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Observations of the thermal structure of Langmuir circulation

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A near-vertical array of thermistors has been towed through the water beneath several hundred well-defined wind rows formed on the surface of a fresh-water loch in winds of 7–9 m s^{-1}. The loch was stably stratified in the mean, temperatures decreasing with depth, and the air warmer than the water. The temperatures at ten levels in the water and the positions of the wind rows were recorded. These measurements were supplemented by photographs of the wind rows and observations of bubbles, using sonar.

The data has been analysed to produce average temperature sections across the wind rows. Near the surface a core of warm water can be distinguished beneath the wind row in the average section (although not in general in the unaveraged records) and colder water between rows, consistent with there being a Langmuir circulation pattern. At depths greater than about 0·4 times the average distances between rows, it is, however, apparent that the temperature anomalies slope to the left of the wind direction as depth increases.

The anomalies (although generally significantly different from the mean) are much less than the standard deviation of the local fluctuations in loch temperature and also much smaller than the temperature changes at the 'ramps' described earlier (Thorpe & Hall 1980), here observed to extend to within 0·4 m of the surface. There are thus two co-existing, but possibly independent, thermal structures which can be recognized in the turbulent mixing layer.

1. Introduction

In moderate to strong winds, lines composed of foam or floating debris aligned in the wind direction can usually be seen on the surface of lakes or the sea. These lines are called wind rows. They appear to be caused by convergence of near-surface water towards the position of the rows (Langmuir 1938). Near the rows themselves the water accelerates in the wind direction and appears to sink, leaving the floating material at the surface. It is postulated that the circulation in the plane normal to the direction of the wind is completed by rising, or upwelling, water between the rows. This circulation pattern of repeated pairs of counter-rotating vortices aligned in the wind direction is referred to as the Langmuir circulation. It is supposed that this plays an important role in mixing above the seasonal thermocline.

Whilst the general structure of the phenomenon near the surfaces has been known for some time (Faller 1971; Pollard 1977), only recently has a comprehensive explanation been proposed. In this theoretical model the rows are found to result from an interaction between waves and current (Craik & Leibovich 1976; Craik 1977; Leibovich 1977*a*, *b*, 1980; Leibovich & Radhakrishnan 1977; Leibovich & Paolucci

1980). Laboratory experiments by Faller & Caponi (1978) in neutral conditions of stratification support the conclusions of the theory. The model predicts the generation of a circulation, not only when the water surface is neutral or cooling, but also when the water is stably stratified.

Evidence of thermal patterns associated with wind rows is to be found in the radiometric observations of McLeish (1968), who produced maps of the sea surface temperature with lines of colder water aligned with the wind. (In a later study McLeish, 1970, reports observing wind 'slicks' with surface temperatures 0·23 K lower than their surroundings.) We are not, however, concerned here with the existence and nature of the Langmuir circulation pattern very near the water surface (for which there appears to be ample evidence and viable theoretical explanation) but with its effect and penetration below the surface. Of this there is little observational evidence, and the theoretical studies, relying on a parametrization of turbulence by eddy diffusion coefficients and disregarding the whole spectrum of instabilities which might develop, are less reliable. There is, moreover, evidence that in some circumstances structures with axes aligned *across* the wind direction are a dominant feature of the near-surface mixing-layer temperature field (Thorpe & Hall 1980).

Leibovich & Paolucci (1980) have calculated isotherm contours in a section across a wind row in a numerical model in which the vertical temperature gradient is initially constant, warm water uppermost and the surface temperature maintained constant. The temperature field below the surface is rapidly distorted by the presence of the developing circulation, with relatively warm water appearing in the water column below rows (where the descending currents advect water from the warmer surface layer) and cold water in the upwelling regions between the rows. The anomalies extend to the depth of the circulation. This model indicates that the temperature field should be a good indicator of the presence of Langmuir circulation. The measurements of Scott *et al.* (1969) of wind rows in Lake George, New York, in light winds show the presence of a relatively warm region extending to 3 m below a wind row, and also suggest the potential of temperature measurements.

2. Observations

We have investigated the thermal structure in the water below wind rows by towing a near-vertical array of ten thermistors in Loch Ness. The loch is about 1·5 km wide and 34 km long, the axis being orientated NE–SW, and is fresh water so that temperature may be used to infer the density of the water (see Wedderburn 1907 and Thorpe 1977, for a description of the loch and of the typical vertical profiles of temperature and current). The measurements were made between Achnahannet and Inverferigaig where the fetch to SW winds is some 20 km and the water depth exceeds 50 m (and is mostly in excess of 150 m). The thermistors were mounted along a pole with vanes attached to align the sensors into the flow. The pole was hung from a beam extending over the side of a small cabin cruiser, and kept nearly vertical by hanging a heavy streamlined weight from its lower end. This assembly was towed, usually across the wind direction at about 75 cm s^{-1} with the sensors on the windward side of the cruiser. The cruiser position was recorded by a time-lapse camera mounted on the hillside overlooking the loch. A second camera with telephoto lens recorded the wind rows visible in an area of 23 × 105 m some 250 m from shore.

