THE EQUATORIAL COUNTER CURRENT IN THE ATLANTIC OCEAN AND ITS ORIGIN

(According to recent research work)

by

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(Extract from the "Annalen der Hydrographie" of 15th July 1941, pamphlet VII, p. 201).

A. — THE PHENOMENON OF THE COUNTER-CURRENT.

1. *The counter-current according to A. Defant and A. Schumacher.* — It is advisable to restrict considerations on the equatorial counter-current to the Atlantic Ocean, in which the greater part of the observations have been made, since, although in the Pacific Ocean the conditions are quite similar, in the Indian ocean, the monsoon gives rise to anomalies which necessitate a very special representation, as the documentation relating to this subject has been largely increased recently.

In 1940, A. SCHUMACHER treated briefly in this publication, the question of the phenomenon of the counter-current on the ocean surface on the basis of the erroneous dead reckonings of some German ships, so that it will suffice, here, to draw attention briefly to a few points (1). The counter current begins, starting quite far away between Longitudes 46° and 53° West, between the meridians of Cayenne and the Amazon Estuary, then splits up on the Atlantic rise into a western and an eastern counter currents and still exists even where the african monsoon does not help it. During the months from July to October the two parts develop into a single whole, while during April the western portion no longer exists. It often occurs, that eastward movements, are inbedded in the westward equatorial current, which SCHUMACHER explains as being the surface resurgence of a deep running counter current. A large number of reports speak of current overfalls (2). The velocity of this current lies as a rule between 15 and 30 nautical miles per ship's run for 24 hours (32 to 61 cm./sec.). Along the Guinea Coast as much as 89 miles for a day's reckoning has been recorded, in the far end western portion a velocity of 71 miles per day's work has also been experienced.

As regards the force of the equatorial currents, A. DEFANT, in his study of the troposphere of the Atlantic Ocean (1936) (3) on which the author reported in this publication (1937) (4) has noted the existence of a density discontinuity layer. This layer stretches across the Ocean under the equatorial currents and forms a couple of bulges separated by a hollow (Fig. 1) and also cuts off a more or less thick and fairly homogeneous upper layer from the heavy water of the subtroposphere (see Table 29 of the Report referred to (1937).

(1) Arnold SCHUMACHER. *Monthly surface current charts in the North Atlantic Ocean.* (5° South to 50° North). Hamburg, Deutsche Seewarte — Annalen der Hydrographie, 15th April 1940, pamphlet IV, pp. 109-125, 2 Fig. 3 tables.

(2) A. SCHUMACHER. *On current overfalle, especially in the Guinea current and its vicinity.* — Annalen der Hydrographie, 15th Oct. 1395, Pamphlet X, pp. 373-382.

(3) A. DEFANT. — *The Troposphere.* Research Work of the "*Meteor*" 1st Part, 3rd. Section, p. 123, 1936.

(4) H. THORADE. — *The stratosphere and Troposphere of the Atlantic Ocean.* — Annalen der Hydrographie, 15th April 1937, Pamphlet IV, pages 174 to 184.

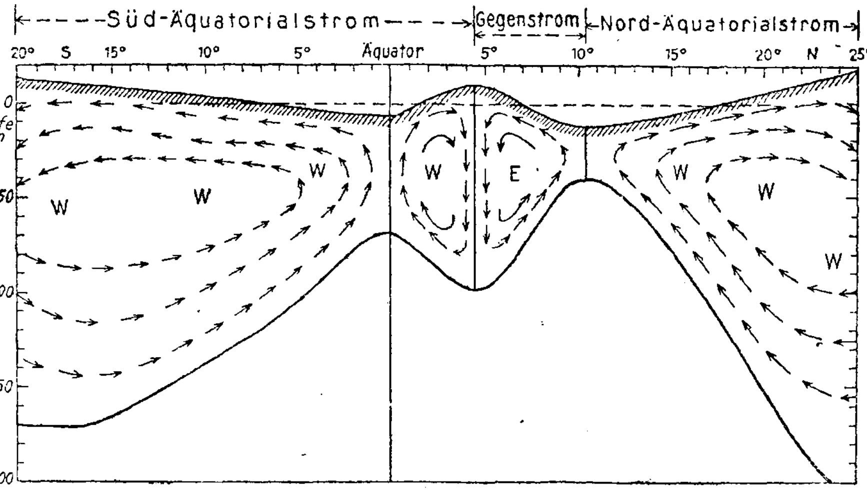

FIG. 1.

