CHAPTER III

PHYSICAL AND CHEMICAL PROBLEMS OF THE SEA WATER

Sea water, next to air and to fresh water, is the most uniform of all the substances common on this planet, in chemical and physical character. Therefore it does not offer to the physicist or to the chemist the opportunity that it does to the biologist for the solution of the basic problems that are today most alluring in his particular fields of study.

The immediate task of the ocean physicist, for example, is not so much to investigate the inherent properties of matter as to explain the existing manifestations of heat, light, and motion within the sea water itself. The problems most immediately pressing in these fields center about the responses of the water to solar radiation, to the atmospheric circulation, to the force of gravity, and to the centrifugal force that is set up by the rotation of the earth. These forces are all directly measurable, and can be stated in quantitative terms. Essentially, therefore, physical oceanography is an exact science. If we are not yet in a position to handle its manifestations in an exact way, it is more because our regional knowledge of the sea is still incomplete, and because our methods of mathematical analysis are not sufficiently

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advanced, than because of failure to understand the
classic physical or cosmic principles that are involved.

The studies of the chemistry of sea water that are
at present in progress, like those of its physics, chiefly
aim at enlarging our factual knowledge of regional
variations, and our understanding of events that
take place in the cycle of matter there, rather than
at clarifying the nature of chemical processes as
such. Thus they bear to the science of physical
chemistry as a whole a relationship more subsidiary
than do oceanic biology or physiology to current
attempts to fathom the riddle of life. We may also
remark that a line should be drawn between pro-
blems in the sea that involve analysis of the chem-
ical reactions that actually take place there, and
those which include chemistry only in so far as it is
necessary to determine the amounts of one sub-
stance or another present in the solution or in the
sediments that clothe the ocean bottom, as adjuncts
to other problems. The first of these categories falls
truly within the province of the chemist; but the
chemical phase of the latter consists merely of rou-
tine analyses, and so may concern the theoretic
chemist only in some secondary stage. As an ex-
ample of the first category we might cite the pro-
blems of lime chemistry (page 114). Examination of
variations in the nitrate content of the sea water per
se might illustrate the second; it is promoted to the
truly chemical category when the cause and the
effect of such variations in nitrate concentration
come into account.

Sea water occupies the greater part of the surface
of our planet. A study of its physical and chemical
characters and of the circulatory movements by
which it responds to external and internal forces is,
therefore, an important item in our broadening view
of the physics and chemistry of the earth, sufficient
reason for making this a primary subject. But at the
same time the temperature of the water, its chemis-
try, and the mechanical manifestations of oceanic
circulation so obviously govern the whole economy
of life in the ocean, produce geological results so im-
portant, and go so far to govern climates on land,
past as well as present, that there has often been a
tendency to treat physical, chemical, and especially
dynamic oceanography chiefly as auxiliary to oce-
anic biology, to meteorology, or to geology. The
fact that oceanographic work on the two sides of the
Atlantic has long drawn its chief impetus from the
economic pressure of fisheries problems has further
tended toward a relegation of ocean physics and
chemistry per se, to secondary positions. This, how-
ever, has seriously retarded the advance, not only of
our knowledge of these aspects of the ocean, but even
of the very branches that it was hoped to further; for
it may be taken as axiomatic that only when any
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scientifc field is considered as worthy of intensive cultivation for its own sake can satisfactory advances be expected therein.

One effect of this tendency has been that studies of the physical and chemical state of the waters have rarely been the primary objects of the oceanographic undertakings of the past. This has applied, for example, to many of the deep-sea explorations, ‘Blake,’ ‘Albatross,’ ‘Valdivia,’ and ‘Siboga,’ among others. In America, where most of the older oceanographic exploration was sponsored by institutions whose chief interests lay in biology, the physical and chemical sides were even more neglected than in Europe, from the days of the ‘Blake’ until the renaissance of oceanography there in the first decade of the present century.

New viewpoints, developed of late, have, however, greatly stimulated interest in the problems of ocean chemistry and physics at all the centers where oceanographic research is now being actively prosecuted. Thus the principal programmes of the recent German expedition to the South Atlantic on the ‘Meteor,’ of the exploration of Davis Strait in 1928 by the United States Coast Guard cutter ‘Marion,’ and of the recent cruise of the ‘Carnegie,’ have been chemical, physical, and dynamic, recalling the attention devoted to the chemistry and physics of the sea water on the cruises of the ‘Challenger’ and of the
‘Pola.’ One or other or both of these phases of sea science are also primary objects for the Geophysical Institute in Bergen, for the Institut für Meereskunde in Berlin, for the Scripps Institution in California; as well as for the International Ice Patrol operating around the Grand Banks of Newfoundland; also for some of the Atlantic cruises of the fisheries services of European countries, of the Biological Board of Canada, of the United States Bureau of Fisheries, and of the Museum of Comparative Zoology.

At present, the attention of ocean physicists is chiefly focused on the following fields: (1) the distribution of temperature and of salinity within the sea, (2) oceanic circulation in detail, with the causes thereof, and (3) the penetration into it of the sun’s rays and effects of the same. The problems most to the fore in oceanic chemistry today center around the concentration and distribution of the different solutes in the sea water, and around the reactions (organic or inorganic) by which the constancy of this remarkable solution is maintained or disturbed.

1. THE TEMPERATURE AND SALINITY OF THE SEA WATER

There is as good reason from the biologic side as from the strictly physical for studying the temperature of the sea, because this, more than any other one feature of the water, directly controls the distri-
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bution of marine life, animal and plant. Because of
the important rôle of temperature in governing the
rates of animal and plant metabolism, touched else-
where (page 154), the seasonal changes in the
temperature of the water present special problems
to the marine biologist in his studies of important
events in the life cycles of animals and plants, such
as their breeding periods, the duration of the periods
of incubation or of larval life, rate of growth, feeding
activity at different seasons, seasonal migrations,
and many others. The temperature optima and the
lethal limits need also to be determined at different
stages in development for every species the life his-
tory of which is under examination. This question
is of practical import in the case of several important
food fishes, crustaceans and mollusks: the thermal
knowledge that the biologist needs in such cases is,
furthermore, of an extremely detailed sort.

Apart from the perfectly defensible wish to extend
our knowledge of every phenomenon in the sea,
the distribution of temperature engages the physical
oceanographer in his studies of the movements of the
different masses of water, both as affording direct
evidence of such movements and because this is one
of the two constants controlling the internal hy-
drostatic forces that tend to maintain a system of
thermo-dynamic circulation within the oceans. The
close relationship that exists between the tempera-
ture of the surface of the sea and that of the overlying air, introducing the whole broad question of the control of land climates by the high thermal capacity of the sea water and by the regional distribution of heat within the latter, also gives a directly practical reason for studying the temperature of the oceans (page 237).

Next to the regional charting of temperature (and approachable only thereby) the thermal problems now most pressing in the sea center chiefly around (a) detailed examination of the temperature cycles of regions that may be especially interesting from some particular standpoint; (b) the general variation in temperature with the seasons offshore, especially in the deeper strata; (c) the irregular non-seasonal fluctuations that are known to occur from year to year, or over periods of years, with their causes; (d) the thermal relationship between the surface of the sea and the air above it; and (e) the interplay of the several cooling and warming agencies. Under the last heading, empiric studies of the cooling effect of evaporation in different parts of the sea are now much to be desired. Quantitative analysis of the chilling that Arctic and Antarctic ice actually does (not theoretically may) bring about as it melts would be of great value. And tests are urgently needed as to whether the bottom water of the abyss receives an appreciable amount of heat from the
underlying earth, as some observations have suggested, or whether the slight rise in temperature recorded close to the bottom of the abyss in several cases is simply the result of adiabatic heating, because any warming from below would have a far-reaching influence on the vertical circulation in the deepest layers.

Small regional differences in the salinity of the sea water are secondary in the biologic complex as compared to the variations in temperature. However, it is now generally appreciated that they offer the most reliable of all qualitative indices to the broad-scale circulatory currents of the ocean basins and to the sources of different water masses. Illustrative regional problems now urgent in this respect include the entire oceanographic complex along and among the labyrinth of islands that fringe the coast of Alaska; the Asiatic fringing seas; the movements of the bottom waters of the Sulu Sea, as well as of other enclosed bowls; the expansions and contractions of the warm North Pacific drift with the seasons; the transferences of water through Bering Straits; the upwellings along California; likewise in the Humboldt current along the coasts of Ecuador and Peru, where hardly anything is known about the regularity or amplitude of the seasonal variations in salinity — to mention only a few of the more urgent cases.
Profiles of salinity even more than of temperature along several meridians for the Indian and Pacific Oceans, similar to those obtained by the 'Meteor' in the South Atlantic, are essential for working out the general circulatory systems of those oceans. First-hand information is also needed as to the exact combination of salinity with temperature from which to calculate the specific gravity, around the sub-polar margins (where the formation of oceanic bottom water is believed to take place) at the season when mass sinking may be expected to occur there (page 82). It is because of the practical difficulty of obtaining these data that we have so weak an observational basis for our theories of circulation in the crucial regions around the Antarctic and Arctic ice fronts.

