THE DEEP CIRCULATION IN THE ATLANTIC OCEAN

by

CAMILLE VALLAUX

I. THE CONTROL LAYERS, ACCORDING TO G. WÜST.

It is essential that we first summarize, in terms as concise and clear as possible, the conceptions of Dr. G. WÜST relating to the deep circulation in the Atlantic Ocean.

As a starting point a basic distinction, which has become classic in German oceanography, is made between the marine *troposphere* and the marine *stratosphere*— the troposphere, a thin surface layer whose movements are more or less related to those of the lower atmopshere; the stratosphere, i. e. the greater part of the mass of the ocean, the movements of which, being much slower, do not reveal any relationships of this kind.

We shall not specify here the true nature of the demarcation between the two masses, but shall return to it later. Let us note simply that for G. WÜST, in the work we are studying, the demarcation between the troposphere and the stratosphere, between latitudes 45° S., and 55° N., coincides with the principal minimum of oxygen dissolved in the sea water, which also coincides with the isotherm of 8° C at the average depths of 500 to 600 metres.

The average depth of the Atlantic Ocean being at least 3500 to 4000 metres, therefore by far the greater part of the volume of the ocean goes to make up the stratosphere.

The observations which lead to a clear comprehension of the deep circulation have been compiled by WÜST not only from the measurements taken by the *Meteor* but also are based on data from 70 other vessels obtained between the years 1873 and 1933.

Let us remark at once that the data thus assembled, which results from observational instruments of different kinds — often defective, as WÜST acknowledges in another work — are not all worthy of the same credence.

They are, further, insufficiently numerous to permit the establishment of certitudes. Thus, for the thermal indices and at depths greater than 4000 metres we have available only 852 measurements taken since 1869, of which 315 are due to British cable vessels and 537 to scientific vessels; of the latter source, 197 were provided by the principal explorations — those of the *Challenger* and those of the *Meteor* (1).

The indices to which G. WÜST has recourse in order to determine the

(1) G. WÜST: *Über die Bedeutung von Bodentemperaturenmessungen für die ozeanographische, morphologische, chemische und geologische Erforschung der Tiefsee* (J. JOHNSTONE's Memorial, pp. 241-255).

stratospheric circulation are three in number: the *index of oxygenation*, the *index of salinity* and the *thermal index*.

The index of oxygenation, or the quantity of oxygen dissolved in the sea water, aside from the oxygen in combination, is calculated by two methods by oceanographic chemists: either in percentage of saturation or else by the number of cubic cm. of oxygen dissolved in a litre of sea-water (1). WÜST has adopted the second method; in reality the most expressive and best adapted to the conditions in the medium.

The index of salinity gives, in grammes, the global weight of salt dissolved by a litre of sea-water. The thermal index, or the temperature of the water under consideration, may also be calculated in two ways: by the temperature *in situ* — the actual temperature of the water at the level from which it is drawn — or the potential temperature, i. e. that of the water raised adiabatically to the surface which, in the case of water drawn from the deep layers, is always lower than the first. Although he does not specifically state the fact in the work we are studying, WÜST bases his inductions on the potential temperature, the variations of which seemed to him to be the more indicative of deep lateral currents as they are rather slight, whereas the variations of the temperature *in situ*, determined by the components of the vertical movement are more pronounced (2).

The data furnished by these three indices reveal in an indubitable manner the discontinuities in the equilibrium, from whence arise the movements in the mass of the stratosphere. But how make use of these data?

G. WÜST observes that the simple longitudinal profiles or the horizontal sections (as they are ordinarily drawn) do not produce an accurate representation of the movements of the mass, which develop along inclined planes or curved surfaces. Thus he proposes and applies the ingenious method of liquid control layers (*Kernschichten*). This consists in establishing the curves showing the normal relationship between the thermal index, the saline index and the index of oxygenation, calculating the percentage ratio for each liquid body, and then treating the liquid layer as individualized so long as this percentage remains above a certain figure, for example, 50 %.

For the Atlantic stratosphere, this method has led G. WÜST to a representation even more complicated and more disconnected than that proposed by MERZ as a working hypothesis, in the general plan of the expedition of the *Meteor*.

From the plane of demarcation between the troposphere and the stratosphere, extending to the bottom of the ocean, WÜST distinguishes five superposed liquid control layers.

The first, having a north-south component, is constituted by the *intermediate antarctic current*: cold and poor in salt. From 100 metres in depth

(1) T. G. THOMPSON and R. R. ROBINSON: *Properties of sea-water dissolved oxygen* (Bull. of the Nat. Res. Council, Physics of the Earth, V, Oceanography), pp. 158-162.

