Benthic Observations on the Madeira Abyssal Plain: Fronts

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ABSTRACT

Analysis of data from a mooring with five vector-averaging current meters between 10 and 70 m above the bed of the Madeira Abyssal Plain reveals the existence of narrow regions with relatively large gradients of potential temperature, or "fronts." The orientation and structure of the fronts is examined by combining the temperature and current data and plotting contours of equal potential temperature on the progressive vector diagrams, a procedure justified because of the known horizontal coherence of the currents and the relatively long time-scales of evolution of the benthic boundary layer. Sections through the fronts show that they are typically ~300 m in width. They extend horizontally for at least 8 km. The temperature differences across the observed fronts are only 2–4 mdeg C. The frontal surfaces are tilted at ~10 deg to the horizontal, the observed cold fronts being steeper and with isotherms more closely compacted in the lower levels, than warm fronts. These features possibly result from the straining of the temperature field by mesoscale motions as proposed by Armi and D'Asaro.

1. Introduction

Armi and D'Asaro (1980) have described the results of an experiment to investigate the Benthic Boundary Layer (BBL) on the Hatteras Abyssal Plain. One of their principal observations was that horizontal processes of advection and convergence appear to be important in determining the vertical profile of potential temperature or density in the BBL; simple vertical entrainment was not enough to explain the changes measured by a mooring carrying seven vector-averaging current meters (VACMs) between 15 and 85 m off the sea bed. One particular feature which they described was a warm front. (Here we specifically use the terms warm and cold to indicate that there is an increase or decrease, respectively, in temperature at a particular position as the front passes). The temperatures at all VACM levels increased by ~50 mdeg C over a period of one day, and the current changed by some 2 cm s^{-1}, in a sense appropriate to geostrophic balance existing across the front. The slope of the isothermal surfaces was estimated as 0.04 from their measured rate of ascent and the mean horizontal advection velocity. (The slope might have been even greater if the velocity was not measured normal to the frontal surface; the orientation of the front was not known). The advection of the front past the mooring produced an immediate change in the temperature profile in the near-bottom water, and the water at the level of the upper instruments remained warmer for a period of several weeks. The rapidity of the observed change, and those described later, may be gauged against the 10 day time-scale estimated for the development of a BBL by vertical mixing processes (Richards, 1982).

Elliott and Thorpe (1983) interpreted temperature changes of 2–3 mdeg C measured by a single VACM with rotor 1 m above the bed of the Madeira Abyssal Plain as being due to the advection of thermal fronts with a horizontal width of only a few hundred meters, but no vertical structure was measured to support this conclusion. This omission is now rectified. The existence of fronts in the deep ocean emphasizes the role of horizontal processes leading to frontogenesis (Hoskins and Bretherton, 1972) in determining the boundary layer structure and changes in it. Recognizing a probable similarity to atmospheric fronts, these regions are likely locations of significant vertical transfers from the BBL into the overlying water column; that is, they are effectively regions where the largely horizontal advective and diffusive spreading of water (and particulate matter in it) in the BBL adjoining the sea bed is replaced by injection into the interior, mid-ocean water, where the immediate effects of boundary layer processes, notably enhanced vertical mixing, are no longer present.

2. The data set

On 21 January 1981 a mooring with five VACMs at 10, 20, 30, 50, and 70 m above the sea bed and an Aanderaa current meter at 100 m was deployed on the Madeira Abyssal Plain at 33°10.1'N, 21°59.8'W, in a depth of 5293 m. This was part of an experiment designed by Dr. P. Saunders at the Institute of Oceanographic Sciences to examine the forcing of, and variations in, the BBL using an array of current meters and clusters of neutrally buoyant floats. The mooring was recovered after 173 days.

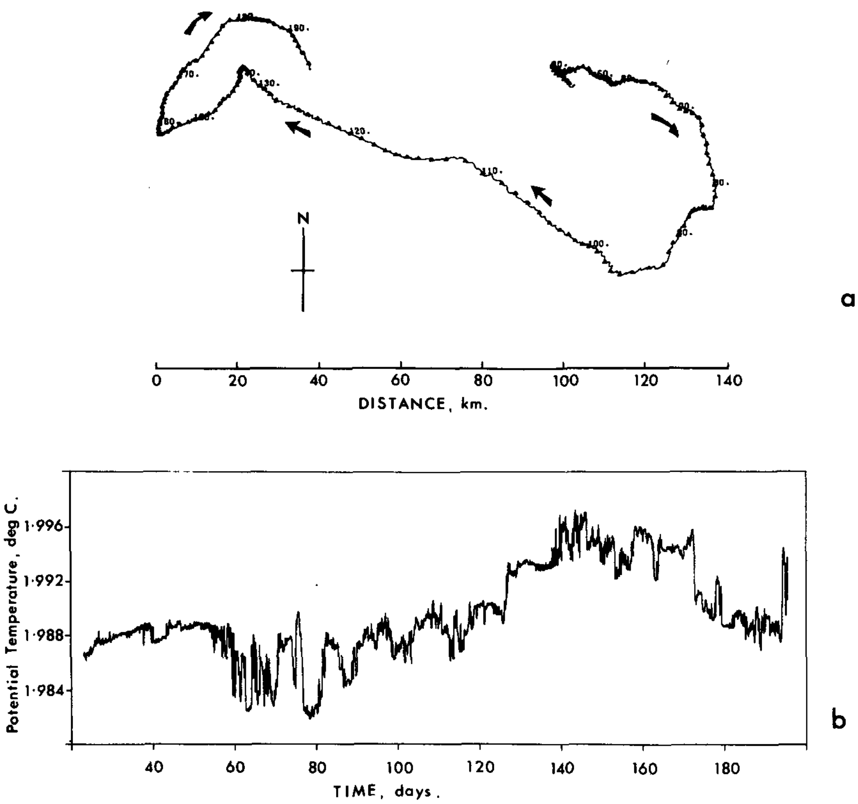

FIG. 1. (a) Progressive vector diagram with positions marked every day, and (b) potential temperature–time plot at 30 m above the sea floor for the whole period of the mooring.

The data from the Aanderaa current meter will not be discussed here because its temperature resolution (2.5 mdeg C) was found to be too poor to be of much value.