Schematic Section of the Tropical Atlantic Ocean.
Discontinuity layer represented as a dividing line according to A. Defant.
The letters indicate the direction of the Currents towards West and East.
The arrows indicate the inner circulation. The discontinuity layer slopes are very much amplified, those of the upper surface still more so.

The counter current becomes very much weaker below the discontinuity layer and even reverses in still greater depths. In the largest part of the region, the salinity still increases from the surface down to the vicinity of the discontinuity layer and diminishes again lower down. It is only on the two bulges that such a maximum salinity is not reached, from which Defant infers an upward movement of the water and draws his circulation scheme in Fif. 1: a convergence on the upper sea surface corresponds to a divergence in the depth, and vice versa.

2. *Method of the Density surfaces* [5] (Dichtefiächen) (Isentropic Analysis). R. B. MONTGOMERY [6] has dealt with the problem in another way by following C.G. ROSSBY's ideas and giving predominance to lateral exchanges over vertical exchanges (see A. DEFANT's report and critical notes [7] ROSSBY points out the minor importance of hitherto known bottom currents, which makes it very unlikely that they can compensate the large bodies of water which are carried away by great sea currents. It should therefore be a matter for reflection to ascertain what other possibilities could obtain to account for the origin and location of a large number of wind stirred currents, for instance. He came therefore to the idea to which he attached great importance, that the water of sea currents mixes continually with the edges of adjacent waters and so spreads out far away, as G. WÜST [8] somewhat similarly worked it out (1935) in connection with the Atlantic Ocean Stratosphere.

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(5) *Half a century ago,* A. MOHN *put forward the idea of a density surface* (Dichtigkeitsfläche) *with a different meaning in oceanography* (see the Author's article in the Annalen der Hydrographie, May 1935, Pamphlet V, pp. 282-286. *But as the Mohn's method is practically no longer in use and his idea of a density surface is still less in demand, a change in the meaning of the word could only be misleading.*

(6) R.B. MONTGOMERY. .. *Circulation in upper layers of southern North Atlantic deduced through isentropic analysis.* — Pap. Phys. Oceanogr. and Meteorology, VI, N° 2, Cambridge and Woods Hole, p. 48, 1938.

(7) A. DEFANT. - C.G. ROSSBY. — *Dynamic of stationary ocean currents in the light of experimental current teachings.* — Annalen der Hydrographie, pp. 58-68, Fig. 7, Pamphlet II. 15th February 1937.

(8) G. WÜST. — *The Stratosphere.* — Research work of the "*Meteor*", Volume VI, 1st Part, 1st Section, p. 106, Fig. 16, Supplement 8.

ROSSBY and MONTGOMERY attribute therefore a far greater importance to the horizontal mixing than to the hitherto almost exclusively considered vertical mixing. The latter, with the exception of the upper layer, is only conspicuous, along the coasts, in the upper areas of small organisms, in divergence areas and exceptionally in other places, as for instance before the entrance to the Straits of Gibraltar. As a rule the sea is stratified in too stable layers to allow confused upward or downward movements.