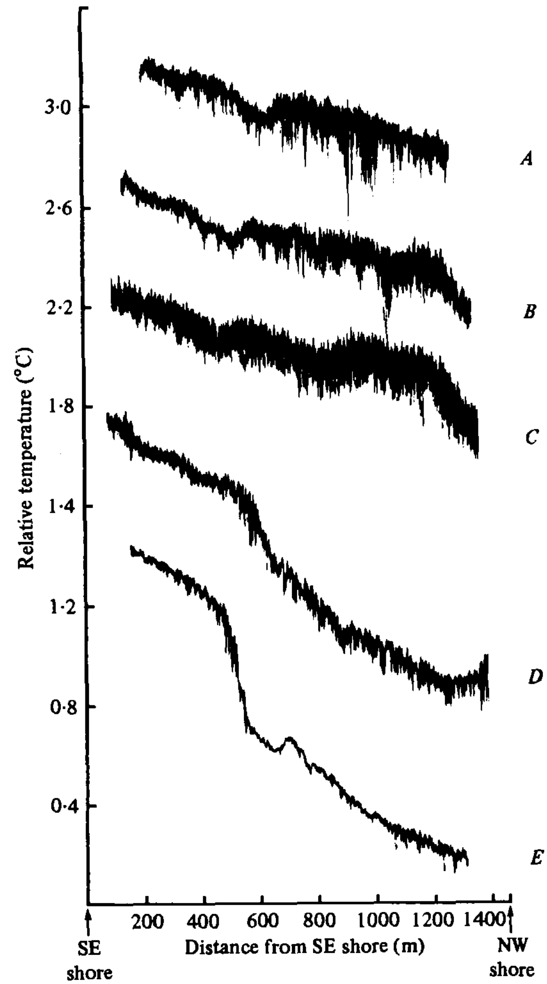

FIGURE 1. Five temperature sections across the loch from SE to NW on 1 June 1980. Ten thermistor records between 0·4 and 3·55 m are plotted for each section, and each section is off-set from its predecessor by 0·5 K. The wind varied between 5 and 15 m s^{-1}. Mean wind SW, 8·2 m s^{-1}, air temperature 11·2 °C (wet bulb depressed by 2·9 K), water surface temperature 9·1 °C. Cloud cover about 3/10 and frequent whitecaps. Wave period 2·1 s, height 40 cm. Times of sections (GMT): *A*, 0926–0946; *B*, 1000–1023; *C*, 1039–1103; *D*, 1334–1359; *E*, 1439–1522. *A*, *B*, *C* and *E* were along the same course to within ± 68 m along 218 deg. T. Although *D* begin on the same course, the direction was some 7 deg. N of the others and ended some 288 m to the NE. This variation in course was caused by changes in wind speed and was typical of the other sections made.

Every second the temperatures were recorded on magnetic tape with a resolution of about 1·7 mK together with a 'scan' number, and these numbers were noted whenever the array passed through a wind row. A voice recording was also maintained and the scan numbers (which fixed the times at which wind rows were crossed) were later checked and corrected. Wind rows were usually composed of foam, with a few leaves or twigs. Some effort was made to describe the nature of each wind row as it was crossed, and we devised several categories: rows which were long, compact, broad (sometimes 50 cm wide) bands of foam (class *A* rows); narrow and somewhat broken, but yet long, bands; broad but fragmented bands of foam, or simply isolated fragments of foam, left by waves which had recently broken (these were disregarded in subsequent analysis). Double rows, a well-defined row accompanied by a secondary weaker row, or bifurcating (dividing or joining) rows of about equal intensity, were also noted. The clearest, most prominent, and (unlike the wind rows) persistent bands of foam were subsequently found to be associated with thermal fronts. These bands could frequently be seen at a distance of over a kilometre, and extended unbroken for at least 3–4 km, fairly straight and usually approximately parallel to the shore and several hundred metres off shore. These were also disregarded in subsequent analyses, probably being produced by a mechanism different from that of the wind rows. There were often other lines of foam some 10–20 m off-shore, running parallel to the shore line but separating from it at promontories, presumably associated with the shallow near-shore circulation. These were too close to shore to be measured.

Figure 1 shows five temperature sections across the loch during southwesterly winds on 1 June 1980. (The details of the conditions are given in the captions of this, and later figures.) Each section contains traces from ten thermistors, so that the spread of temperatures in each section is a measure of the stratification. In the early sections, A to C, this amounted to about 0·08 K, but reduced to 0·02 K by E. The mean vertical gradient was 23 mK m^{-1}. The temperature of the loch at the SE side was greater than that on the NW side throughout the day. The changing trend of temperatures through the five sections shows that the loch was becoming colder on the NW side, the near surface temperature falling by about 0·85 K, but rising on the SE side by about 0·07 K between sections A and E. The cross-loch gradient thus increased, with a front developing about 540 m from the SE shore, with an abrupt change in temperature of about 0·35 K and accompanying bands of foam roughly parallel to the SE shore.

The histogram of distances between neighbouring wind rows determined using the mean speed of the cruiser and the times at which wind rows were crossed, is shown in figure 2(a). The mean separation is 9·45 m.