Measurements of the average values of current and temperature over 30 min periods were recorded every 30 min by each of the five VACMs (synchronized to within 4 min). The currents were generally small, less than 12 cm s^{-1}, and the VACM rotors were stalled, on average, 20% of the recording period. During these times, which, on average, lasted for 100 min, the current data set was "reconstructed" by linearly interpolating the current components. The mean current recorded by the VACM at 50 m was slightly less than those above and below that level (see Figs. 3, 6 and 9). This is attributed to instrumental inaccuracy. The greatest tilt of any part of the mooring, estimated from the maximum observed currents (and consistent with readings of a pressure sensor on the Aanderaa meter) was less than 4°.

Temperatures recorded by the meters were calibrated against those of four CTD casts made 2–4 days after the mooring was deployed, and the equivalent potential temperatures were calculated and used in the analysis. At the start of the record, however, the sensor on the VACM at 20 m was found to be drifting relative to those above and below it, and the calibration was set so that its mean was equal to the mean of the temperatures at 10 and 30 m at the earliest time, day 42–43.5,[1] at which it appeared to be recording normally.

The recording resolution of the VACM temperature sensors is 0.03 mdeg C but the instrumental noise level is uncertain. Judging by the similarity of features seen in different VACM records (see for example Fig. 5a) it is less than 0.3 mdeg C, neglecting long-term drifts. The relation between potential temperature and potential density in the near-bottom water was established from CTD casts. There is a close relationship between potential temperature and salinity, so that potential density can be inferred from temperature alone (Saunders, 1983). Examination of 16-day sections of the record[2] (see Section 3), however, showed that negative differences in potential temperature between neighboring instruments of up to

[1] Time is here, and later, given in terms of day number in 1981, e.g., 2.5 is 1200 GMT on 2 January.

[2] The length of these sections was chosen as being sufficiently long to cover the "events" which were being examined, and short enough for easy manipulation and analysis.

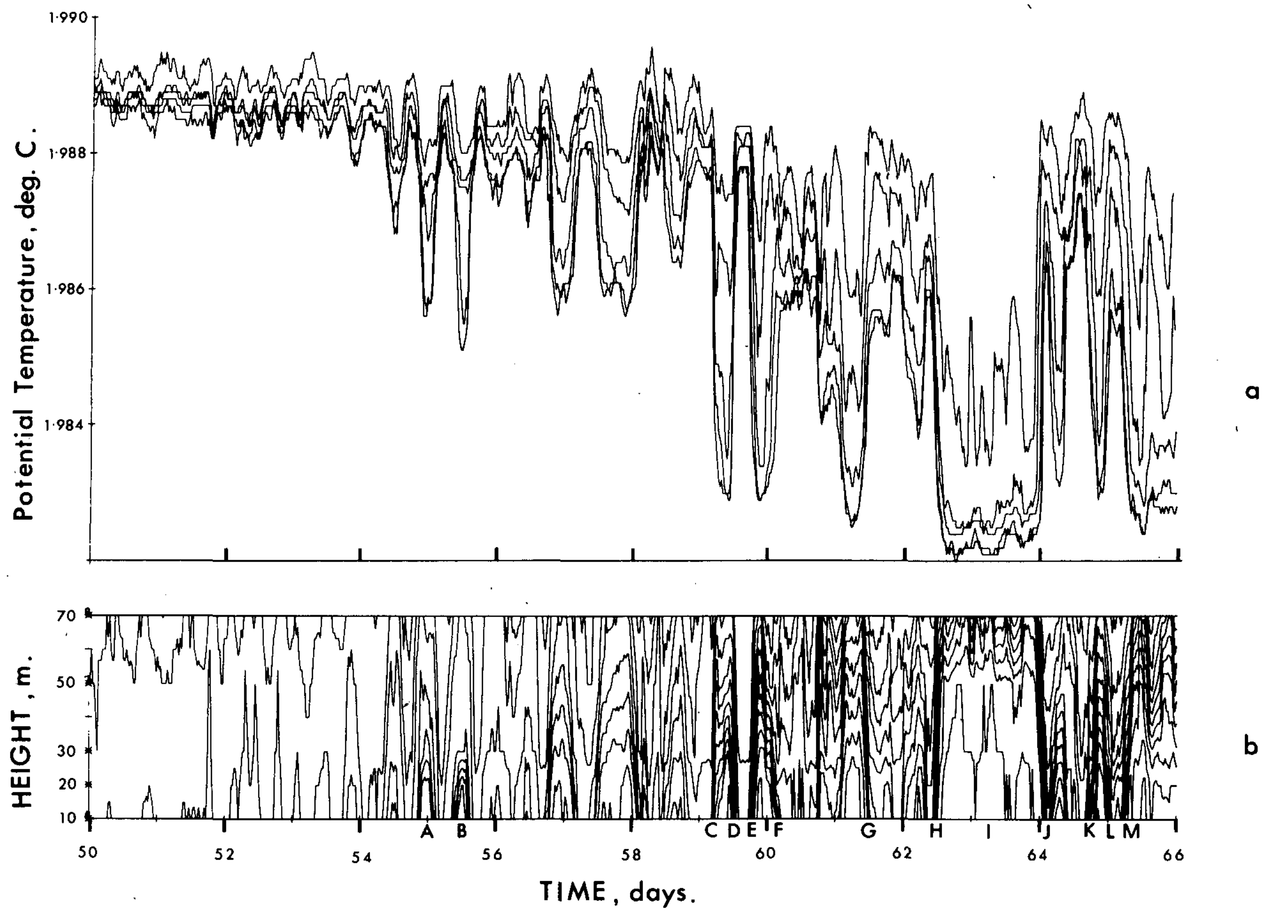

FIG. 2. (a) Potential temperature–time plots from the five VACMs, and (b) the corresponding contours of potential temperature, for the period day 50–66. The temperatures at 20 and 50 m were adjusted by ±0.1 mdeg C from the calibrated values to avoid inversions (see text). The contour interval is 0.5 mdeg C. Features referred to in text are labeled A–M on the time axis.

