A Study of Oceanic Fronts[1]

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Abstract

Oceanic fronts and frontal layers are defined. Temperature data obtained at two fronts in the equatorial Pacific are presented and a particular circulation, considered basic to the existence of a front, is proposed.

Vertically isothermal warm water overlies the stable frontal layer. This suggests that vertical mixing in the isothermal water maintains the frontal layer in the same way that wind-induced vertical mixing maintains sharp thermoclines.

The data suggest that the depth of vertical mixing is different in the warm and cool water masses adjacent to one of the fronts. It is suggested that the change in vertical mixing regimes contributes to the horizontal gradients of properties across this front.

Introductory Remarks

Atmospheric "fronts" are studied daily by weather forecasters and the term is in widespread popular use. This paper is concerned with an analogous occurrence in the ocean. It is the phenomenon often called "current rip" or "tide rip" in English literature on the subject, although these terms have been applied to a number of different phenomena. Recent observations in the central tropical Pacific revealed a subsurface structure near "current rips" similar to that at atmospheric fronts and led us to adopt meteorological terminology.

The majority of investigations into the nature of oceanic fronts have been by the Japanese. Their interest centers around the fact that fish and whales are abundant along fronts (UDA, 1938, 1953, 1954). UDA (1938) has published a paper including a history of observations of fronts and many descriptions of visual manifestations of the phenomenon.

A surface front is often visible as a narrow band of agitated wavelets. This band may follow a sinuous path, and, if there is floating debris in the area, it concentrates along the front. There is frequently a sound, apparently produced by breaking wavelets, and which, on occasion, has been reported as a "roaring noise". UDA (1938) reports a front audible at a distance of three miles.

Definitions

We know of no definition of an oceanic front. It seems necessary to start with one, but it will be inadequate and will be expanded by discussion and specific examples.

A *front* will mean a band along the sea surface across which the density changes abruptly. Our measurements across fronts are of temperature by a recording thermograph. Throughout this paper, which deals with fronts in the open ocean where salinity variations are small, we will interpret abrupt temperature

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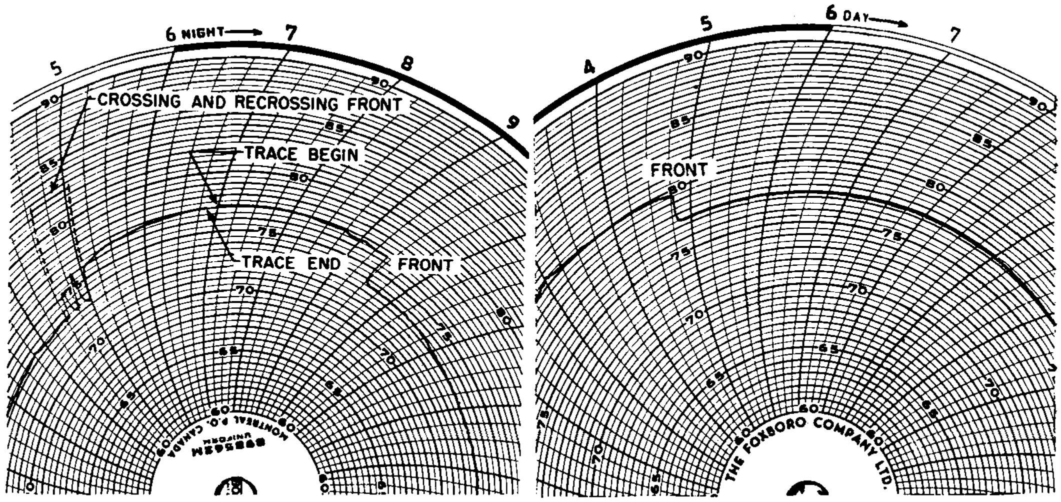

a b

Fig. 1. Examples of surface temperature gradients in the central tropical Pacific. Ship speed during recording, about 9 knots so that each hourly interval (marked along the top) represents about 9 miles. Frontal system corresponding to trace a. appears in cross section in Fig. 3 and that corresponding to trace b., in Fig. 4.

changes as indicative of abrupt changes in density.