Figure 3 shows the temperature fluctuations from section D. Each thermistor record has been detrended by removing a running average over 49 s† and normalized by dividing by the standard deviation of the detrended record. The vertical bars at top and bottom mark the times at which the array crossed wind rows. The large fluctuations at all thermistors between 530 and 600 s are at the position of the developing front (cf. figure 1). Several other features can be seen which are coherent throughout the sampled depth range. The correlation coefficient between pairs of thermistors however falls to 0·5 for a vertical separation of only 1·3 m so that on average the records are generally incoherent between top and bottom of the array. (The average time-lagged correlation coefficient falls to 0·5 in a time of about 2·35 s equivalent to a horizontal distance of about 2·0 m across the loch.) The most important conclusion from the figure is that it is not possible to recognize any obvious association between the temperatures and the position of wind rows; high (or low) temperature values are not uniquely associated with wind rows.

† This time was chosen in an *ad hoc* way, being much greater than the average time to pass from one wind row to the next and much less than the record length.

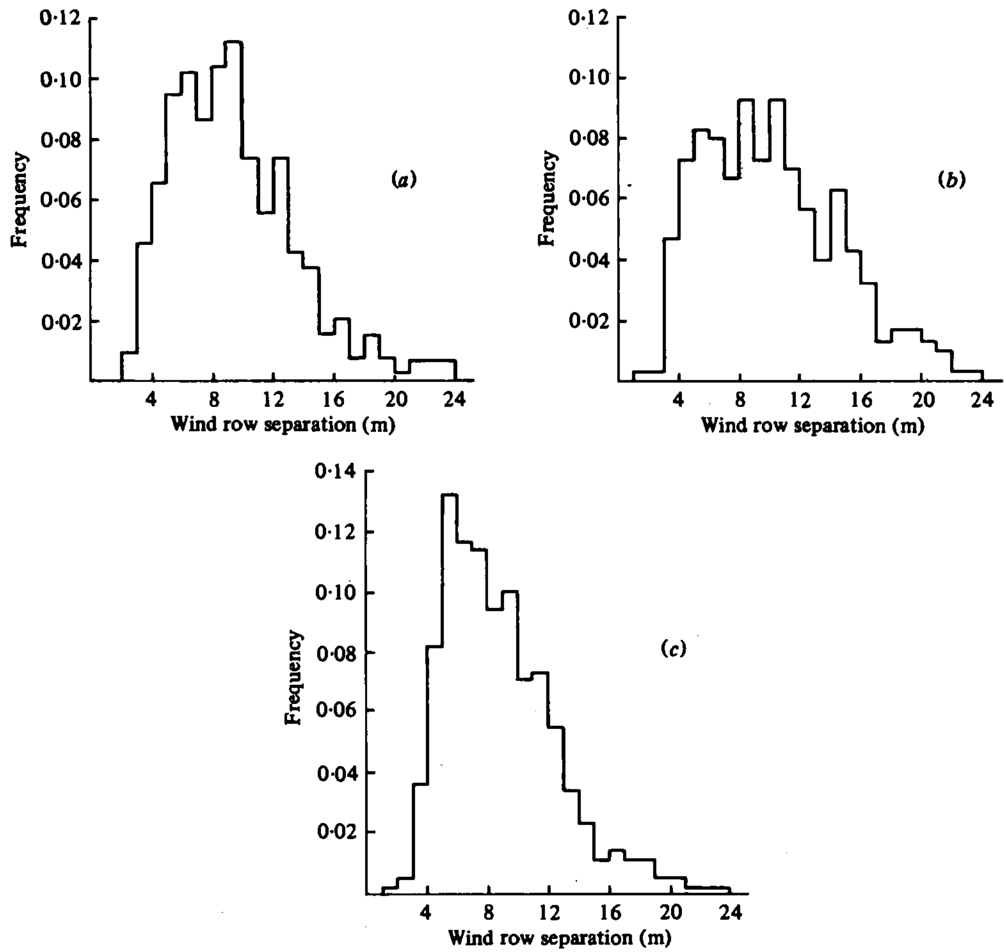

FIGURE 2. Histograms of distances between successive wind rows on (*a*) 1 June 1980, (*b*) 3 June 1980, (*c*) 27 June 1979.

We have therefore resorted to a more direct way of seeking a thermal signature of wind rows by making average temperature sections in the water between wind rows. The temperature records between neighbouring rows have been divided into 10 equal intervals and the temperatures at each interval (and at the level of each thermistor) averaged through the ensemble of wind rows. Figure 4 is the average section of 431 wind rows from SE to NW (i.e. looking up-wind). The time sequence of data on which this is based has been corrected for an observed angle of tilt of the array, about 20 degrees. The mean distance between neighbouring wind rows, $\lambda = 9{\cdot}45$ m, has been used to normalize the distance across the row, and the depth. The figure shows that, on average, there is a core of relatively warm water below the position of a wind row extending to about 3 m below the water surface. The core appears to be about 3 m in width and has a temperature anomaly of about 2 mK. The standard deviations of the detrended temperature fluctuations in the cross-loch sections varied from 31 mK at the lowest thermistor to 17 mK at the top, and these far exceed the observed anomalies across the wind rows. It is thus not surprising