0.5 mdeg C were occasionally present, indicating unstably stratified water. These may be due to real inversions in potential density (although it is unlikely that these could be maintained for very long), the presence of anomalous salinity variation or particulate matter in the water column, or instrumental drift. We have removed the negative differences by shifting the whole record of potential temperature of an instrument for the 16-day section by the smallest amount necessary to make the differences everywhere positive or zero. These adjustments are noted in the captions to Figs. 2, 5 and 8. In view of the similarity of these adjustments, it is probable that instrumental drift is the main source of inversions. Such changes to the calibration do not, however, significantly alter the pattern of contours shown later in the figures since the major features are determined by potential temperature differences which exceed 1 mdeg C. Henceforth when temperatures are mentioned, potential temperatures are implied.

Figure 1 shows the progressive vector diagram (PVD) and temperature–time plot at 30 m for the full duration of the record. The currents and temperatures were generally highly coherent over the vertical extent of the mooring, and the gross changes in flow and temperature illustrated in the figure were followed at all levels. Three parts of the record draw attention and are described as case studies in Section 3. These are the period of oscillating temperature, but low flow, near day 60 (Section 3a), the abrupt temperature change on day 127 (Section 3b), and the period of change in flow direction occurring near day 156 (Section 3a). Other interesting parts of the record might equally well have been examined, for example the temperature oscillation near day 139 or the rise at the end of the record, but the periods selected for description here appear to typify the record and, in particular, reveal structures which, because of their small horizontal width but large horizontal extent and vertical coherence, are identified as fronts.

The major techniques for analysis are the superposition and contouring of the temperature field on the PVD of each VACM and the reconstruction of frontal cross-sections once the orientation of the front

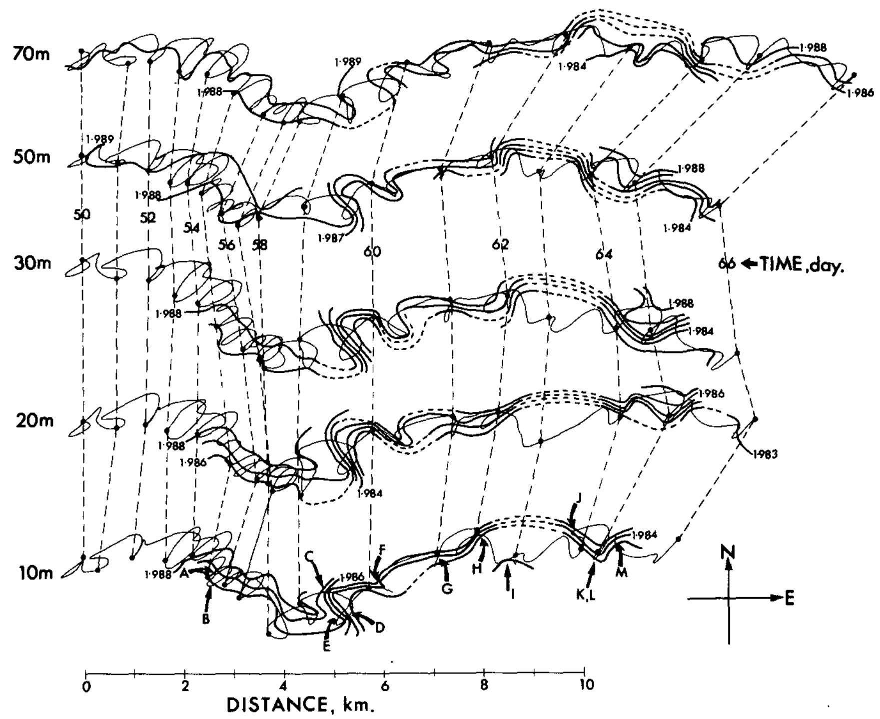

FIG. 3. The progressive vector diagrams (thin lines) at each of the five VACM levels, and superimposed contours of constant potential temperature at 1.0 mdeg C intervals (thick lines) with calibration adjustments as in Fig. 2, for period day 50–66. The dashed lines join points at the same day number. Features corresponding to those in Fig. 2 are marked A–M.

has been established. These are described in the first case study, but used in all three.

3. Case studies

a. Day 50–66; Temperature oscillations

During this period the temperatures at the current meters, shown in Fig. 2a, show an oscillation of period 12–14 h, growing in magnitude and eventually, on day 63, stabilizing at a value some 6.5 mdeg C lower than that at the beginning of the record. Although reminiscent of an internal undular surge, the feature is due to a different origin. The temperature contours (Fig. 2b) shows that considerable changes occur in the vertical stratification well beyond the uncertainty in the temperature estimates. The initial stratification is weak in the whole sampled column, but increases occur at day 55 (labeled A and B) and particularly during days 59 (C, D and E) and 61–62 (F, H), although by day 63 (I) the stratified region is mainly confined to the 50–70 m height range, and below the stratification is again weak. Restratification resumes at day 64 (J) and remains until the end of the period. The vertical shear is not shown but was generally weak (less than 1 cm s^{-1} over 50 m) being greatest on days 63 and 65. Larger, but not maintained, shears also occurred on days 55 and 59 when the abrupt changes in temperature occurred.

The temperature changes may be interpreted by reference to Fig. 3. This shows the PVD at each of the five VACM levels (thin lines) with temperature contours (thick lines) joining the positions at which a set of constant temperature values was reached. If the temperature field was simply advected by the current and not changed by diffusion (a Taylor hypothesis) and if the currents were *uniform* over horizontal planes (and they are known to be coherent over horizontal scales of ~30 km; Saunders, 1983), the five plots represent the spatial distribution of the contours of temperature at each VACM level, but with the coordinates *reversed,* that is east to the left and north downwards. The hypothesis that the temperature field is "frozen" is, over time-scales of a few days, supported by Richards' (1982) estimates of BBL evolution times. The positions of midnight on each PVD have been joined by dashed lines, and features A–M labeled on the 10 m plot to correspond to those in Fig. 2b.