Much more attention must also be paid to the processes that most directly affect the salinity of any given mass of surface water, namely, rainfall and evaporation. As has been recently remarked by a leading oceanographer, we still await an acceptable quantitative explanation for the fact that the waters of the North Pacific as a whole are considerably less saline than those of the Atlantic.

Quantitative measurements are also needed of the extent to which the freezing of sea ice actually increases the salinity — hence the specific gravity — of Arctic and Antarctic seas in the cold season, and how
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the process of freezing alters the chemical composition of those seas. Conversely, a better quantitative measure of the freshening of the surface that is caused by the melting of ice in lower latitudes and of the difference in this respect between sea and glacier ice is essential before we can correctly estimate the importance of this process in the salinity complex.

Detailed knowledge of regional variations in salinity is also as essential as is that of temperature in every dynamic study of ocean currents, salinity being the other factor that determines the specific gravity of the water at any given time and place.

It is appropriate to consider next in what measure the raw data that are needed for the solution of problems of these categories have been gathered so far.

The temperature of the surface of the sea can so easily be measured, and the importance of a knowledge of ocean temperatures, not only to the geographer and to the biologist, but to the navigator as well (as evidence of the current in which he sails), was so early appreciated, that great numbers of such readings had been recorded along a great variety of trade routes by the first half of the last century. In fact, as early as 1873 Thomson spoke of the observations previously taken in the North Atlantic as almost infinite, while Petterman had at his disposal more than 100,000 temperature records for his paper on the Gulf Stream, published in 1870.
Many surface temperatures had also been gathered from the other oceans, thanks largely to Maury's efforts, and have been accumulated since that time by the hydrographic services of the various maritime nations. In short, our knowledge of the general distribution of temperature at the surface of most parts of the sea has reached a point where no far-reaching modification of the existing thermal charts for the surface is likely.

However, there is no part of the open sea for which the normal surface temperature is yet known for any season, in the detail demanded for the solution of many pressing problems, or the normal variations from season to season. And to trace the irregular fluctuations that exert wide-reaching effects within the sea and in the atmosphere, but of whose amplitudes we, as yet, know very little, is one of the most urgent tasks that now face the oceanographer. Here are formidable undertakings (though no technical difficulty is involved), for they required the collection of great numbers of records over a wide range of localities, with the subsequent analysis of the same.

The prevailing thermal state of the underlying waters has been established in its broad outlines. So rapidly, in fact, did it prove possible to learn the abyssal temperature, once attention was focused thereon, that the basic distribution of deep-sea temperature had become generally understood within
ten years of the time (in 1873) when Wyville Thom-son had found it necessary to combat the view that the whole basin was filled with water at 4° Centi-grade. So many deep-sea temperatures have subse-
quently been obtained in the North and South At-
lantic that the general distribution, in the deeper layers, can now be plotted with some confidence for these oceans, though nowhere as yet in detail.

The recent work of the ‘Carnegie’ and ‘Dana’ has also made this possible for the bottom water of the Pacific, where, up to 1928, our only warrant for making generalizations outside certain restricted areas or along scattered profiles had been the great regional uniformity that characterizes abyssal temperatures in general, and the narrowness of the limits within which they have been found to alter over long periods of time. But even in the Atlantic basin, much more so in the Pacific basin, a vast amount of work remains to be done before a correct picture can be drawn of the general character and seasonal am-
plitudes of the regular alterations that take place from season to season in the temperatures of the water, below the stratum that comes within range of ‘surface’ readings, down to depths of 500 to 1000 fathoms.

Up to 1928 only about 100 serial determinations of temperature had been taken in the Indian Ocean to a depth greater than 500 fathoms; only six of these
to a depth greater than 1500 fathoms; although the last of these submarine contours encloses practically the whole of the Indian basin outside the continental slopes and slopes of the insular crests. And subsequent observations have been confined to the equatorial belt and to the African side. It is evident, then, that the thermal chart of the deep strata of that ocean cannot reach even to the elementary standard so far attained for the Pacific until serial records of the temperatures for all depths, surface to bottom, have been obtained over a much wider range of well-selected localities than has yet been done.

The gaps that still remain in our knowledge of the salinity of the oceans are far more serious than for temperature, both for the surface and for the deeps. Partly this is because only a fraction as many records have yet been obtained (accurate methods of measuring salinity, convenient enough for general use, are comparatively recent developments); partly because this feature of the water has engaged serious scientific attention through a much shorter period of time than has temperature; and partly because the considerable significance (in the study of circulation) of even the smallest variations, together with the unexpectedly complex regional inequalities that have actually been found to exist, make it less safe to deduce within significant limits the salinity of inter-
vening sectors of water from widely separated observing stations.

The only considerable areas for which oceanographers can yet claim even an outline of the normal seasonal cycle of salinity for the entire column of water, surface to bottom, are the parts of the northeastern Atlantic with its marginal seas (Norwegian Sea, North Sea, Baltic, and Mediterranean) that have been covered by the cruises of the international commissions; a much smaller coastwise sector off the east coast of North America between Cape Cod and Labrador; Californian and Japanese coastal waters; and the Javan and South China Sea where records were obtained quarterly for the period 1917 to 1920. Even for these regions we need a much closer knowledge of the seasonal fluctuations with the causes of the latter, especially of the irregular annual transgressions of one or another water mass which often play a disturbing (even destructive) rôle in the general economy of the sea.

In the ocean basins far from land modern requirements as to serial determinations of salinity have, with few exceptions, been met only by the major deep-sea expeditions, whose tracks, reasonably close-meshed in the Atlantics, have covered the Pacific and Indian basins (and especially the Southern Ocean) with a very sparse web indeed. Thus only about seventy such complete serial determina-
tions of salinity combined with temperature from the surface down to the bottom had been published for depths greater than 1,500 fathoms in the Atlantic, north of the equator, about twenty north of 20° north latitude previous to 1928, nor had a single record of salinity been obtained below that level anywhere in the northwestern part, north of lat. 20° N. and west of long. 45° W., though the upper 500-fathom stratum of the North Atlantic had been examined, as to its temperature and salinity, on many occasions at many localities.

Thanks to the 'Meteor' we have today a better picture of the physics of the deep waters of the South Atlantic, in its regional and bathymetric aspects, than for any of the other ocean basins as a whole, an interesting illustration of the amount of exploratory work that a single well-planned and well-equipped deep-sea expedition can accomplish, while much information as to the southern extensions of the South Atlantic has recently been contributed by the explorations of the 'Discovery I' and 'Discovery II.'

Until very recently the case was worse for the Pacific, where only thirty-one complete observations (salinity plus temperature) deeper than 500 fathoms had been published up to 1928 for all the vast area from the American coastline westward to longitude 180°; only 85 so deep for the entire Pacific
basin; and only seven deeper than 1500 fathoms. A large number of serials deeper than 500 fathoms (since published) have also been taken in the eastern margin of the Pacific within the last few years by the United States Bureau of Fisheries, and by the United States Coast and Geodetic Survey; but these have all been located close in to the American coast or around the Hawaiian Archipelago. And a dozen stations, extending out from the coast of Chile, gave the only accurate data, up to 1928, as to the salinity of the bottom of the Southern Pacific on the American side.

The whole southeastern part of that ocean had, therefore, remained nearly virgin, with respect to its abyssal salinities, until crossed by the 'Carnegie' in 1928-29; its northeastern basin hardly less so. And while the stations occupied by her on her last ill-fated voyage, and by the 'Dana,' in 1928, have made the salinity of the bottom waters of the temperate and tropical Pacific perhaps as well known as those of the corresponding belts of the Atlantic, blanks (so far as actual record is concerned) still remain in the northwestern as well as in the eastern tropical parts. Actual records of abyssal salinities for these regions are desiderata, to show whether the extraordinary uniformity in the salinity of the bottom water and the regular gradation from north to south revealed by the 'Carnegie' profiles is actually as char-
acteristic over the floor of the Pacific as a whole as now seems probable. Serial observations must be greatly multiplied and much more evenly distributed over the Pacific before meridional projections, in profile, of the salinity of that ocean, or circulation deduced therefrom, can be accepted as anything more than first approximations.

In the Indian Ocean we find a considerable number of serial records of the salinity of the superficial 500 meters of water for the equatorial belt, the coastal belt on the African side, for the northern part, and also for the sub-Arctic front which has been made fairly well known by the various Antarctic exploring expeditions. But not a single serial, even for this moderate depth, has yet been taken in the southeastern part, from longitude 80° E. right across to Australia, south of the equator. The determinations deeper than 1500 fathoms that have so far been made in the Indian Ocean have also been situated in the equatorial belt, in the eastern and western sides and south of Africa. When we turn to the Antarctic front of the eastern Indian Ocean, south of Australia, and right across the southward extension of the Pacific, we meet a terra incognita, uninterrupted (so far as knowledge of salinity is concerned) by even a single deep reading, from longitude 100° E. to the longitude of Cape Horn, and from latitude 40° S. right down to the ice edge. And
when we remember that knowledge of the Antarctic water complex is as integral in any sound understanding of the origin and movements of the deep strata of the Pacific as it is of the Atlantic, oceanographers realize but too well the inadequacy of the data on which we must perforce base our present views as to the physical and chemical conditions, as to the lines of dispersal from its source, and as to the circulation in general, of the bottom waters of the largest of the oceans, and the one that, in all its features, can be most truly named 'oceanic.'