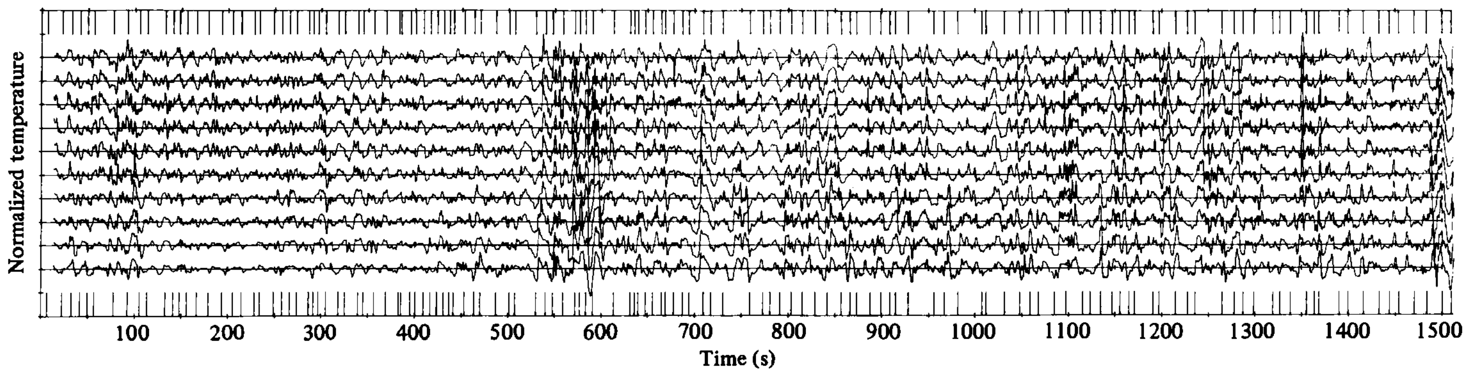

FIGURE 3. Deviation temperature from running mean versus time for section D, 1 June 1980, for the 10 thermistors. The times at which wind rows were crossed are shown by the vertical lines at top and bottom. The temperature records are arranged in order according to the depth of the thermistors, which are as indicated in figure 4.

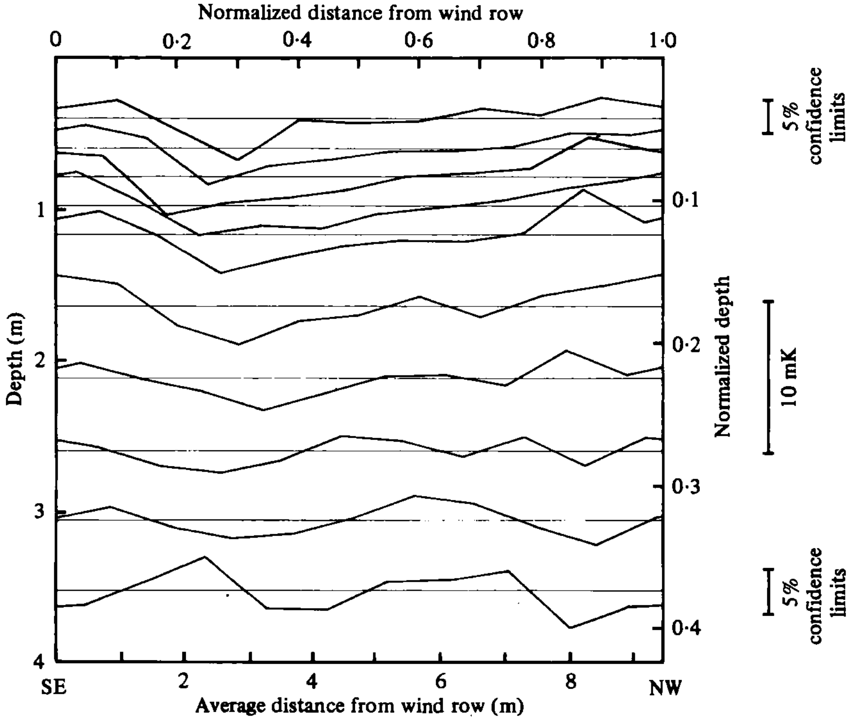

FIGURE 4. Average temperature section across 431 wind rows on 1 June 1980. The horizontal lines are drawn at the depth (shown at the left) of the thermistors. The temperatures shown are the average variations at each position from the detrended mean centred at the depth of the thermistors. The mean distance between neighbouring rows, 9·45 m, has been used to normalize the distance from the row and the depth.

that a pattern associated with the wind rows cannot be seen in figure 3. The anomalies are nevertheless just significant at the 5% level.† Figure 4 also shows that the vertical gradients in temperature do not differ very much on average across the wind rows; the gradients below the foam lines are not significantly less than those between. An investigation of the structure of vertical and horizontal mean square gradients and of the frequency of temperature inversions across the set of wind rows failed to detect any significant pattern.

A set of 147 rows graded 'class *A*' was also analysed. A thermal signature similar to that of figure 4 was again found, but with a peak positive anomaly below the wind row of about 8 mK. The appearance of colder than average water at 3 m below the wind row (also seen in figure 4) suggested a splitting of the central core.