The PVD's show that the currents are generally weak and oscillatory. They respond primarily to an inertial oscillation. The fluctuations in temperature in the early part of the record can now be seen to be due to the advection of a narrow band of relatively large horizontal temperature gradient past the position of the mooring (see especially day 54–58). This band, or *front,* almost completely passes the mooring

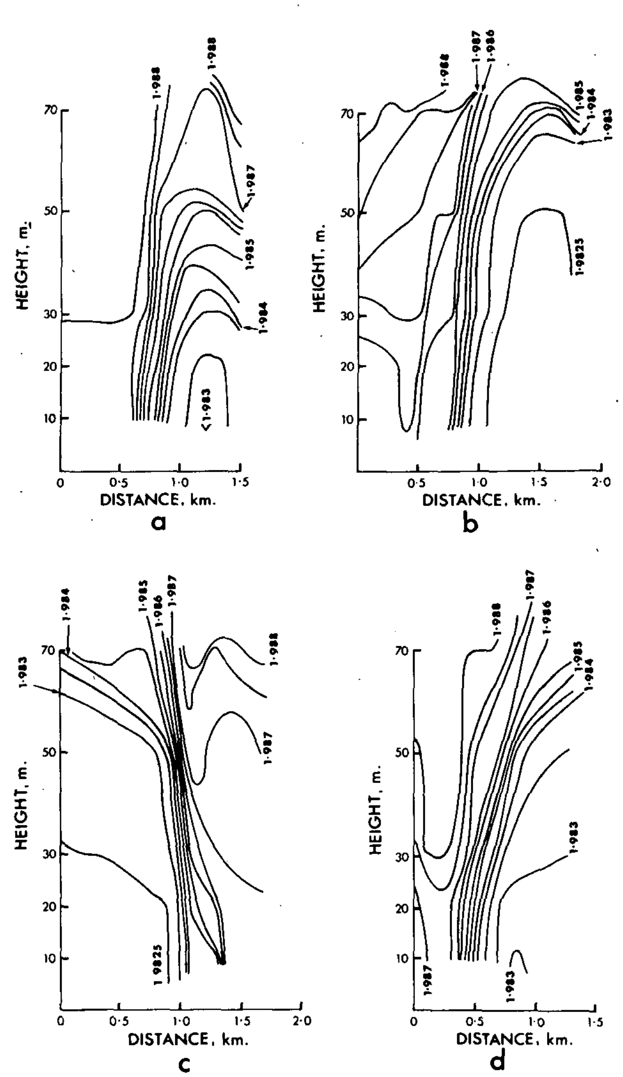

FIG. 4. Sections of potential temperature to fronts identified in Figs. 2 and 3. (a) day 59–60 (C, D, E); (b) day 61.5–63 (H); (c) day 63–64.5 (J); (d) day 64.5–65.5 (K, L, M). The temperature contours are drawn at 0.5 mdeg C intervals.

during day 59 (C, D, E) but is then for a while advected back (F) to clear the mooring again at day 63 (I). The feature is again carried across the mooring at day 64–65 (J–M). The general trend of this front, seen at all levels, is east–west, although small-scale meanders are apparent, especially that at day 59 which locally rotates the front by some 130 deg. The front is carried over the mooring by the oscillating flow three times on this day (at C, D and E) with the local meander apparently maintaining its NW–SE orientation during this short period. This is indeed an important part of the record for it appears to demonstrate unequivocally that the abrupt changes in near-bottom structure which occur during it arise from horizontal advection of narrow regions of relatively large gradients rather than by vertical mixing. It also provides a further justification for the hypothesis that, on sufficiently small time-scales (i.e., those needed for a front to pass over the position of the mooring, typically one day), the resolved temperature field is frozen. While there is inevitably some ambiguity and uncertainty about drawing the temperature contours of Fig. 3 if taken at their face value, the frontal region extends at least 8–9 km.

Fig. 4 shows sections normal to the frontal contours. These were constructed by first producing a PVD from the average currents at the five VACMs. A set of 100-m wide bands was drawn[3] lying parallel to the local mean orientation of the front as seen in Fig. 3, and the average temperatures of each of the VACMs was found for times at which the points on the PVD lay within each band. On occasions when the front crossed the mooring more than once, these sections are thus averages of the several individual sections. The four sections in Fig. 4 correspond to the periods marked (C, D, E), H, J and (K, L, M) in Figs. 2 and 3. The horizontal distance is that measured normal to the local front on the PVD and in each case corresponds also to increasing time so that, for example, Fig. 4a represents the passage of a cold front over the mooring.

The temperature contours are strongly tilted, typically at about 10° to the horizontal and are narrow, about 300 m in width, with temperature differences of 3–4 mdeg C. These changes may be compared with the mean vertical potential temperature gradient of about 3.1 mdeg C per 100 m in the water column between 5100 and 5300 m at the commencement of the experiment. It seems plausible that these four sections are of the same front seen over a period of 5–6 days. The tilt of the front may account for the cooling at the bottom meter at day 55 (see Fig. 2b); the front appears to have approached the mooring but only the lower edge of the frontal wedge crossed its position before it was advected away (see also Fig. 3). Any currents associated with the fronts themselves were generally masked by the dominant, and vertically coherent, inertial or tidal currents even in the partial averaging process employed to construct Fig. 4. The corresponding current contours (not shown here) were thus almost vertical and did not individually reveal a pattern which could be associated with the thermal front.

b. *Day 117–133; Abrupt temperature change*

Figures 5 and 6 show the temperature–time plots and contours, and the temperature-contoured PVD. Currents are generally larger than on days 50–65 and

[3] 100 m wide bands were chosen so that at least one (and usually 2–10) time points on the mean PVD fell into each band. In practice the bands were set up in a computer program and not literally drawn. Using 50 m wide bands made no significant change to the patterns.

