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LARGE-SCALE 'TURNOVER' IN THE OCEANS

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LARGE SCALE "TURNOVER" IN THE OCEANS

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FOREWORD

This study pertains to unique oceanographic developments in near-surface layers which are determined to a great extent by meteorological and sea-air interaction processes.

Large-scale turbulence in the ocean, which may occur in specific conditions, may not only affect the safety of submarines but also influence the conditions for propagation of sound and the formation of intermediate and deep water masses.

The present study is a background summary of the little available knowledge of this important subject. One of the main purposes has been to create awareness of large-scale turbulence and its effects on submarines.

The project was initiated under the Naval Ships Systems Command sponsorship (Mr. K. B. Couper, Project Supervisor) at Fleet Numerical Weather Central. The bulk of the study was completed at the Environmental Prediction Research Facility whose mission includes the development of local environmental analysis and prediction techniques.

One of the authors, Mr. D. Dale, is affiliated with Fleet Numerical Weather Central.

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ABSTRACT

Evidence of turbulence and large-scale[1] vertical motion is presented together with a condensed review of vertical mixing processes and stability in the sea. Physical models of large-scale vertical motion and descriptions of areas, times, and conditions under which it can be expected are discussed. Comments are given concerning the implication of large-scale vertical motions on the safety of submarines.

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[1] Large scale refers to a scale in excess of 100 meters.

1. PURPOSE OF THE REPORT

Large-scale vertical motion (turnover, large-scale turbulence) in the sea may represent a serious hazard to submarines operating in the area. In fact, several submarine accidents have occurred in areas where physical considerations indicate such large-scale vertical turnover could be expected. The purpose of this paper is threefold: (a) to review the evidence of large-scale vertical motions and turbulence; (b) to construct plausible physical models; and (c) to describe the possible conditions and areas where such vertical motions can occur. In addition, a brief review is given of the practical knowledge of vertical mixing and stability problems in the ocean. This report can serve as a background for further detailed investigations of the occurrence and dynamics of large-scale turbulence in the ocean and its effect on submarines.

2. VERTICAL MIXING PROCESSES IN THE SEA

It is generally accepted that turbulent mixing in the ocean can occur only in the surface layer. In the deep layers of the ocean vertical motion is greatly suppressed. A highly stable intermediate layer separates the deep water from the surface layers and also inhibits vertical motion. Furthermore, any vertical turbulence requires at least four orders of magnitude more energy expended than for a similar displacement in the atmosphere.

Vertical mixing processes in the ocean can be divided into two general categories: (a) mixing due to convective motion; and (b) forced (mechanical) mixing, e.g., wave action. Convective mixing can occur if the surface layers become more dense than the underlying layers by loss of sensible and/or latent heat at the surface. Forced (mechanical) mixing in the surface layer must be considered a continuous process which is increased by any convective motion which may develop. The major problem in modelling such motion lies in the determination of values for the thermal diffusivity and kinematic viscosity for medium and large-scale motion.

The primary energy input for the ocean is at the surface. The mixing by wave action and by wind-induced small scale local currents cause forced mixing of the surface layer. The depth to which forced mixing reaches is generally a function of the strength of the surface wind. It is on the order of ten times the significant wave height (Laevastu and Hubert, [7]). It should be noted that forced mixing in the surface layers does not affect the deeper layers of the ocean. In general, the greater the forced mixing at the surface, the larger the density gradient in the pycnocline[1] and the more energy required for any mass displacement through it. Obviously there is also forced mixing in the horizontal by sheer in horizontal currents. This type of mixing is of primary importance in shallow water where strong tidal currents predominate and along sharp boundaries of major fast moving current systems.

Bottom topography often causes eddies and convergence zones of short duration in shallow water which affect vertical motion. Eddies can also be one of the main causes of the large-scale vertical displacements in deep water and will be considered in a later chapter.

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[1] Layer of steep density gradient similar to the temperature thermocline.

3. EVIDENCE OF LARGE-SCALE VERTICAL MOTION IN THE SEA

Conclusions have long been drawn about areas of intermediate and bottom water formation and the large-scale vertical motions connected with these circulations. The vertical motions have, however, been assumed to be extremely slow and the motion of the water mass as a whole during formation of intermediate waters is pictured as a slow sliding process with a very small vertical inclination. While this model works in general, there can be limited areas in the ocean where the vertical velocities are higher (say on the order of a few centimeters per second), but they can occur only under very limited and specific conditions. One of the first investigators to point out the possibility of such motion and its possible effects on submarine safety was Columbus O'Islin, although he never followed this up with detailed investigations. His suggestions and inspiration have been partially responsible for this investigation.

The second investigator to point out the possibility of large-scale rapid vertical motion in the ocean, under specific and limited conditions, was Britton [3]. He has found evidence of large-scale vertical turnover from continuous recordings of sea-surface temperature during storms at Ocean Station Kilo.

It has long been accepted that vertical motion of considerable scale can occur in the northern part of the

Tyrrhenian Sea and the Ligurian Sea in the winter during the formation of Mediterranean bottom water. Extensive proof for this was brought forward during the multi-ship survey MEDOC-1969 (Miller, [9]). Figure 1 is reproduced from Miller's report. It indicates that in a limited area, there must have been a breakthrough by the cooler, more dense surface water into the intermediate, more saline but warmer Levantine water. Voorhis and Webb [18] carried out vertical current measurements during the same expedition. They observed large up-and-down movements of the water, generally in excess of 2.5 cm./sec. They concluded, as did Britton, that up-and-down movements occur in "bursts" and that the rise of the water takes place in cyclonic loops. Density inversions in this area have been reported by Allen [1] (see fig. 2).

Other kinds of vertical motions created by internal waves occur on the continental slope. These internal waves can cause capsizing and cascading of water masses at steep continental slopes and in submarine canyons. Possible vertical displacements at oceanic fronts (Oyashio-Kurishio type fronts) have been suggested by Uda [16, 17] and a review of some vertical movements in the ocean has been given by Cooper [4].

