THE CAUSES OF THE GULF STREAM.

Shortly after the first voyage of Columbus, the existence and some of the characteristics of the Gulf Stream became known, and with Franklin's experiments as to its temperature, scientific observations upon it began. Since then, many other observations as to its depths in places, temperature and direction have been added to the sum of information on the subject, knowledge of which, in the form of scientific reports, monographs and magazine articles, has more or less found its way to the public; some of the accounts, however, stopping very far short of the ultimate interest in the subject derivable from determination of the causes of the stream. The statement that the trade winds heap up the equatorial waters on the eastern shore of Central America, thereby giving a 'head' to the Carribean Sea and the Gulf of Mexico, seems to suffice to most persons for an all-sufficient explanation of the generation and behavior of the Gulf Stream. But it ought to be obvious that, although winds do, as is observable in small areas, heap up waters against obstructive lines upon which they impinge, the movement of the equatorial waters towards the west cannot be the sole cause of the Gulf Stream. On the contrary, whatever head actually exists there is produced by several agencies causing the thrust of waters in the form of a mighty current.

Seeking for a single cause of the phenomena, one will be foiled. He would make an attempt at the bottom of much unproductiveness in research, arising from seeking in nature for some one cause to account for any phenomenon in its entirety. In seeking, therefore, for the cause of the Gulf Stream, we must resolve the idea of cause into that of causes, called, if one will, primary, secondary, etc., but still, in the aggregate, activities of many existing conditions. These are the globular form of the earth; its rotation on its axis; the difference, in correspondence with latitude, of its rotary velocity; the difference in temperature, involving density, between polar and equatorial waters; the direction and force of the trade winds; the head of water produced by those winds and other agencies at the the Gulf Stream, and the correspondingly lower level at the places whence a portion of its waters are so derived; the volume of discharge contributed to the Carribean Sea and the Gulf of Mexico by the rivers flowing into them; the increase in volume of those waters through the long continued heat to which they are subjected while confined within the caldron formed by those basins—these, and nothing less, represent in fact the assemblage of the causes of the Gulf Stream.

The Coast and Geodetic Survey of the United States has, within the last few years, made very valuable additions to knowledge of the Gulf Stream, through the investigations of Lieutenant Pillsbury, of the Navy, commanding the steamer Blake, but these relate to details, which although interesting, do not involve the largest question relating to the stream in its very existence. Lieutenant Pillsbury established the fact of the absence of the supposed hill ranges, in and parallel to the trough in which the stream for a while flows in its course along the shores of the United States; the indeterminateness of the position of its boundary line, constituted by Arctic water lying between it and the coast, well described by the term 'cold wall,' and he also proved the indeterminateness of the bands of alternating warm and cold water in the stream, caused by the irregular dispersion of surface water by winds. The impossibility of recognizing at all times by temperature the position of the axis of movement of the stream is thus clearly shown. He discovered fluctuations in the stream, in direction and strength, as dependent upon the

position of the moon; and the influence of the pressure of the atmosphere over large conterminous areas of high and low barometer, in accelerating or retarding the current. He also determined the presence of a fringe of current on the east of the Gulf Stream proper, proceeding at a slower rate than it, and conformably in direction. These and other points make a very interesting series of discoveries, but they do not touch the causes of the Gulf Stream. They relate solely to the agencies which modify it. Were all these conditions absent, the Gulf Stream, merely as a body of water flowing in the direction which it now pursues, would still exist substantially as at present.