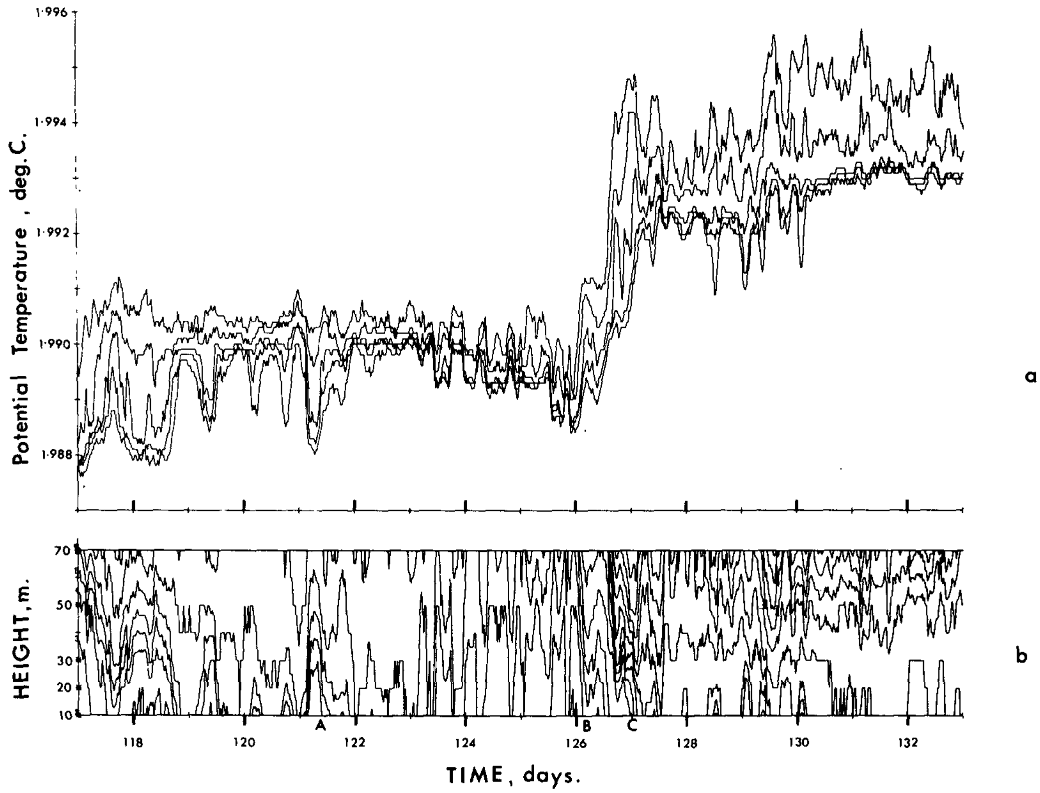

FIG. 5. (a) Potential temperature–time plots for the five VACMs, and (b) the corresponding contours of potential temperature for the period 117–133. The temperatures were adjusted from the calibration values by (bottom to top) 0.0, +0.5, −0.2, −0.5, −0.3 mdeg C respectively to avoid inversions (see text). The contour interval is 0.5 mdeg C. Features referred to in text are labeled A, B and C.

are not now reversed by the fluctuations which, during this period, are dominated by M_2 tidal oscillations. The temperature oscillations in the early part of the record (see especially day 120–122) are associated with the advection of a weak horizontal gradient (coldest to the north) across the mooring by the tides. The abrupt temperature change at day 126–127 (marked B, C) in fact occurs over a 36h period and appears in Fig. 5 as a two-step rise because of the oscillation in the current (see Fig. 6).

The section constructed normally through this warm front, Fig. 7, shows it to be a tilted feature, some 450 m wide, with more intense gradients between 50 and 70 m than at lower levels. The front is, however, seen at all the VACMs. At each level shown in the plan view of Fig. 6, the orientation of the contours is strongly constrained by the convolutions of the PVD in the neighbourhood of the front and is thus well determined. With the exception of the 50 m level, one contour crosses the PVD at at least three points. The orientation of the front is consistent at the five levels and is approximately ENE–WSW (Fig. 6). The strong temperature gradient seen in Fig. 5b at the lower VACMs at day 121 is perhaps the edge of the front. If so, its horizontal extent is at least 14 km.

c. Day 150–166: Change in mean current direction

This period was selected from Fig. 1a as being a period of low currents but with a notable change in current direction. Figure 8 and 9 show the temperature–time plots, temperature contours, and temperature-contoured PVD. The major changes in temperature can again be interpreted as being due to the horizontal advection of temperature gradients. The oscillations in days 150–153 are primarily due to the movement of a weak SE–NW gradient. At day 153 an abrupt decrease in temperature (marked A) occurs at all sensors as a region of colder water arrives. Although the mean currents are small during the period for which this colder water is present (say, 154–157) the oscillations (again tidally dominated) are sufficient to advect the warmer region back temporarily (B, C) before the increasing northerly flow again establishes the warm water at the mooring on day 158 (D). During the period 155–157 the temperature gradient is fairly uniform although there is evidence of temperature fluctuations equivalent to vertical displacements of 5 m and period 2–3 h. (This is somewhat less than can be accounted for by internal waves which are not Doppler shifted; the local stability frequency is estimated as 0.15 cycles per hour). A further