(2) This notion of the *potential temperature* has led WÜST to that of *potential density* which obliges him to calculate, in deep strata, densities greater than those of the above-lying strata; which, remarks W. EKMAN, seems absurd (W. EKMAN, in *Journal du Conseil pour l'exploration de la mer*, Vol. IX, N° 1, 1934, pp. 102-104).

near Lat. 48° S., it descends to around 900 to 1000 metres from Lat. 37° to 30° S., in the West of the Ocean, to about 800 to 900 metres in the East, where it is less perceptible. Morphological influences cause it to ascend to 650 to 800 metres near Lat. 10° N. Hugging the coast of Brazil, in the southern hemisphere, as a result of the deflective force due to the earth's rotation, it retains the same orientation in the northern hemisphere as a result of the *gradient forces of deep penetration* deriving from the Guinea current and the current from the Caribbean Sea. In all of the eastern part of the ocean (to the eastward of the central ridge), this current is not discernible except as a diffusion movement whence a part of the original water becomes lowered to at least 50 %.

There follow then three superposed strata having generally north-south components for all three of which the region of origin lies in the North Atlantic: the upper deep water, the intermediate water and the lower water.

The upper deep water is characterized essentially by its high salinity, its principal source being the bottom current from the Straits of Gibraltar which transports into the Atlantic the warm and highly saline waters of the Mediterranean. The control layer of this Mediterranean water lies between 1000 and 1250 metres to the north of Lat. 20° N. diffusing towards the west. It is found again at a depth of 2750 metres towards Lat. 35° S., always with a definite trend to the west of the ocean. The values of the percentages which range from 25 % to 50 % in the north Atlantic fall rapidly in the south; but the upper deep water can still be distinguished at 500 metres depth in the high austral latitudes.

The two following strata of the north Atlantic waters are determined essentially by their relatively high oxygen content. The intermediate water is supposed to have its origin near Greenland. Forced to the westward in the northern hemisphere as a result of the deflective force of the earth's rotation, it is held there in the southern hemisphere also as a result of morphological influences (the central ridge) which is distinctly manifested at this level (2000 to 3000 metres). The same is true of the lower water, the origin of which is not clearly explained.

Finally, on the bottom is the drift current having a north-south component, *the antarctic bottom current,* which is assumed to develop through 110° of latitude, always on the western side of the ocean, the characteristics of which, however, WÜST admits are much less well-defined. Only the thermal index permits the existence of this deep strata to be clearly ascertained.

Summarizing the totality of lateral movements in the stratosphere, WÜST admits that these are truly discernible and comparable to currents in the western part of the ocean only. In the eastern part, i. e. to the eastward of the central ridge, it is impossible to interpret them other than as regional diffusions and as localised gyratory movements.

WÜST admits also that the lateral exchanges he describes cannot completely depict the movements in the stratosphere.

To these exchanges he adds, following DEFANT and THORADE, the *movements of water in the vertical sense* and the *miscibility of the waters* of different signs along the borders and in the interior of the liquid control layers. According to him, these two movements of different orders, necessitated as compensatory movements as a result of the stable character of the waters of the stratosphere itself, are manifested when part of the liquid control layer, as determined by his method, falls to at least 50 %.

This theory is directly opposed to that of the *fossilized waters*, stabilized from geological epochs, which was recently expounded by Ed. LE DANOIS.

The demarcations accepted by WÜST are based primarily upon the intermediary minimum of the index of oxygenation and on the planes of discontinuity of the thermal index. It should be stated here also that in addition to the five principal components of the stratosphere he admits two weak arctic and antarctic components which brings the total to seven control layers (Kernschichten) in all.

The asymmetry of the deep currents is determined above all by the orographic and the morphologic character of the bottom. The deep warm waters in the tropic of cancer, which constitute, as I have stated before (1) one of the most striking geographic features of the ocean, cannot derive, according to WÜST, from the vertical convection of the warm tropical waters, for the reason that the principal minimum of oxygen, which is located in this region about 600 metres above the isotherm of 8° C. shows on this plane a sharp division between the surface waters and the deep waters.

WÜST admits, however, that in the west, in the tropic of cancer along the course of the Gulf Stream, the oxygen minimum is forced down to a depth of about 1000 metres and shows *an extension in depth of the troposphere in that region.*

In spite of the stability of the general relations in the marine stratosphere, there are, at long periods, changes which are certain or probable. It is difficult to subject them to calculation according to the BJERKNES hydrodynamic method, primarily for the reason that the effects of friction and miscibility prevent the application of the formula. It has therefore been impossible, up to the present, to make accurate estimates of the velocity of these deep currents.

Such is, exactly summarized, the ingenious synthesis of G. WÜST. It can neither be accepted nor rejected as a whole, even as a working hypothesis. It now calls for certain comments.

II. THE INDEX OF OXYGENATION.

Among the three indices which aid in estimating the movements of the deep waters, G. WÜST gives first place to the oxygen dissolved in the sea water, or the *index of oxygenation.*

No account was taken of this index by MERZ when he drew up his constructive plan and his working hypothesis for the deep currents in the Atlantic Ocean. It appears that the importance of the index of oxygenation was brought to light by H. WATTENBERG, the chemist of the *Meteor.*

(1) C. VALLAUX : *Géographie générale des Mers,* p. 409.