On the same day as these measurements were made, an upward pointing echo sounder was moored in mid-water at 34·2 m below the area of the loch's surface covered by the second time-lapse camera, to record the acoustic returns from the clouds of bubbles produced below the surface as a result of breaking waves, or white-caps (Thorpe & Stubbs 1979; Thorpe & Humphries 1980). The system recorded the

† The temperature fluctuations were near Gaussian, having low skewness and excess near 3. The limits given assume Gaussianity. A 5% confidence limit implies that there is only a 5% probability that the average temperatures differ by an amount exceeding this limit as a result of random processes. Values exceeding the limits are thus significantly different from the mean.

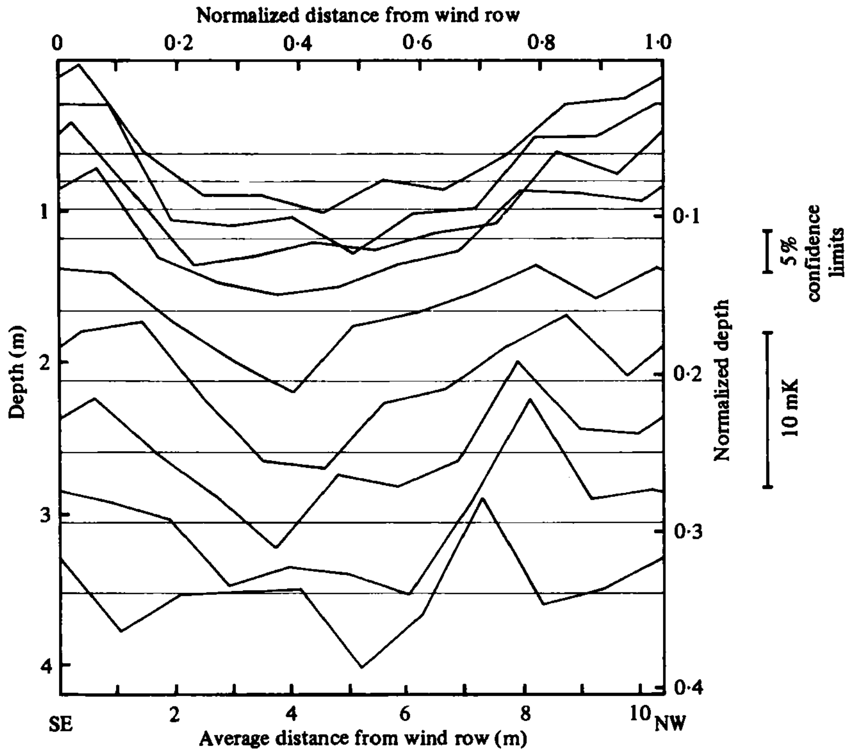

FIGURE 5. Average temperature section across 141 wind rows on 3 June 1980 drawn as in figure 4. Wind was fairly steady, SW, averaging 9·8 m s^{-1}. Average air temperature 14·3 °C (wet bulb depressed by 1·1 K), water surface temperature 9·3 °C. Wave period 2·4 s, height 40 cm. The mean vertical temperature gradient was 19 mK m^{-1}. The average separation between neighbouring rows is used to normalize distances.

depth to which the clouds penetrate and the acoustic scattering cross-section of the bubbles (roughly proportional to their total area or number) per unit volume, M_v, at several levels below the surface.

Nineteen wind rows were photographed drifting slowly towards the SE at speeds of typically 2–4 cm s^{-1} and crossing the echo sounder 'footprint' on the loch surface. The values of M_v below individual rows did not appear to differ in any systematic way from the mean, some being greater and some less. Significantly high *average* values were, however, found below the wind rows at levels from 0·5 to 2·3 m depth, but those at 2·8 m were not significantly different from the mean at that level.

Figure 5 shows another averaged section across wind rows on 3 June 1980. (Figure 2 (*b*) shows the histogram of distances between neighbouring rows on this day.) The wind was again SW and fairly steady for 4 h preceding the observations. A significant positive temperature anomaly extends to at least 3·0 m below the wind row. The anomalies are more pronounced than in figure 4, perhaps because of the greater air–water temperature difference or because the wind was steadier. There is evidence of the presence of positive average anomalies between the wind rows, particularly at about 3·5 m depth some 3 m to the SE of the rows.

Figure 6 shows another average temperature section but extending further below the surface (for 27 June 1979; see figure 2 (*c*) for histogram in distances between wind