Perhaps the fuzziest part of the definition lies in the degree of abruptness of the density gradient required for a front to exist. Only qualitative remarks can be made about this requirement.

Fig. 1 shows thermograph records which illustrate sea surface temperature gradients encountered in the central tropical Pacific. Generally the gradient of surface temperature in this region is of the order of degrees per ten or hundred miles as can be seen in the figure. At fronts, however, the surface temperature gradient is often of the order of degrees per hundredth or tenth miles. Examples of the gradients encountered at these fronts in the central Pacific appear on the thermograph traces in the figure.

Besides density, temperature and salinity, additional properties may change abruptly across a front, including current velocity and concentrations of dissolved and suspended materials, sometimes with striking changes in water color and transparency. Only a change in density is required by the definition, however, for the existence of a front.

From the front, a stable layer inclines downward, separating a warm water mass of low density above, from a cooler one of greater density below. This transition zone will be called the *frontal layer*, a feature that is analogous to that occurring in association with atmospheric fronts. There is an upper, *warm boundary* and a lower, *cool boundary* to the frontal layer. We wish to emphasize that the frontal layer extends in three dimensions and to refer to certain characteristics of the temperature gradient across it. In particular, an important characteristic is the clarity with which the warm and cool boundaries are defined by the BT traces. For example, on bathythermograph traces 61 and 62 of Fig. 2, the warm boundary is clearly defined by a sharp curvature maximum on each trace, whereas the cool boundary is defined less clearly by minor curvature maxima. At some fronts the cool boundary is more sharply defined than it is here.

Temperature distributions near fronts

1. Bathythermograms were obtained close to a front in the equatorial Pacific on October 27, 1952, by G. I. Murphy from the Pacific Oceanic Fishery Investigations' hydrographic vessel SMITH (Fig. 2). The front was clearly visible as a band of agitated wavelets about 150 feet wide, oriented east-west. The two "cool" traces, 58 and 59, were obtained 9 miles and

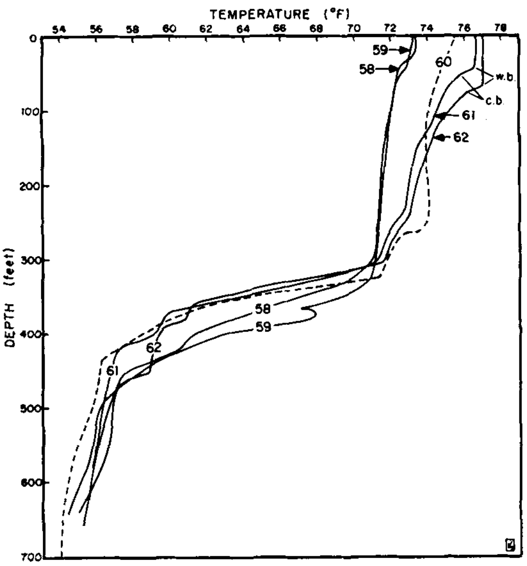

Fig. 2. BT traces on the cool side (58 and 59) and on the warm side (61 and 62) of a front. BT trace no. 60 is in the front. The warm boundary (w. b.) and cool boundary (c. b.) of the frontal layer are indicated. This frontal system appears in cross section in Fig. 3.

150 feet south of the front, respectively. Trace 60 was obtained at the northern edge of the zone of agitated wavelets. Traces 61 and 62 show the thermal structure 3 and 5 miles north of the surface front. It is apparent that the horizontal temperature change is much greater across the front than it is for many miles in either the warm or cool water masses separated by the front. There is an abrupt density change across the front.

We feel that the character of the vertical temperature gradient on the warm side of the front is significant. The warm water is vertically isothermal and the frontal layer begins abruptly at the bottom of this isothermal layer. This suggests that there is intense vertical mixing in the warm water above the frontal layer and also the further possibility that this mixing plays a part in *maintaining* the frontal layer in a manner that will be described in a later section.