The entire reconsideration of current views as to the circulatory movements of the different strata in the mid-levels of the Atlantic basins as a whole, especially as to the northward extensions of water from the Antarctic, and as to the regions of sinking and upwelling, that has been made necessary by meridional salinity profiles of the two sides of the South and Equatorial Atlantic, constructed from the 'Meteor's' data, illustrates the fertility of result that may be expected from equally detailed surveys of the salinity of other seas. And this applies not only to the great ocean basins, but to many areas of relatively small extent that may be especially interesting in the oceanic complex, from one standpoint or another.

To quote a few specific examples, some for waters easily accessible from headquarters of oceanographic
activity, others more remote: the mean state and seasonal variations still offer an attractive problem all along the Atlantic shelf of the United States south of Chesapeake Bay, in the Caribbean, in the Gulf of Mexico, and in the outflow from the latter through the straits of Florida; information essential for understanding the secular shifts in the Gulf Stream drift. Data as to the alterations that the highly saline water of the Sargasso Sea undergoes as it drifts outward from its center of concentration, with more detailed knowledge of the seasonal fluctuations in the African side that are associated with the seasonal migrations of the trade-wind belts to north and south, are equally needed before we can reconstruct the inter-movements of the surface waters in the tropical belt of the Atlantic.

Did we know as much about the salinity of the water off Morocco as we do of its temperature, we could better judge the importance (in the general Atlantic complex) of the water that wells up there from the deeps, in bringing up a supply of dissolved nutrients to help maintain the fertility of the surface stratum for plant life. The seasonal alterations in the salinity of the surface around South Africa, reflecting the alternate contractions and expansions of the warm Alguhlas and cold Benguela currents, also remain to be plotted in detail.

Particularly intriguing problems in this respect, in
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the Pacific, are associated with the interchange of water into and out of Bering Sea; with the upwelling Humboldt current; with the mass transference from west to east in high southern latitudes; with the seasonal expansions and contractions of the warm Japan current; and with the coastal belt along southern Alaska. It is hardly worth while to specify particular lacunae in our knowledge of the salinities of the Indian Ocean; the first chart of mean surface values for the basin of the latter that can be accepted as approximately correct appeared in 1928.

Within the polar seas precise measurements of salinity have been taken only by the recent exploring expeditions. Ice — plus stormy weather — has also limited satisfactory surveys of salinity around the ice fronts for the most part to the warm season. In the cold half of the year, when data are special desiderata for these belts, as bearing on the problem of the sites of the mass sinkings that supply the ice-cold and richly oxygenated bottom waters of the oceans, few observations have been obtained. This applies, for example, to the East Greenland current, to the Baffin’s Bay source of the Labrador current, to Davis Strait, to the waters south of Greenland, to Bering Sea and to northeastern Siberian waters in the one hemisphere; to the entire Antarctic front in the other.

Ice has similarly prevented, to date, any winter
survey of the salinity of the Gulf of St. Lawrence, though this inland sea is close to the seaside laboratories of eastern Canada and of the United States. Neither had any detailed examination of Hudson Bay been attempted until 1930, when its midsummer state was surveyed by a Canadian expedition.

2. CIRCULATION

It is as essential for the oceanographer to understand the circulatory movements of the water if he is to comprehend any of the events that take place in the sea, whether biologic or geophysical, as it is for the meteorologist on land to understand the systems of winds.

Until comparatively recently this phase of physical oceanography was confined to the stage of exploration; first, by the fragmentary state of our knowledge of all the phenomena involved; second, by the lack of any method for calculating quantitatively, from data obtainable in convenient practice, the tendency that internal hydrostatics exert to set the water in motion. Lacking which it was impossible to analyze the relative importance of the internal archimedean forces of the water on the one hand, and of the external forces exerted by the wind on the other, as the causes of the great ocean currents. In fact, this still remains one of the outstanding problems in oceanography (page 96).
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In practice, the study of ocean currents can never be divorced from that of the more static physical features of the water as represented by salinity and temperature, both because the latter give evidences of the former and because the circulation is largely responsible for the distribution of temperature and salinity as actually existing. We think of the transference toward the poles of great volumes of water that have been heated near the equator by the sun, of the return movements toward the tropics of water cooled around the Arctic and Antarctic fronts, and of the mass sinkings in high latitudes, because of which (as directed by the outlines of the continents and basins) the distribution of temperature in the sea does not vary directly with the latitude, but is asymmetrical, warmest in the eastern sides of the oceans in the northern hemisphere, in the western sides in the southern,\(^\text{1}\) and the abyssal basins kept icy cold.

Cold currents also have a peculiar importance, because responsible for the drifts of ice from the Antarctic and Arctic to melt in lower latitudes, with all that this entails as to sea chilling, effects on terrestrial climates, and so forth, while this same melting process produces circulatory effects in the near-by waters that have been the subject of much

\(^1\) This is controlled to some extent by differences in the efficiency of alternate summer warming and winter cooling, \textit{in situ}, along the windward and leeward sides of the continents.
dispute. It is, therefore, impossible to understand the thermal problems in the sea if we do not understand the phenomena and causes of its circulation, and *vice versa*; this applies equally to the problems of salinity; likewise to the regional and bathic variations in the concentrations of oxygen as well as of the various solutes, and to the maintenance of conditions approaching equilibrium with regard to the alkalinity, and so forth, of the water. Circulation, of one kind or another, also plays an active part in the events of submarine geology, by sorting and transporting sediments, attacking shorelines and slopes, and so forth. No argument, indeed, is needed to justify the study of ocean circulation from the geophysical standpoint, for here we face an earthly phenomenon of the first rank. Currents in the sea also intrude constantly on the attention of oceanic biologists; partly because this would be true of anything that controls the temperature of the water, but also as agencies active in the migrations and dispersals of a wide variety of animals and plants. This phase is of great concern to students of the problems of the marine fisheries. The mobility of the waters of the oceans (with their high specific gravity) also concerns the biologist as making possible the planktonic existence of many groups of animals and plants, while permitting other categories of animals to lead a stationary existence fixed to the bot-
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tom, where they depend on the waters to bring their food to them, instead of upon their own powers of locomotion to carry them to their prey (page 145).

The knowledge of currents that is needed by the biologist calls, furthermore, for examinations of special regions so detailed that we commence to see the circulatory bases for vital economy in only a few areas, all of them near land; the North, the Norwegian and the Barents Seas, for instance; the Baltic, the Mediterranean; the Gulf of Maine; the Gulf of St. Lawrence; the Californian and Japanese coastal waters.

Currents, like temperatures (page 119), also bear directly on human affairs via the disturbing effect that any sporadic departure from the normal state must have on the temperature of the water, hence on the temperature and barometric pressure of the overlying air, to be reflected in weather abnormalities over the neighboring lands (page 242). The importance of ocean currents in navigation as they assist or impede passing ships, and as the relative directions of current and of wind affect the heights and shapes of waves, also as the agencies responsible for the menace to the traffic lines by icebergs, is self-evident.

There is, in short, no field of study of sea or of its contents that is not immediately concerned with the circulation of the water. We must emphasize that
this concern extends to every type taking place, and to every force, external or internal, that is able to set the water in motion, because every class of circulation that exists has far-reaching effects in all the fields just mentioned, while, because of the almost perfect fluidity of water, a variety of forces produce motion within it. Furthermore, every circulatory problem involves both the observable events and their causes.

For the purpose of these remarks circulatory phenomena in the sea may be divided into (a) tidal, set in motion by the gravitational attraction of the sun, of the moon, and of other heavenly bodies; and (b) non-tidal, including all other currents or disturbances of whatever sort.

The study of the tides is now so admirably cared for by the tidal surveys of all the more important maritime nations that it will be omitted from this discussion.

For convenience, the non-tidal currents may, in turn, be divided into (a) the progressive horizontal, (b) those with a prevailing vertical component, and (c) the non-progressive oscillations which do more work in the sea than is generally appreciated. But it is necessary to realize that all three of these types may, and usually all three of them do, combine to produce the movement actually existing in the open sea at any given time or place. The first of these
groups covers all the more apparent ocean currents, also the slower mass drifts, whether at the surface or in the deeps. The second group refers to the mass sinkings and updrafts (equally important if less obvious elements in the closed system); likewise to the violent churnings that take place along certain sectors of coastline, as, for example, at the mouth of the Bay of Fundy, and over some of the most productive fishing grounds; it also refers to the turbulent effects of tides and waves in general. The third refers to wave-motion, including, besides wind waves, the so-called ‘tidal waves’ which in reality are set up by volcanic action or by earthquakes beneath the sea; and submarine waves mentioned below.

