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A STUDY OF MIXING PROCESSES OVER THE EDGE OF THE CONTINENTAL SHELF

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ABSTRACT

By means of T-S area diagrams, a method of analysis is developed for the study of closely spaced hydrographic data. In a transitional zone, such as that over the continental shelf off southern New England, this method is useful for following the continuity of the mixing process. Changes in salinity at the edge of the shelf are due, for the most part, to horizontal advection. There are indications of nonisentropic mixing on a smaller scale. From the turbulent features of the region, as indicated by instabilities, this condition is not unexpected.

INTRODUCTION

The edge of the continental shelf off the northeastern coast of the United States is a region where unlike water masses meet. In this paper a study of these waters is attempted by tracing their origin and following their transformation over the shelf.

The 100-fathom curve, coincident with the edge of the continental shelf, is considered to be the general boundary between coastal and oceanic water (Iselin, 1939). However, the actual boundary is poorly defined, since each water mass is found occasionally in the other's territory; this variability is fairly well known (Bigelow, 1933; Bigelow and Sears, 1935; Bumpus, 1948). The mean of the fluctuations follows approximately the 100-fathom contour, and for this reason the location is strategic for observing the exchange between coastal and oceanic waters. In general, according to Iselin (1939), a semipermanent circulation exists parallel to the shelf due to differences in density between the two water masses. The fresher coastal water, being normally the lighter of the two, tends to flow over the other, but it is deflected to the right by Coriolis' force. Along the northwestern Atlantic shelf a southwesterly drift usually prevails. At times, the difference in density is small and even vanishes. The winds are free then to shift large masses of water away from or into the area.

Another feature of the shelf circulation is the apparent existence of offshore-onshore components to the general drift, these being suggested

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by the evident salt exchange across the shelf. With depth, the salinity of the coastal water usually increases whereas that of the oceanic water decreases (Iselin, 1939). The offshore-onshore movement is accounted for in at least two different ways. Compensatory exchange may occur across the boundary as one mass moves out and another enters. Possibly this is of intermittent or sporadic occurrence depending on temporary local conditions. Small-scale mixing may occur at the boundary with a steady exchange of salt between the two masses.

METHOD OF SOLUTION

Were it not for the shallowness of the region, a logical tool for tracing the origin and transformation of waters over the shelf would be the widely used Temperature-Salinity correlation method (Helland-Hansen, 1918; Jacobson, 1929; Stockmann, 1946). In most cases the use of this method in shallow waters is inadvisable because, over a period of time, local factors such as evaporation, precipitation, and solar radiation influence the water (Tibby, 1941; Pollak, 1947). Nevertheless, in a limited area, in which mixing processes are proceeding rapidly relative to the disturbing influences of these factors, the method may supply useful information provided nearly synoptic data are employed.

DATA

The usefulness of the method has been tested by the treatment of observations sufficient in number to describe the water in the area. Hydrographic data across the edge of the continental shelf in the vicinity of Hudson Canyon were obtained during several traverses made by the U. S. Fish and Wildlife Service vessel ALBATROSS III in November, 1948 (Fig. 1). These observations were obtained by means of the Sea Sampler (Spilhaus and Miller, 1948), and they were closely spaced in time, distance and depth. For example, a 55-mile traverse was completed in five hours and was comprised of 10 hydrographic stations with an average of 10 observations at each station to depths of about 100 meters. All of the data were collected in one three-day interval.

A continuous bathythermograph trace, together with samples of sea water at each station, was obtained. Density figures were computed from temperatures read at the respective sampling depths (Spilhaus and Miller, 1948). The distribution of temperature, salinity, and

\[ \text{Three sections were made during the cruise. Section III does not cross the shelf, and hence it will not be specifically referred to in this paper.} \]
Figure 1. Chart showing positions of hydrographic stations off the coast of southern New England.

density (sigma–t) along two of the sections is shown graphically in Figs. 4a, 4b, 4c, 5a, 5b, 5c. The use of the bathythermograph trace in accurate hydrographic analysis is usually minimized to the extent that its chief worth is considered to be in the relative values of a single BT observation. Once confidence is gained in the consistent performance of an individual instrument, however, a sequence of BT observations becomes particularly valuable. Since the Sea Sampler had been calibrated recently, it was estimated that the temperature curves were accurate to \( \pm 0.2^\circ \text{F} \). The water samples were titrated for salinity with an accuracy of \( \pm 0.03^\circ /\text{o} \).
ANALYSIS

Before attempting to analyze the data, a basic theorem of the T-S correlation method is restated: "Water masses homogeneous in respect to temperature and salinity are represented by single points. Different water masses formed by mixing of two homogeneous water masses will be found in the diagram lying in a straight line" (Jacobsen, 1929). Straight-line mixing is the keynote of the following analysis.

