# NOTES AND CORRESPONDENCE

## The Skewness of Temperature Derivatives in Oceanic Boundary Layers

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ABSTRACT

The skewness of the derivative of temperature measured by sensors in the upper-ocean boundary layer in convective conditions has been measured and is observed to have a sign opposite to that found in conditions of stable heating. This is consistent with observations in the atmospheric boundary layer. High resolution measurements in the benthic boundary layer on a continental rise show a variation of skewness during the $M_2$ tidal cycle (which dominates the motion), with negative skewness, consistent with conditions favoring convection, occurring during the upslope phase of the motion. The observations are compared with laboratory studies of the reflection of internal waves from a slope. We suggest that information about the gross features of a turbulent oceanic boundary layer flow may be derived from relatively simple measurements.

### 1. Introduction

The skewness of the time derivative of temperature measured both in laboratory and naturally occurring turbulent boundary layers at fixed distances from the boundary itself is observed to be significantly nonzero. The origin of the skewness, $S$, reflecting an asymmetrical distribution of temperature derivatives, appears to be due to a pattern of temperature ramps, sudden rises or falls in temperature, associated with coherent eddies of scale comparable to the boundary layer thickness.

Measurements at fixed positions in a convectively unstable atmospheric boundary layer and laboratory measurements in a variety of conditions were analysed by Gibson et al. (1977), who noticed that the sign of the skewness of the temperature gradient $\partial T/\partial x$, measured in the mean flow direction, $\mathrm{sgn}S(\partial T/\partial x)$, was given by $\mathrm{sgn}[\mathbf{x}\cdot(\Delta\mathbf{T}\times\omega)]$, where $\mathbf{x}$ is a unit vector in the flow direction, $\Delta\mathbf{T}$ is a vector in the direction of the mean temperature gradient (supposed normal to the boundary) and $\omega$ is the vorticity of the mean flow (in a plane parallel to the boundary). The magnitude of $S$, $|S|$, varies between 0.4 and 1.3 with a mean value near 0.8 (Screenivasan and Antonia 1977).

An extensive review of the measurements is given by Antonia et al. (1979). They also report additional observations made by themselves in convective, and by others in both convective and stable, boundary layers and establish the connection between locally measured temperature ramps to those at other levels on surfaces tilted in the direction of shear, thus pointing to an association with large-scale coherent structures embedded in the temperature and velocity field of the boundary layer. In convective conditions the vertically coherent ramp structure appears to be confined to a distance from the boundary of order $|L|$, where $L$ is the Monin–Obukov length scale.

Screenivasan and Tavoularis (1980) conducted experiments in a wind tunnel with a heated grid, found that $S$ differed from zero only when both the mean temperature gradients and mean shear were nonzero, and deduced empirical forms of $S$ as either shear or temperature gradient were varied. They concluded that the mean shear causes a preferential orientation of the large scale structure of the flow which then interacts with, and strains, the mean temperature field to produce regions of large temperature gradient. Screenivasan and Tavoularis further suggested that although the shear itself persists, the orientation of turbulent structures does not evolve beyond a certain "equilibrium" state, leaving the observed, large gradient, tilted structures embedded in the flow—further orientation by the mean flow being counteracted by some unspecified strain-releasing mechanism.

Thorpe and Hall (1980) suggested that the evolution of thermal ramps by large eddies has a dynamical similarity to frontogenesis in the atmosphere and that although for the most part the temperature field plays a passive role, buoyancy forces may be important in the ramps (or tilted "fronts") and contribute to opposing the strain in the mean flow and to maintaining the quasi-equilibrium postulated by Screenivasan and Tavoularis.