Every student of the sea has fully realized the importance of the horizontal ocean currents in the scheme of things; so has every intelligent seaman, for the first important application of currents to be appreciated was the navigational. The problems of this phase of oceanic circulation that now seem most pressing unfold themselves along three chief lines; (1) What is the normal current system of the ocean in all its parts, in all its depths, and at all seasons of the year? (2) What is the magnitude of the variations from this normal state, and how often do they happen? (3) What are the motive forces for the continuing system of currents in the sea and for the deviations therefrom?
From the dawn of the art and science of navigation, ship captains have realized that knowledge of the currents was necessary for the safety and expedition of their voyages; by the middle of the last century the gradual collection and digestion of vessels' log books had given the navigator a rough picture of such of the major currents as affected him the most, especially in the North Atlantic. Even though it was chiefly by suiting the sailing routes to the prevailing winds that the use of Maury's and more recent sailing directions expedited voyages, it is certain that advantage taken of the prevailing current was partly responsible for the consequent savings, so long as sailing ships continued to carry the bulk of the world's commerce. And while full-powered steamers now run more independent of the current, continued collection of such data has been considered so important that the Hydrographic and Meteorologic Offices of Great Britain, of Germany, of Holland, and of the United States had together gathered more than 27,000,000 notes on the wind, weather, surface temperature, and surface drift of the sea, up to 1904, while a vast quantity of such data has been accumulated since then.

And yet, no one who stops to consider the vast areas covered by the oceans, the great expense of special expeditions, and the difficulty of making direct measurements of the current anywhere except
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close to land and in very shoal water, will be surprised that even the surface currents can yet be pictured only in a very generalized way. This is due in part to the nature of the information available from log books, in which any leeway that the ship may have made is usually included in the recorded ‘drift.’ But a more serious difficulty is that ocean currents do not progress like smooth-flowing rivers, but are constantly varying in velocity and direction, eddying (even temporarily reversed by the wind) in a way so complex that it is not yet possible to state the details for any part of the sea at any season of the year. Furthermore, surface data, taken by themselves, may give a very erroneous picture of the actual circulation, because a knowledge of the movements of the underlying water is equally essential. In this last respect reports from passing ships do not help us at all.

Since it has not proved feasible to use current meters frequently enough in deep water, or at stations enough there to be of general value, it is necessary to turn to indirect sources of information to learn the direction of the horizontal flow in the deeper layers. The sorts of data from which this drift may be deduced are various. The distribution of oxygen gives us some information. So does the distribution of the different kinds of sediments on the bottom; also the geographic distribution of various plants and

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animals. But far the most reliable indices to the movements of water masses below the surface—apart from measurements taken with current meters—are their temperatures and salinities. Hence it was not until a satisfactory deep-sea thermometer was invented and a method both accurate and convenient for measuring the salinity (or the specific gravity, for the one can be calculated from the other) that science was in a position to gather empiric knowledge of the movements that geographers had long postulated for the bottom waters of the oceans.

With these tools at command, one is able, by tracing the expansions of cold or of warm water, of high salinities or of low, to recognize such things as Arctic or tropical currents; land water fanning out off the river mouths; lines of dispersal for the highly saline waters that result from evaporation at the surface in certain enclosed seas (Mediterranean and Red Seas) as well as in the trade-wind belts; updrafts from the underlying strata; regions where water, chilled to a high specific gravity, sinks obliquely from the surface; regions of active turbulence where the surface is chilled, the bottom warmed; and so forth. The evidence of salinity is especially instructive with respect to deep currents, because in this respect a body of water below the surface is altered only if it be forcibly intermingled with water of some
other character, whereas cold water may be warmed, or warm water cooled by radiation, without any such mixing. And while the knowledge of currents to be obtained from temperature and salinity (each weighed *per se*) is strictly qualitative, up to date this has been almost our sole reliable clue to the movements of the waters of the deeps.

Nor must the modern development of quantitative methods of studying ocean currents lead to any neglect of the simpler qualitative evidence afforded by temperature and salinity *per se*, because the two lines of attack open up different aspects of the circulatory problem. The first throws light on the direction and velocity of flow prevailing at the time of observation, and to be expected as long thereafter as conditions continue stable. But when we find, let us say, a tongue of cold water extending down along the Grand Banks from the north of Newfoundland, with bergs floating in it, we see the result of events that have been taking place for some time previous: i.e., we glimpse oceanographic history. And by plotting these simple physical features of the water, periodically, it is possible to follow the relative contractions and expansions of different water masses as long as these continue. Thus in physical oceanography, as in every one of the geophysical sciences, the qualitative-descriptive method of study must proceed hand in hand with the quantitative, if we
are to gain a just picture of events as they actually occur in nature.

In this case, as is usually true of broad-scale phenomena, the dependability of the results rests largely on the number of observations taken. And as we have to do with dynamic phenomena, rather than with static, the more nearly simultaneous the observations can be made the better. Naturally, these technical requirements have best been met in the more frequented and more fished parts of the North Atlantic and of its tributary seas. Qualitative studies of the currents at different depths have, in fact, been prosecuted so intensively in limited areas in the North Sea, in the Norwegian Sea, in the Bay of Biscay, in the Straits of Gibraltar, in the Gulf of St. Lawrence, in the Gulf of Maine, around the Grand Banks, also in and off the straits of Florida that at least the characters of the prevailing systems of motion have been worked out there, surface to bottom. This applies also, if in less degree, along the coasts of southern California and around Japan; but nowhere else as yet.

When we turn to the ocean basins, outside the margins of the continents, we find crying need for the raw data (temperature and salinity) for current plotting (pages 55, 59). Lacking this, we still fail to comprehend more than the most general aspects of the drifts over the floors of the abyss — movements that are as important a part of the picture from every
point of view (except the navigational) as is the circulation of the surface. And our ideas as to the dominant drifts and interchanges in the mid-strata of the ocean basins are only now crystallizing. This is especially true of the vast and lonely expanses of the Pacific, which have been traversed by scientific expeditions only at long intervals, and along tracks far apart; where, consequently, and for the Indian Ocean, knowledge of the underlying circulation might be expected to lag far behind that for the Atlantic, though their closure to the north (complete for the Indian Ocean, nearly so for the Pacific) simplifies their circulatory characters.

Risings and sinkings of the water are not as apparent to the casual observer as are the horizontal drifts. In fact, movements of this sort are, as a rule, so slow that they are not to be detected—much less measured—by ordinary instrumental observation, but only indirectly by their effects upon the temperature and salinity of the surface waters of the regions in question. Since they are not of direct interest to the navigator (omitting the mythical or more actual whirlpools in narrow straits, and so forth) their existence was not recognized until theoretic discussions of the circulatory systems of the oceans made clear the necessity for assuming the existence of something of the sort, and until they were deduced from observations on the winds.

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Modern oceanography is, however, much concerned with the oblique updrafts and sinkings that are now known to take place on a vast scale, because it is certain that the presence of a thick stratum of water in the abyss, colder than the mean temperature of the underlying crust of the earth, is the result of mass sinkings, near the poles, of water that is cooled and so given a high specific gravity at the surface. Conversely, we need more than our present sketchy view of the compensating updrafts, known to prevail along the coasts of Morocco; off Southwest Africa; off California; off Ecuador, Peru, and Chile. From what depths do these chiefly draw? What are their velocities, their seasonal fluctuations, the volumes of water involved? Just how do they control the physical characters of the upper strata of water, and what is their effect on the vital economy of the seas where their physical effects are greatest? Only for the California upwelling can we yet answer these questions even in the roughest way; while the rôle played in the hydrologic complex of the South Pacific by the South American — Humboldt current — upwelling still offers one of the most attractive problems in general oceanography.

Important in this connection is the rôle of these updrafts as conveyors, to the surface, of water that is rich in dissolved plant nutrients. It seems clear enough (in fact, numerous analyses of phosphates,
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nitrates, and so forth, establish) that as the carcasses of animals and plants are constantly sinking, the chemical compounds to which they finally decay would tend to accumulate in the mid-levels out of the reach of the photosynthetic plant world were there no such updrafts and no churnings of the water. For diffusion takes place too slowly in motionless water and on too small a scale to account for the regeneration of dissolved foodstuffs that is known to occur in the upper stratum. But in the sea interchanges (vertical as well as horizontal) of water masses having different qualities are constantly being brought about by upwellings, eddyings, and turbulences of all sorts, with effects agreeing with what would happen if the coefficient of diffusion were high. That is to say, while water, denuded of some of its load of chemical nutrients is carried down, other water masses that have been enriched during their sojourn below are brought up.

