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Coastal currents and the fisheries *

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THE WATERS over the continental shelf from Labrador to Cape Hatteras have been examined and described many times over the last 40 years or so. Certain characteristic features of the distribution of temperature and salinity are to be found along this whole stretch of coastline. Here many clear-cut examples of the basic problems of the circulation of coastal waters are to be encountered, yet it cannot be claimed that much additional understanding has been gained since the pioneer studies of BIGELOW (1927; 1933).

When the present writer was a graduate student at Harvard, Dr. BIGELOW had reached the conclusion that significant advancements in marine biology would in all probability have to await a much better understanding of the circulation of the ocean. He planned his own work, and also the early programme of the Woods Hole Oceanographic Institution, accordingly. After 25 years, the best that can be said is that we have gained a clearer picture of the deep-water current systems, and that there is hope that a corresponding advance will soon take place in the more difficult problems of coastal currents. The purposes of this paper are to discuss briefly the present status of the shallow-water circulation problem, to point out the more promising lines of attack, and especially to give fisheries biologists some hope that physical oceanographers will soon be able to answer some of their more pressing questions concerning fluctuations in the physical and chemical environment of coastal fisheries.

Certain general rules of coastal circulation have become well established. In the northern hemisphere the average flow is parallel to the shore line with the land on the right hand side. It follows that the average motion of the surface water is anticlockwise in a bay or gulf and clockwise around a bank. The reverse is of course true in the southern hemisphere. There is a tendency for the most pronounced surface current to be located near the 100 fathom curve, but it is also characteristic to find a second—somewhat shallower and fresher—band of current near the beach. Unfortunately, from the biological standpoint it is the rates of cross-current transport at different levels that are important, and these we know very little about as yet.

It is typical of coastal waters that salinity everywhere increases with depth. The only exceptions to this statement are to be found briefly in winter where convection has extended downward to the bottom, or where tidal stirring is especially vigorous. In any case, whether or not vertical stability is present, salinity increases gradually across the continental shelf and then increases more suddenly near the 100 fathom curve, where the contact between the relatively fresh coastal water and the more saline oceanic waters is usually located. It is also characteristic of coastal waters from the higher latitudes on the westward margin of an ocean that, throughout much of the year, there is a temperature minimum at mid-depths. The reason for this is that there is an inshore component to the flow of the bottom water, and an offshore

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component to that of the surface water. Along the whole stretch of coastline under consideration here the bottom water near the 100 fathom curve has the characteristics of truly oceanic water. That is to say, salinity approaches $35^\circ/_{oo}$, and temperature is at least several degrees higher than is to be found over the continental shelf at mid-depths at the latitude in question.

The temperature-minimum layer normally extends offshore as a tongue a few miles beyond the 100 fathom curve. This cold tongue overlies a maximum-salinity layer that appears to have an inshore component, and an origin well offshore in the slope-water area. The mixing processes at the contact between the coastal water and the oceanic water are by no means clear. As normally drawn from serial observations of temperature and salinity the isotherms and isohalines cross each other at a considerable angle near the extremity of the cold tongue, a pattern which is difficult to explain, if indeed it really exists. On none of the sections so far examined have sufficiently closely spaced salinity observations been secured for one to be certain of the changes in the T–S correlation curve as one moves from typical coastal water to typical slope water. It is evident that vertical mixing plays an important role near the outer limit of the coastal water.

Not only are the small-scale mixing processes near the 100 fathom curve complex and poorly understood, but also large-scale mixing processes are present. Bubbles or tongues of nearly undiluted coastal water are often encountered just below the surface layer in the slope-water area, even as far offshore as the outermost filament of the Gulf Stream System. Much less frequently has oceanic water been observed invading the area inside the 100 fathom curve, except very near the surface and close to the bottom. While the coastal water near the 100 fathom curve is clearly on the average moving towards the south and west, just beyond it the apparently detached masses of coastal water often seem to have an easterly component. In short, it is as yet impossible to describe a sector near the edge of the continental shelf in three dimensions in a reliable manner. No network of observations has been sufficiently closely spaced to permit only one solution to the contouring of the physical properties. The situation, although on a much smaller scale, may be even more ambiguous than FUGLISTER (1955) has recently shown to be the case further offshore in the Gulf Stream System.