Indirect evidence that large-scale vertical motions must have occurred in the deeper layers of the oceans can be inferred from many other observations such as spreading

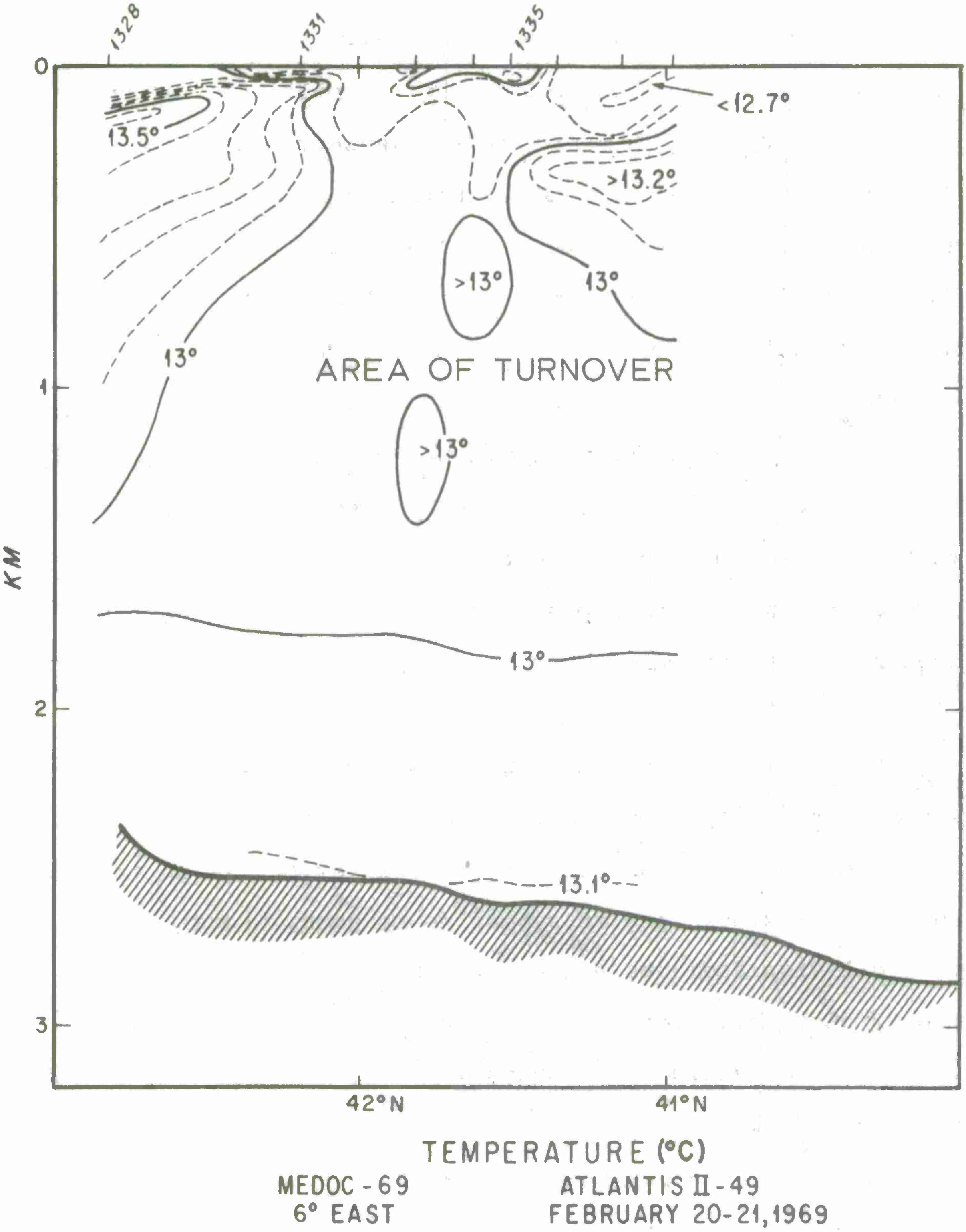


Figure 1. A Temperature Section From the Northern Part of the Tyrrhenian Sea, Winter, 1969 (from Miller [9]).