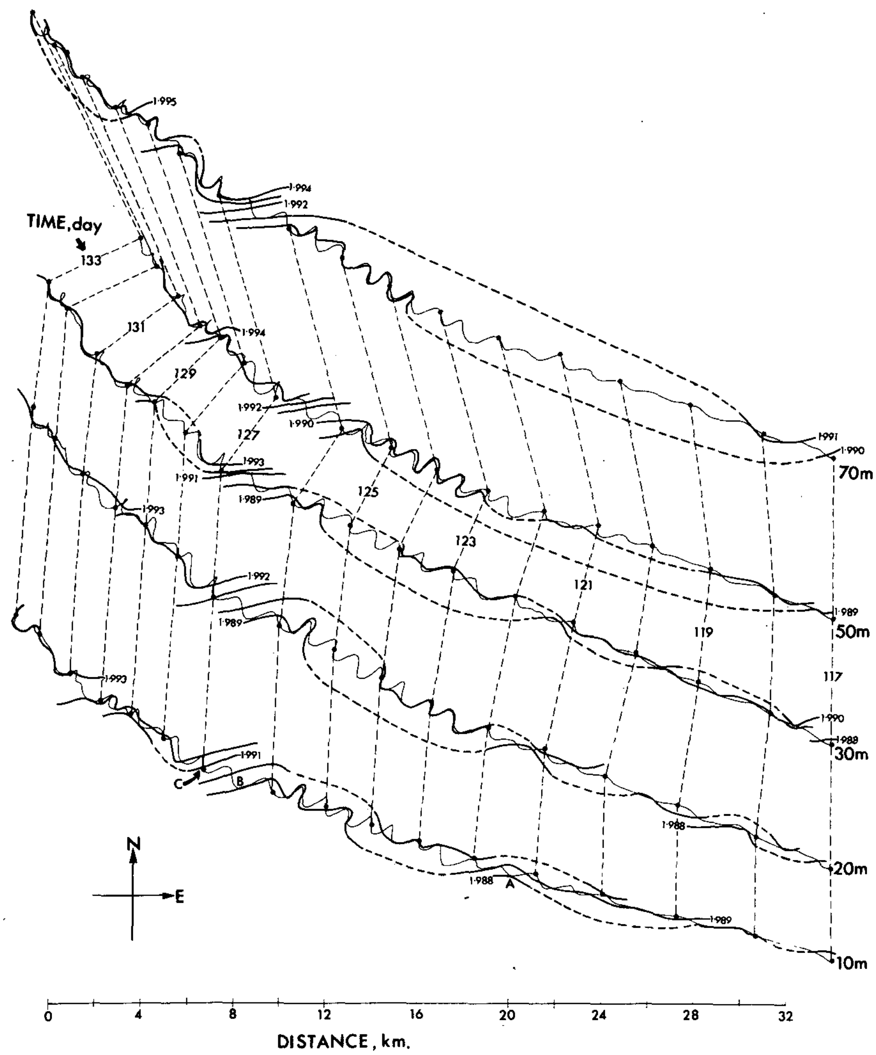

FIG. 6. The PVDs (thin lines) at each of the five VACM levels, and superimposed contours of constant potential temperature at 1.0 mdeg C intervals (thick lines) with calibration adjustments as in Fig. 5, for the period 117–133. Positions of equal times are joined by dashed lines. Features corresponding to those in Fig. 5 are marked A–C.

change occurs at about day 162.5, when water of similar temperature to that present in days 153–155 reaches the mooring. This has notably larger gradients in the upper part of the sampled depth range than at other times in the record. Finally, two abrupt changes in temperature pass in days 163.5–164.5 (F, G), the double structure resulting from the changes in current which produce a small loop in the PVD. Figure 10 shows some of the reconstructed normal sections across the fronts.

The abrupt change in the direction of the mean current does not appear to be associated with any obviously related immediate adjustment in the temperature structure in the near-bottom water.

4. Discussion

The most notable features in the temperature record leading to changes in boundary layer structure are the fronts. Since these are sometimes carried back and forth across the mooring position several times, particularly if they are almost aligned with the direction of the mean flow (as in Section 3a), it is not possible to provide an estimate of, say, the average time between the arrival of "new" fronts or of their average separation. If, as seems likely, they are related to the distortion field produced by the flow around mesoscale eddies, their separation may be of the order of 50–100 km so that, in the weak mean flows of 2–3 cm s^{-1}, fronts may arrive about every 18–50 days. The frequency of occurrence of abrupt, or oscillatory, changes in Figs. 1b is not inconsistent with this notion.

Sections across the fronts are shown in Figs. 4, 7 and 10. Four may be classed as warm fronts (Figs. 4c, 7, 10b, 10d) while the remainder are cold. Comparison shows that the cold fronts are more compact,

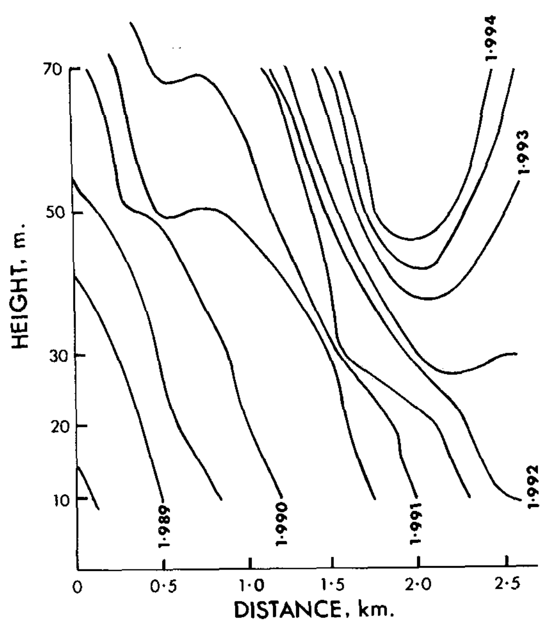

FIG. 7. Section of potential temperature normal to the front identified at B, C in Figs. 5, 6. Temperatures at 0.5 mdeg C intervals. The section spans the time period 126–127.5.

the isotherms are more closely bunched especially at the lower levels, than are the warm fronts, and they have a significantly greater slope (mean value 0.212) than do the warm fronts (mean slope 0.093; this compares with Armi and D'Asaro's value of 0.04 which may be an underestimate, see Section 1). Both of these features are found in atmospheric fronts (see, for example, Hoskins and Heckley, 1981). Although, in view of changes which are derived primarily from the advection direction of what is probably the same front over the mooring, it is unlikely that the proposed explanation in terms of the differences on the forward and backward faces of baroclinic waves can be valid. The slopes of atmospheric fronts are generally less (warm atmospheric fronts have a slope 4×10^{-3} to 8×10^{-3}; cold fronts, 1×10^{-2} to 2×10^{-2}) than observed here.

The widths of the fronts do not vary significantly, warm fronts averaging 340 m and cold fronts, 260 m. If the width of the fronts is determined by a balance between horizontal convergence produced by the large-scale current field and turbulent diffusion, we may write