"In order to understand the circulation" says H. WATTENBERG, "the "oxygen content of the sea water gives an important aid; it strengthens "the results obtained from temperature and salinity; it supplements them "at the point where they have reached the limits of their action (1)".

This means, in WATTENBERG's opinion, that it is primarily the deficiency in oxygen which matters, as indicating the demarcation between the liquid layers renewed by the currents and those which are but slightly or not at all renewed. The waters poor in oxygen are those which are very nearly stagnant.

WÜST has taken a further step in giving to the oxygen content, in the deeper layers, a positive importance, because he makes it the essential criterion for the existence of the *intermediate deep waters* and the *lower deep waters*.

The study of the index of oxygenation has been extended, since the *Meteor* expedition, to the Atlantic and to the Pacific, where the *Dana* and the *Carnegie* have multiplied the useful data. These data conform to those obtained by WATTENBERG in the Atlantic in the following points: strong oxygenation at the surface and sub-surface; rapid decrease up to the minimum, often very low (for instance, 0.04 mg. per litre in the Gulf of Panama) to 400 to 800 metres depth; then, a new increase in the index of oxygenation (2).

But, in the Pacific, these values do not again increase to the surface and sub-surface values, while in the Atlantic, according to WATTENBERG, the strata of 2000 to 3000 metres are often more highly oxygenated than the surface itself. Near the very bottom, on the other hand, and always in the Atlantic, there is a new and sudden drop in the oxygen content (3).

A comparison between the observed data and the synthesis of WÜST, invites several comments.

If, as WÜST shows, the minimum of oxygen coincided with the essential demarcation between the stratosphere and the troposphere, it would be necessary to grant that the tropospherical layer (subjected to the variations at the surface) is singularly thin in the tropical Atlantic, and thin beyond all resemblance, we should say, in that region where the surface and sub-surface currents are very strong.

In fact, on the profiles XII-XIV of the *Meteor*, between Lat. 0° and 20° N., WATTENBERG identified a superficial layer saturated with oxygen between 100 and 200 metres, then a very rapid impoverishment from 200 to 500 metres down to a minimum of 2 - 3 cm^3 per litre. This was followed by an increase, no less rapid (up to 5.2 - 5.8 cm^3) in the masses of deep water, until a new drop occurred very close to the bottom. This can be verified as well in the eastern as in the western portions of the tropical ocean (4).

(1) H. WATTENBERG: *Bericht über die chemische Arbeiten* (Zeitsch, der Ges. für Erdk. 1926, N° 1, p. 66).

(2) C. VALLAUX: *L'Exploration de l'Océan Pacifique* (Ann. de l'Inst. Océanogr. t. XIII, Part. 3, 1933, pp. 112-114). T. G. THOMPSON & Others: *Distribution of Dissolved Oxygen in the North Pacific Ocean* (J. JOHNSTONE's Memorial), pp. 203-226.

(3) See Fig. 1.

(4) H. WATTENBERG: *Bericht über die chemische Arbeiten* (Zeitsch. der Ges. für Erdkunde, 1927, N° 5/6, pp. 300-315).

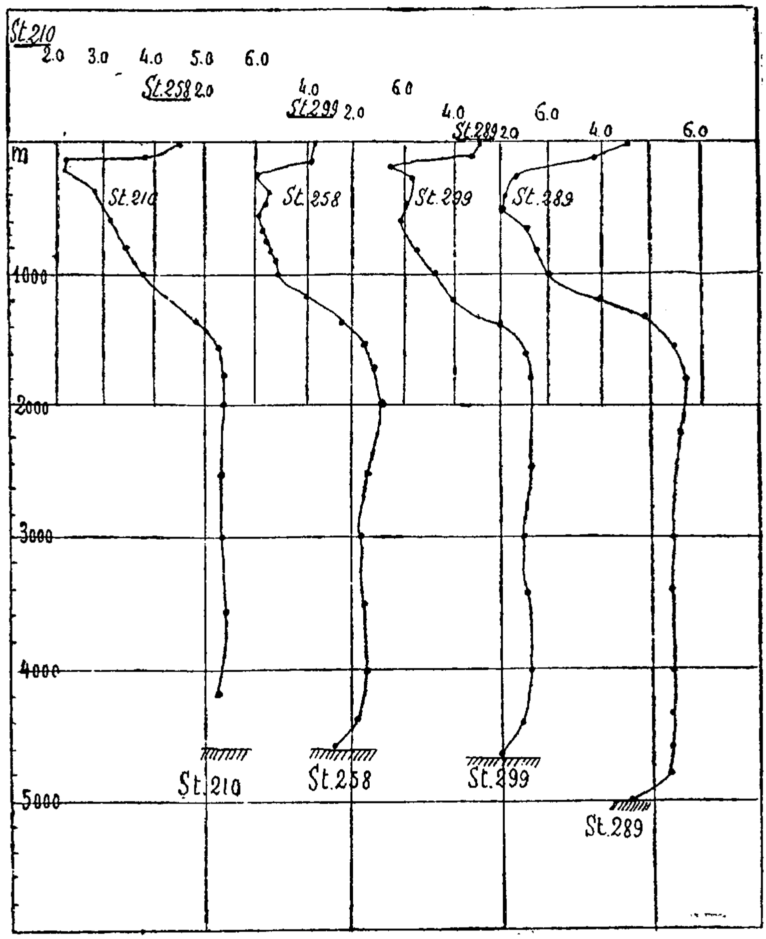

FIG. 1

Oxygen dissolved in sea water (cm³/litre) in the western equatorial Atlantic according to H. WATTENBERG