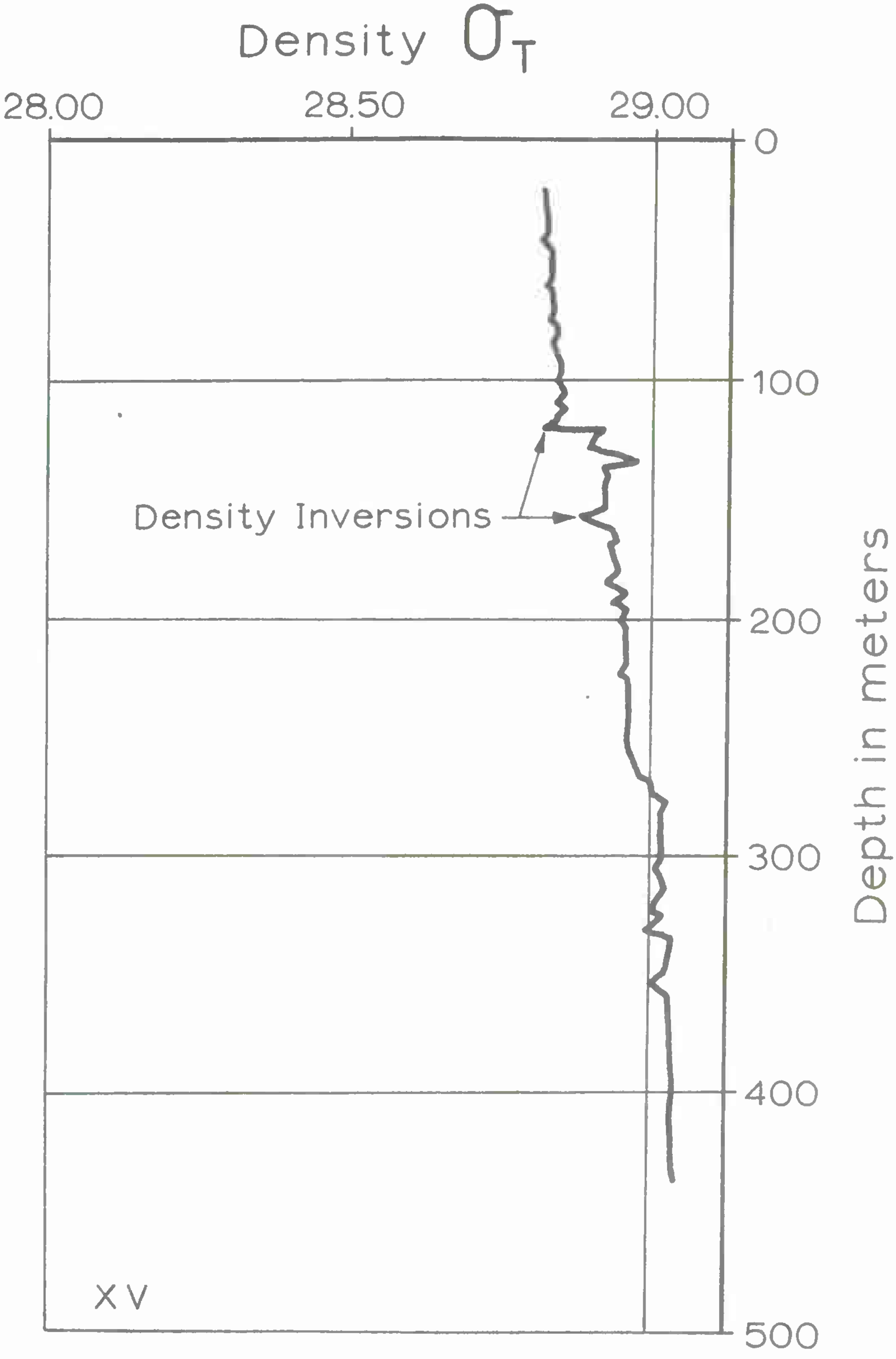


Figure 2. Density Profile at Station XV on 15 February 1969 in Northern Tyrrhenian Sea (from Allen, [1]).

of Mediterranean water behind the Gibraltar Sill, the overflow of Norwegian Sea water over the Faeroes-Iceland Ridge, Greenland-Iceland Ridge, and other similar circumstances. Except for those of the MEDOC-1969 expedition, other direct observations on vertical motions are nearly absent.

4. STABILITY IN THE SEA

4.1 Static Stability

The static stability (E_s) in the ocean is a direct function of density increase per unit depth.

$$E_s = \frac{d\rho}{dz} \qquad (1)$$

Following the arguments by Hesselberg and Sverdrup (Sverdrup, Johnson, Fleming, [14]), the stability in the upper layers of the oceans (E') can be presented as a function of σ_t. (σ_t is the density of a parcel of water at standard atmospheric pressure but at in situ temperature and salinity.)

$$E' = 10^{-3} \frac{d\sigma_t}{dz} \qquad (2)$$

In deriving this expression the adiabatic temperature changes (which are small in the ocean) and small nonlinear salinity and temperature effect terms have been neglected. This stability criterion (2) is most useful in applied oceanography.

Various other static stability parameters in oceanography have been reviewed by Pollak [10]. Although some of the refined static stability parameters are of use in some theoretical considerations, they have not been found to contribute much to the present problem of finding a useful criterion for the existence of instability and the onset of large-scale vertical motion.

Various dimensionless numbers have been useful in a number of theoretical considerations of stability and turbulence (Grashof, Prandtl, Eckart, and Rayleigh numbers). However, these numbers (with the exception of the Rayleigh number which is treated in section 4.2) do not lend themselves as useful tools to the present problem of determining the possibility of large-scale turbulent turnover.

Some use can be made of buoyance criteria (Anati, [2]) in considering stability and deriving a dynamic large-scale turbulence model.

$$b = g \frac{\rho - \bar{\rho}}{\bar{\rho}} \tag{3}$$

where b is the buoyancy criteria, g is acceleration of gravity, ρ is the density in the layer under consideration and $\bar{\rho}$ is the mean density of the column below the layer. However, the buoyancy criterion in formula (3) does not offer any materially new concept or approach over and above formula (2).

4.2 Instability: Causes and Criteria for Onset of Large-Scale Turbulence

There are three basic processes which tend to create large-scale instability in the ocean. These processes occur only in certain areas and seasons. Only the first process can occur over relatively large areas (during the later part of the cooling season). These three processes are:

(a) Rapid cooling at the surface (evaporation and sensible heat transfer) caused by large sea-air temperature and water vapor pressure differences and strong winds. As "mechanical" mixing by wave action is normally also present during this cooling process, the lower boundary of the resulting instability is determined by the depth of the mixing by wave action and is about ten times the wave height (Laevastu and Hubert, [7]).

(b) Capsizing and cascading of internal waves on the continental slope. This process may cause only temporary, limited internal instability and large-scale turbulence.

(c) Flow of higher density water over lower density water. This can occur only in very limited areas and only at sharp current boundaries.

Mixing processes in the form of small-scale turbulence can reach relatively deep in some areas. During the winter when the mixed layer depth (MLD) is deep, it appears that large-scale turbulence (turnover) is associated with large-scale quasi-horizontal "sliding" motions and involves large-scale vertical motion. Preliminary dynamic models for this purpose will be developed in the next chapter.

Of the few instability criteria which have been investigated for the atmosphere, only one, the Rayleigh [12] instability criterion, promises some application to the ocean for prediction of the onset of large-scale vertical turnover:

$$\frac{\rho_2 - \rho_1}{\rho_1} > \frac{27\pi\kappa\nu}{4g\zeta^3} \qquad (4)$$

where: ρ_1 and ρ_2 are densities of the two layers under consideration,

ζ is depth of the upper (unstable) layer,

κ is diffusivity (of temperature or salinity),

g is acceleration of gravity,

ν is kinematic viscosity coefficient.

Assuming $\rho_1 = 1.029$, $\kappa = 10^4$ cm.^{2}/sec., $g = 981$ cm. sec.$^{-2}$, $\nu = 10^4$ cm.^{2}/sec., and $\zeta = 6000$ cm., a quite unrealistic value for ρ_2 is obtained. This is greatly due to large values of κ and ν for the water (for air the corresponding values are: $\nu = 0.14$; κ $5/2\nu$).