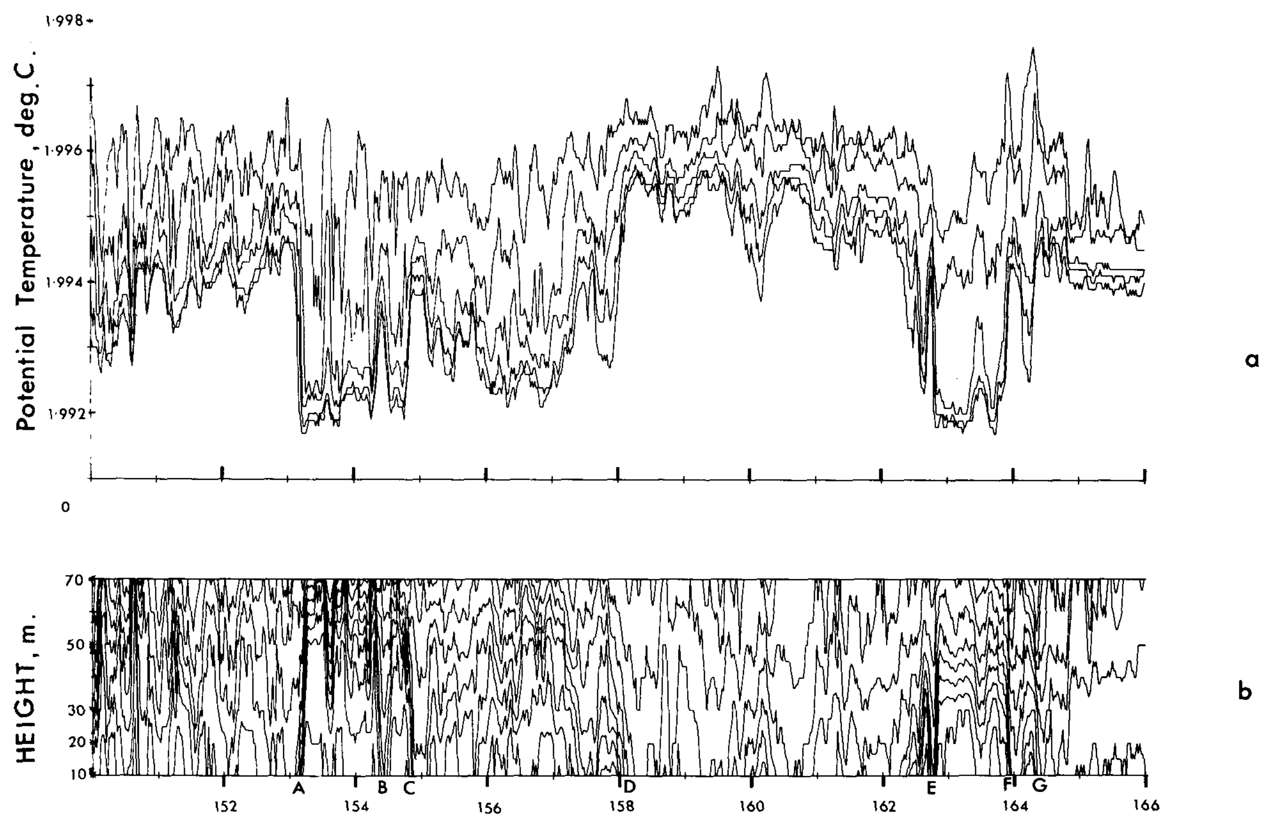

FIG. 8. (a) Potential temperature–time plots for the five VACMs, and (b) the corresponding contours of potential temperature for the period 150–166. The temperatures were adjusted from the calibration values by (bottom to top) 0.0, +0.5, 0.0, −0.5, −0.3 mdeg C respectively to avoid inversions. The contour interval is 0.5 mdeg C. Features referred to in the text are labeled A to G.

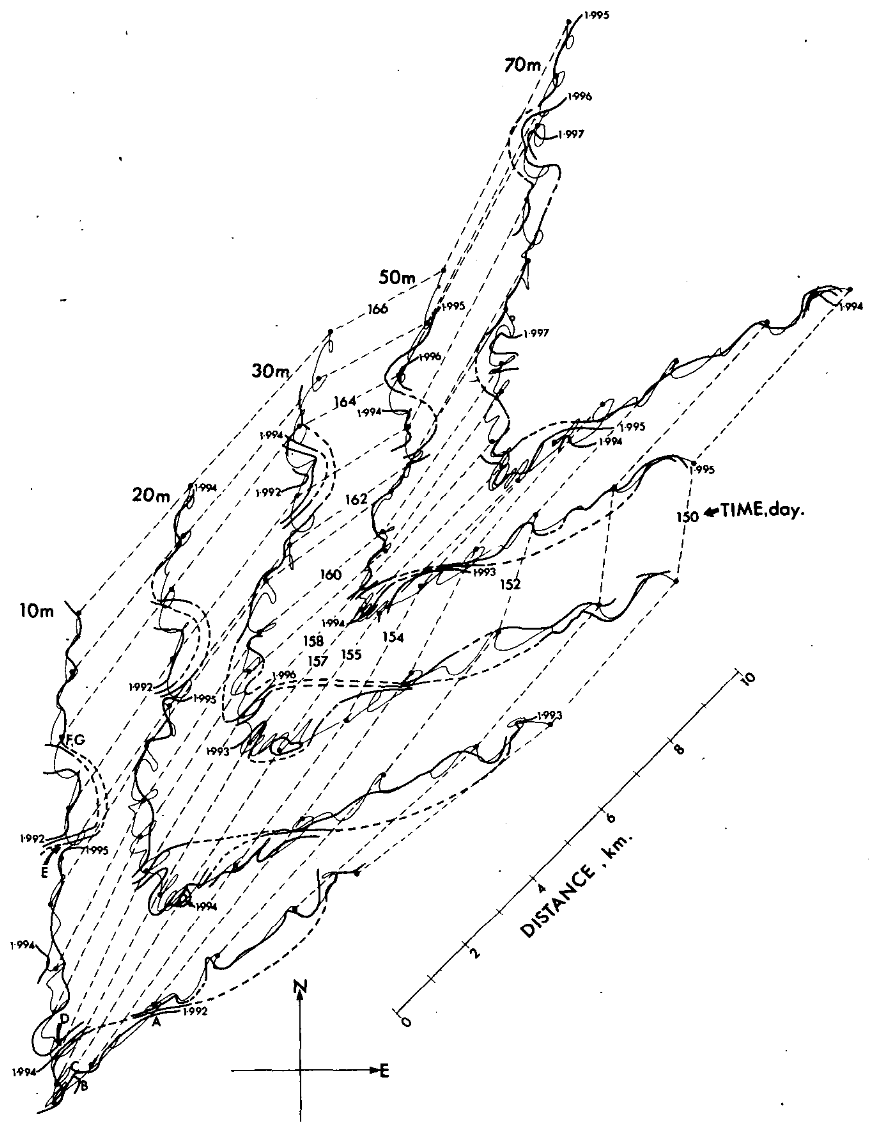

FIG. 9. The PVDs (thin lines) at each of the five VACM levels, and superimposed contours of constant potential temperature at 1.0 mdeg C intervals (thick lines) with calibration adjustments as in Fig. 8, for the period 150–166. Positions of equal times are joined by dashed lines. (Day 156, when the mean flow was very small, is omitted). Features corresponding to those in Fig. 8 are marked A to G.

$$-\alpha x \frac{d\theta}{dx} = K_H \frac{d^2\theta}{dx^2}, \quad (1)$$

where θ is the potential temperature, K_H the horizontal eddy diffusion coefficient, x is a horizontal coordinate normal to the front and αx models the convergent flow. Solutions of (1) can be found in terms of error functions. The width of the front W is given by

$$W \approx 2\left(\frac{K_H}{\alpha}\right)^{1/2}. \quad (2)$$

The mooring array was used to provide an estimate of α. Root-mean-square values of $\sim 1 \times 10^{-6}$ s^{-1} were found (Saunders, 1983), so that for a front of width 300 m, $K_H \sim 2 \times 10^{-2}$ m^2 s^{-1}. This is rather small, being within the range of values reported for K_V, the vertical eddy diffusion coefficient, in the near-bottom water at a number of stations during GEOSECS by Sarmiento *et al.* (1976), but is reasonably consistent with the square power-law relationship observed by Saunders (1983).