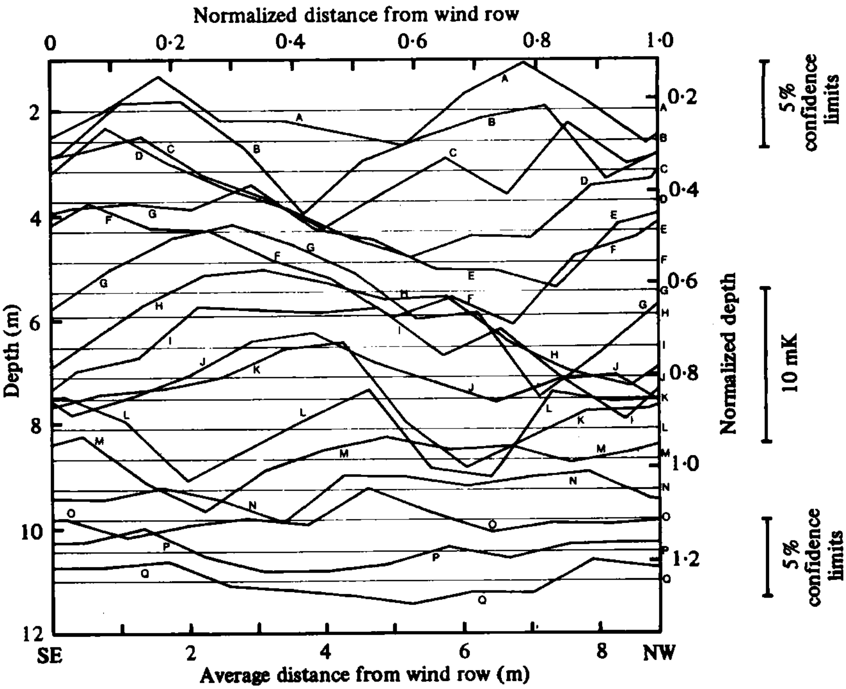

FIGURE 6. Average temperature sections across 188 wind rows (measured at a depth of 2·0–7·2 m) and 86 wind rows (5·7–11·5 m) on 27 June 1979, drawn as in figure 4. Wind was SW, averaging 7·1 m s^{-1}. Average air temperature 12·1 °C (wet bulb depressed by 2·7 °C), water surface temperature 9·1 °C. The mean vertical temperature gradient in the water was 35 mK m^{-1}. The average separation between neighbouring rows, 8·9 m, is used to normalize distances. Labels *A* to *Q* mark temperature sections and their corresponding levels.

rows). The winds were again southwesterly. The mixing layer, measured by a vertical profiling instrument operating from the shore (Thorpe 1977), was 12 m or more in depth. The significance of individual points is lower than seen in figure 5, but a coherent pattern can be seen to a depth of about one wind-row spacing, with positive and negative anomalies trending to the NW as depth increases. This pattern is, for clarity, drawn in figure 7 and has been extended above 0·2λ by using the data of figures 4 and 5. The region *A* of negative anomaly below the wind row, and particularly the positive anomalies on either side, are not dissimilar to the features seen at similar depths in figures 4 and 5. The positive anomaly *B* is not significant at the 5 % level, but appears in the records of two of the thermistors.

In contrast to the results presented so far, figure 8 is a temperature section made *upwind* 460 m from the NW shore on 1 June 1980. This shows recurring ramp-like structures (marked by arrows) coherent throughout the depth range and with an amplitude of about 200 K, some three times the mean (detrended) standard deviation. These features have been described in detail elsewhere (Thorpe & Hall 1980) and are due to narrow, transient, but vertically coherent, thermal 'fronts', tilted forward in the wind direction, which are thought to be formed by a distortion of the mean thermal field by large turbulent eddies transverse to the wind direction. The new evidence of figure 8 is that the fronts sometimes extend much closer to the surface than it was previously possible to measure. (There are examples in the figure of

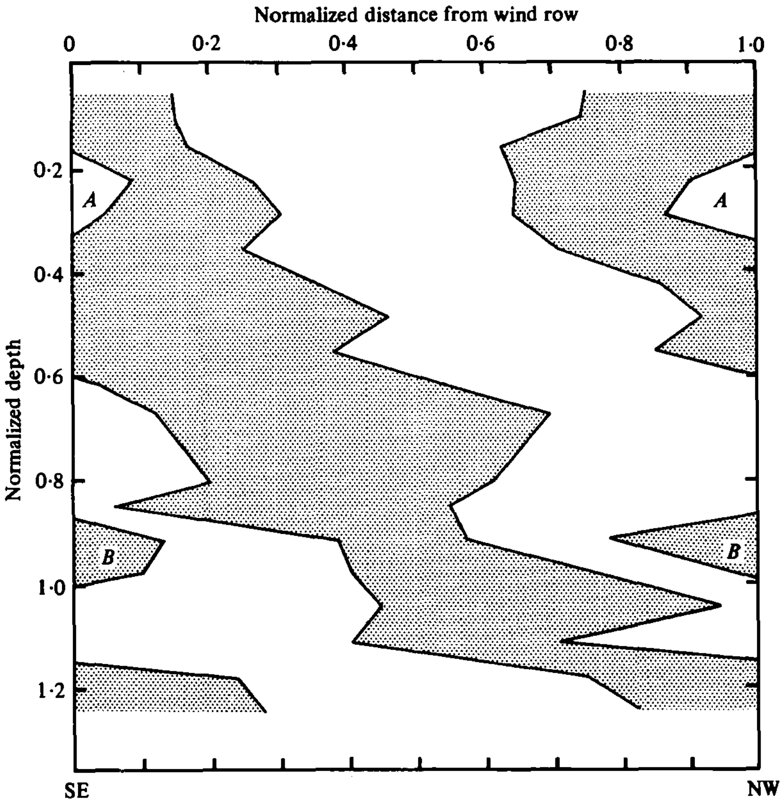

FIGURE 7. Regions of average positive and negative temperature anomalies in a section between wind rows. The stippled areas have positive anomalies. The mixing layer extends to at least 1·3λ.