Temperature-Salinity Correlations. Fig. 2 shows the observations plotted as a Temperature-Salinity diagram. The superimposed curve to the right of the observations represents the characteristic Slope Water curve for December (Iselin, 1936) near the area under observation. It defines the upper limits of salinity for water of a given temperature in the area.

There are at least two different water types indicated by the T-S correlation. The well defined distribution of the warmer water (C'C D)\(^3\) may be interpreted as the result of coastal water (C'C) mixing with the surface oceanic water (D). The source of the cooler

\(^3\) C'C are observations taken well inshore from the edge of the shelf and are not of primary importance in the coastal-oceanic water exchange.
water (AB) is not as clear; from its distribution near the slope water curve, this subsurface water (AB) is assumed to be slope water somewhat modified by dilution.

The oceanic water observed in the shelf region at depths of less than 100 meters is separated into three water types. The cold portion, which is in agreement with Iselin's slope water curve, includes water that occurs normally between 200 and 600 meters (B) in the deeper slope water region (Iselin, 1936). For purposes of definition, parts of the slope water curve shown in Fig. 2 will be named as follows: The warm, saline portion (A) of the curve will be called Intermediate Slope Water, that is, water occurring immediately beneath the thermocline; the cooler, less saline portion (B) will be called Mid-depth Slope Water; the saline, surface water (D) will be called Surface Slope Water. The presence of all three types of water in the upper 100 meters over the shelf is not surprising when one refers to the upward slope of density (sigma-t) lines in profiles crossing the continental slope (Iselin, 1936; Montgomery, 1938).

The supposed sources of water over the edge of the shelf are now defined. The observations shown on the T-S diagram which lie between the slope water curve (AB) and the coastal water (C'C D) are as yet unexplained. Observations made within this area of the diagram, shown by open circles in Fig. 2, came from samples drawn from a sharply pronounced thermocline. From this fact one can deduce a limited transfer between the upper and lower water layers described by that part of the diagram. The remaining intermediate T-S points convey little information at this stage of analysis.

By study of the salinity profiles one can infer some water movement only to have it confused or refuted by the temperature profiles (Figs. 4a, 4b, 5a, 5b). The density (sigma-t) profiles (Figs. 4c, 5c) would clarify the situation somewhat if it were not for the unstable stratification (Spilhaus, Ehrlich and Miller, 1949). Apparently, then, a clear understanding of water movement due to mixing over the shelf is not to be gained by the study of these profiles. However, the uncertainty will be less obscure if we analyze the T-S observations in the manner described below.

The Quadrilateral Grid. A means of describing the T-S characteristics of the data by vertical profiles was found by considering the following postulates, which are based on the theorem which represents mixing processes by a straight line, as mentioned previously.

Consider an idealized situation where a given water type is described by a point in a T-S diagram which lies on a straight line between points representing two other water types. The latter types, when
mixed in quantities inversely proportional to the distance of their points from that of the given water type, result in a mixture identical with it. In this statement homogeneity of the water type is implied. However, if one associates water type with water mass, homogeneous water, in the absolute sense, would rarely be found in the ocean. On the other hand, relative homogeneity can be assumed if a water mass is sufficiently described in a T-S diagram by a cluster of observations about an imaginary point. It follows, then, that if the mixing water types can be described by discrete circles enclosing clusters, one obtains a limited area bounded by two lines tangent to the circles rather than a line between them.

True homogeneity is lost, but the sense of Jacobsen's postulate is retained in the following: If a given water type in a T-S diagram lies in such an area between two other water types, the latter types, when mixed in proper proportion, result in a mixture similar to it. From these postulates it is evident that our concept of mixing is not confined to one-dimensional lines. Within reasonable limits, an area of mixing is conceived in which two source waters are considered, with intermediary observations being proportional mixtures of these. This is a valid conception provided the intermediary observation has not
acquired its properties through some external influence other than mixing; in this case that influence is assumed to be negligible.