In the WATTENBERG sections, one cannot discern the separate indices of oxygenation indicating the individualisation of the three deep currents in the North Atlantic given by WÜST. They are also not perceptible in the sections given by WÜST himself in Fig. 1 of his article, especially the lower current.

But, serious as these discrepancies may be, they are of less interest than the following general question : - Is it true that the variations in the index of oxygenation indicate, at the places where they are negative, a stagnation of the deep layer, and lateral movements of the liquid control layers where they are positive ?

Is it not more probable that the variations of the index of oxygenation disclose the variations in biological deportment of the deep waters and that these changes may be more readily interpreted as vertical movements of very slight amplitude ?

The oxygen dissolved in the surface and sub-surface waters comes essentially from two sources: the penetration of the atmospheric air and the liberation of oxygen by the phytoplankton. The rapid reduction in oxygen content which becomes pronounced near 200 metres and which increases towards 800 metres stands in close relationship to the complete disappearance of the phytoplankton and to the great abundance which, according to all of the plankton percentages, the animal microplankton manifests at these levels. It does not become rarefied except towards 1000-1200 metres.

One fact which strengthens this point of view is that at the 200 to 800 metres level the carbonic acid, a product of animal life, increases in proportion to the reduction in oxygen (1).

At lower levels, the increase in oxygen will correspond to the extreme pronounced rarefaction of the animal microplankton from 1200 metres on. This rarefaction should permit an increase in the oxygen content to be manifested, either as a result of vertical convection or by means of lateral exchanges in depth proceeding from remote communications with the surface. As for the reduction at contact with the bottom, noted by WATTENBERG, this is in evident agreement with the oxydation of numerous deposits on the submarine soil (for instance, manganese nodules).

The work of the American oceanographers in the Pacific strengthens that view, which without excluding lateral exchanges in the depths, is inclined to limit greatly their import, especially in the region of the minimum index of oxygenation.

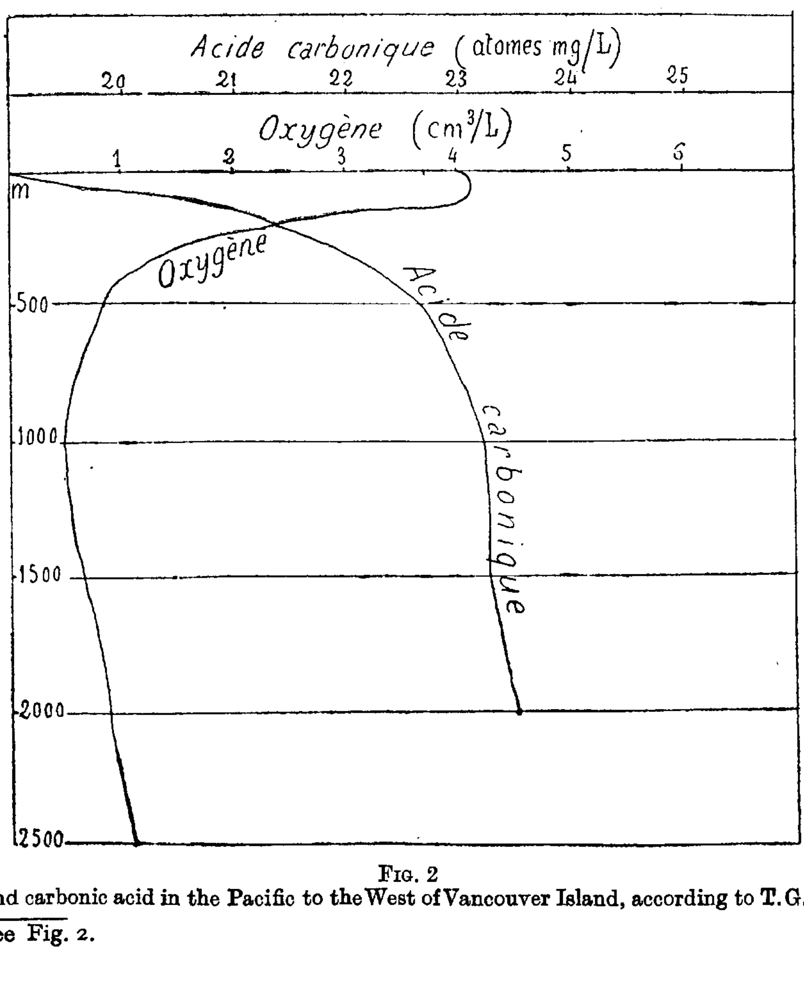

FIG. 2
Oxygen and carbonic acid in the Pacific to the West of Vancouver Island, according to T. G. THOMPSON

(1) See Fig. 2.