The least complex stretch of coastal water in the area under consideration, and the one having the most sluggish circulation, is to be found between Nantucket Shoals and Cape Hatteras. Along this 500 mile stretch of coastline many rivers are continually pouring in fresh water which reaches the sea with a salinity of about $30^\circ/_{oo}$ after having undergone the mixing processes at work in the estuaries. In the further mixing which occurs over the continental shelf the salinity is gradually increased, both in the offshore direction and, as KETCHUM has recently shown (1955), also in the downstream direction. Since the flow past Nantucket from the Gulf of Maine is weak and probably intermittent, and since little coastal water passes Cape Hatteras, if one assigns an average salinity to the water leaving the continental shelf of $33^\circ/_{oo}$, and a value of $35^\circ/_{oo}$ to the slope water inflow along the bottom, then it is evident that the offshore component must approximate 16 times the volume of all the land drainage.

As previously stated, part of this exchange between coastal and offshore waters is accomplished by small-scale mixing processes, both vertical and horizontal, and part of it by much larger eddy-type movements. The first process probably proceeds at a fairly constant rate, while the second is likely to be intermittent in character and to be triggered off by the offshore currents. It is the intermittent large-scale losses of coastal water that are probably the important events from the standpoint of a fisheries biologist. If physical processes are an important factor in the widely fluctuating annual recruitment of young fish, then it seems likely that major changes in the environment must be involved. Presumably the fish, even very young ones, are able to deal with the normal, small-scale mixing mechanisms. Thus we can ask the question: from the standpoint of a fish, what constitutes a physical catastrophy? The answer may be somewhat different for each species of fish.

The two primary variables in coastal circulation are undoubtedly the river inflow and the weather. The former supplies most of the energy, and the latter is important both in maintaining the small-scale mixing processes and also in causing the mass movements of considerable bodies of water, especially in winter. How great a variation from the normal can be produced by either factor? The larger eddying motions of an intermittent character occurring near the edge of the continental shelf are a third factor capable of producing considerable variations in the coastal environment. South of New England the available evidence indicates that these are most likely to take place along the southern edge of Georges Banks and off Chesapeake Bay. In both cases the currents of the Gulf Stream System are relatively close to the 100 fathom curve. If it is true that the offshore currents can sometimes cause relatively large eddies to form, and thus remove considerable masses of coastal water, then these events are probably not unrelated to the variations in transport of the Gulf Stream System.

If the above summary of the problem is reasonably correct, a physical oceanographer, in order to be of help to his friends concerned with fluctuations in the fisheries, needs to find answers to the following questions. By how much does land drainage have to change before the normal environment of coastal water is seriously affected? How abnormal does the weather have to become before the winds produce a corresponding change? How important to the larger-scale exchange of coastal and oceanic waters are the variations of the deep, offshore currents?

The available observations of temperature and salinity cannot be expected to yield clear-cut answers to these questions. The data consist of spot observations, separated widely in time and usually also in space. Observations from some of the extreme winters, for example 1918 and 1934, are entirely lacking. While the winds and the inflow of several of the rivers are known continuously for a good many years back, the only reasonably continuous oceanographic data are some temperature records close to the beach, and these of course mainly reflect the local weather. Offshore on the bottom where the main commercial fisheries are located we have no continuous information, nor do we have records of the variations in the offshore component of the upper half of the water column.

Why have we at Woods Hole seemingly so long avoided problems in coastal circulation? In the first place, of course, the more spectacular problems of the Gulf Stream System were close at hand. In 1933 and 1934 we did survey the Gulf of Maine on 17 occasions. Not a single paper dealing with the dynamics of the system appeared. None of us interested primarily in the causes of the circulation were able to use these extensive data to add anything of significance to Dr. BIGELOW'S classical studies. Tidal currents and internal waves so complicated the picture that one could draw no important additional conclusions from the relatively complete grids of new stations.

Much improved navigation is of course now available. Underway instruments such as the bathythermograph can now provide much more detailed profiles (about 75 such profiles across the continental shelf have been accumulated), but the fact remains that nobody has had the courage to make a sustained attack on the three-dimensional mixing mechanisms going on near the 100 fathom curve. Without the help of entirely new techniques it has seemed too difficult an observational problem, and it has been clear all along that the important clues were to be found in this zone.

