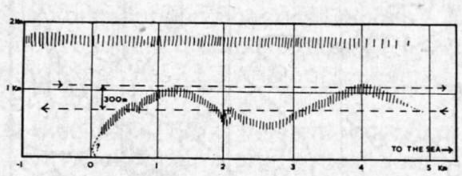

Fig. 7. Rectified diagram from r.h.i. radar display, 1844 GMT.

6. Profile of the Head of the Front

Fig. 7 is a rectified diagram from a radar r.h.i. display taken at 1844 GMT. This was the clearest r.h.i. view obtained; others showed a much more disturbed interface, but reached similar heights. Two almost continuous lines appear. From our balloon ascents a region of wind shear was found near the height of the upper layer which probably represents the inversion layer. The lower line of echo can be associated with the maximum refractive index fluctuations at the sea-breeze front and its position is consistent with the position of the structure function maxima as measured from the aircraft. Fig. 7 shows how a difference of 300 m in a cross-section flight could produce the observed distribution of humidity fluctuations.

Water tank model gravity currents (Fig. 8) help visualisation of the flow at the front. The profiles of atmospheric fronts are similar, and other characteristics in the model have also been shown to be related to the atmospheric flows (Simpson, 1969). Tank models show that a gravity current can retreat while still retaining a well defined frontal structure with appreciable upcurrents but that the profile is somewhat different. Thus soaring conditions can be expected even when a front is retreating; for example, Milford and Simpson (1972) measured air with a mean ascent of over 1 m/s along a 10 km run at a slowly retreating shear-line.

7. Reasons for the Retreat of the Front

During the afternoon of 5 June 1973 pressure rose over the south-east corner of England, relative to the rest of the country (Fig. 9), causing a strong pressure gradient to develop orientated north-east–south-west over the extreme south-east. This halted the advance inland of the sea-breeze front in this area and later caused it to retreat south-westwards.

This pressure anomaly can be explained in terms of the different amounts of heat supplied to air off the North Sea according to the time it has

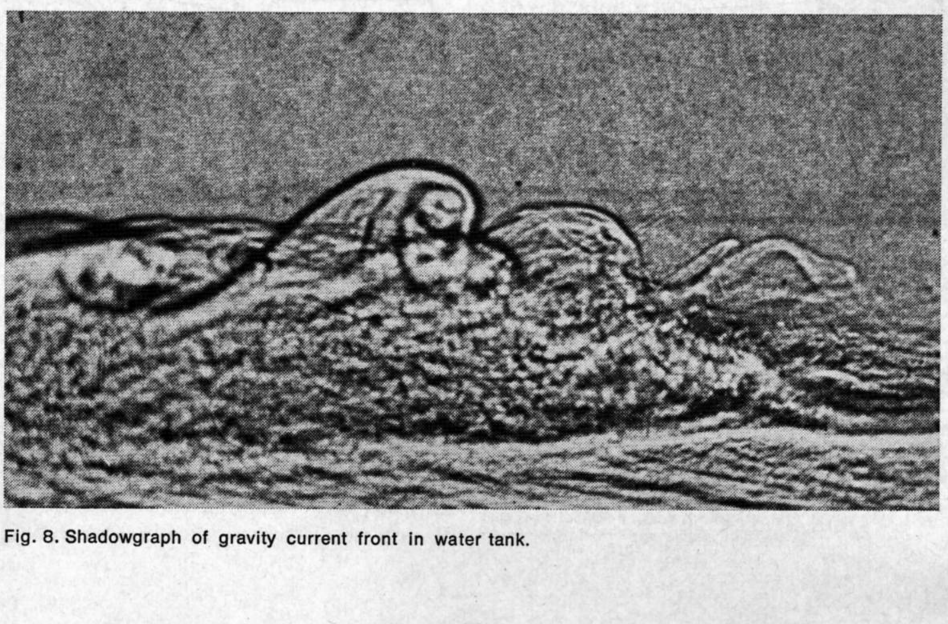

Fig. 8. Shadowgraph of gravity current front in water tank.

spent flowing over the land. At first during the morning all the air begins to warm up equally, except that very close to the coast, but the coastal influence slowly spreads inland at a rate determined by the wind speed. Well downwind from the coast the temperature rises steadily and a heat low can develop. However, nearer the coast the fresh supply of sea air reduces the temperature rise and as the solar heating decreases in the afternoon the temperature will begin to fall again as the amount of heat supplied to the air after crossing the coast decreases. Inland the temperature continues to rise, though at a slower rate, and hence the pressure continues to fall while it may begin to rise again nearer the coast. Note that the screen temperatures do not give a reliable measure of this effect as the super-adiabatic gradient close to the surface may be stronger in the cooler air.