Thus in order to make Rayleigh's instability criteria applicable to the oceans, proper eddy diffusivity and eddy viscosity coefficients must be used. These eddy coefficients are, however, known to vary over a large range and plausible values to be used with Rayleigh's instability criteria are at present unknown. Both theoretical and experimental investigations are required to clarify the manner of application of this criteria. An additional question is whether large-scale turbulence turnover resulting from the collapse of an instability, such as implied by Rayleigh's criteria, is possible in the sea under realistic conditions.

4.3 "Convection Energetics"

A two layer system with a heavier layer resting above a lighter layer presents a source of potential energy. It is of importance to take this energy into consideration in constructing a dynamical model of large-scale convection in the oceans, as well as in evaluating the effects of convection on submarines.

Proudman [11] showed that the gravitational potential energy (E_g) per unit surface area for a two layered system is:

$$E_g = - g\rho h(1/2h) - g\rho' h'(h+1/2h') \; ; \qquad (5)$$

where: g is acceleration of gravity,

ρ and ρ' are densities of two layers,

h and h' are the thicknesses of the layers.

If the waters were completely mixed the potential energy (E_{gm}) per unit area would be:

$$E_{gm} = -1/2g(\rho h + \rho' h') \; (h + h') \; , \qquad (6)$$

and the decrease of the potential (ΔE_g) energy due to mixing is:

$$\Delta E_g = 1/2g(\rho' - \rho)hh' \; . \qquad (7)$$

If formula (7) is applied to Hydra Station 212 in the Tyrrhenian Sea (Miller, [9]) (see fig. 3) it will be found that the potential energy change due to mixing in this particular profile is 350 ergs cm.$^{-3}$. The best estimate of dissipation of turbulent energy in the sea has been made by Stewart and Grant [13]. Using values for the magnitudes of rate of dissipation of turbulent energy from their work,

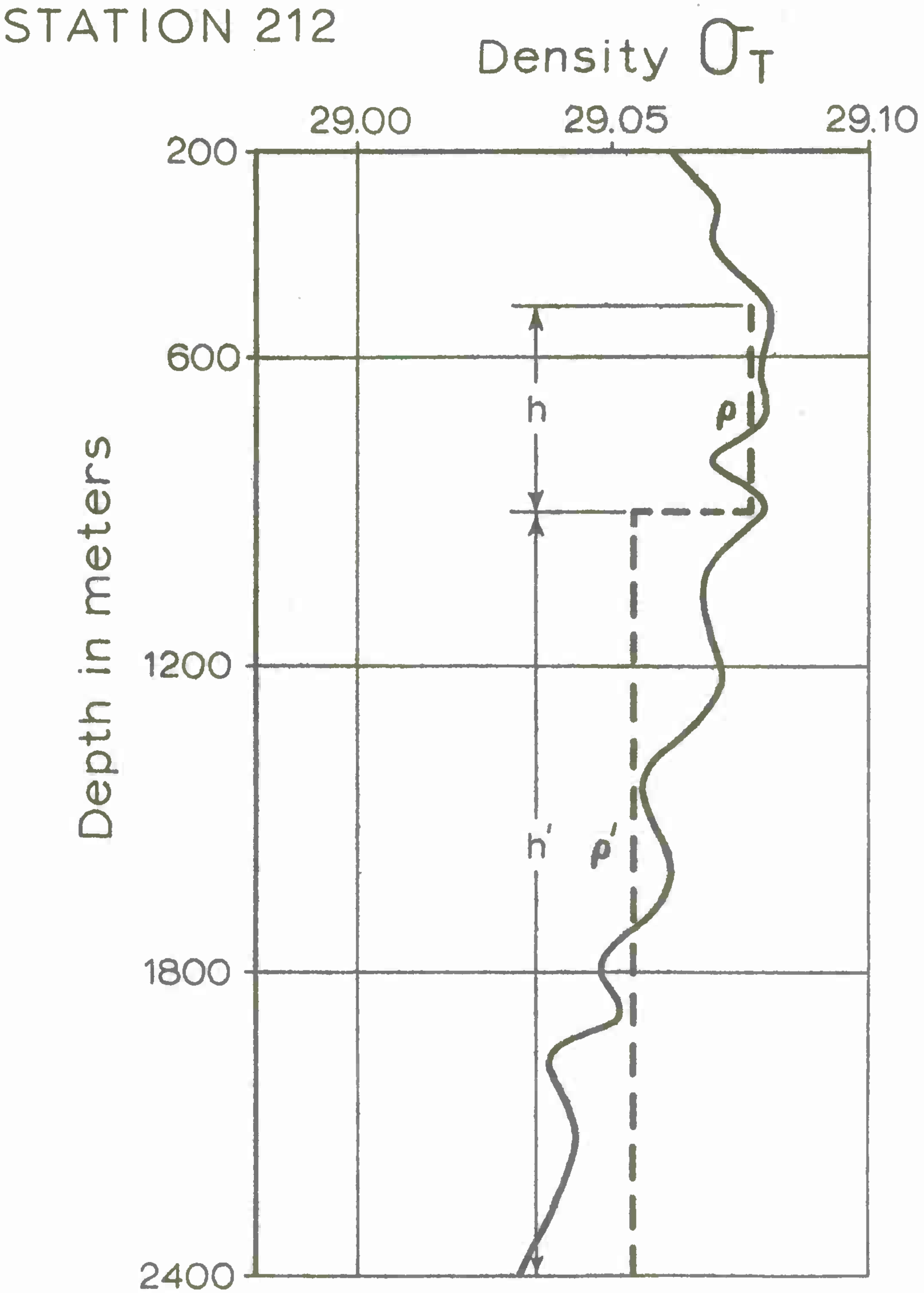


Figure 3. Density of Hydra Station 212 During Winter 1969 in Northern Part of Tyrrhenian Sea (from Miller, [9]).

it will be found that with the dissipation rate of 10^{-2} ergs cm.$^{-3}$ sec.$^{-1}$, the mixing energy will dissipate in about ten hours and with a rate of 10^{-3} ergs cm.$^{-3}$ sec.$^{-1}$ in about four days.