The fact that planktonic plants have been found in depths so great that they cannot be supposed to carry on photosynthesis there does not argue against the view that this replacement of barren water with rich is a vital factor in the maintenance of organic fertility in the sea, because they have been taken most abundantly under regions where the surface flora (hence the sinking carcasses) are also most abundant, suggesting that this abyssal plant plank-
ton really represents a saprophytic community—just as when we grow rhubarb, and so forth, in our cellars in the dark. Empiric tests of the actual events are, however, much needed, because theory has far outstripped observation in this field; needed especially with regard to the degree of obliquity of the mass updrafts. These are often named 'upwellings,' but it is certain that this is a misnomer if taken to imply direct vertical movement, for in all probability the angle of ascent is, in most cases, so slight that if represented in profile a great exaggeration of the vertical scale is needed to show any departure at all from the horizontal.

Closely associated with the mass movements just mentioned are the problems of turbulence in the shoal marginal seas where most of the important sea fisheries are concentrated. In such situations this type of circulation is a physical factor of the very first rank, because it does the same work there, in bringing rich water up from the bottom to the surface, and in maintaining the circulation of oxygen, that the great rising currents do for the ocean basins far from land. In high latitudes the interchange of water between surface and bottom that is brought about by turbulence also plays an active rôle in the thermal complex of shoal seas, by bringing cold water from the deeps up within the direct influence of the sun and carrying warm water down in sum-

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mer, while assisting the loss of heat by radiation in the same way in winter.

The activity of turbulence at any given time and place is determined by the interplay of many factors: strength of the tidal current, for instance; shape of the bottom; contour of the coastline; strength of the wind; height and shape of the waves; likewise by the degree of vertical stability given to the water by the vertical distribution of specific gravity prevailing at the time. Turbulence, moreover, varies from hour to hour with changes in the tide and wind. Thus wide regional and seasonal variations may exist in this respect between stations only a few miles apart, making local investigations extremely complex, especially since the turbulent movements are of such a nature as to preclude direct measurement. But interpretation of regional variations in the thermal and saline cycles of shoal seas in mid and high latitudes (where there is the greatest abundance of plants and animals), and of many events in the life histories of fishes and other animals, as well as of the periods of multiplication for the planktonic plants, depends so directly on knowledge of the varying degrees of turbulence that this general subject deserves much more attention than it has received. We see in the Bay of Fundy a striking example of turbulence as the determining factor, to mention but a single notable example.

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The distribution of oxygen in the sea is so closely associated with the general problems of vertical circulation that it is best mentioned here. It seems certain that the intake of oxygen occurs exclusively at and near the surface, (a) in the surface film, or within the upper few feet where air bubbles are entrapped by breaking waves, and (b) throughout the upper illuminated zone where plants carry on photosynthesis; no sources are known from which the water can absorb free oxygen in the deeper levels. Quantitative data as to the rapidity with which any deficiency in oxygen is renewed from these sources of supply (particularly the efficiency of the latter out in the open sea) are therefore present desiderata. The relative importance, from the standpoint of oxygen intake, of coastlines of different characters, with their different types of wave action and of turbulence, offers an interesting problem. How effective a source of oxygen supply for the surrounding neighborhood is, for instance, a rocky headland upon which the surf beats constantly? We have yet to learn how deep simple turbulence is able to maintain the oxygen supply close to the saturation point in different regions under different conditions.

The underlying waters, contrasted with the surface stratum, can be described as the zone of oxygen consumption, for they are constantly being robbed of their supply of this dissolved gas, not only by
animals in their respiration, but by the oxidization of the decaying carcasses of animals and plants, as these sink down. Measurements of the actual rate of impoverishment under the varying conditions actually existing in the sea are much wanted in connection with a variety of biologic problems.

If there were no means of renewing oxygen from above, the underlying water would soon be absolutely stripped of this vital necessity, as the deeps of the Black Sea actually are. And within the last few years it has been found — (notably by the 'Carnegie' and by the 'Dana') that the mid-depths are, in fact, decidedly poor in oxygen in mid and low latitudes in the Pacific — also over large areas in the tropical Atlantic; so poor, indeed, that one is inclined to marvel at the wealth of animal life that exists there. But, underlying this oxygen-poor stratum, the bottom waters of the ocean basins carry a much richer load of this gas. In the present state of our knowledge, it seems that the only way in which stratification of this sort can be maintained is by sinking currents carrying down into the deeps, water that has become saturated with oxygen near the surface in high latitudes, coupled with consumption in the mid-stratum, rapid enough nearly to denude of its oxygen the water that is brought up from below by rising currents. But we urgently need information as to whether these mass sinkings of oxygen-laden
water are as strictly confined to the Arctic and Antarctic Seas, in their respective winters, as now seems probable; also how this water continues so nearly uniform in oxygen over vast areas on the sea floor in spite of the wide local variations in abundance of animals that are constantly consuming it there; and how far it is safe to deduce the drifts for the deepest stratum from the variations in the concentration of oxygen that do exist there.

The relationship that the paucity of oxygen in the equatorial mid-strata of the Atlantic bears to the drifts, toward the equator, of sinking water from mid-latitudes north and south, that are revealed by the 'Meteor's' profiles, remains to be worked out. Similarly we await a satisfactory interpretation, in terms of circulation, of the much more general poverty in oxygen of the mid-strata of the Pacific. The local factors (e.g., abundance of plants and animals, amount of decomposition of organic matter taking place at different levels) responsible for the very notable divergence between the quantitative distribution of oxygen and that of salinity, as revealed by the most recent meridional profiles of the oceans, also offer interesting problems. And the very rapid falling-off of oxygen, with depth, in the upwelling waters off California where extremely low values have been found close below the surface, introduces the question how far this state is generally character-
istic of the other regions where updrafts take place on a broad scale.

Certain problems associated with oscillatory movements of the sea next deserve a word. Two classes of phenomena come principally in question here; one, the ordinary storm waves (often complicated by tidal churnings); the other, the internal boundary waves or vertical undulations at some mid-level that winds and other forces are known to set in motion, and that have also been observed on occasions when no apparent cause could be ascribed to them.

Although the importance of learning the depth of storm-wave base, and the efficacy of storm-wave oscillations down to that level, as transporters of heavy materials, is obvious from the geologic standpoint, very little is yet known (except for shoal waters) about the absolute depths to which it is effective. For example, can we assume as representative of the sub-tropical belt of the Atlantic as a whole the conditions prevailing on the Challenger Bank, off Bermuda, where considerable masses of calcareous algae are rolled to and fro, often enough for these to stay alive on all sides, down to a depth of fifty fathoms or so, presumably by storm waves? How much deeper is effective wave-base in the Antarctic where swells might, theoretically, travel right around the globe without meeting any obstacle — and perhaps actually do so? What is the
velocity of such oscillation at different depths, when set in motion by storm waves of different shapes, lengths, and so forth, and traveling at different speeds? For that matter the shapes and run of the surface waves themselves offer an interesting field; in fact the stereogrammic studies by recent expeditions, notably those of the 'Meteor,' have given the first exact topographic pictures of the very complex corrugations into which the surface of the sea is thrown by the wind.

Our present knowledge of submarine boundary (or internal) waves in the open oceans has hardly advanced beyond the realization that such things exist and that they may be set up by a variety of forces. We need to learn what conditions give rise to progressive boundary waves, what conditions to standing waves; their periods; their relation to the free tidal wave; and their rôle in general in the sea, including such points as their frequency in different regions at different seasons, their vertical amplitudes, their lengths from crest to crest, and so forth.

Perhaps the most pressing of the broad problems in physical oceanography today, made so by its direct bearing, not only on events of all sorts in the sea, but on land climates as well, is that of the irregular fluctuations in the ocean currents, with the causes of such events.

It is certain that if the present scheme of ocean
circulation were materially to change, the climates of the continents would soon differ widely from the present state; and for the worse, so far as man’s welfare is concerned. The effect of the ocean currents on land climates is so much a commonplace, stressed in every textbook of physical geography or meteorology, that we need only cite (a classic example) the effect of the Gulf Stream or North Atlantic drift in making habitable the most northerly parts of western Europe (reflected in the fact that the mean temperature for January is about 40° F. higher in northern Norway than is normal for that latitude), contrasted with the opposite side of the Atlantic, where the icy Labrador current from the north so chills the climate of the coastal strip all along Labrador as to make agriculture impossible at latitudes corresponding to those of Ireland and England. Any variations in the currents that shift the previously existing distribution of temperature in the oceans, as any considerable alteration is bound to do, will have a still more direct bearing on animal and plant life in the sea; one almost certainly destructive to some species, but perhaps temporarily favoring the production or extending the geographic boundaries of others. The almost total destruction of the tile fish off the east coast of the United States in 1884, presumably by a flooding with cold water, is probably to be explained on this
basis; similarly the immigration of fishes of temperate thermal affinities into high latitudes that were reported as taking place north of Europe in 1922, and in the northwestern Pacific in 1922–24.