Enough BTs were obtained near this front to represent the thermal distribution in cross-section (Fig. 3). The warm and cool boundaries of the frontal layer are indicated using heavy solid lines. The thin lines are isotherms. Regions where water is nearly isothermal vertically are indicated by shading. The hypothesized basic water circulation, discussed below, is indicated by arrows.

The drawing in the vicinity of the surface front may need some explanation. BT trace No. 60 (Fig. 2) shows water of 72F at 288 feet at the northern edge of the frontal zone. Water of this same temperature occurs at 98 feet on BT trace No. 59, obtained ten minutes earlier and approximately 300 feet to the south. Thus, the 72F isotherm rises 190 feet over a horizontal distance of approximately 300 feet. The actual slope of this isotherm is at least 190 ft./300 ft., or approximately 2 feet of rise per 3 feet horizontal distance.

Because of the vertical exaggeration in the section (760: 1) the 72F isotherm appears to rise vertically beneath the surface front be-

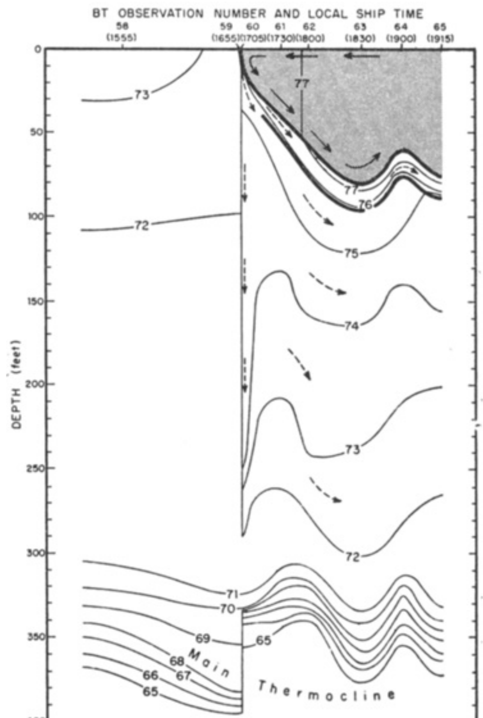

Fig. 3. Vertical temperature distribution across front at 1°12'N, 120°11'W, on October 27, 1952. Isotherms for each °F, thin lines. Frontal layer enclosed by heavy lines. Water nearly isothermal vertically, stippled. Hypothesized basic circulation indicated by arrows. The solid arrows indicate water involved in cell-like motion in this plane. Vertical exaggeration 760 : 1. Surface thermograph trace across this front appears as Fig. 1, a.