It is clear that an observation in a set of data which does not fall in the T-S area between two source waters is not a mixture of the two. But assuming that it is a mixture, a third and possibly a fourth water source may be involved. In a region where mixing occurs, one must find in the data those observations which represent more closely the source waters of that region. In this investigation we find four types of water whose characteristics could not be justified as a result of mixing within the area of investigation. These waters were the point sources to which the observations were related.

Four straight lines were drawn between A, B, C, and D (Fig. 3). The corners of the described quadrilateral represent water with definite characteristics, hereafter referred to as primary water types. For instance, C represents coastal water; in like manner, D is surface slope water; A, intermediate slope water; and B, mid-depth slope water. All observations within the quadrilateral were assumed to be resultant mixtures of the four primary water types. This assumption is rather bold, for it is quite possible for alien waters to mix and form a type similar to one composed of the four bases. However, some indication of this intrusion would be apparent in the surrounding observations.

The next step was to find the proportions of the basic types in the observed samples. For this purpose the quadrilateral was subdivided proportionally to form a grid containing 16 rectangular areas. Along the line CB, which forms one side of the quadrilateral, observations falling on the segments closest to C contain proportionately more C water than B. Along the line CD the segments closest to C describe mixtures containing more C water than D. A mixture described in the three rectangular areas adjoining the above segments is predominantly C type water, that is, water in which C is greater than 50% of its volume. In like manner the other three types extend their influence over adjoining areas. In the four central rectangular areas the relative contributions of each water type is more ambiguous. It is probable that a given source is the major constituent in the closest central rectangle, but the argument is uncertain in a core about the center. This is not a serious drawback, however, for in actual distribution the volume of water described by this doubtful core is a small part of the whole.

By enclosing the set of observations in a grid constructed on a T-S

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* Water type is used rather than mass so that stress will be put on the T-S description of the water rather than on the specific connotation of the word mass.
diagram, the assumption was made that all of the observations were products of the mixing of water types represented by the extreme corners of the grid. Since the positions of the grid lines are uniquely determined by the distributions of temperature and salinity along them, it is possible to transfer the grid with correct distortions to a diagram that shows the hydrographic section.

The distribution of the relative water type mixtures in two of the hydrographic sections was drawn in the following manner. By means of the bathythermograph temperature curves, continuous T-S curves for each station were constructed for graphic interpolation between the vertical salinity observations (Stommel, 1947). The depths at which each sample was collected were also marked on the curve. By superimposing each T-S curve on the quadrilateral grid, the depth at which it intersected each grid line was noted. (Comparison of the lines of intersection with the temperature curve was useful for obtaining accurate depth.) These depths were plotted in vertical sections whose coordinates were distance and depth. Finally, lines corresponding to the grid lines were drawn through their respective depths in the sections. The areas bounded by these lines represent water types with ranges of definition in accord with those of the master
grid. The final profiles for Sections I and II are shown in Figs. 4d, 5d.

It is easy to visualize the T-S description of the water in each section by imagining that the grid is placed on an elastic sheet which is pulled and pushed in such a way that the grid lines of definition finally take the shape represented in the figures. In this analogous operation it would be difficult to conceive the sequential relations being interrupted. A face on a rubber balloon is still a face no matter what the distortion.

The continuity of the method provides a means for detecting errors in observations. If observations do not fit the grid pattern, then they should be questioned just as they would be in other methods of analysis. On the other hand, there were observations in the data whose authenticity was not confirmed by ordinary T-S analysis (Sverdrup, Johnson and Fleming, 1942). However, continuity of the grid pattern was fulfilled by including these observations. The finer details of the water type sections (Figs. 4d, 5d) are examples. (In all of the sections no data were omitted.) It would seem that the method has some analytical value in this respect.
Figure 4c. Section I. Density (sigma-t)

Figure 4d. Section I. Water type distribution.
Figure 5a. Section II. Temperature.

Figure 5b. Section II. Salinity.
Figure 5c. Section II. Density (sigma-t).