Investigations in the near-surface waters of a lake (Thorpe and Hall 1980) and in the upper-ocean boundary layer (Thorpe 1985) in conditions of *stable* heat flux were fully consistent with the earlier atmo-

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spheric and laboratory results. In the lake, measurements were made from a fixed three-dimensional moored array, including measurements of temperature and horizontal current speed, and from a vertical array towed through the water at speeds greatly exceeding the mean flow. Temperature and speed records both exhibited "ramps." The sign relationship of $S$ was tested making a "frozen eddy" hypothesis. Tows made in the lake and at sea in directions at an angle to the wind showed the magnitude of $S$ to be smaller than found in directions up- or downwind. Also observed was a slight asymmetry depending on whether the direction of tow was to the right or left of the wind direction. These observations were interpreted (Thorpe 1985) as showing that, while the temperature ramps themselves are associated with transient fronts lying predominantly across the wind direction, there may be an effect of the Ekman flow to shift the orientation slightly across wind (see Fig. 1).

Observations have now been made in the upper-ocean boundary layer during *convective* conditions (see section 2); the measured skewness conforms to the Gibson et al. (1977) sign convention. This is important as it adds to the growing evidence of a similarity between the atmospheric and oceanic boundary layers, at least beyond a zone dominated by turbulence induced by wave breaking. Measurements in the benthic boundary layer on a continental rise (section 3) also show evidence of nonzero skewness with a periodicity associated with the dominant wave variability, here $M_2$ baroclinic internal tidal waves, and point to the possible use of relatively simple measurement techniques to investigate the complex structure of oceanic boundary layers.

## 2. The upper-ocean boundary layer in convective conditions

A streamlined spar carrying an array of 12 thermistors (Thorpe and Hall 1987) was towed, hanging below a surface-following catamaran, ahead of the wave-wake of a vessel, the RV *Sea Searcher,* in an area near 64°N, 9°W, to the W and SW of Iceland in April–May 1988. The thermistors provide measurements of temperature from close to the surface to 8.6 m below the surface with a resolution of 0.25 mK, and with a maximum, top to bottom, calibration uncertainly in their relative accuracy of 10 mK. The array was sampled at 4 Hz so that, with a towing speed of 2 to 2.5 m $s^{-1}$ the effective horizontal resolution is 0.5 to 0.6 m. Two mutually perpendicular inclinometers show that the spar towed at an angle of 11 deg (std. dev. ± 5 deg) to the vertical. The spar also carried a pressure transducer and a forward pointing 1 MHz sonar transducer with a 5 deg beam angle, a pulse length of 0.1 ms and a 4 Hz pulse repetition frequency. The returned signal was sampled at time delays that corresponded to target ranges of 3.4 and 9.2 m ahead of the spar.

Six periods, totaling 5 hours of data, were selected in which the wind speed was constant to within ±2 m $s^{-1}$, the mean water temperature did not change by more than 0.3 K (avoiding major fronts), solar heating was uniform and convective conditions prevailed. Sensible and latent heat fluxes and wind stress were calculated using the bulk aerodynamic formulation of Large and Pond (1981) from shipboard measurements. Downward shortwave radiation was measured and the (small) net longwave contribution was calculated from the sea surface temperature and humidity. A section