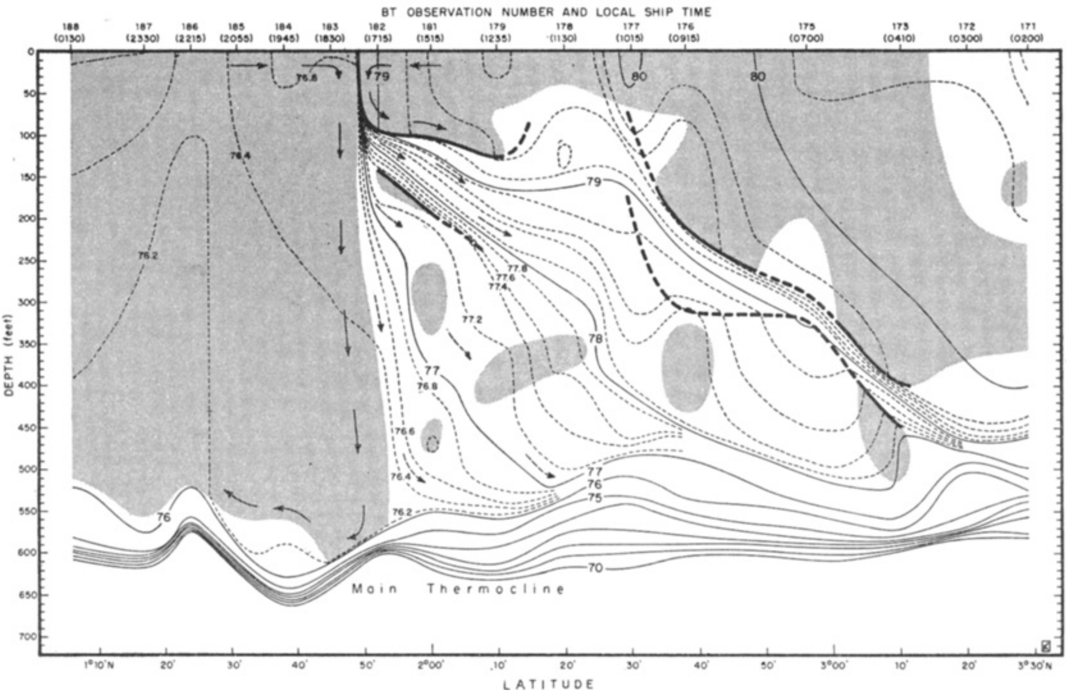

Fig. 4. Vertical temperature distribution across front at 1°50'N, 172°00'W, on February 5, 1950. Isotherms for each °F, thin lines, and for each .2F, thin dashed lines. Frontal layer enclosed by heavy lines (where clearly defined by BT observations) and heavy dashed lines (where diffusely defined). Water nearly isothermal vertically, stippled. Hypothesized basic circulation indicated by arrows. The solid arrows indicate water involved in cell-like motion in this plane. Vertical exaggeration 760: 1. Surface thermograph trace across this front appears as Fig. 1, b.

tween 288 and 98 feet. Successive isotherms of higher value, found at considerable depth on BT trace No. 60 in the frontal zone, are found closer to the surface or not at all on BT trace No. 59 in the cool water. Thus, the nearly vertical line extending upward from 290 feet is made up of several isotherms, some of which intersect the sea surface at the front.

The deep penetration of warm water locally beneath the surface front is based on a single BT observation, No. 60 (compared to those nearby). It suggests the existence of a steeply inclined "frontal wall". Closely spaced BTs, obtained recently by R. A. Schwartzlose from the Scripps vessel HORIZON, at a front off Lower California, revealed no such feature. More observations are needed to determine whether or not a frontal wall is a real feature of some oceanic fronts.

2. Data were obtained near a front encountered Feb. 5, 1950. A cross section showing the thermal structure at this front was drawn by CROMWELL (1953) and has been redrawn by us in the light of additional information about fronts discussed in this paper and to show greater detail (Fig. 4). Typical BTs near this front are reproduced in Cromwell's paper. There was no observation immediately at the position of the front.

This frontal layer is more complex than the other. It appears to be "broken", 30 miles north of the surface front. In this region the frontal layer is spread upward and downward so that it occupies a large part of the surface layer. Further, the warm and cool boundaries of the frontal layer through this region are not discernible. The frontal layer is defined again, farther to the north.

As at the front in Fig. 3, the warm water adjacent to this front is nearly isothermal and the frontal layer begins abruptly at the bottom of this isothermal layer. Data obtained near two additional fronts, not presented here, revealed this same basic thermal structure.

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The circulation near fronts

There are, to our knowledge, no published measurements of subsurface currents near oceanic fronts. No such measurements were made at the fronts shown in the cross sections in this paper. However, it seems to us that a reasonable speculation can be made as exhibited by arrows in the sections.

Surface convergence along fronts:

Many observers have noted that foam, kelp, and floating debris sometimes collect in conspicuous bands. It seems almost axiomatic that there is a component of surface flow directed into these zones. Feebly swimming plankton observed in fronts (BEEBE, 1926; UDA, 1938) are probably concentrated there by the convergent surface flow. The physical data, in particular the abrupt temperature changes across fronts, are consistent with this idea. Surface waters of different temperatures, by virtue of their different origins, are brought into juxtaposition by the convergent flow.