In the particular not relating to influences merely modifying the stream, but to the question how such portion of its waters as have passed into the Carribean Sea and the Gulf of Mexico, under the influence of the trade winds, have been translated thither, the present writer cannot agree with Lieutenant Pillsbury. For, whereas Lieutenant Pillsbury's observations at the Windward Islands show, as their result, that the water there entering the Caribbean Sea, as a current, represents only about half of the volume which he determined as flowing out of the Straits of Florida, as the Gulf Stream, he accounts for the other half by supposing that, in addition to the flow into the Caribbean Sea at the Windward Islands, a great amount is also delivered there by the toppling of the seas towards the west as they roll on towards and through the passages between the islands. That any force of wind, however great or small, could be resolved, on the one hand into a current, and on the other into waves, and the volume of the latter be available in helping to fill an interior basin through openings of an archipelago, does not agree with dynamic laws known and admitted. Toppling seas proceeding in any given direction resolve themselves into and quicken current; in fact, current in water, as derived from wind, is conditioned upon the ruffling of the surface, whether in the form of a ripple or a billow. Therefore current and wave are not dynamically separable as agencies of transportation. It follows that, if the Windward Islands' observations show only about half the volume of water delivered into the Atlantic by the Gulf Stream, the remainder is chiefly to be accounted for by a volume of the polar current underrunning, and running by the sides of the Straits of Florida. Plus the other supplies already mentioned, and minus evaporation, we have then the sum-total volume of water with which nature is dealing in the production of the stream.

The primary causes of the Gulf Stream are the rotation of the earth, the difference of density between its polar and equatorial water, and the presence of the American continent. For, if we will eliminate in imagination every agency but these, including the trade winds, we shall shall see that we have, through the facts of the form of the earth and this difference of density, the resultant of two lines of force represented by the tendency in the direction of waters so constituted to flow. On one of these the centrifugal force of the earth's rotation draws the waters as a sub-marine flow from the poles to the equator, resulting in a supra-marine flow from the equator to the poles; while, on the other, the rotation of the earth on its axis, at right angles to those directions, tends to make the waters move directly towards the east. If there were no continents at all on the surface of the earth, the effect of this, as viewed from the equator, would be to make the sub-marine flow from the pole, in the northern hemisphere, assume a southwesterly curve convex towards the equator; and to make the supra-marine flow, from the equator to the same pole, assume a northeasterly

curve, concave towards the equator. Similarly, with reference to the southern hemisphere, as viewed from the equator, the submarine flow from the pole would assume a northwesterly curve, convex towards the equator, and the supra-marine flow from the equator to the pole would assume a southeasterly curve, concave towards the equator. The reason for this is that the sub-marine flow, coming from the north or the south pole, would reach successively degrees of latitude of greater and greater velocity of rotation, and therefore would assume a more and more westerly direction, whereas the flow going from the equator towards either pole would successively reach degrees of latitude of less and less velocity of rotation, and therefore would assume a more easterly direction.

The very same causes are operative now to produce the very same effect, and the chief reason that it does not exist in the simplicity described is on account of the presence of continental lines disposed in a northerly and southerly direction. Yet, despite the complication thereby introduced into the phenomenon of ocean movement by that and other causes, the surface waters of the ocean, without regard to the streams coursing through them, move in a general direction in the northern hemisphere towards the northeast, and the sub-marine waters towards the southwest; while, in the southern hemisphere, they move correspondingly, the surface waters towards the southeast, and the sub-marine waters towards the northwest. Owing to the causes which have now been detailed at sufficient length, the sub-marine waters lag behind the surface waters, and therefore the surface flow from the equator to the poles assumes a relatively easterly position with respect to the sub-marine flow from the poles to the equator. The inclusion of the agency of the north and south continental lines, and the presence of constant winds in certain quarters of the earth, do not create the movements of the oceans, but merely serve to modify with great intricacy the general flow.

The movements just described as deducible from general principles, and long previously held to be true, have in quite recent times been proved true by various scientific observations, notably by those of the British ship Challenger, Captain Nares, in 1873–1876. Having thus settled once for all in our minds that the primary cause of the Gulf Stream is not the influence of the trade winds, to which it has long been ascribed, but that it is derived from causes which were the basis of theory broached many years ago, the correctness of which is fully established, let us proceed to introduce for the completed phenomenon the chief subsidiary agencies which make the Gulf Stream what it is as observed.