'ramps' which do not extend to the highest thermistor but are clearly visible at lower levels.) These appear to be the largest coherent thermal structures generally and widely found in the mixing layer of Loch Ness during the period when the loch is being warmed, and probably account for some of the coherent features seen in figure 3.

3. Discussion

In interpreting the data presented in §2, several limitations of the observations deserve comment. The resolution of the thermistors is adequate to describe the cross loch sections (figure 1) and is some ten times better than the standard deviations of the detrended records. It is however barely adequate to resolve the small anomalies of temperature across the wind rows. Although the thermistor response time was sufficient, the sampling rate of 1 Hz at the towing speeds used (about 75 cm s^{-1}) was only just adequate to resolve the rows and a higher rate would have been desirable. (Lower cruiser speeds would have made it impossible to hold course in strong winds.) Although the fixing of wind row positions was probably to within 1 s (about 75 cm) the estimates of the width of the warm core and its peak value are both subject to some doubt on the grounds of inadequate resolutions and averaging inaccuracies.

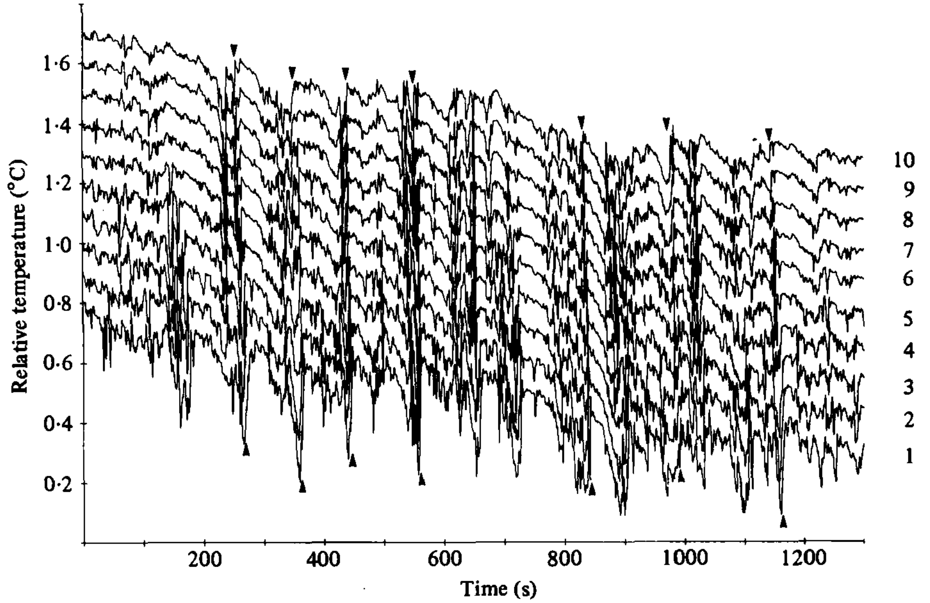

FIGURE 8. Temperatures measured in a section upwind, parallel to and mostly between wind rows on 1 June 1980 starting at 1127 G.M.T. The cruiser speed over the bottom was 39 cm s^{-1}. (The speed through the water was not measured.) Each successive record has been offset by 100 mK so that the features can be seen. The records are arranged in order of their depths, which are as indicated in figure 4. Arrows mark the temperature 'ramps' which occur progressively later, the greater the depth of observation. Similar 'ramps' were observed in sections parallel to the wind on 3 June 1980 and 27 June 1979, and on other occasions.

Care was taken however to select observations carried out in conditions in which the wind rows were clearly visible. The roll of the cruiser caused the thermistors to move vertically, typically by 20 cm in cross loch tows, and this may have influenced the measurement of small-scale horizontal gradients and horizontal coherence, but should not have significantly degraded the averaged data of figures 4–6. The array was judged to be sufficiently far from the cruiser at the water line for the cruiser wake not to interfere significantly with the flow near the sensors.

The temperature sections of figures 4–6, summarized in figure 7, are consistent with a Langmuir circulation with, on average, a downward mean flow near the surface beneath the wind rows and an upward flow between. Horizontal temperature differences near the surface could perhaps be produced beneath slicks by the 'stagnant film' mechanism described by Saunders (1967), and turbulent diffusion with no advection might then explain the observed patterns. The increased acoustic scattering from bubbles below the wind rows, however, appears to provide less controversial evidence of a circulation pattern, especially in view of the observations that waves break as often at wind rows as between (Thorpe & Hall 1980) and hence provide a uniformly distributed source.