Sinking at fronts:

Continuity demands that there be a flow to compensate for the horizontal convergence that occurs along fronts. This could be accomplished by sinking beneath the surface front and such flow has been observed, strong enough to sink fishing nets at fronts off Japan (UDA, 1938). Recently we observed a similar occurrence.

On November 30, 1953, the authors placed a crude drag near a front off San Diego harbor to observe its motion. The drag consisted of two mutually perpendicular 3 ft. by 3 ft. planes of 1/32 inch sheet iron, attached by 40 feet of line to a surface float (corks), pole and flag. Upon reaching the front, the pole, which previously had lain tilted, became suddenly vertical and sank slowly as though pulled from below. Although we remained in the area for an hour and watched for the flag, it was not sighted again.

Divergence at depth:

Given these two features of the flow, there must be horizontal divergence at depth. If there is a main thermocline which remains stationary, the divergence must occur somewhere in the surface layer.

These three features of flow, 1) convergence along the front, 2) sinking and 3) divergence below, are shown in the cross sections. Water which sinks in the front and which must have a temperature somewhere between that of the warm and cool water masses probably sinks to intermediate depths in and below the frontal layer as shown by the dashed arrows. In Fig. 3 a jet is indicated downward beneath the surface front, but, again, it should be mentioned that more data are needed to determine whether or not a deep penetration of warm water is a real feature beneath some oceanic fronts. In the vertically isothermal water masses, where stability would not oppose them, cell-like circulations are drawn. We have no information about where water rises to the surface to compensate for that which sinks along the front.

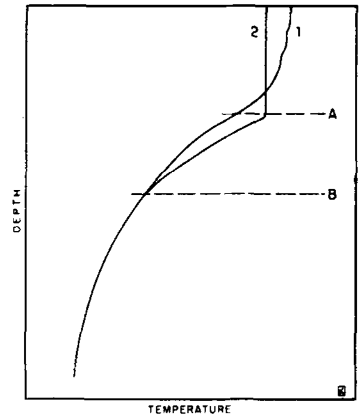

Fig. 5. Effect of wind-induced turbulence on the vertical temperature gradient in the ocean, Curve 1: Before a strong wind. Curve 2: After a strong wind has blown for some time.

An hypothesis concerning the maintenance of frontal layers

The maintenance of frontal systems involves the problem of the maintenance of the thin, stable, frontal layer in spite of diffusion across the layer which should act to destroy it. A process that may maintain the frontal layer is suggested by a different, but, presumably, related phenomenon, i.e., the maintenance of sharp thermoclines by wind-induced turbulence.

Some effects of wind-induced turbulence on the vertical temperature gradient:

Curve 1 of Fig. 5 pictures a typical vertical temperature gradient in the ocean. Curve 2