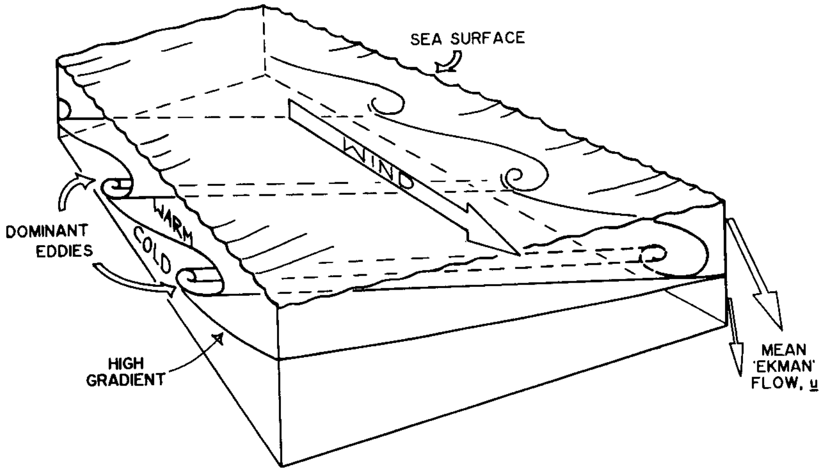

FIG. 1. Sketch describing the orientation of dominant eddylike coherent structures associated with temperature ramps in stable heating conditions in the upper ocean boundary layer. The mean Ekman flow, $u$ is somewhat to the right of the wind, rotating the alignment of the eddy structure. Tows made downwind encounter abrupt temperature falls, $S < 0$, while those upwind find $S > 0$. Lower absolute values of $S$ are found in cross-wind tows, but those to the right of the wind are negative while those to the left are positive.

of the temperature record is reproduced in Fig. 2. It includes short periods typical of all the records in convective conditions in which lower-than-average temperatures were encountered, frequently almost simultaneously at different positions along the spar. As a result, the temperature at a fixed depth below the surface is negatively skewed. (Comparable observations of skewness have been reported in the atmospheric boundary layer by Tillman 1972). Following the procedure described by Thorpe and Hall (1987), the data were conditionally sampled by selecting those times at which the temperature anomaly at a given sensor was less than the mean temperature by more than two standard deviations. The profiles of temperature immediately preceding and following these times were then ensemble averaged to produce a characteristic cross section of temperature through a temperature anomaly. In conditions of low wind speed (< about 1.5 m $s^{-1}$) with $L \sim -2$ m the analysis revealed a structure symmetrical about the vertical, about 5 m in width and extending from the surface to a weak thermocline at 7 m. In windy conditions however (about 9 m $s^{-1}$) with $L \sim -28$ m, the observed temperature structure was broader, about 10 m wide, and tilted downwind some 40 deg from the vertical. No thermocline was found to the extent, 8.6 m, reached by the spar. In this case the cold core of the "plume" had a high (ensemble-averaged) scattering strength relative to the ambient, suggesting its association with the downward transport of bubbles produced by breaking waves. No significant correlation could be found between the thermal structure and the pressure or spar-tilt angle; there was no evidence that the plumes were associated with locally breaking waves; rather that they were associated with downward convection. The skewness of the near-surface temperature time derivatives (Table 1) were consistently negative when the angle, $\Theta$, between the vessel course and the upwind direction, was acute. Skewness was positive for obtuse angles. This contrast with the results found in conditions of stable heat flux (Thorpe 1985: see Fig. 3) when the signs were the reverse but is perfectly consistent with the conclusions drawn from the studies in the atmospheric boundary layer. No clear trend with $z/L$, where $z$ is the depth, was apparent. Values of the mean skewness were in the range reported by Screenivasan and Antonia (1977) with a mean value of $S/\cos\Theta = 0.505$.