"The marked correlation between the concentration of dissolved "oxygen and the carbonic acid, especially in the intermediary region of "the oxygen minimum, shows that the diminution of oxygen results "almost entirely from the oxydation of organic matter. The layers which "are almost devoid of oxygen have become thus, either because they have "remained for a long time in a state of relative stagnation or perhaps on "account of actual contact with the bottom of the ocean. Such condi-"tions would explain the disappearance of the oxygen, due to biological "activity, to the action of bacteria, and to the chemical oxydation of "the reducible bodies." (1)

III. THE AFFLUX OF THE DEEP WATERS OF THE MEDITERRANEAN.

For the formation of "deep currents" in the North Atlantic with north-south components, Wüst attaches great importance to the afflux of the deep waters of the Mediterranean, considered primarily from the point of view of their high saline index, as shown by the comparison between Figures 7 and 8 (Salinity in depth and Percentage of the Mediterranean component).

Wüst's sketch prolongs the Mediterranean component of 50 % into the middle of the Atlantic along Lat. 30° N., and also extends the 30 % component into the Sargossa Sea as far as Cape Blanc of Africa.

With regard to the volume of this afflux from the Mediterranean, we have very accurate data which is being enriched daily.

At the Straits of Gibraltar, where the width is 20 kilometres and the depth 350 metres, the relatively fresh and lighter surface waters, having a depth of 100 metres, flow from the Atlantic towards the Mediterranean at an hourly rate of 2 to 3 miles. Below, the heavy waters of the Mediterranean diffuse towards the Atlantic at a higher rate (4 miles). The calculations of Nielson (the *Thor* expedition) indicate an annual afflux of 56200 cubic kilometres volume from the depths of the Mediterranean into the Atlantic, (2) or about 154 cubic kilometres per 24 hours.

But these estimates themselves are too simple. They do not take into consideration the mixing, which according to the observers on the *Albacora*, occurs between the waters of the Atlantic and the Mediterranean, from the Straits of Gibraltar and along the isobath of 200 metres. Further, it does not take into account the vertical oscillations observed by the *Dana* in the Straits of Gibraltar. These oscillations are produced in the layer of 100 to 200 metres and correspond with the semi-diurnal tide. This results in the fact that at 100 metres depth, the isohaline is displaced by 37 %, by about 90 metres at spring tide and 42 metres at neap tide. (3)

Thus, from the depths of Gibraltar on, it is difficult to discern clearly the "liquid control layer" of the Mediterranean. Let us suppose that it preserves its autonomy in the Gulf of Gibraltar between 1000 and 2000 metres,

(1) T. G. Thompson & Others : *Distribution of dissolved oxygen in the North Pacific Ocean* (J. Johnstone's Memorial, pp. 203-226). Re-translation from a french translation.

(2) C. Vallaux : *Géographie générale des Mers*, p. 635.

(3) J. P. Jacobsen and H. Thomsen : *Periodical variation in temperature and salinity in the Straits of Gibraltar* (J. Johnstone's Memorial, pp. 275-293).

as admitted by the observers on the *Albacora*: what becomes of it further on ? In order that the inductions of WÜST should be true, the Mediterranean strata should manifest itself as a general deep diffusion current spreading out fanshaped to the west. This is the manner in which he symbolises it.

We have, however, for this part of the North Atlantic, the studies of deep currents between the depths of 100 to 2000 metres made by means of the dynamic method of Bjerknes, by HELLAND-HANSEN and NANSEN, on the vessel *Armauer Hansen* (1). These do not confirm the conjectures of WÜST, but it is understood that the latter makes reservations regarding the efficacy of the dynamic methods when applied to the deep currents.