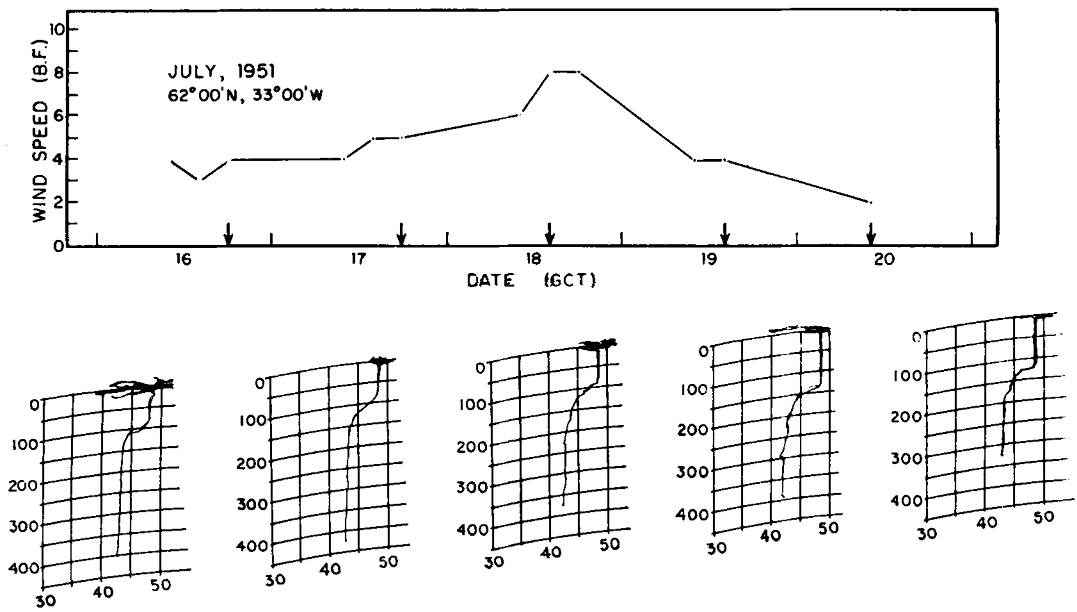

Fig. 6. Selected BTs illustrating "confined mixing" in the surface layer. Wind and BT data obtained at weather patrol station by USCGC UNIMAK. Times of BT observations indicated in wind speed diagram by arrows.

presents the gradient in the same region after a strong wind has blown for some time. This picture is virtually the same as figure 2 in H. O. Misc. 15360 prepared by SCHULE, *et al.* (1952).

The strong wind increases turbulence at the sea surface and, presumably, downward through the surface layer. This turbulence alters the vertical temperature gradient in three respects pertinent to the present discussion: 1. Mixing, which is made more intense by the turbulence, reduces or eliminates the gradient throughout a layer adjacent to the sea surface. This is shown schematically in the figure between the surface and depth A. 2. The gradient is *intensified* in a layer immediately subjacent to the mixed layer, as illustrated between depths A and B in the figure. 3. The transition from the surface layer to the thermocline layer becomes more abrupt, i.e., the curvature at the "knee" of the trace is increased. One or more of these events have been described by various authors (SVERDRUP, *et al.*, 1942, p. 497; Anonymous, 1946; LAFOND, 1954), but to our knowledge no data illustrating their occurence have been published.

FRANCIS and STOMMEL (1953) used fifteen BT series obtained at weather ship stations before and after (and in some cases during) gales to show that the depth of the thermocline increases during a strong wind. These data, lent to us by the Woods Hole Oceanographic Institution, show clearly the events described in the preceding paragraph. Selected BTs from one of the series appear as Fig. 6.

What occurs, as a result of the increasing wind, might be called "confined mixing" because the turbulent mixing induced at the sea surface is bounded below by a stable layer. The stability of the confining, stable layer is increased during the process. A concise physical explanation of how or why this phenomenon occurs, has not been given.

The maintenance of frontal layers:

The correlation that appears in the cross sections among the isothermal warm water mass, the subjacent stable frontal layer and the abrupt transition between the two suggests that the frontal layers are maintained by the same process that maintains sharp thermoclines, i.e., confined mixing. The question arises as to the source of the turbulence.

The frontal layer is overlain by a mixed layer of neutral stability. Turbulence within the mixed layer is not damped by action of the Archimedean force. Turbulence created at the sea surface by the wind or by cooling and subsequent overturn can extend downward to the frontal layer. There is another source of turbulence which may be of basic importance in the maintenance of frontal layers.

Circulations like those drawn in the warm water in each section have been suggested by UDA (1938) and have been reported to occur in Lake Mead (VETTER, 1953). It is necessary, now, to postulate that the "mixed" water overlying the frontal layer is not perfectly homogeneous. One would expect heterogeneities of density to exist near the surface of this water mass by virtue of small scale variations in the factors that control the heat and water transfer processes at the boundary; for example, small scale variations in wind speed. If the warm water mass is not perfectly homogeneous, the hypothesized circulation in the warm water intermittently will bring parcels of low-density water into vertical juxtaposition beneath relatively dense water. Instability, so produced, will provide a continuing source of energy for turbulent overturn. Stommel has suggested that closed circulations, required by the presence of lateral boundaries, may be of importance in producing isothermal layers bounded by thermoclines (POLLAK, 1954). A front seems to provide a "fluid boundary" which allows this process to occur in the open ocean.