In a general way, the waters of the central parts of the open basins can be described as extremely stable in their physical character from year to year, and over long periods of years, if compared to the atmosphere. The close correspondence between temperatures and salinities recorded at several stations in mid-Atlantic by the 'Challenger' in 1877–78, and at near-by localities by the 'Michael Sars' in 1910, the 'Bache' in 1914, illustrates this fundamental constancy. Around the oceanic fringes, however, and especially toward the outer boundaries of the prevailing mass drifts, conditions are far less constant, not only seasonally, but as a result of wide-scale, but irregular, expansions or contractions of water masses of different physical characters, or because of shifts in their relative locations. The most widely heralded event of this sort that has come under human observation in recent times (because its effects or accompaniments both on land and in the sea were destructive) was the abnormal development of the warm drift from the north along the west coast of South America in the winter of 1925, accompanied either by a slackening of the cold Humboldt current (or upwelling) which normally bathes these
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shores, or, perhaps, by its diversion offshore. During that same winter and the preceding autumn a westward deviation of the cool Benguela current was reported as similarly accompanied by an expansion toward the south of the warm Guinea current along the west coast of South Africa. Sporadic events of the same sort have also taken place in high latitudes, within the memory of men now living. Between 1892 and 1897, for example, there occurred what has been described as an ‘outburst’ of ice from the Antarctic, sending many floes and icebergs northward into the southern ocean. A similar outburst of Arctic ice was reported in 1901, when Barents Sea was full of pack ice up to May, while ice is said to have come closer to the Murman and Finmark coasts than usual. On the other hand, an expansion of warm Atlantic water was reported to have taken place into these northern seas in the summer of 1922.

It is true that departures from the normal so noticeable as these are rare events, and up to recently it has only been these major departures that have forced themselves on general attention. It has long been known, however, that smaller fluctuations do take place from year to year in the boundaries and extensions of the warm North Atlantic drift. Similarly, the International Ice Patrol has found that the interrelationships of the Labrador and Gulf

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Stream currents around the Grand Banks are not alike in any two successive years, either in the seasonal schedule or in the volumes, temperatures, or velocities of the two currents. And these differences are reflected, not only in the yearly variations in the amount of ice drifting down past the Grand Banks, but in the tracks followed by individual bergs. In fact, wherever ocean circulation has come under continuous observation for a period of years, it has been found to vary, more or less, in a non-periodic, and up to date in an unpredictable, way.

There is, as yet, no general agreement of scientific opinion as to the causes of these variations, for all that has yet been possible, in any individual case, has been to show an apparent correlation between the event and some outstanding solar or other cosmic happening. Some students have regarded such fluctuations as due, in the last analysis, to variations in the amount of energy (i.e., heat) that reaches the earth from the sun, but others maintain that these solar variations are insufficient to account for phenomena known to take place. And even if the solar-control theory be accepted, the intervening mechanism by which variations in the strength of the sun’s radiation might be translated into the variable pulses and curious dislocations shown by the ocean drifts is still to be worked out. Does this take place via the medium of changes in the prevailing strength
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and direction of the winds, caused by shifts in the locations of the centers of high and low atmospheric pressure? Does more or less active heating of the waters around the tropic belt send greater or lesser volumes of warm water poleward, or is the Antarctic shelf perhaps a cradle for world-wide disturbances in the circulatory systems of the oceans, as at least one eminent oceanographer would have us believe?

Or must we conclude, as do some students, that the solar variations are too small, and the ability of the sea to absorb and smooth out their effects too great (owing to the great capacity of water for heat), for fluctuations of the currents to be explained in this way? In that case the theory that periodic changes in gravitation are responsible, caused by the regular secular changes in the relative positions of earth, moon, and sun, must be critically weighed.

The possibility that events taking place around the sub-Antarctic belt, where vast masses of ice break off, may exert far-reaching effects, translated in the end into climatic variations in distant parts of the earth, brings to our attention another problem with which physical oceanographers have long been much concerned; namely, the relative importance that melting ice plays in the complex of factors that keep the oceanic circulation in motion. Here the present need is not so much for rehashing the old
arguments, pro and con, as for much more extensive investigation actually around the ice edge than has yet been feasible. At first sight this might seem an especially favorable subject for experiment under laboratory control, for one can easily put a piece of ice in water and observe what takes place as the ice melts. But one of the reasons why the relative efficacy of melting ice as a causative agent for ocean circulation is still a matter for dispute is uncertainty as to whether the results seen in laboratory tanks, or in some small fjord, do actually simulate the conditions that prevail over the broad expanses of the open ocean, closely enough (quantitatively as well as qualitatively) to be accepted as representative of what happens in nature.

The regional and descriptive phases of oceanic circulation lead naturally to a discussion of the present state of knowledge and of theoretic opinion as to the interplay of forces that maintain this circulation. New viewpoints in this field have followed the recent development of quantitative methods of estimating the relative efficiency of the two major forces most obviously concerned; namely, the internal hydrostatics of the water itself on the one hand, and the frictional effect of the winds on the other. Until mathematical expressions were made available to take account of the various factors (e.g., wind fric-
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tion, internal friction, regional differences in specific gravity, defluctive force of earth rotation), quantitative estimation of the velocity of currents, in the sea, could be made only by the use of current meters. But, generally speaking, the use of these instruments is confined to shoal waters near land, i.e., to situations where tidal currents are not only strongest, but are veering if not reversing; hence where they so constantly confuse the picture that continuous observations over long periods are necessary before the dynamic or other broad-scale movements can be distinguished from the local and temporary ones.

Many such current measurements have been taken on special tidal surveys along the various coastlines; likewise from lightships in the North Sea, in the Baltic, and off the east and west coasts of North America; also in the straits of Florida where Pillsbury carried out his classic studies of the volume and velocity of the outflow from the Gulf of Mexico. But, by the nature of the case, quantitative estimation of the drift of the whole mass of water for any considerable area of the open ocean demands more generally applicable, hence deductive, methods. For such advances in this field as have yet been made, we must chiefly thank the theoretic development of ocean physics that has followed Bjerknes's contributions to hydrodynamics, chiefly at the hands of Scandinavian oceanographers; combined with

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Ekman’s mathematical discussions of the characteristics of wind-driven currents.

The raw data that are needed for the dynamic investigation of areas that may be selected as test cases are not only easily obtained, but are of a sort that have long been collected in ordinary routine, i.e., a record of the temperature and of the salinity at a sufficient number of depths-levels, at a net of stations sufficiently close, and taken nearly enough simultaneously to allow horizontal projection of the dynamic state prevailing over the area, as a whole, that is under study. And mathematical procedure by which such projections may be arrived at from primary data has been so simplified that it can be mastered by any physical oceanographer. However, it has not yet been developed to a point where it is possible to include in the equations all the factors that are pertinent. And until this stage is reached, certain very serious sources of possible error will remain, which prevent this method from being the ‘cure-all’ that its simplicity and mathematical defensibility might suggest. In the first place, the results can never be more than relative to some other mass of water which may be taken as the base for calculation. Consequently, unless the velocity of the water chosen as this base be measured, or unless this water be known to be stationary, the calculated result cannot give the actual current. In favorable
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cases, with serial records of temperature and of salinity for a sufficiently dense network of stations, it may be possible largely to overcome this difficulty. But we urgently need empiric tests, on a much broader scale than it has yet been possible to make, of the magnitude of the error that is introduced into the calculations by the fact that even the deepest water layers are actually not stationary.

The contour of the bottom also introduces a factor that can seldom be stated numerically, for if a current set in motion by internal hydrostatics strike a ridge of the sea floor, or a coastline, it may be given a character quite different from that calculated for the 'free ocean,' of which oceanographers speak so glibly, but which no one of us will ever see.

Therefore, we urgently need some general expression of the degree to which such calculations are applicable to regions where the depth differs much from station to station, or, to compensate for this confusing factor of depth, some numerical allowance more rational than the arbitrary corrections that have so far been proposed.

Similarly, it is not yet possible to include, in a satisfactory way, in the equations the friction between water layers or masses that differ in velocity, and while it is certain that this frictional effect depends on the state of motion of the water or air (leading to the concept of 'eddy viscosity'), knowledge of
its exact effect in the circulatory complex is in its infancy. Neither have mathematic expressions yet been developed to include the immediate and varying effect of the wind in given cases, though there is general agreement now as to the fundamental nature of wind currents as controlled by the deflecting effect of the rotation of the earth.

To check the magnitudes of these several sources of error, and of others that future studies may bring to light, regional dynamic examinations of the sea should be carried on hand in hand with any direct means that may be feasible for discovering the velocity and the direction of the current at the time, whenever and wherever opportunity allows. In the few cases where such a comparative examination has yet been undertaken, the agreement between the calculated drift and the type of circulation indicated by other lines of evidence as prevailing at the time has been close. Thus, in several instances the tracks followed by individual icebergs, drifting down past the Grand Banks of Newfoundland, have corresponded to the dynamic current charts made simultaneously by the ice patrol cutters closely enough to warrant the hope that such calculations will be of practical service to the patrol. Similarly, a recent dynamic analysis of the velocity and direction of the outflow from the straits of Florida, based on observations taken by the United States Coast and Geo-
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detic Survey Steamer ‘Bache’ in 1914, agrees in general with earlier measurements with current meters. Dynamic circulatory tendencies calculated for different seasons of the year for the Gulf of Maine have been corroborated by various other lines of evidence, direct as well as indirect, at least in their broad outlines; so, too, for the Norwegian Sea; for the North Sea; and for the northern sector of the Labrador current. In short, many oceanographers believe that we now have at hand a tool by which it is possible to approximate, numerically, the movements of the whole mass of water at a given time for situations where regional variations in specific gravity indicate a calculated drift so strong that it can hardly be masked by the probable error of the method, i.e., where regional differences in hydrostatic pressure are great enough to produce a current of considerable velocity.