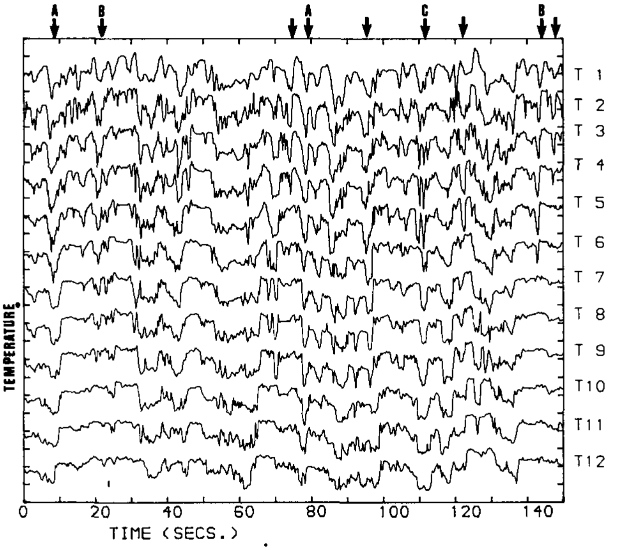

FIG. 2. A typical section of data from the 12 thermistors on the catamaran spar. The vertical divisions are 10 mK and temperature traces are displaced by 20 mK from their neighbors with temperature increasing upwards. The top thermistor ($T1$) was at 0.76 m and the bottom ($T12$) at 8.15 m. Some of the temperature troughs are marked by arrows. The pattern is best seen by looking parallel to the vertical temperature axis at a small angle from below. Some of these temperature signals are coherent throughout the depth of the spar (as at A while others are coherent only above some depth (as at B) These temperature signals are interpreted as convective plumes. Sometimes one or more small "plumes" merge (as at C).

## 3. The benthic boundary layer on a slope

### a. Observations

The continental rise of the Porcupine Bank at 3000 to 3500 m, which lies SW of Eire, has a bottom slope of some 3 deg. The local dynamics at 3000 to 3500 m depth are affected by a long-slope poleward eastern boundary current of 2–3 cm $s^{-1}$, low frequency variations of 5–6 day period sufficient to cause the mean current to reverse, and relatively high frequency $M_2$ baroclinic fluctuations that produce cross-slope currents of ±2 cm $s^{-1}$ in the lower 100 m (Thorpe 1987). These baroclinic motions are asymmetrical, relatively rapid falls in temperature being recorded while the current is upslope, reflecting the advection of colder, deeper water, followed by slower rising temperatures as the $M_2$ tide recedes.

A vertical array of platinum resistance thermometers (BERTHA, standing for Benthic Resistance Thermometer Array) was deployed at 50°29.6′N, 14°38.5′W in a water depth of 3445 m. It recorded temperatures at six levels, 1.5, 3.8, 7.0, 9.3, 13.0 and 20 m, off the bottom to a resolution of 0.1 mK, but with a best-achieved relative accuracy of about 0.5 mK, sampling at intervals of 20 s, well below the mean buoyancy period of about 9000 s, for 6.7 days. The array was part of a mooring, which included vector averaging current meters at 4.5, 10, 25.5, 70 and 170 m off the bottom. The direction vane was unfortunately lost from the current meter at 4.5 m.

Figure 3 is one 12.5 h period recorded by the array. It shows the rapid rise in isotherms about 2 hours into the record. This was accompanied by frequent inversions in temperature at the lower levels (i.e., the potential temperature was observed to increase with water depth between neighboring sensors by more than the relative accuracy) and was followed by a generally less rapid isotherm fall completing the tidal cycle. Colder

TABLE 1. Measurements of skewness in the upper-ocean boundary layer.

| Record length (min) | Wind speed ($m\ s^{-1}$) | Sea surface temperature (°C) | Air temperature @ 16 m (°C) | Solar shortwave radiation ($W\ m^{-2}$) | $-L$ (m) | Wind direction relative to tow angle $\Theta$ | Skewness $S$ | $z/L$ |
|---|---|---|---|---|---|---|---|---|
| 40 | 0.9 | 6.6 | 4.6 | 0 | 2 | +130 | 0.18 | 0.66 |
| | | | | | | | 0.45 | 1.52 |
| | | | | | | | 0.33 | 2.48 |
| | | | | | | | 0.15 | 3.69 |
| 30 | 9.4 | 6.3 | 4.2 | 0 | 25 | +115 | 0.17 | 0.05 |
| | | | | | | | 0.34 | 0.12 |
| | | | | | | | 0.34 | 0.19 |
| | | | | | | | 0.23 | 0.29 |
| 40 | 8.5 | 6.5 | 1.4 | 10 | 25 | +115 | 0.19 | 0.05 |
| | | | | | | | 0.05 | 0.12 |
| | | | | | | | 0.32 | 0.19 |
| | | | | | | | 0.49 | 0.29 |
| 80 | 9.1 | 6.5 | 1.4 | 15 | 28 | +30 | −0.29 | 0.05 |
| | | | | | | | −0.43 | 0.11 |
| | | | | | | | −0.53 | 0.18 |
| | | | | | | | −0.43 | 0.26 |
| 30 | 9.9 | 7.1 | 0.4 | 44 | 35 | +30 | −0.18 | 0.04 |
| | | | | | | | −0.13 | 0.09 |
| | | | | | | | −0.21 | 0.14 |
| | | | | | | | +0.01 | 0.21 |
| 30 | 10.7 | 6.8 | 1.0 | 98 | 70 | +40 | −0.45 | 0.02 |
| | | | | | | | −0.59 | 0.04 |
| | | | | | | | −0.36 | 0.07 |
| | | | | | | | −0.49 | 0.10 |