It should be added here, that it seems quite possible on this point to adopt a decision for future reference if or better when a turbulence takes place in the sea between two superposed water layers. It is a known fact that the movement of a homogenous fluid becomes turbulent when Reynold's number $\frac{ud}{v}$ (u = velocity, d = linear coefficient of fluidity, V = Cinematic viscosity) exceeds a certain limit value: it gives the relation between the influence of inertia and that of viscosity; if the latter in too strong-in the case of a syrup, for instance the movement of a particle tending to penetrate from one layer into an upper or lower one is checked; this movement remaining in the stratum (in the current line). But if the fluidity is stably stratified, any particle tending to move upwards or downwards will be prevented from doing so by gravity, as its specific weight is either greater or smaller than that of the layer into which is attempts to penetrate. The action of gravity against the exchange is all the stronger as the stability is greater, which according to Hesselberg is measured by the expression $E = \frac{\delta \rho}{\rho \, dz}$ (ρ = density, $\delta \rho$ = difference of potential density on the vertical space dz). On the other hand, the formation of eddies is facilitated by the difference in velocity of layers sliding one over the other; it therefore reaches with $\frac{du}{dz} = u'$ a value which can also be called: "*Scherung*".

L.F. RICHARDSON (9) (1920, p. 364) has represented the relation between the two actions by the value $\theta = g \frac{E}{u'^2}$ (henceforth called Ri), the greater it is the more the exchange movements are hindered by the stability (Reynold's number expresses the reverse; the greater it is the more the movement is turbulent. When Richardson's number exceeds a certain swelling value no turbulence will be any longer possible, as a rule; it is therefore questionable whether this limit value can ever be exceded in the sea.

There is indeed up to the present no absolute certainty as to the amount of this swelling value. According to H. SCHLICHTINGS' investigations (see the Report in the "Annalen der Hydrographie" 1938, p. 13) in Göttingen, it was sufficient when experimenting with a heated wind tube to give Ri a value of 0.04 to eliminate any turbulence. But is seems that this value cannot be used in spheres of such extent as the sea. G.I. TAYLOR has shown (1931, see A. DEFANT 1936, p. 296) (10) that the exchange is suppressed directly Ri is more than AB/AT (AB being the exchange coefficient for the movement, AT for the temperature, salinity etc.). From observations made in the Kattegat and Ramderafjord J.P. JACOBSEN (11) (1913) found values of between 3 and 60 for the relation between both coefficients; the stability was therefore high, but still the movement proved turbulent

For a deep sea, a rough estimate can be made, by taking as examples the antarctic bottom current B_s and the subantarctic intermediate current Z_s (G. WÜST, 1933, 1935) (8). In the first case, according to DEFANT 1936 (10) a power of 400 m. with a maximum velocity of 4 cm/sec. can be reckoned with on the Para rise, while the stability according to V. SCHUBERT (1835) (11 bis) is about $E = 10.10^{-8}$. Richardson's number would then have the

(9) L.F. RICHARDSON. — *The supply of energy from and to atmospheric eddies.* — Proceedings Royal Society, London XCVII, 1920, pp. 354-373, Fig. 1, c.T.s. bes, page 364.

(10) A. DEFANT. — *Diffusion and mixing phenomena of the Antarctic bottom current and subantarctic intermediate current.* — Research work carried out by the "Meteor", Vol. VI, second part, 2nd section, p. 42, Fig. 7, Annex 2.

(11) J.P. JACOBSEN. .. *Contribution to the Hydrography of Danish Waters.* — Medd. Komm. Havundersögelser, Series Hydrografi, Volume II, N° 2, Copenhagen 1913, p. 94, Fig. 17, i.T. 14 Tables.

(11 bis) O.S. SCHUBERT. — *Stability conditions.* — Research work carried on by the "Meteor", Vol. VI, 2nd Part, 1st Pamphlet, 55 pages, 11 Fig., 7 Annexes.

highest value of about 10 000. As a matter of fact, the density of B_s varies only between $\sigma_t = 27{,}87$ and 27,92 from the Antarctic to the North Atlantic Ocean, which can well be considered as mixing without vertical exchange in the sense expressed by Rossby and Montgomery. On the other hand, is found for Z_s with 10 cm/sec. and a power of 300 m., a value of Ri equal to about 7000. But here, the density of Z_s grows from $\sigma_t = 27{,}01$ to 27,45 on its way to the North Atlantic Ocean and it seems questionable whether this change in density does not suppose the existence of vertical exchange movements. So that, although it appears that the vertical exchange in the sea does not play the part which is frequently attributed to it, a decision in connection with this statement which might revolutionize the theory of currents should await future investigations to be made in the sea as well as in experimenting canals.