It can be assumed that the time required for the dissipation of mixing energy is of the same order of magnitude as the time required for the complete mixing of the two layer system. It can not, however, be assumed that the mean vertical velocity involved in the mixing is in any way proportional to this time interval. This means that if mixing takes 3×10^5 sec. (approx. 4 days) and the two layers are mixed to a depth of 10^5 cm., it can not be assumed the maximum velocities are 0.3 cm./sec. The mixing process involves turbulence in various scales. Vertical velocities in excess of 2.5 cm./sec. have been observed by Voorhis and Webb [18]. Furthermore, Lafond and Lafond [8] have inferred considerable vertical circulation in the upper 250 meters of a stable water column. The scales of the circulation in these two cases were not determined, but a scale in the range of 100 m. can not be ruled out. The possibility of such a scale of turbulence should be investigated both theoretically and emperically. It is this scale of motion which represents the greatest potential hazard to submarine operations.

5. CONDITIONS UNDER WHICH LARGE-SCALE VERTICAL MOTIONS CAN OCCUR

5.1 Conditions Favoring Large-Scale Vertical Motion

Large-scale vertical motions involve large-scale mass displacement of water. Large-scale vertical displacements are most likely to occur in the following areas:

- (a) In a system of divergence/convergence such as created by cyclonic and anticyclonic gyrals.
- (b) At oceanic fronts (convergence of different currents).
- (c) At submarine ridges.
- (d) At the continental slope.

5.1.1 Vertical Motion in a Cyclonic Eddy

A precondition for large-scale vertical motion is a deep mixed layer with a very low stability in relation to the water directly below. In addition, there must be a rapid cooling at the surface and the presence of horizontal motion. The latter two conditions can occur if there is a strong offshore wind and the air temperature and water vapor pressure are initially low (see fig. 4). This can happen in the northern Tyrrhenian Sea during late winter, for example, when katabatic winds (e.g., mistral) cause evaporation and uptake of sensible heat from the sea and thus rapid cooling at the surface. Furthermore, the strong winds set up surface currents which can evolve into

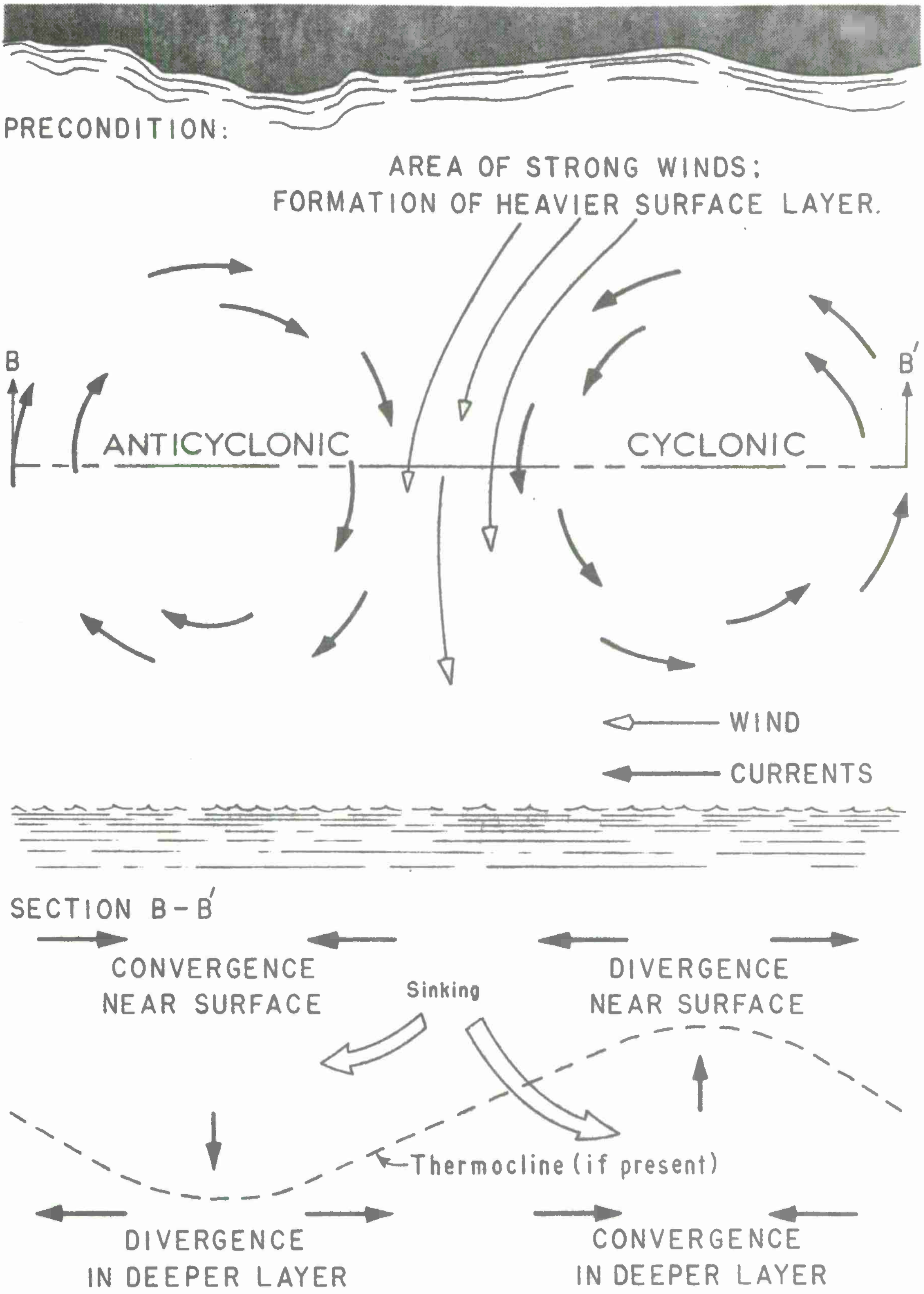


Figure 4. Schematic Presentation of Large-Scale Vertical Motions in an Eddy.

large-scale eddies (the shape of which is affected by the curvature of the wind field, coast lines, etc.).