water than any seen initially in the water column is found near the seabed at 2–8 h, and provides evidence of upslope advection consistent with the observed currents shown in the stick diagrams.

The full temperature record has been divided into periods of 2800 s, 1/16 of the tidal cycle. Each was detrended to remove the gross effects of rise or fall, the skewness of the temperature derivatives was found for each period, and average values for the whole 6.7 day record determined to reconstruct the variation of mean skewness over a tidal cycle at each of the six levels. The contours of skewness, together with the mean currents at 10 and 25.5 m and the horizontal vorticity in these currents, are shown in Fig. 4. The tidal cycle is divided almost equally into two periods. The skewness, $S$, is negative during the period of onslope flow and positive when the flow is off-slope.[1] The mean value of $|S|$ is 0.35 and the maximum value of $|S|$ is about 0.8. The currents rotate with depth towards the seabed, those at lower levels being slightly to the right of those above, so that the horizontal vorticity, $\omega$, is not at right angles to the mean flow but typically at ±135 deg to it.

### *b. Discussion*

The observations of the size of $S$ are, if translated to a horizontal boundary layer, consistent with a convective regime during upslope flow and a stable regime during a downslope flow. The general pattern of change shows evidence that unstable conditions are indeed favored during the period of upslope flow while an overall stable stratification dominates the downslope period of flow.

Laboratory experiments by Thorpe and Haines (1987) have shown that during periods of upslope flow associated with the reflection of a train of internal gravity waves from a slope, fronts develop with a cleft and lobe structure similar to that described by Simpson (1972) in his study of density currents. Dense (or cold) fluid advancing upslope overrides the less dense fluid, hence producing convective conditions (Fig. 5a). Behind the front is a linear pattern orientated up and down the slope similar to that observed in convective conditions with shear. This linear pattern disappears during periods in which the flow is downslope (Fig. 5b). It should be stressed however that the Reynolds number of the laboratory flow regime was quite small

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[1] A similar, but less distinct and more patchy periodic pattern of mean skewness variation has also been observed using BERTHA on the Hebrides slope at a depth of 1705 m. Here the longslope current is much greater, typically 18 cm $s^{-1}$ compared to the $M_2$ upslope currents of 2 cm $s^{-1}$ and perhaps this accounts for the weakness of the signal in $S$.