Below $0{\cdot}2\lambda$, the trend of the horizontal position of the anomalies towards the NW (figure 7) also indicates an advective, rather than diffusive, process of heat transfer. It is interesting to note that the trend is the opposite of that found in the circulation cells which result from the instability of the Ekman layer studied by Faller & Kaylor (1966; that work suggests that the trend observed here, to the NW,

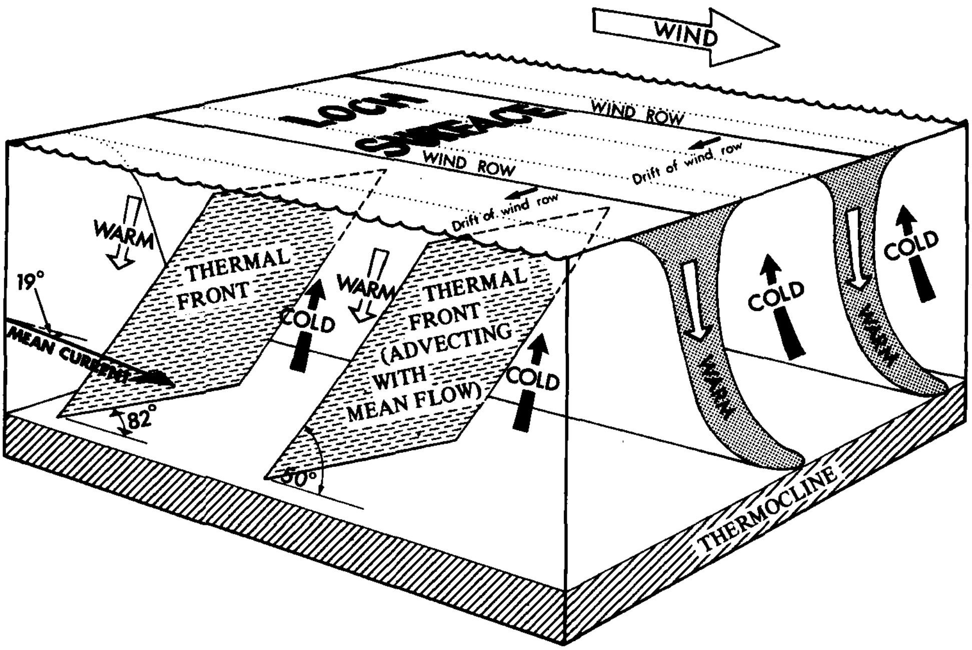

FIGURE 9. A sketch of the large-scale mean thermal structures in the mixing layer and the inferred associated vertical water movements.

should be associated with a loss of energy by the perturbation and a gain by the mean flow). It is thus unlikely that the thermal structure derives (solely) from an Ekman-layer instability. On twelve of the fifteen days on which wind rows were photographed in SW winds there was a slow, 1–4 cm, sideways drift to the SE, a direction consistent with an Ekman transport. During periods of the remaining three days, there was also a south-easterly drift. (It was unfortunately only possible to see wind rows from the vantage point of the camera on one day during NE winds. Their movement was to the NW.) This drift is in a direction consistent with that of the mean current in the mixing layer which was found to be directed at 19° to the right of the axis of the loch (Thorpe & Hall 1980). The slope of the temperature anomalies, and the drift of wind rows, may well be the consequence of an Ekman-like flow and the effect of such a flow deserves consideration in further theoretical models.

The temperature signature of wind rows is a very minor signal in the turbulent near-surface layer and would be very difficult to identify unambiguously without the guidance of the surface foam streaks which mark the rows. Even near the surface below the best defined rows on 1 June 1980 the thermal anomaly is very much less than the amplitude of the r.m.s. variation, and corresponds, in the mean gradient, to an equivalent vertical displacement of less than 35 cm. This equivalent displacement is about 60 cm on 3 June 1980 but still far less than that predicted in the model by Leibovich & Paolucci (1980, see especially figures 9 and 18). The parameters of the model do not, however, correspond too closely to the observations. Disregarding the questions of how to assess eddy coefficients appropriate to a numerical model which is itself driving a motion leading to an increase in fluxes which would be included in measurements, and whether or not these coefficients should be uniform in space and time, the observed vertical temperature gradients were much greater than those of the model, and the appropriate Richardson number, *Ri*, consequently greater. Except for the neglect of the Earth's rotation, other parameters were probably in reasonable agreement (see Thorpe 1978 for estimates of diffusion coefficients). The effect of an increased *Ri* is likely to be a reduction in scale and perhaps intensity of the circulation.

No connection between the thermal 'fronts' (figure 8) and the wind rows has been established. Although it is not impossible that the two may be linked (the fronts might, for example, be an instability associated with the vertical gradient of velocity in the wind row circulation), it is our interpretation of the measurements that there are two co-existing, but possibly independent, thermal structures in the turbulent mixing layer of the loch (see figure 9). Both appear to extend through the depth of the layer. The wind rows extend downwind with an apparent circulation in the plane normal to the wind. The fronts are largely transverse to the wind direction (but of unknown lateral extent) and are related to an apparent circulation in a vertical plane close to the wind direction. We have not been able to measure, or infer, the vertical heat flux associated with either of these phenomena, it being difficult to measure vertical currents with sufficient accuracy and resolution. Studies of heat flux and of the thermal structure of lakes at other times of the year, particularly during the time they are cooling, would be very worthwhile and would give a valuable insight into processes occurring in the ocean.

The extensive and persistent front which often develops in the loch (see figure 1 and observations by Simpson & Woods 1970) appears to be a feature of the wind-driven circulation and merits further investigation.

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