The presence of a cyclonic eddy makes possible upward motion which occurs in the center of such eddies in the northern hemisphere as the result of the Coriolis force. The compensating sinking takes place only at the outer edge of the cyclonic eddy and the heavier surface layer can either slide towards the center of a neighboring anticyclonic eddy in the upper layers or towards the center of a cyclonic eddy (in deeper layers) to replace the diverging flow at the surface. This type of large-scale vertical motions in eddies have been observed during MEDOC 69 expeditions (Miller, [9]).

5.1.2 Vertical Motions at Oceanic Fronts

Large-scale vertical displacements can also occur at major oceanic fronts (e.g., Labrador and Gulf Stream front) where the converging currents are strong and there is a considerable salinity and temperature difference. The causes of vertical displacements are the differential heating/cooling on different sides of the fronts (operative only during specific meteorological conditions); frontal eddies, and wind caused cross-front current components; and tidal currents. Schematic examples of motions at oceanic fronts are shown in figure 5.

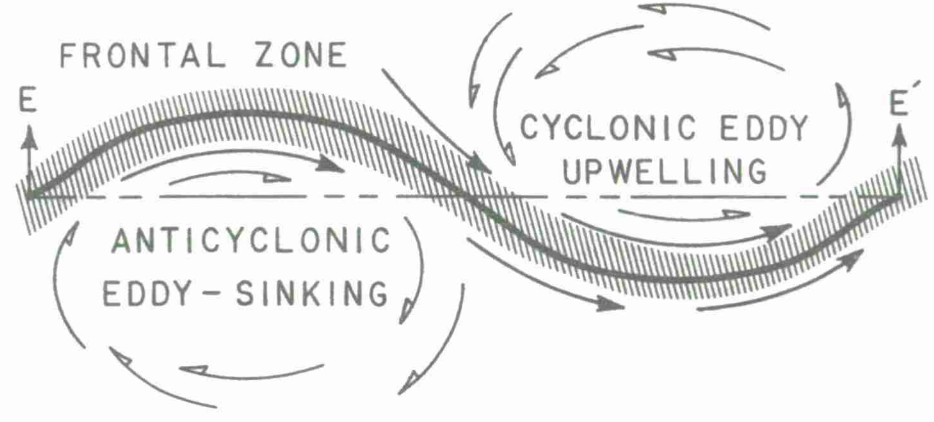


Figure 5A

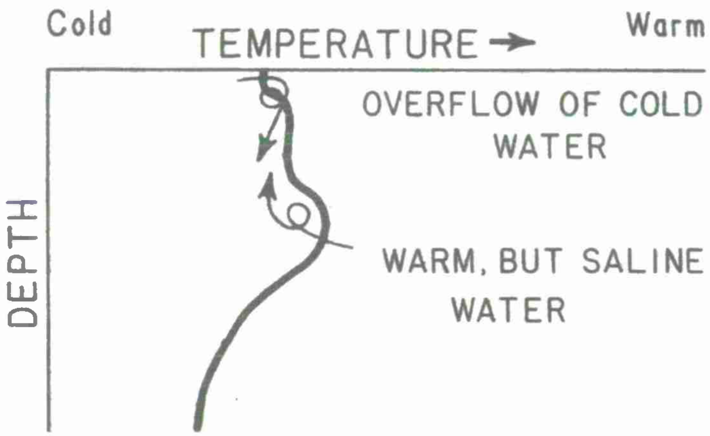
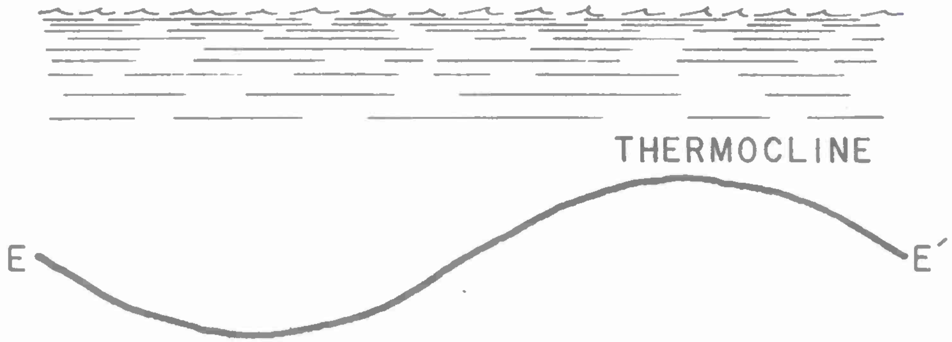


Figure 5B



SECTION E - E´

Figure 5. Schematic Presentation of Motions at an Oceanic Front. (Figure 5A is a horizontal surface view of frontal eddies. Section E-E' is a vertical cross-section through the eddies with the deformation of thermocline topography. Figure 5B is a temperature profile at a front.)

5.1.3 Vertical Displacements at Oceanic Ridges

Noticeable vertical displacements over a submarine ridge can occur if the sill depth is shallow and strong currents are operative in the upper layers. This displacement is usually intermittent and maintained by tides. The pronounced internal waves observed in the Strait of Gibraltar might be a by-product of such tidal overflows. Extensive investigations of overflows have been made at the Faeroes-Iceland Ridge from which vertical displacements on the Atlantic side can be deduced (Tait, [15]). Direct overflow at the ridge at the Strait of Gibraltar has not yet been observed, although it can also be deduced from available hydrographic data. A schematic example of overflow is shown in figure 6.

5.1.4 Vertical Motions at the Continental Slope

Large-scale vertical motions at the continental slope are caused by internal waves or by onshore-offshore movement at the surface caused by wind regimes (Dodimed and Pickard, [5]). This process is schematically shown in figure 7.