In any study, in this general field, it is also essential to remember that while regional inequalities in the specific gravity of the water, by setting up archimedean forces, will set the water in motion, the existence of such inequalities itself results in most cases from other precedent motion of the water. Examples are the introductions into various regions of water alien in physical character, by currents such as the Arctic discharge via the Labrador current, the fresh discharge from rivers, or surface waters driven by
the wind from afar. Discrimination between what is cause, what effect, is therefore integral in any attempt to deduce, from dynamic calculations, the existing circulation.

Some different quantitative procedure is needed, furthermore, for situations where the dynamic gradients are slight. A method based on the amount that the surface temperature departs from the value normal for the latitude and season, and on the thermal effects of evaporation, recently worked out at the Scripps Institution for Oceanography, and applied with promising results to the waters off the coast of California, may prove generally applicable to other regions where upwelling takes place on a broad scale; it may also provide a useful check on horizontal velocities deduced from dynamic gradients in other regions.

It is essential to hold firmly in mind the realization that such methods, or any others, are after all only a means to an end; i.e., tools of research, not the ultimate aims of the latter. In the fields of physical oceanography the perfection of quantitative technique and the further amplifications that are to be expected are not to be followed per se, but to serve two chief lines of attack upon circulatory problems. In the first place, it now seems reasonable to expect that they will lead to a rapid advance in our knowledge of the state of circulation actually prevailing
over large ocean areas and at all depths from the surface downward, especially for parts of the sea where there is a wide regional variation in specific gravity from place to place. In fact recent dynamic studies of the northeastern Atlantic by Scandinavian oceanographers have already materially altered the prevailing concept of the northern boundaries of the general North Atlantic drift and of its extension toward the Norwegian Sea, though these matters are still far from settled. And similar studies of the waters off Alaska have added greatly to the existing knowledge of the circulation of that part of the northeastern Pacific. During the summer of 1928, a Danish expedition worked northward along West Greenland into Baffin’s Bay, while simultaneously the United States Coast Guard carried out a general dynamic survey of the circulation of the region of Davis Strait with fertile results. We similarly expect from the numerous observations taken by the ‘Meteor,’ in the Equatorial and South Atlantic, a general circulatory picture for that ocean, for comparison with the schemes deducible from the distribution of temperature and of salinity or from the drifts reported in ships’ log books. And data obtained by the ‘Carnegie’ will add much to knowledge of the circulation of the Pacific.

From the standpoint of ocean physics as a whole, however, the greatest service to be expected from
such developments in quantitative analysis is that here, at last, we look forward to a means of numerically testing the relative efficiency, as a motive power for ocean currents, of one of the two great forces that have usually been invoked as the underlying causes for the existence of a continuing non-tidal circulation in the sea. We refer to the broad-scale inequalities in the local specific gravity of the ocean waters that are maintained by heating at low latitudes, chilling at high, combined with the regional differences in salinity that result from river inflow, from evaporation, and from rainfall.

In this field, the task immediately urgent is to determine, for as many sectors of different currents as possible, and for as many different ocean areas, whether the internal hydrostatic forces at work are, or are not, quantitatively sufficient, and do, or do not, act in the direction proper to produce the general type and velocity of circulation that other lines of evidence have shown to prevail. More specifically, examinations of particular sectors of the so-called ‘Gulf Stream,’ of the Labrador current, of the East Greenland, the Benguela, the Alguhlas, or the Japan currents (among others) may be expected to show (when checked with direct measurements) how far such highly developed and definitely localized drifts receive impetus from internal archimedean forces acting along their courses, or how far some
other force (i.e., the winds) must be invoked to explain their existence and persistence. Certain dynamic studies carried on in the northwestern Atlantic since 1926 have had this as one of their immediate objects; the results, to date, justify the extension of explorations with this definite aim.

Before the frictional effect of the winds as a major motive force relative to that of internal hydrostatics can be finally established (scientific opinion has long swung first to the one, then to the other), wind currents must also be analyzed more searchingly and on a much larger scale than has yet been possible. The mechanical principle in question here is simply the downward propagation, into the water, by friction, of motion given to the surface film by the direct frictional drag of the wind. But it awaited a mathematical genius to prove that the earlier concepts of wind currents were erroneous because they did not correctly allow for the deflective force of the earth's rotation, or explain the peculiar spiraling of such currents with increasing depths. And the fact that the wind drift actually recorded has often failed to coincide, by many degrees of azimuth, with the theoretic requirements shows that more critical quantitative treatment is still needed to establish some numerical expression for the effects of vertical density gradients and of the contour of the bottom (which have, to date, confused the cal-
calculations of the velocity, volume, and direction of the current that any given wind will set up in shoal water), as well as to make sure that all the pertinent factors have received due weight in the equations in given cases. Known methods of estimating the effect of a coastline in the direction of a wind-driven current account for some of these apparent discrepancies, but others remain to be explained.

When we turn to the chief regional problem of the wind as a motive force — i.e., how far the great trans-oceanic drifts under the trade-wind belts, and around the Antarctic Ocean are, in fact, kept in motion by the wind, or in what proportion wind friction combines here with internal hydrostatics, — we find few data at hand for quantitative treatment.

In these and similar cases theoretic discussion of physical potentialities can provide a series of accurately solved type problems. But here (as in the case of tank experiments with melting ice) the conditions under which such discussions apply are far simpler than those prevailing in nature: in nature, furthermore, factors are involved that it has not been possible to account for, satisfactorily. The dynamic oceanographer is therefore urgently concerned, at present, with determining, by critical examination of selected parts of the sea, to what extent these theoretic discussions actually meet the needs of the case, and to develop them to meet these needs.
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3. Penetration of Radiant Solar Energy into the Sea

This subject is mentioned above, in connection with the penetration of heat. But the visible part of the solar spectrum is also so important in the vegetable and animal economy of the sea that the biologist constantly turns to the physicist for information as to the depth into the water to which light rays of different wave lengths penetrate with intensity great enough to serve plants in their photosynthesis, or to affect the tropisms or metabolism of animals. The theoretic coefficient of absorption of light by pure water has been calculated many times. What is now needed is empiric test of what does actually happen in the sea, at different localities, with the sun standing at different heights above the horizon, and under the widely differing conditions of turbidity and wave action that actually prevail. In this, as in other phases, the stage of quantitative measurement has been reached some time since; the next rational step is the accumulation of data over the widest possible range of latitudes, locations relative to the coastline, varying abundance of suspended silt or plankton, different seasons of the year, states of the surface of the water, and so forth, and then subsequent syntheses to make clear the order that prevails.
4. CHEMICAL PROBLEMS OF THE SEA

As the whole cycle of matter in the sea depends upon the fact that the latter is filled with salt water (a solution, not a mere mechanical mixture), it follows that chemical problems are more or less inherent in every phase of sea science. Consequently the reader will find repeated references to various chemical questions in the sections on oceanic biology and on submarine geology. In the present chapter we wish simply to outline the sorts of problems that center around two chemical questions that are fundamental in oceanography, (a) precisely what is sea water, and (b) why is it that the major furrows of the earth’s surface are filled with this particular saline solution, not with some other, or with a variety of others?

Growing evidence that the rarer substances in the solution may be the most significant, from the biological standpoint, has made it clear that the published analyses of sea water can be accepted only as first approximations, for it seems certain that sea water carries every element in solution, some of them perhaps entirely ionized. Several institutions, both in Europe and in America, are now devoting much effort to sea-water analyses, but a vast amount of work remains to be done before any approach to an adequate picture can be gained of the average levels of concentration, and of the periodic and regional
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variations in amount of the rarer substances. As knowledge increases, first one and then another of these attracts attention. At the present time interest in this field centers largely around the concentrations of phosphates, of the salts of nitrogen, and of silicates because of their service as nutrients for pelagic plants: around calcium, both as a material for skeleton formation and because of its import in many of the chemical reactions that proceed on a large scale in the sea. Recent tests for iron, caesium, rubidium, and for radio-active substances might also be mentioned.

Adequate methods have already been developed to measure the amounts that now seem significant of some of these in the water. But we still lack a satisfactory technique for determining the nitrates that are present in solution. And as others of the rare solutes attract attention, refinements of technique will be needed, because chemists have, in these cases, to do with solutions so attenuate that they are close to the lower limit at which accurate analysis is possible. In fact, some substances are at present known to exist in sea water solely because they have been detected in the bodies or skeletons of marine animals and plants, which could only have obtained them from their aqueous environment. As examples of this we might mention the vanadium recognized in the blood of Ascidians and of Holo-
thurians; the cobalt in the tissues of lobsters and mussels; the nickel in mollusks; and the lead that has been found in the ash of various marine organisms.