The Equatorial Current is known technically as a drift current, that is, one formed by the friction of the wind on the surface of water. The Equatorial Current is, in consequence, not a deep current. According to Sir Charles Wyville Thomson, scientific director of the Challenger expedition, its movement does not reach below fifty fathoms in depth. Moreover, it is not, as commonly spoken of, a single current, but is divided into a northern and a southern stream. The thermal equator does not coincide exactly with the geographical equator, but lies two or three degrees north of it. In consequence, as the trade winds, the cause of the Equatorial Currents, blow from the northeast and southeast, the position of those winds is determined by that of the thermal equator, and the whole equatorial system of winds and currents tends more to the north than to the south of the equator, the southern limit of the northeast trade winds, with the southern declination of the sun, not reaching, by two or three degrees, to the geographical equator, while,

on the contrary, the northern limit of the southeast trade winds sometimes passes, with the northern declination of the sun, as much as five degrees above the geographical equator. Between these two currents, whose north and south limits are respectively above the line of the Tropic of Cancer and below that of the Tropic of Capricorn, depending upon the annual declination of the sun, and always ranging higher above the Tropic of Cancer than below the Tropic of Capricorn, lies the region of equatorial calms, squalls and variable winds, called by sailors the doldrums, within whose eastern area a counter current, of length varying according to the season, contributes to the Guinea Current on the coast of Africa, also contributed to by the cool southerly current along the northwest coast of Africa, called the North African Current.

It will readily be seen from the above statement and from examination of the map of the Atlantic that, during the summer season of the northern hemisphere, the largest contribution by the Equatorial Currents must be made to the Gulf Stream, for not only is the whole of the North Equatorial Current then, as always, north of the equator, but the South Equatorial Current not only overlaps the equator, but extends then for some distance to the southward in a favorable position for the entrance of much of its water, deflected to the northwest by Cape Roque, and then known as the Guiana Current, to enter the Carribbean Sea. In both seasons the Atlantic northern hemisphere must therefore receive and deliver from near the equator a larger supply of surface-moving water than the southern Atlantic hemisphere ever thence receives and delivers. The slower current in the same direction, on the eastern edge of the Gulf Stream mentioned by Lieutenant Pillsbury, is clearly shown by the observations of the Challenger, in ascending and descending the coast of the United States, to be the edge of a broad band of water enveloping the Bermudas. It is therefore part of the great general easterly and northeasterly movement of the Atlantic waters of the northern hemisphere, a portion of which movement eventually impelled by the anti-trade winds gradually goes to constitute the reflux flow towards Africa, called the Northern Connecting Current.

It has been here said that the body of water which enters the Caribbean Sea as drift currents, produced by the northeast and the southeast trade winds, leaves the residuum to be chiefly supplied by the flow of the polar current under and beside the Gulf Stream issuing from the Straits of Florida. To this is to be added the volume discharged into the Gulf of Mexico and the Caribbean Sea by the various rivers, and we have what makes, allowing for increase and diminution of volume from temperature and evaporation, the sum-total volume to be reckoned for as creating the head of water in the Gulf of Mexico. Taking the temperature of the general sea surface on a line just outside of the Greater and Lesser Antilles to be about 74 F., it is well below that recorded in the Straits of Florida by Lieutenant Pillsbury and other authorities, as often over 80 F., one of them giving a record as high as 86 F. That there should be a considerable rise of temperature between the equatorial waters and those of the Gulf of Mexico, in the Straits of Florida, should not surprise anyone who knows that, according to the investigations of the Challenger, cool water has been found to rise more closely to the surface nearly under the equator than elsewhere in the Atlantic and the Pacific, the temperature of 40° F. reaching to within three hundred fathoms of a surface at nearly 80 F. The equatorial surface generally is surprisingly cool, considering its geographical position, and the equatorial waters are of a lower salinity than are the tropical waters on either side. We

thus see at a glance, not only that they are polar waters which we find immediately below the surface under the equator, but that the moderate temperature and density of the surface are due to their proximity and intermingling with others. Starting, as they do, with greater density than that which, without their translation, would be possessed by waters at the equator, they become, through conduction and convection of heat, of less density than the equatorial surface water, because their pristine density was due to cold, which they finally lose. To suppose that the whole body of water in the Caribbean Sea and the Gulf of Mexico should rise in temperature through all its strata, intermediately to its passage out of the Straits of Florida, would be preposterous; but when we remember that the course taken by these various strata before culminating in a current departing for the high seas represents weeks of time and coincident confinement in a landlocked embayment of the ocean, we ought to perceive that their increase in volume, if not general, must be considerable.