Estimates of the velocity differences across the fronts show considerable scatter. Measured vertically between different instruments, the mean velocity difference is 0.22 ± 0.57 (one standard deviation) cm

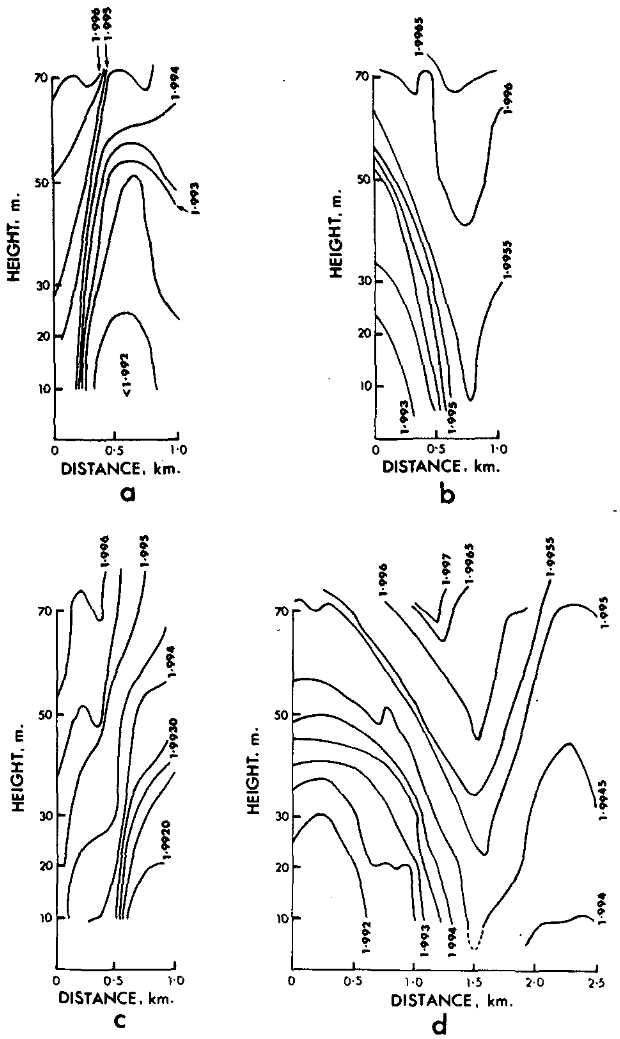

FIG. 10. Sections of potential temperature normal to fronts observed in Figs. 8 and 9. (a) day 152.7–154 (A); (b) day 157–159 (D); (c) day 161.5–163 (E); and (d) day 163–165 (F, G). Contours are at 0.5 mdeg C intervals.

s^{-1} while measured horizontally (or in time at a given instrument) it is 0.81 ± 0.92 cm s^{-1}, both means being in a sense appropriate for geostrophic balance. Examining the available near-bottom CTD profiles made just after the mooring was deployed, we find that a change in potential temperature of 2 mdeg C, typical of that across a front, corresponds to a change $\Delta\rho$ of 2.2×10^{-7} in potential density referred to 4000 m. For geostrophic balance, the velocity difference across a front is Δv given by

$$\Delta v = \frac{gs\Delta\rho}{\rho_0 f}, \qquad (3)$$

where g is the acceleration due to gravity, f the Coriolis parameter, ρ_0 a reference density (unity) and s is the slope of the front. For the mean value $s = 0.17$ we find $\Delta v \sim 0.58$ cm s^{-1} which is within the observed range.

5. Conclusions

We draw the following conclusions from this study of the changes in the potential temperature structure of the slowly moving water between 10 and 70 m above the bed of the Madeira Abyssal Plain:

1) Major changes in temperature unaccompanied by significant changes in current occur over periods as short as one day, and appear not to be due to simple vertical mixing. It is concluded that they are due to fronts, possibly resulting from the distortion of weak horizontal thermal gradients by mesoscale eddies, which are advected past the mooring. Oscillations occurring in the temperatures recorded by fixed instruments are sometimes due to the horizontal advection of fronts in fluctuating currents produced by tidal or inertial oscillations.

2) The fronts are typically 300 m in width, in accordance with earlier observations at 1 m above the sea bed (Elliott and Thorpe, 1982), with a temperature difference of ~2 mdeg C and horizontal extent of at least 8 km. The temperature difference is much less than that of the front described by Armi and d'Asaro (1980) in the more energetic flow on the Hatteras Abyssal Plain.

3) The fronts are tilted at about 10 deg to the horizontal, more so than atmospheric fronts. There may be some structural differences between cold and warm fronts.

4) Meanders in the fronts occur on scales of 1–2 km.

5) Although in accordance with there being (on average) a near-geostrophic balance across the fronts, the current differences are too small to establish whether such a balance indeed exists.

6) The vertical extent of the fronts has not been adequately examined. In some of the fronts (for example Fig. 4c) the isotherms rise from the 10 m to beyond the 70 m level of the upper VACM as the front passes. (The signal is beyond the uncertainty in calibration.) Changes associated with the fronts could sometimes be detected at the level of the Aanderaa current meter at 100 m, and on other moorings at 600 m. If, as Armi and d'Asaro have suggested, the fronts are regions where the BBL is "scraped off" the sea bed to become an interior layer, it would be valuable to know how far the isotherms may be raised, and to estimate the contribution which the fronts make to the net vertical flux from the BBL.

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This research (allocated report number DOE/RW/83.067) has been carried out under contract for the Department of the Environment, as part of its radioactive waste management research program. The results will be used in the formulation of government policy, but at this stage they do not necessarily represent government policy.

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