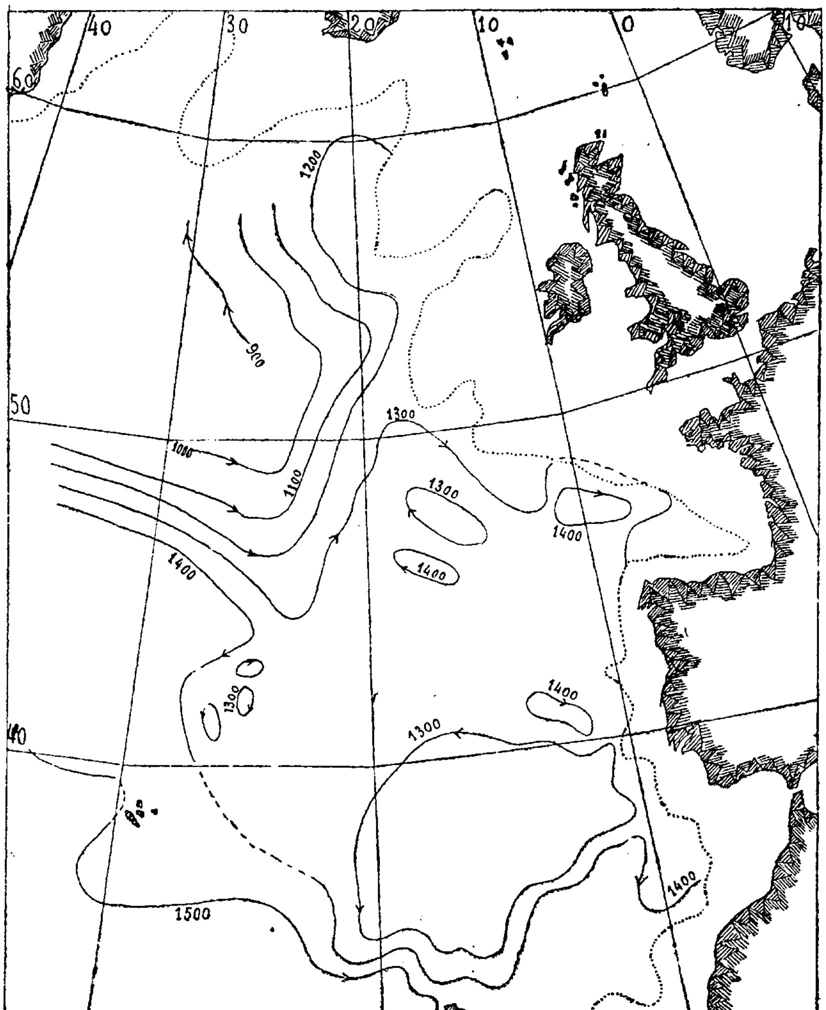

FIG. 3
Deep currents in the east of the North Atlantic according to B. HELLAND-HANSEN and NANSEN.

(1) B. HELLAND-HANSEN : *Meeresforschung mit kleinen Forschungschiffen* (Verhandl. der ozeangr. Konferen., 24-26 May 1928, Zeitschr. der Ges. für Erdk. Ergänz. III, Berlin, 1928, pp. 16-17.

B. HELLAND-HANSEN shows in the middle of the Ocean an orientation of the principal current lines towards the south as far as the Azores, then a retrogression towards Madeira and the coasts of Portugal, which indicates a principal rotary movement with subordinate gyrations. "It is possible", he adds, "that these gyrations are illusory and that it is necessary to seek the cause of these local demarcations, not in the convection currents but in the vertical and quasi-vertical oscillations." We should add that these rotary movements appear to reveal, *even at mean depths*, the very great influence of the bottom configuration on the direction of the striae; this is a point of view already adopted by EKMAN (1).

To this we might add further that it seems highly improbable that a volume of water relatively shallow in depth such as that which escapes from the Straits of Gibraltar, should become the "liquid control layer" for such a vast expanse as that indicated by WÜST.

We should rather depict the Mediterranean waters as forming a series of globular masses dispersed both in depth and expanse through the Atlantic, gradually merging with it at various distances, but not by any means extending to the limits of expansion given by WÜST. If we may be permitted a rough analogy, we might compare these waters to the bubbles of gas which rise in a boiling liquid and are dissipated at the surface.

With MURRAY and HJORT (2), we attribute, in the centre of the tropic of cancer, the excess temperature and salinity in the depths to the vertical convection of the warm and saline wateis, as a result of the evaporation in the tropical regions. This agrees very well with the hypothesis of BUCHANAN on the exchanges of waters in the vertical direction at mean depths. This concept is not accepted by WÜST, on account of his "water-tight partitions" which, according to him, are erected at the oxygen minimum at 500 to 600 metres' depth. But we believe to have shown in Para. *II* that this minimum depends upon the *biologic deportment* of the sea water and does not prejudice in any way the vertical exchanges of mass.

The fragmentation of the Mediterranean waters after the departure from the Gulf of Gibraltar and their globular deportment seems to us to be confirmed by the stations of the *Xauen* off the coast of Portugal, from Cape St. Vincent to Vigo (3).

IV. VERTICAL DISPLACEMENTS AND INTERNAL TIDES.

For the rest, it is only just to acknowledge that WÜST has given a legitimate place to the vertical exchanges in the mechanism of the deep layers, which have been too much neglected by German oceanographers since the *Meteor* expedition. "In the face of the horizontal movements and with relation to them," he states, "the water exchanges in the vertical sense have been very much neglected up to now."

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(1) See Fig. 3.
(2) J. MURRAY and J. HJORT: *The Depths of the Ocean*, p. 194.
(3) See Fig. 4 — according to Rafael de BUEN, *Observaciones oceanograficas entre Malaga y Vigo* (Minist. de Fom. Notas y Resumenes, Ser. II, N° 51, 1931).

On the contrary, these exchanges were brought to light by the hypothesis of BUCHANAN; the descent of the heavy waters in the deep seas of the tropical regions; the welling up of the lighter, fresh waters near the coasts and the shoals (1).