Dr. Carpenter, whose influence was largely instrumental in bringing about the voyage of the Challenger, and who freely uses the data collected by it, says, in his article, *The Atlantic*, in the last edition of the Encyclopædia Britannica: "It is not a little remarkable that the subsurface stratum of water, having a temperature above 40 F., is thinner under the equator than it is in any other portion of the Atlantic from the Faröe Islands to the Cape of Good Hope. Notwithstanding the rise of the surface-temperature to 76°–80° F., the thermometer descends in the first 300 fathoms more rapidly than anywhere else; as the polar water is met with at a much less depth than in the North Atlantic, and 100 fathoms nearer to the surface, than even in the cooler South Atlantic; whilst the temperature of the bottom is but little above 32° F." Again, he remarks, in the same article: "The isotherm of 40° F., which, in latitude 22° North, lies at a depth of 700 fathoms, gradually rises as the equator is approached, and it is between the equator and 7° South Latitude, where the temperature rises to nearly 80° F., that cold water is soonest reached—the isotherm of 40° F. rising to within 300 fathoms of the surface, while that of 55° F., which in latitude 22° North lies at nearly 400 fathoms' depth, and in latitude 22° North at about 250 fathoms, actually comes up under the equator within 100 fathoms of the surface."

Both Dr. Carpenter and Professor Lenz, of St. Petersburg, however, the latter of whom, from observation made as early as 1825–1826, in the voyage of the Kotzebue, had propounded a theory of such oceanic circulation as that implied by the preceding facts. Dr. Carpenter, in ignorance of having been anticipated, adopted the same views, ascribing the general oceanic movement to a general vertical oceanic circulation sustained merely by the difference of temperature between the polar and the equatorial regions; which theory unwarrantably omits the agency of the rotation of the earth on its axis as one of the primary factors in the phenomena concerned.

It is generally conceded that the Gulf Stream is no longer recognizable as a current beyond 30° West Longitude, but it is not therefore to be supposed that all the waters belonging to it just previously are frittered away and have mysteriously disappeared. As it gradually thins and spreads out in its passage towards the northeastward across the Atlantic, and at the same time gradually diminishes in temperature, it becomes more and more a portion of the grand sweep of surface water from the equator towards the northeast, becoming an integral portion of that movement; and because it is no longer recognizable as a current beyond 30° West Longitude, it does

not follow that its force, added to by the anti-trade wind movement, is expended, but on the contrary, that its force, although imperceptible as a distinct current, is merged in that of the more generally eastwardly movement, and contributes to the general effect. With what vehemence this general movement may act is seen through the report for 1893, of the Fishery Board of Scotland, which, through a scientific exploration of the coast of Norway, the North Sea, and the channels between Scotland and Iceland, in which the Orkney, Shetland and Faröe Islands appear, has discovered that a warm drift current from the Atlantic often sweeps in one place towards the North Sea from the Atlantic. Whether or not it is wholly a drift current, that is, one due to wind, the extraordinary warmth of the northeast Atlantic is thereby affirmed, and the correspondence of the fact with the previous statement is clearly perceptible.