This effect would be present whenever the gradient wind is east or north-east, but the apparently rare occurrence observed on the 1°W line is explained by its distance from the East coast. Under these conditions the nearest upwind coast is the Thames Estuary which is 150 km to the east-north-east. With a wind speed of 7 m/s (the windspeed on the 5th over the extreme south-east) the influence of the East Coast will take 6 hours to reach this line and only begin to become important a few hours after this. If the wind is any stronger, the sea-breeze is not likely to advance very far inland. If the wind strength is less the coastal influence is not likely to be significant as far west as the 1° line, though the effect should still occur further east.

Other occasions of retreating fronts observed by the network appear to be cases when there is an opposing gradient wind. In this case the front retreats in the evening as the heating is cut off and the pressure pattern is advected out to sea. A notable example is the sea breeze of August 22nd 1972 when the front advanced nearly 25 km inland by about 1430 GMT before retreating very nearly at the same speed as it advanced (Fig. 10). On this occasion the early retreat can be associated with a widespread strengthening of the opposing wind.

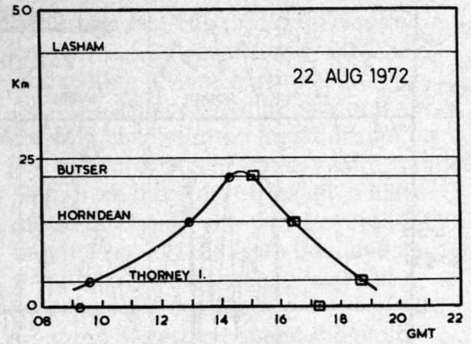

Fig. 10. Advance and retreat of sea-breeze front on 22 August 1972.

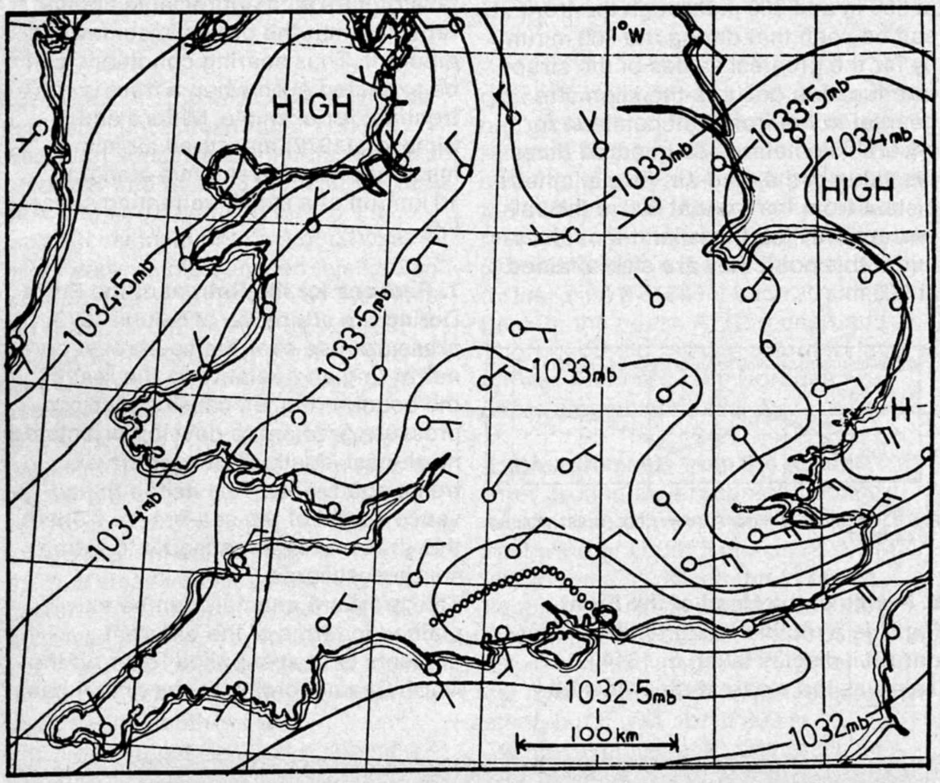

Fig. 9. Pressure and winds over Southern England, 1800 GMT, 5 June 1973.

8. Acknowledgements

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