As we have shown above, WÜST does not seem inclined to accept, at least for the North Atlantic, this explanation of the vertical exchanges. It appears that he considers these exchanges solely as necessary compensations for the horizontal currents.

To our mind, this is simply a way of evading the difficulty, not to resolve it. It is not quite clear how the two orders of movements combine, except perhaps in the high latitudes north and south where the researches of the *Meteor* and of the *Discovery II* have thrown some light on the subject. But there are also vertical exchanges of water in the low latitudes.

The exchanges sometimes give rise, as we know, to deep waves comparable to a swelling of the tide, whence the name *internal tides* has been given them since the work of O. PETTERSSON. We grant that the hypothesis of BUCHANAN, based on the molecular descent and ascent of the water, does not take into consideration the questions of mass, which appear to characterize these internal waves.

But, as A. DEFANT concedes, the origin and nature of these internal waves still remain very mysterious. Let us give, according to him, some idea of what they might be as derived from the most interesting data of the *Meteor*.

At her station No. 254 (Lat. 2° 27' S., Long. 34° 57' W.) the *Meteor* observed a large and unique value which persisted at that station for eight hours. It was manifested solely as a vertical displacement of the liquid layers. While the wave was passing there were no perceptible alterations in the surface current, although at a depth of 50 metres, where the measurements were repeated, it was believed that currents of rather great velocity had been determined (at least 20 cm/sec. according to the calculations of EKMAN). "This is a type of internal wave developped theoretically under the influence of the earth's rotation, and is therefore a progressive wave" (2).

DEFANT further believes that the tides of the Atlantic are produced by the superposition of the progressive waves, coming from the south, and from stationary waves. But he holds also that it is not necessary to believe that the tidal currents of the surface are related to the internal waves, although very often they undergo variations in common.

According to PETTERSSON, the internal tide has nothing in common with the surface tides, except that its periodicity is determined by the rotation of the Earth. It consists of *forced vertical oscillations*, which result as much from the lack of homogeneity of the liquid layers as from the fact that the waters of the Ocean are enclosed between solid walls (3).

(1) J. Y. BUCHANAN : *On similarities in the physical geography of Oceans* (Accounts of work done and things seen), Cambridge, 1919, pp. 111-112.

(2) A. DEFANT : *Die Gezeiten und inneren Gezeitenwellen des Atlantischen Ozeans* (Wiss. Erg. d. Deutsche Atlant. Exp. Band VII, Teil 1), Berlin u. Leipzig, 1932.

(3) O. PETTERSSON : *La Marée interne* (J. JOHNSTONE's Memorial), pp. 294-309.

The problem therefore remains integral. All that we can say to-day is that it is rather extended and that all future synthesis of the ocean circulation in the depths must take it into consideration.

V. MISCIBILITY OF THE DEEP WATERS AND THE DEEP GYRATIONS.

The almost constant association, recognized by WÜST, of the vertical movements with lateral movements, cannot fail to result in some mixing of the lower layers, facilitated, it would seem, by the rather small differences which exist between the constituent characters of the liquid control strata. The total absence of oxygen dissolved in the deep waters, appears to be a myth, particularly in the Atlantic.

The researches made during the course of the past few years in the two regions of the polar front, where the different liquid strata converge upon each other at shallow depths, leave no doubt regarding the importance of the mixing. (*Vermischung*).

On the northern polar front, in the Denmark Strait, there has been found in summer, during the period of minimum of nutritive salts, waters rich in salts of that nature (nitrates and phosphates) coming from the deep waters. "Those are the results of cyclonic movements along the 'polar front' which force towards the surface the deeper waters rich in nutritive salts; the waters of the polar front are a mixture of different waters" (1).

H. U. SVERDRUP, studying the sub-antarctic convergence in Drake Straits and in the southern Caribbean Sea, recognised in the waters of mean depth (up to 900 metres) the existence of "trajectories of liquid particles which traced complicated spirals" (2), which necessarily involves a mixture of the waters.

Without doubt, in the near future we shall be able to obtain some idea of the mean miscibility based on the mean dosage of bacteria, the number of which in sea water varies from zero to 29400 per cub, cm. The greater numbers are found on the edges of the oceanic currents, at the place where the waters of different kinds come into contact. "These higher numbers," says Selman A. WAKSMAN, "are due, either to masses of plankton which die in the borders of the streams, or also to a vertical mixture of waters at the limits of the two currents, from which there results a welling up of bacteria from the lower layers to the higher" (3).

The vertical movements, combined with the lateral movements and the miscibility determine the deep gyrations of large and small radius.

As we have seen, B. HELLAND-HANSEN and NANSEN recognised the movements of this kind of greater and smaller radius, and WÜST appears disposed to admit that in all the eastern part of the Atlantic, the deep movements partake of this character.

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(1) G. BÖHNECKE and Others : *Beiträge zur Ozeanogr. des Oberflächenwassers in der Danemark Strasse und Irminger See* (Ann. d. Hydr. u. Mar. Meteor. LX Jahrg. Heft VIII, 1932).