Leaving further discussion of the Gulf Stream at this point, it is proper to conclude with a brief description of the reflux movement of the waters of the Atlantic, corresponding with their westward movement, described in connection with the generation of the Gulf Stream. To speak first of the North Atlantic, the anti-trade winds, and a reflux from the North Equatorial Current, form a current called the Northern Connecting Current, which sweeps around towards the east, in the North Atlantic, from the shores of North America towards those of Africa, enclosing between itself and the North Equatorial Current the well-known waters covered with floating weed, called the Sargasso Sea. Nearing the coast of Africa it passes towards the southeast, and although a portion of it is drafted off into the Guinea Current, another is swept into the North Equatorial Current to renew its ceaseless round. Turning to the Southern Connecting Current we find that a portion of it, known then as the Brazilian Current, passes down along the coast of Brazil, is then deflected towards the east, in a curve corresponding with reference to the equator to the curve of the Northern Connecting Current, and that it finally passes towards the northeast, off the coast of Africa, where a portion of it is drafted off to form the cool South African Current, while another portion turns into the South Equatorial Current, to continue with reinforcements a round similar to that of the Northern Equatorial Current. The reflux Equatorial Current between the North and South Equatorial Currents flows into the Bight of Biafra, helping with the cool North African Current to compose the Guinea Current.

The influence of the rotation of the earth is well exhibited by these movements. The Brazil Current, in passing southward soon to become a portion of the Southern Connecting Current, is going towards degrees of latitude where the earth's rotation is less swift than it is in the place whence it started. Hence it gradually assumes a curve towards the east, when, finally, it is deflected in quite an eastwardly direction by the pressure on its flank of the Antarctic Current, crowding up along the shore of South America, and additionally receives the impulse of the anti-trade winds of the region towards speeding it on its journey towards the east. Very nearly the same thing takes place in the northern hemisphere with reference to the Northern Connecting Current, the sole difference being that in the latter case the Gulf Stream receives the shock of the Arctic Current on its flank, and thereby shields the North Connecting Current from encroachment on its flank, to which, however, it would be less liable on account of the difference of the lay of the land in North America as compared with its lay in South America.

As both the Northern Connecting Current and the Southern Connecting Current run for the greater part of their courses due

east, and, therefore, the direction of their courses is not, during that portion of their journey, influenced by the rotation of the earth, and as the flow in the opposite direction of the North Equatorial and the South Equatorial Current is perennial, if not strictly constant, and lastly, as there is so great a discharge of water from the Equatorial Currents into the North Atlantic, a constant replenishment of the waters at the sources of the Equatorial Currents is implied with a certainty which involves the certainty that the level of the ocean off the southern coast of Africa is lower than that off the coast of Central America. That the difference between these levels, whatever it may be, is relatively but a small factor in the movement of the Gulf Stream, is self-evident, but as an entering factor it is proper that it should be mentioned. We can justly conceive, however, of a modified Gulf Stream, even if the level of the Caribbean Sea and the Gulf of Mexico were precisely the same with that on the African coast, at the sources of the Equatorial Currents, because it is dynamically part of a movement larger and inclusive of the waters of the whole globe; but we cannot conceive of difference of oceanic level not being an indispensable factor in the movement of the Gulf Stream as it actually exists, and in that larger movement. Whatever agencies, single or collective, are in play must be associated with differences of ocean levels. Assume changes in the present differences of level, and we must recognize that the phenomena of ocean movement would enter upon new phases. Assume that there is no difference of level anywhere, and we should see that the present phenomena would become inexplicable.