5.2 Areas and Times Where Large-Scale Vertical Motions Can Occur

The areas where different types of large-scale vertical motion and turbulence can be expected in defined conditions are shown in figure 8. The areas 1A and 1B in the Tyrrhenian and Ligurian Seas are the areas where Mediterranean bottom

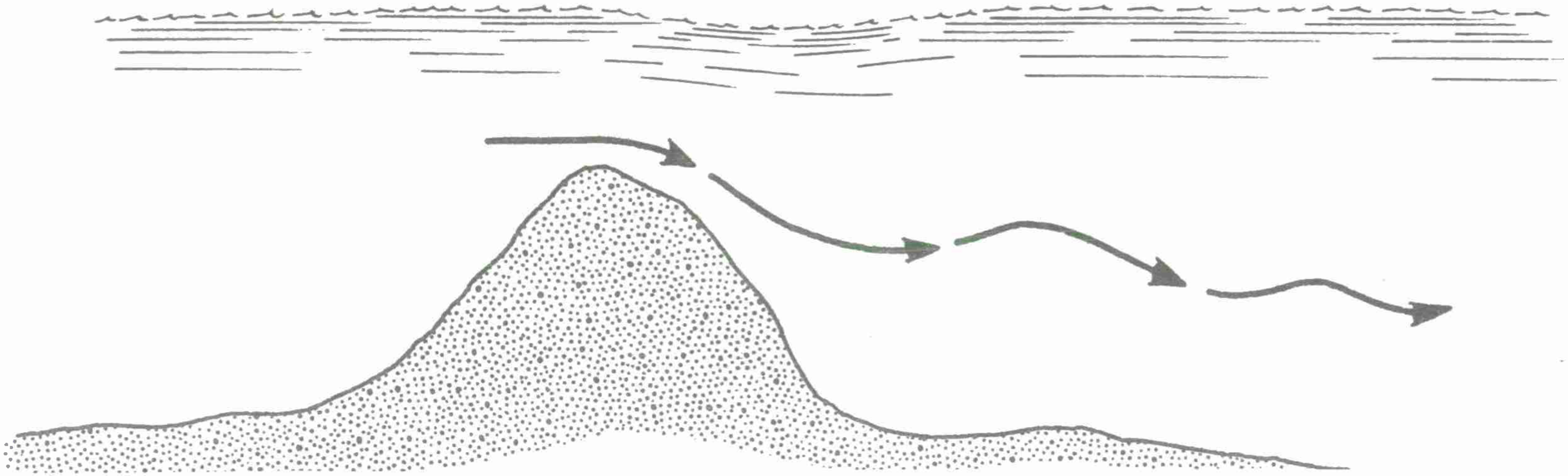


Figure 6. Schematic of Flow Over a Ridge.

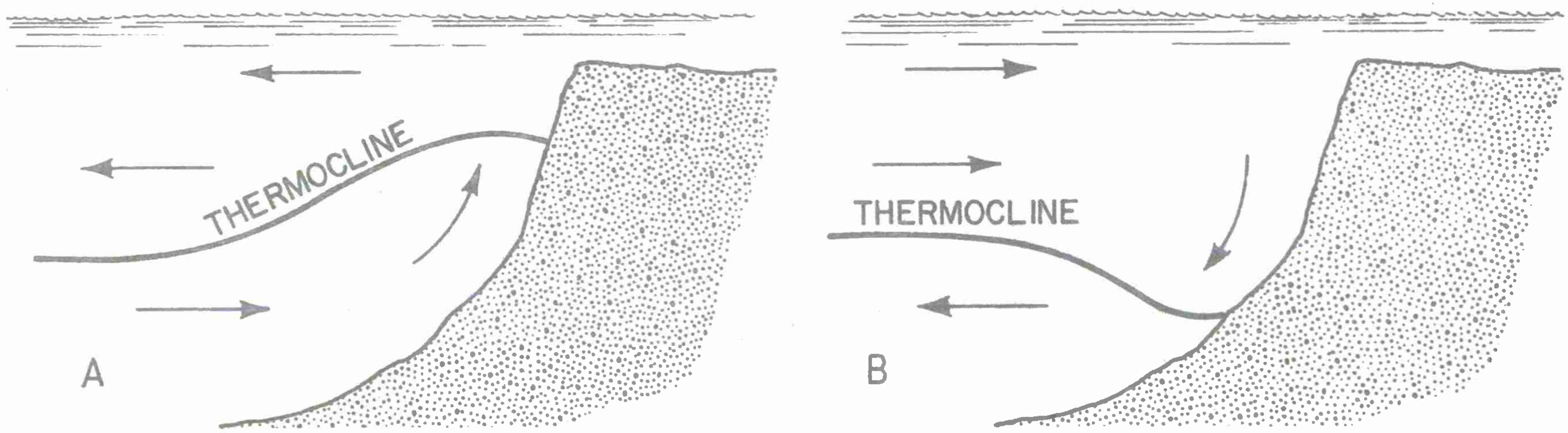


Figure 7. Scheme of Vertical Movements at Continental Slope.