Figure 5d. Section II. Water type distribution.
CONCLUSIONS

By considering a set of observations as resultant mixtures of primary water types, a relation between the observations is established through their T-S characteristics. Those observations which are most similar to the basic water types are assumed to represent the source water in the region. This assumption is valid if the base has an extreme value of salinity or temperature, since it, in turn, must have its source outside the region that is being studied. By observing the character of the mixtures one is able to follow the mixing paths in a set of data.

Fig. 6 summarizes the water distribution for both sections. The shaded portions represent the areas of transitions between the water types. The transition from oceanic slope water to coastal water is accompanied by an apparent upwelling of the deep mid-depth slope water. This seems to occur in sufficient volume to effectively bar the intermediate slope water from taking an important part in the mixing process. This water, type A, occurs only at the most seaward hydrographic stations. The mixtures between A and B are not
necessarily local phenomena, since water with like characteristics is
indicated in the seaward stations.

Major transfer takes place between the surface slope water and the
coastal water. This is suggested by the relative volume of the mixed
C and D water. It is a condition to be expected because the density
differences are small between these two types. On the other hand,
where the density differences are great, an appreciable exchange occurs
between the “upwelled” water and the coastal water. This nonisen-
tropic mixing suggests an internal energy source which may be localized
at the edge of the shelf, for it does not appear to break up the sharp
density gradient between the surface and intermediate slope waters
where the density difference is smaller.

In this set of data it is seen that the boundary between oceanic and
coastal waters is sharply defined and is in the neighborhood of the 50
fathom rather than the 100 fathom curve (Figs. 4d, 5d). Extending
seaward from this boundary is a long, slender, subsurface tongue,
which is a mixture of coastal, surface slope and mid-depth slope water.
Hachey (1934) has shown a similar tongue in a laboratory experiment
that demonstrates an intermediate movement of mixed water away
from a mixing area. The fact that this tongue retains its identity over
a distance of 5 to 10 miles is noteworthy. One would expect the
 turbulence and instability of the region to effectively destroy the thin
layer in a short period of time. However, the tongue persisted over a
three-day period for a distance of at least 40 miles along the edge of the
continental shelf. It is probably a primary mixing effect which is
maintained as long as there is sufficient water of a suitable type to
replenish the particular mixture.

The juxtaposition of the steady state, as evidenced by the tongue,
and the turbulence shown by instabilities, has a plausible explanation
in an internal surf process such as that described by Defant (1948).
In his laboratory tank experiments, where a two-layered medium was
used, internal breakers were produced at the interface while the
surface remained undisturbed. This experiment is analogous in
some respects to the condition found over the edge of the shelf.

Although we have no direct internal wave measurements, we do have
a combination of circumstances which point strongly to the occurrence
of an internal surf process at the edge of the continental shelf. The
nonisentropic mixing is a final outcome of the process and is better
understood when one considers that we are dealing with a many-
layered medium, the layers of which are converging on the edge of the
shelf. An internal wave traveling in the direction of the shelf is
affected by the slope and is upset at the edge so that its energy is
expended in mixing water types of different density. In this manner
type B or mid-depth slope water becomes mixed with the surface layers. The mixing mill at the edge of the shelf must be supplied with grist to grind, or otherwise it must run down. Also it must have a means to carry off the final product or else die out. Coastal water and surface slope water are the principal ingredients. It is a fair assumption that the mixed product is carried off in the general southwesterly drift. However, type B water must necessarily be replenished from deeper sources in order to maintain its effectiveness, and a certain amount of water must be carried off to compensate for the intrusion of type B water. It is suggested that the long tongue is the direct path by which excess water is drawn off.

It has been emphasized that type B has had its origin in greater depths offshore. Furthermore, it is assumed that it upwelled at the shelf. The assumption is likewise justified by oxygen analyses (not shown) which show that this water is low in oxygen content (about 3 ml/L). This water is raised to the 100 m. level, stirred at the edge of the continental shelf and added to the surface layers to become part of the coastal and surface oceanic circulation.

There are no indications to suggest that this upwelling is directly induced by the wind. The scope of this investigation is too limited to suggest a cause for upwelling other than that obtained in the general dynamics of oceanic circulation. The fact that it does occur is biologically significant because of the nutrient value of upwelled water.

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