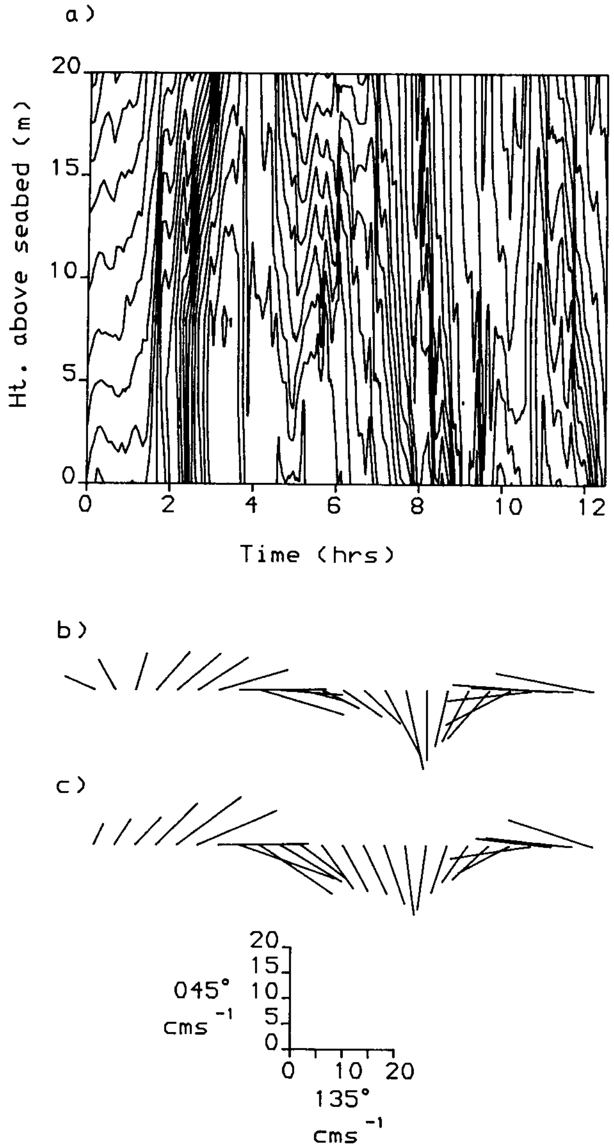

FIG. 3. (a) Contours of potential temperature for a 12.5 h period of the BERTHA deployment on Porcupine Bank. Values are averaged over 5 min periods and the contour interval is 5 mK. Stick plots of the onslope (in direction 045 deg up the line of greatest slope) and longslope (135 deg in a direction parallel to mean isobaths) slope current for the same period are also shown for the current meters at (b) 25.5 m and (c) 10 m above the seabed. Currents have been averaged over half-hourly periods, and a scale is indicated below (c).

and that while the overall features of the flow on the Porcupine Bank slope appear to be reproduced, good quantitative comparison is neither expected nor appropriate. It would be valuable to extend the laboratory studies to higher Reynolds number regimes more representative of the ocean.

## 4. Conclusions

The measurements made from the towed spar (section 2) confirm the hypothesis that skewness of the temperature derivative in near surface convective conditions has a sign opposite to that in conditions of stable heating. Similar results have recently been reported by Soloviev (1990) using data from a probe mounted on the bow of RV *Academic Kurchatov* in the tropical Atlantic.

The changes observed on the Porcupine Bank slope appear to be consistent with the cycle of convection or stable conditions found in laboratory studies of internal gravity wave reflection from a slope (Figs. 5a,b) and with the pattern of change in $S$ then expected from