Changes in properties across fronts

Convergent flow appears to be partially responsible for the change of properties that occurs across a surface front. Surface waters, of different properties by virtue of their different origins, would be brought into juxtaposition by flows like those shown in the cross sections. Water motion hypothesized to occur near the front shown in Fig. 4 leads to an additional partial explanation for the change in properties that occurs across this front. Both the warm and cool water masses are nearly isothermal vertically. It is proposed that cell-like circulations in the warm and cool water masses lead to turbulent overturn and mixing, as already described. This overturn maintains vertically mixed layers of *differing thickness* in the warm and cool water.

Specifically, in Fig. 4, vertical mixing extends from the sea surface to a depth greater than 500 feet in the cool water south of the front and to a depth only a little greater than 100 feet in the warm water just north of the front. This vertical mixing has virtually eliminated the vertical temperature gradient. Mixing in the warm water north of the front is confined by the stable frontal layer. South of the front, vertical turbulence has extended downward to the main thermocline and it seems reasonable that the surface temperature has been lowered by mixing with this deeper water. This process may contribute to the change in temperature observed horizontally across the front.

The mixing that redistributes the temperature gradient will also redistribute gradients of other properties and will, in general, contribute to the changes in all properties horizontally across the front. For example, the resulting surface velocities in the cool and warm water masses separated by the front will, in general, be different, and thus the vertical mixing may contribute to the horizontal shear across such a front. Analogous reasoning suggests that there should be large shear across the frontal layer. Shear, then, is envisaged as possibly a *result* of the processes that maintain such a front.

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REFERENCES

Anonymous, 1946: The application of oceanography to subsurface warfare. *NDRC Summary Technical Reports*, Division 6, v. 6A, 106 pages.

BEEBE, WILLIAM, 1926: *The Arcturus Adventure*. New York and London. G. P. Putnam's Sons, ch. 2, pp. 41—70.

CROMWELL, TOWNSEND, 1953: Circulation in a meridional plane in the central equatorial Pacific. *Journal o Marine Research*, **12**, (2), pp. 196—213.

FRANCIS, J. D. R. and HENRY STOMMEL, 1953: How much does a gale mix the surface layers of the ocean?

Quarterly Journal of the Royal Meteorological Society, **79**, (342), pp. 534—536.

LaFond, E. C., 1954: Factors affecting Vertical Temperature Gradients in the Upper Layers of the Sea. *The Scientific Monthly*, **78**, (4), pp. 243—253.

Pollak, M. J., 1954: Notes from the conference on the thermocline of 25—27 May 1953. *The Chesapeake Bay Institute*, reference 54—2, 49 pages.

Schule, J. J., Jr., L. S. Simpson and A. Shapiro. Effects of weather upon the thermal structure of the ocean. *H. O. miscellaneous 15360*. U.S. Navy Hydrographic Office, 81 pages.

Sverdrup, H. U., M. W. Johnson and R. H. Fleming, 1942: *The Oceans*. New York. Prentice-Hall, Inc., p. 497.

Uda, Michitaka, 1938: Researches on "Siome" or Current Rip in the Seas and Oceans. *Geophysical Magazine*, **11**, (4), pp. 307—372.

— 1953: On the Convergence and Divergence in the NW Pacific in Relation to the Fishing Grounds and Productivity. *Bulletin of the Japanese Society of Scientific Fisheries*, **19**, (4), pp. 435—438.

— 1954: Studies of the Relation between the Whaling Grounds and the Hydrographical Conditions (1). *The Scientific Reports of The Whales Research Institute*, No. 9, pp. 179—187.

Vetter, C. P., 1953: Sediment problems in Lake Mead and downstream on the Colorado River. *Transactions of the American Geophysical Union*, **34**, (4), pp. 249—256.