The ionic ratios of different substances in the solution (a matter of much interest from the chemical standpoint) is also to the fore at present.

However, our increasing knowledge of the variations in particular solutes that exist in the sea, or of such phenomena as supersaturation of the water with calcium carbonate, or that it is frequently far from being in equilibrium with the atmosphere with regard to gas tension, must never blind us to the extraordinary uniformity in gross composition of the water in all parts of the open ocean. Whether the sample be taken in the Atlantic, in the Pacific, or in the Indian Ocean, in high latitudes or in low, the total solutes are found to be about 54 per cent chlorine; about 31 per cent sodium; about 4 per cent magnesium; about 1 per cent potassium; 1 per cent calcium; and about 0.2 per cent bromine, with about 8 per cent of sulphate radicals, about 0.2 per cent of carbonate radicals. And this uniformity in the relative proportions of the commoner constituents is now so well established that it is customary, not only to regard sea water as a substance practically constant in its composition, but in practice to employ the concentration of one group of its salts as a dependable index to the total saltness.

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The variety of conditions and the vast areas throughout which such uniformity prevails make this one of the outstanding phenomena of geochemistry. Not only do the oceans cover more than two thirds of the surface of the globe, but in depth, temperature, light intensity, and pressure they run the whole gamut from warmth, bright illumination, and freedom from any superimposed weight save that of the overlying atmosphere, to icy cold, permanent darkness, and subjection to pressures of 800 atmospheres and upwards per square inch. Yet the solution that fills them is certainly the most uniform in composition of any substance common on our planet aside from fresh water and the atmosphere. And most geologists, arguing from the composition of the skeletons of marine animals that have lived in the past, together with that of sedimentary rocks which were laid down at different periods under the sea, believe that comparatively little change has taken place in the sea water itself (apart from its total salinity), except that during the earlier geologic periods the proportion of lime salts in solution may have been smaller than has been the case in more recent times.

This uniformity in time and in space extends, furthermore, to the precise proportion that total bases bear to total acid radicals. In spite of all the life-processes in the water that are constantly tend-
ing to alter this proportion (and do actually so alter it within narrow limits) by adding or withdrawing carbon dioxide and calcium, or by altering the relative proportions of the normal carbonates to the acid bicarbonates in the solution, the balance is so closely maintained at all places and at all times in the open sea that the alkalinity never rises above or falls below the narrow limits within which organic life (as regulated to marine conditions) is able to exist. This phenomenon is as important in ocean economy, and as deserving of the closest chemical examination, as is the stability of the alkalinity of blood serum in human physiology.

To offer, in explanation, that the sea water is buffered against wider fluctuations is to beg the question, for it in no wise accounts for the 'how' or 'why'.

To unravel the interplay of factors which keeps sea water always so nearly the same, and has so kept it for long ages in the past, is one of the most attractive tasks of research in chemical oceanography now before us, because a wide variety of wide-scale processes are as constantly tending to disturb this uniformity. To begin with, sea water (although it has certainly received much of its load of 'salts' by erosion from the land) is very far from being a mere concentration of river water, for not only does the latter vary from river to river in its chemical composition,
but as a whole it differs widely from sea water in kind. Consequently, the discharges of rivers tend to alter the composition of the sea water off their mouths as well as to dilute it. Various explanations have been proposed for the chemical events by which the preponderance of calcium and of carbonates, which characterizes river water, is so uniformly altered into the preponderance of sodium and of chlorides that characterizes the sea water, everywhere and at all times, even under the most diverse conditions. But we believe no one would seriously maintain that any of the explanations are adequate.

It seems clear that we have here to do with something more fundamental than a mere withdrawal of lime by shell-bearing organisms, and of carbon by photosynthetic plants, such as would allow sodium and chlorides to accumulate out of proportion. In fact, recent work suggests that this characteristic state obtains close in to the mouths of great rivers, although the diluting effects of the latter may be apparent for long distances; i.e., that the transition is more sudden with respect to the chemical composition of the water than with respect to its saline concentration. The view that sea water owes its preponderance of chlorides chiefly to the accumulation of the products of volcanic eruptions must be thoroughly tested before any opinion can be expressed as to its soundness.
In the second general category of events that are constantly tending to alter the chemical composition of the water in all parts of the sea are those dependent upon the vital activities of marine animals and plants within it. Obvious examples of this are the withdrawals by the former of lime and silica from the water for the manufacture of their skeletons.

No less significant, in the chemical complex, are the withdrawals, by marine plants, of salts that serve as nutrients: the plant life that we see in the water is the visible product of this draft. The alterations in the state of the water that result when the carcasses of these plants (and the bodies of the animals that feed upon them) go back into solution, after death, are equally significant.

Basic problems, that we may single out for mention in this connection because of their rôle in the general cycle of matter in the sea (page 256), center around the chemistry of lime and of carbonic acid, bound up with the degree of alkalinity of the water. The chemist here meets a very complex series of reactions in which gas tension between water and atmosphere at different temperatures, withdrawals of lime and carbon by organic agency, precipitation of lime, re-solution (which goes forward at different rates for different lime salts, and according to the amount of free carbon dioxide in the water) and alterations in the degree of ionic dissociation of dif-
The chemical aspects of the precipitation of calcium carbonate in tropical waters, where large amounts of the lime out of the water are contributed to the sea bottom, are now being taken up afresh. If this precipitation be chiefly mechanical, as now seems likely (page 29), we need to learn which of the various reactions that have been suggested as the potential causes are actually operative on a large scale in the sea: if bacteria be the active agency, the problem is biochemical.

No general agreement has yet been reached as to the rapidity with which calcium carbonate is dissolved in the sea under the conditions actually existing, especially for deep water. That limy shells, sinking down, may entirely dissolve before reaching bottom if the water be deep, has been widely postulated to account for the fact that there is a lower limit of depth below which there is little accumulation of lime sediments. Solution must also be taken into account in connection with the fact that the percentage of lime has been found to decrease in the oceanic sediments, from the uppermost layer
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downwards, in various localities. Recent data (by
the ‘Meteor’), showing a slightly higher proportion
of bases in water next the bottom than in overlying
strata, also point from another angle to solution of
lime oozes as taking place on a significant scale.
But we have little knowledge as to the actual details
of this process at great depths, in different regions.
It is certain that the last word has not yet been said
as to the solution of lime from coral formations in
tropical waters, or from the accumulations of pre-
cipitated calcium there.

Such problems introduce the basic question of
the efficiency of normal sea water as a solvent, not
only for lime, but for silica, for volcanic substances
that accumulate on the sea floor, and for various
refractory organic substances. Solution of a wide
variety of minerals is also constantly taking place
all around the shores of the continents, in combina-
tion with the processes of mechanical erosion by the
waves and currents. And while this solution is slow,
it is not only unceasing now, but has been unceasing
for past geologic ages. In short, the total amount of
material dissolved in this way has been enormous.
Furthermore, some recent observations with regard
to the concentration of silicates in the water raise the
question whether solution of even these refractory
materials may not take place rapidly enough to pro-
duce regional differences in the amount of silicates

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in the water, according as different sectors of the coast contribute more or less to the sea.

Chemical problems equally fundamental are inherent in present-day studies of the ocean floor, for the oceanographer is directly concerned with the whole gamut of reactions that take place in the abyssal depths of the sea, it being an open question whether many of those that have been proposed (although doubtless falling within the range of potentialities) are actually of the importance that has been accredited to them on theoretic grounds. With regard to the sea bottom, as well as with regard to the water itself, first rank might be given to the problems of lime chemistry, with ramifications too numerous to list in this report. It is not unreasonable to hope that chemical studies of events taking place in sea water today may give a clue to the mode of formation of dolomite in the sea in the past. The reactions that accompany the formation of phosphatic concretions and of glauconite on the bottom also need further examination, while the problem of the chemistry of the deposition of iron on the sea floor is a major one and to date practically untouched (page 34). So, too, the chemistry of the natural distillations of organic materials in the bottom muds that are now widely believed to have been responsible for the formation of petroleum and other hydrocarbons.

As already remarked, we have still to learn the
chemical character of the water that is entrapped within the sediments, a very important matter because the alterations that take place there in the solid materials depend upon the alkalinity, carbon dioxide content, and so forth, of this water.

Recent observations have also led oceanographers to turn their attention afresh to the regional variations in the amounts of oxygen and of nitrogen gas in the water, as indices to various physical and biological events there. Here the immediate need is for thorough regional and bathymetric survey, for this alone can give a sufficiently descriptive picture of the existing state.

The list of chemical problems that center around sea water might be lengthened indefinitely. In all of them, as is so usual in oceanography, two phases are involved. First, the theoretic potentialities must be determined, and these have naturally been the subject of much discussion, leading to substantial agreement with regard to some. The significant task is then to discover in what proportion the theoretic reactions do actually take place in the sea, in what order, and how induced; a task made difficult by the low concentrations of the solutions with which it is necessary to deal.