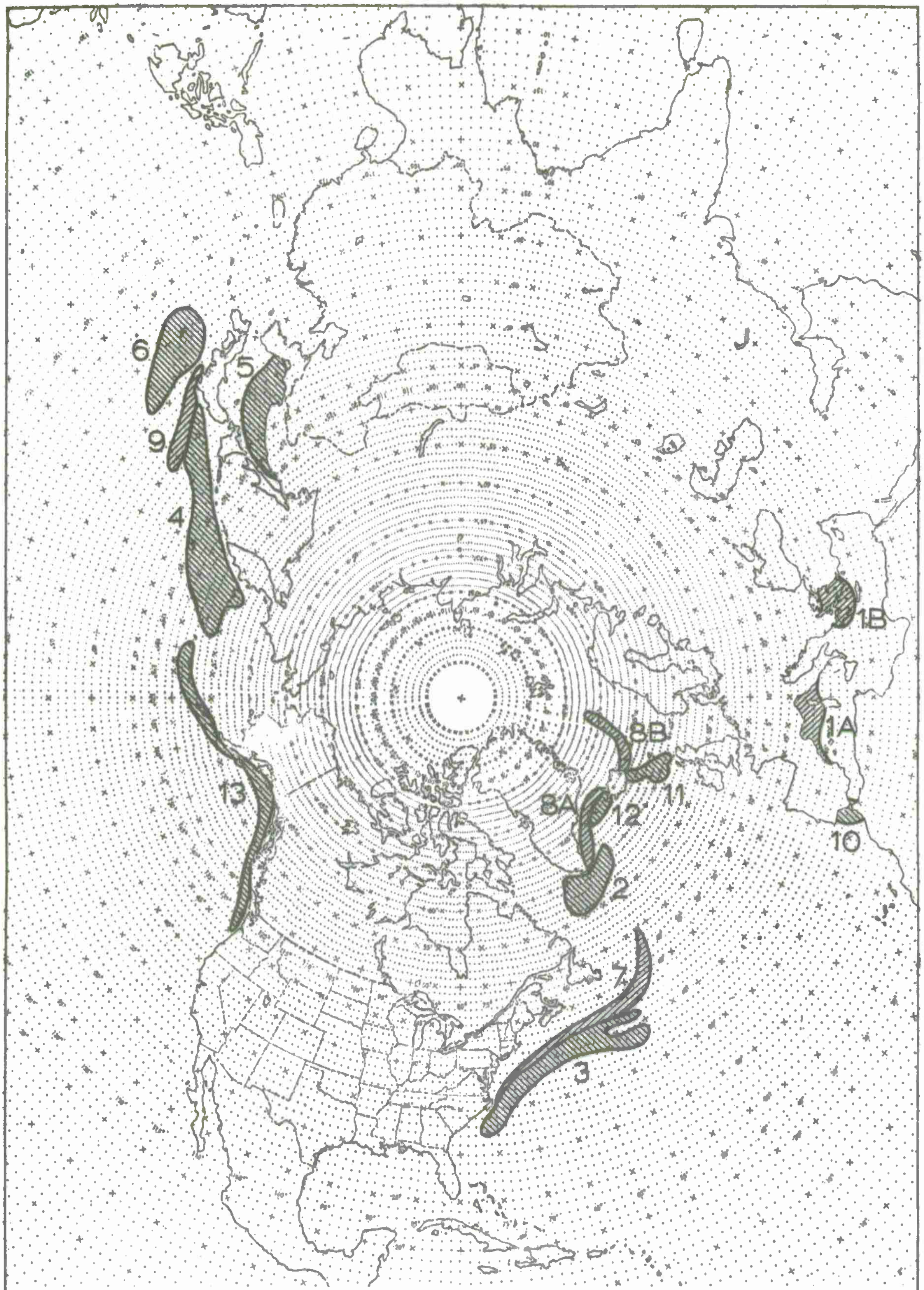


Figure 8. Areas in the Oceans Where Large-Scale Vertical Displacement Can Occur.

water is formed during some winters. Large-scale vertical motions in these areas can be expected in late winter when the waters are nearly isothermal and when strong winds are blowing from the continent causing rapid cooling at the surface.

Area 2, the Irminger Sea, is often mixed and isothermal to a relatively great depth in late winter and early spring. During this season some vertical displacement is possible in this area, mainly during storms and the accompanying cooling at the surface especially during northerly or northeasterly winds.

Area 3 in the Atlantic south of the Gulf Stream boundary can be isothermal (15° to 18° C.) and isohaline from the surface to about 400 meters during the winter. Thus large-scale turbulence can reach this depth during winter isothermal conditions and during storms or surface water advection from the north.

Area 4, the Oyashio region, is the area of formation of intermediate cold water in the North Pacific. This water, cold but of low salinity, causes relatively extensive subthermocline ducts over large areas of the North Pacific. During winter and early spring the thermocline is deep (in some cases down to 350 meters) thus forced mixing can reach that depth. Below about 300 meters, there is warmer but more saline water, the temperature of which again decreases with depth.

Area 5 in the western part of the Sea of Japan is very similar to that of the Northern Mediterranean Sea except that the bottom waters are considerably colder. This is the area of bottom water formation for the Sea of Japan.

Area 6 south of the Oyashio boundary is similar to Area 3 in the Atlantic where the water is isothermal to 400 meters (13° to 15° C.) indicating turbulence can reach this depth during winter.

Areas 7, 8, and 9 are the sharp frontal zones where frontal type large-scale turbulence can occur. Areas 10, 11, 12, 13 and 14 are areas where overflow over submarine ridges can cause considerable vertical motion in deeper layers. Mixing by internal waves on the continental slope can occur in any area of the world.

6. POSSIBLE IMPLICATIONS OF LARGE-SCALE VERTICAL MOTION ON SUBMARINE SAFETY

One purpose of this paper is to indicate some possible implications of vertical motion on submarine safety. Assuming large-scale vertical motions, if the submarine is in neutral stability with respect to the surrounding water, it is quite obvious that the submarine is moved up and down with the motion. If there are differential movements, the scale of which is less than the length of the submarine, the maneuverability of the submarine may certainly be affected.

Any mishap with the ballasting system of the submarine in a neutrally stable water mass might be disastrous due to the rapidly increasing pressure accompaning any significant downward displacement. If the submarine moves in an area of slight instability, it might cause large-scale turbulence by the collapse of this instability. In this case, the vertical velocities of the generated turbulence may be large indeed.

Answers to the possible effects of large-scale turbulence on submarines could be obtained by interviewing officers and screening log books from those submarines which have encountered large-scale turbulence. Furthermore, the mapping of the areas of known submarine disasters compared to the areas of possible occurrence of large-scale turbulence might give some additional clue on this problem.

7. SUMMARY AND SUGGESTIONS FOR FURTHER INVESTIGATION

1. Theoretical considerations and some empirical evidence indicate that large-scale turbulence can occur in the oceans in some areas, especially during the cool season.
2. The likely areas and conditions for large-scale turbulence are indicated in figure 8:
    - (a) Cyclonic eddies in areas and times where the waters are isothermal to great depths and intensive cooling occurs at the surface (usually associated with strong winds).
    - (b) Sharp oceanic fronts.
    - (c) Oceanic ridges and at continental slopes.
3. If large-scale vertical motion occurs, it would affect submarines in neutrally buoyant conditions.
4. No fully useful instability criterion is available for the ocean. The question of whether a moving submarine can cause a turnover in slightly unstable conditions requires some laboratory experiments.
5. In order to pursue the submarine safety aspect of this study further, it is necessary to collect existing evidence of the effect of large-scale turbulence on the behavior of submarines. It is also necessary to map the areas and times of past submarine disasters and analyze the environmental conditions under which these disasters occurred.

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