It is a pleasure to be able to announce here that a new programme in coastal circulation is being planned at the Woods Hole Oceanographic Institution and has already been set in motion. It has been made possible by funds supplied by the U.S. Fish and Wildlife Service, and made available to the Service by the Saltonstall-Kennedy Act. The present writer is most hopeful that this three-year study will be of real assistance to fisheries biologists, because it is planned to obtain continuous data of various kinds at several key points in the system, as well as to secure some periodic ship surveys. As KETCHUM, REDFIELD and AYERS (1951) showed so clearly in their studies of inshore waters off New York, spot observations of temperature and salinity can be illuminating if they must also satisfy some continuous requirement such as the transfer of fresh water through the network of stations. Elsewhere in this volume Dr. KETCHUM has attempted to treat the whole continental shelf area from Nantucket to Cape Hatteras as a very wide estuary. This is an important step forward in our thinking, and perhaps all that is needed to refine and to clarify the picture are some long series of current measurements at various depths.

The new programme will emphasize first of all the more systematic collection of continuous records of temperature and salinity at as many fixed points in the area as possible. The submerged recovery buoy developed by Mr. DAVID H. FRANTZ at Woods Hole will also be used for temperature observations at some critical points where moored surface buoys cannot be easily maintained. Free floating buoys carrying radio transponders will be set out and then located frequently by a plane. Continuous current measurements will be obtained at a number of points, both near the bottom and near the surface. In these ways it is hoped to gain reliable information on how strong and how persistent the winds have to be, to cause a significant disturbance in the normal exchange between coastal and offshore waters.

A recent study by CHASE (1955) has indicated that, at least in the case of young haddock, exceptionally prolonged offshore winds during the early spring can be an important factor on Georges Bank. Lacking any current measurements from the waters in which the young haddock float, CHASE was forced to use the record of the relative success of the year classes as an indicator of wind-induced currents. His reasoning, while satisfactory to a physical oceanographer, leaves something to be desired from the biological standpoint. A physical oceanographer should be able to state with conviction, on the basis of physical measurements, what the large-scale water movements have been, and then leave it to the biologists to decide whether or not these have had any biological consequences.

Once the influence of the winds and of the variations in river inflow have been properly assessed, and once the cause and importance of the large-scale mixing processes at the edge of the continental shelf have been worked out, it should be possible to go back over the available data and indicate when and where the coastal environment was seriously disturbed. The biologists are by no means satisfied that environmental changes of sufficient magnitude have occurred to account for the goings and comings of fish. It is the aim of the new programme to find means of settling this matter one way or another. Even if it only serves to bring the circulation problem into closer contact with biological needs, an important step forward will have been taken.

To summarize the present situation in coastal oceanography, our basic problems can be set forth as follows:

(1) The available data are inadequate to establish how variable the coastal environment may be because of fluctuations in its principal energy source, namely land drainage.

(2) So far as the oceanic currents are concerned, it is believed that the winds, either directly or indirectly, supply most of the energy. Considerable variations in the offshore currents are known to exist, but to what degree these influence the inshore currents remains obscure.

(3) Coastal currents, on the other hand, for the most part operate without the direct help of the winds, yet strong and prolonged winds could be a cause of important variations in the environment from the biological standpoint, especially for fishes which spawn near the edge of the continental shelf.

(4) Occasional surveys of the distribution of temperature and salinity are unlikely to provide more than limited understanding of the coastal currents, for the classical theories of physical oceanography assume steady-state conditions and, because of tidal currents, this simplification is far from being justified in coastal waters.

(5) Continuous observations, even of a rather simple sort at well-selected points over the continental shelf, should provide means of evaluating the influences of variations in river inflow, of the local winds, and of the offshore currents. Fortunately, new means of obtaining such observations have been developed in recent years.

(6) Once these factors have been evaluated, the major environmental fluctuations can probably be deduced as far back as the weather record extends.

(7) The general distribution of temperature and salinity in coastal waters indicates that, except briefly in mid-winter, it operates as a three-layered system. The warm wind-stirred surface layer and the cold stable layer just below both have offshore components, but probably quite different ones. Near the bottom, and especially where gullies and drowned river valleys exist, there is an inshore component. By moving up or down in the water column an organism can be carried either inshore or offshore. By the large-scale interaction of coastal and oceanic water it can either be carried up-coast or down-coast. From the biological standpoint it is important to establish how steady or how variable these current systems may be.

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