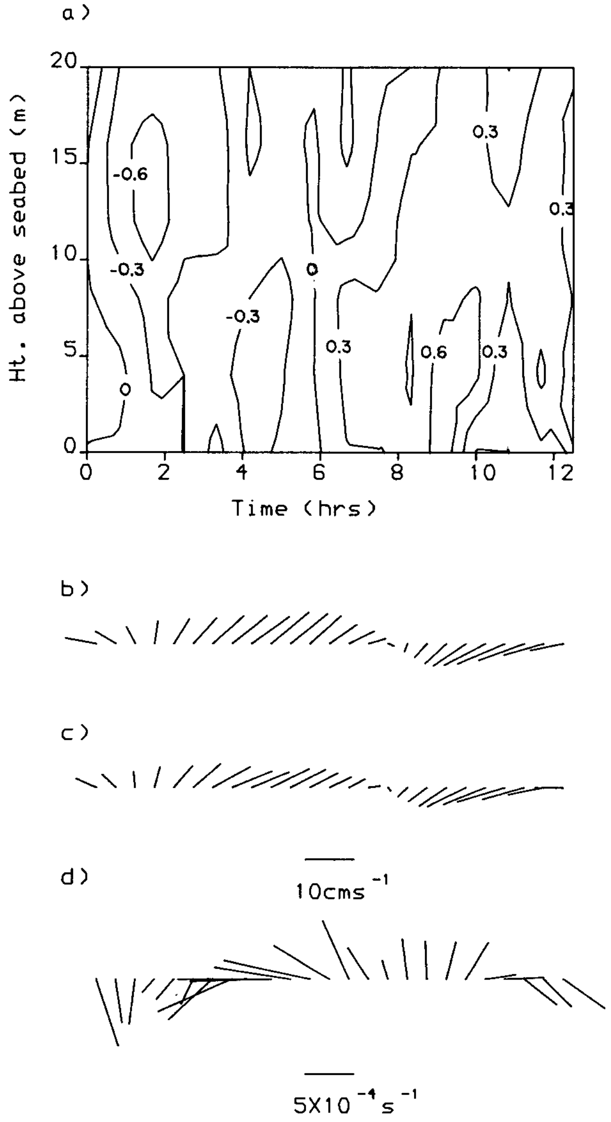

FIG. 4. The mean tidal variation of contours of the (detrended) skewness of the temperature time derivative $S(dT/dt)$. Values are found for 16 equal periods in an $M_2$ tidal cycle, and then averaged over 13 tidal periods. The contour interval is 0.3. Stick plots, calculated as in Fig. 3 are also shown for the mean tidal variation in current for (b) 25.5 m and (c) 10 m above the seabed, (d) the mean horizontal vorticity vector $\omega$ calculated from the data in (b) and (c). The orientation is as for Fig. 3 and scale is indicated below the vectors.

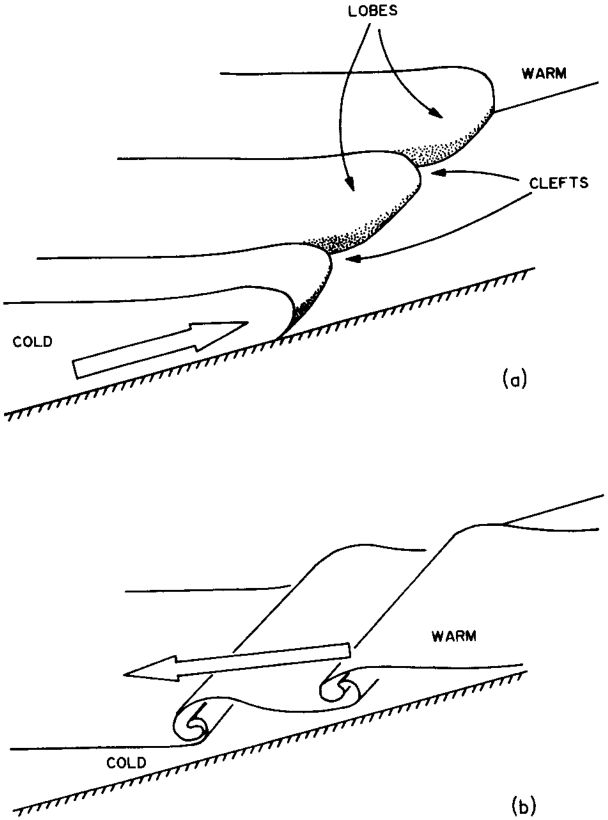

FIG. 5. Sketch showing flow and ebb of internal waves on a slope. (a) A "front" of cold, denser, fluid flowing upslope as a series of 'lobes'. Dense fluid overrides the warm fluid ahead of it, producing a pattern of convection marked by the clefts and trailing linear bands in which the warmer fluid rises through the colder fluid. (b) The ebb flow, with instability induced by shear (as in Fig. 1) resulting from the drag on the sea bed.

studies in natural convective and stable conditions. The values of $S$ are however lower than reported in the two dimensional laboratory studies (see section 1) but this is consistent with the trend towards lower values when the vorticity is not normal to the mean flow (see section 2).

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