It obviously does not follow from appreciation of the valuable results in pelagic history, in the physical hydrography of the sea, and in other departments of knowledge obtained by the Challenger expedition, that one must agree in opinion with the distinguished chief of its scientific staff in all of his conclusions. Comparing the opinion of Dr. Carpenter with the opinion about to be cited from Sir Charles Wyville Thomson, it will become evident that the former, although accepting the fundamental fact acquired by the Challenger, does not, any more than the present writer, agree with a certain one of the conclusions of Sir Charles Wyville Thomson with reference to the cause of the general vertical oceanic movement. Both Sir Charles Wyville Thomson and Dr. Carpenter ascribe the general vertical oceanic movement to the welling up of the cold waters of the Southern Ocean into the Atlantic and the North Pacific. But, whereas both believe that condition to depend upon a movement sustained merely by the difference in density between the polar and the equatorial waters, Sir Charles Wyville Thomson additionally believes the excess of water received at the equator from the Southern Ocean, as compared with the amount received from north of the equator, to be owing to the excess of precipitation over evaporation in the southern hemisphere, which, of course, involves the excess of evaporation over precipitation in the northern hemisphere. Now, although it is recognized that there is in the southern hemisphere an excess of precipitation over evaporation, the degree, in that particular, of difference between the two hemispheres is not, as Sir Charles Wyville Thompson himself admits, even approximately known, and whatever it may legitimately be assumed to be, it is hardly to be recognized as capable of producing the relatively great general flow from the Southern Ocean to the extent indicated by him. Moreover, the theory is not compatible with the fact that as the equator is approached from either pole the specific gravity of the surface water of the ocean becomes higher and higher, and then lower and lower, until the water reaches

its lowest density in the equatorial region. According to the hypothesis, therefore, of the general vertical oceanic circulation (which is true, but not as depending upon temperature alone), and to the superadded hypothesis that the excess of precipitation in the southern hemisphere causes the thrust of sub-marine cold water into the Atlantic and North Pacific, we should find, what we do *not* find, on account of that very excess of precipitation in the southern hemisphere—the surface waters receding everywhere south of the equator, from the equator towards the southeast, to be of very low specific gravity; which contradicts the statement premised with reference to the specific gravity of the surface waters on each side of the equator, which statement truly represents the facts of the case.

As long as the earth under its present physical conditions shall endure, the movements of the ocean must remain as they now exist, passing through phases of maxima and minima of volume and velocity and oscillation in direction, dependent upon their astronomical and terrestrial relations. The present oceanic forces are, in fact, huge hydraulic engines, worked by nature from the north pole and the south, nor less from the equator and the revolution of the earth. The Gulf Stream, with the analogous Japan Current, is merely one of the two greatest products of that machinery, the flow from its colossal pump, in the direction of its discharging tube and the general circulation of the ocean, partially actuated by the earth's rotation and by the sun-generated winds, being ceaselessly engaged in life-giving and life-aiding agency on the globe.

R. MEADE BACHE.

PHYSIOLOGY IN 1894.

No striking discovery in physiological science was made in the year 1894, and yet a large amount of substantial work has been accomplished both at home and abroad. Only a few of the more remarkable researches can be here referred to. It has long been known that the swimming or air bladder of sea fishes contains a much larger percentage of oxygen than exists in atmospheric air. The amount may rise as high 85 per cent. The mode of storage of this large amount of oxygen has always been an interesting question with physiologists, taken in connection with the very small amount of oxygen in sea water. Light has been shed on this problem by the ingenious researches of Professor Bohr, of Copenhagen, who has succeeded in tapping the air bladders of codfish and of drawing off the gas by means of a trocar and an air-tight syringe. He found that the gas contained 52 per cent. of oxygen. In a few hours the bladder was refilled apparently by a process of secretion of gas from the blood in the capillaries on the wall of the bladder, and in one experiment the gas thus secreted contained no less than 80 per cent. of oxygen. Puncture of the air bladder always caused increased secretion of oxygen, but after section of the nerves supplying the organ the evacuated bladder was not refilled with gas. Thus the formation of the gas in the air bladder, which corresponds to the lung of air-breathing animals, is a true secretion of a highly oxygenated gaseous mixture, and the secretion is evidently to some extent under nervous influences. These observations are very interesting when taken in connection with the hydrostatic functions of the swimming bladder. When a deep sea fish descends from near the surface the air bladder is compressed and the body is reduced in size, but to bring the body into equilibrium with the water the fish secretes gas in the air bladder so as to distend it and bring back the body to the original size. This newly-formed gas consists chiefly of oxygen. These experiments by Professor Bohr tend generally to support the theory that the