(2) H. U. SVERDRUP : *On the vertical circulation in the Ocean.* (*Discovery* Rep. Vol. VII, Cambridge 1933), pp. 139-170.

(3) S. A. WAKSMAN : *The distribution and conditions of existence of bacteria in the Sea* (Woods Hole Oceanogr. Institution, Collected reprints, 1934, Contrib. N° 39), pp. 526-529.

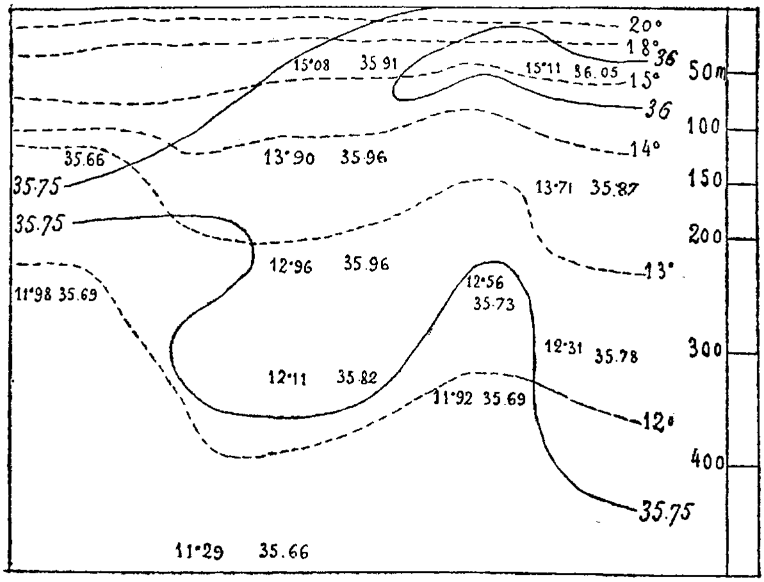

FIG. 4

Temperature and salinity in the depths to the west of Portugal in Lat. 37° to 42° N. and Long. 9° to 10° W.

We ourselves have sought to establish the generality of these gyrations, at least those of small radius, as well for the surface currents as for those of medium depth (1).

From this point of view, an effort should be made to retain the hypothesis of W. EKMAN on the great influence of the configuration of the bottom, even on those currents which occur at some considerable distance above ocean bed (2).

Thus our ideas of the deep oceanic circulation become gradually enriched and develop little by little. The work of Dr. WÜST, with the reservations which we have made, will certainly contribute towards this end.

VI. THE MARINE STRATOSPHERE AND THE MARINE TROPOSPHERE.

But there is one point at which it seems we should stop. This is the line of absolute demarcation established in Germany, as the result of a false analogy, between the *stratosphere* and the *troposphere*.

Agreed, that we may speak at one time of a *surface and a sub-surface circulation* and at another time of the *deep circulation*. At the same time it is not proper to dissociate entirely the one from the other.

Is this simply a question of terminology ? Such questions are not a matter of indifference. They cannot be too accurately formulated. Between the atmospheric troposphere with its water vapour and the stratosphere, which is totally deprived of it, there is a specific difference which does not exist in the ocean, which from the surface down to the greatest depths appears as a practically homogeneous medium.

(1) C. VALLAUX : *Les courants océaniques de surface et les girations secondaires* (Rev. Gén. des Sciences, 30 April 1935, pp. 237-248).

(2) B. HELLAND-HANSEN : *Meeresforschung mit kleinen Forschungschiffen*, p. 15.

There is no agreement amongst oceanographers with regard to the nature and the position of the line of demarcation between the marine troposphere and the marine stratosphere. Some of them determine it in accordance with the "discontinuity layers" (Sprungschicht) of the thermal index. Others, like WÜST, have recourse to the minimum of oxygenation ; and DEFANT acknowledges that the *Sprungschicht* cannot be conceived as a rigorous plane of demarcation (1). There is at least a zone of transition of rather uncertain character.

On two occasions WÜST might have noted the direct influence of the troposphere on the stratosphere ; the first time in the Current of Guinea and the Caribbean, where the surface and sub-surface circulation leaves its mark upon the deep circulation ; the second time, in the Gulf Stream, which induced him to extend the troposphere in depth.

It is quite remarkable also that he does not consider the deep currents of the ocean as true currents, except in the western part of the ocean, while in the eastern part there are either slow or uncertain drifts with gyrations.

Exactly the same thing occurs on the surface, where the Gulf Stream, the currents of the Windward Islands, of Guinea and Brazil, are directly opposed to the currents of the Canaries and of the Gulf of Benguella.

Certainly, it is not simply a question of considering the deep circulation as a simple projection in depth of the circulation on the surface and the sub-surface. Between the one and the other there are too many differences of degree, of intensity, of direction, of secondary contingencies and repercussions. But it is more legitimate to consider them as a coherent synthesis than to make of them two separate worlds.

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(25) A. DEFANT : *Gedanken über interne Gezeitenwellen* (J. JOHNSTONE's Memorial), pp. 310-315.