ROSSBY and MONTGOMERY proceed from the fact that, with the exception of the upper layers which are under the direct influence of the atmosphere, all bodies of water occupy the place to which they are entitled according to their density, they imagine in the sea a group of surfaces of equal potential density lying into one another like a batch of plates; a body of water which sets in, in accordance with its specific gravity, may very well change its salinity and temperature when mixing with adjacent waters or by adiabatic phenomenon, it preserves however its potential density and for that reason remains bound up with the surface of potential density to which it belongs and which is to a certaini extent impenetrable to it. As the changes in density due to adiabatic phenomena within the upper 1000 m. can be disregarded, the surfaces of equal density may be replaced by surfaces of equal σ_t. The first step in "Isentropic Analysis" (12) which on this account can be briefly described here for the moment, if not strictly accurately as the "Method of density surfaces", consists therefore in topographically representing surfaces of equal σ_t by depth lines, (see Fig. 2 and 3 and charts reproduced by MONTGOMERY himself (Annalen der Hydrographie May 15th 1939 Pamphlet V, p. 243). According to EKMAN and HELLAND-HANSEN's proposition regarding parallel fields, currents adapt themselves to depth lines, as a rule. The distribution of oxygen and salinity over each separate σ_t surface provides an other means for the determination of the current direction. In order to find the velocity, dynamic calculation must be resorted to, as soon as hypotheses are found correct, with regard to the impossibility of discerning friction and temporal changes. For the sake of simplification, MONTGOMERY has introduced the notion of Geotropic potential — $\Phi + a\,p$, Φ being the gravity potential, a the specific volume, and p the pressure. If ω represents the angle velocity of the horizon for a given geographical latitude, x and y will be the velocity components $u = \frac{1}{2\,\omega}\,\frac{\delta}{\delta y}\,(\Phi + a\,p)$ and $v = \frac{1}{2\,\omega}\,\frac{\delta}{\delta x}\,(\Phi + a\,p)$, the differentiation being worked out according to the density surface.

It should be pointed out here that the tongue like shape of the lines of equal salinity etc., does not always permit an accurate conclusion a posteriori in connection with currents (Investigations made by the Author in 1931 and 1933, pp. 2911-2914) (13), because the form of the isohalines depends just as much on the exchange as on the current proper, H. V. SVERDRUP (14) gave an instructive example of it when he investigated what would take place in the Atlantic Ocean for a longiutdinal Section of the temperature (or salinity) if it were assumed that there was generally no circulation but only horizontal and vertical exchanges. It was a surprise to find that the lines obtained under such conditions were quite in agreement in their main features with those supplied by observation and interpreted in the sense of the circulation.

(12) *The expression is taken from Meteorology, in which adiabatic phenomena for which the entropy is not altered, play an important part, as in oceanography.*

(13) H. THORADE. — *Current and spreading of the water in tongue like fashion.* — Gerl. Beiträge Geographie — XXXIV, Köppen — Vol. III, pages 57-76, 11 figures.

H. THORADE. — *Methods for the study of currents.* — Handbuch der Biolo. Arbeitsmethoden, hrsg. v. E. Abderhalden, II, 3rd. Part, pages 2865-3095, 126 Fig. 3 tables.

(14) H.U. SVERDRUP. — *Ocean Circulation* — Proc. 5th Congress of Applied Mechanics, 1938, pp. 279-293, 16 Fig.

3) *Montgomery's results.* — Montgomery's lowest surface σ_t $\sigma_t = 27$, Fig. 2) rises from a depth of 840 metres, as a rule, up to 400, but rises to 300 m. against the South American Coast and to less than 200 m. quite close to the Atlantic rise when it forms a summit surrounded by contra solem currents.

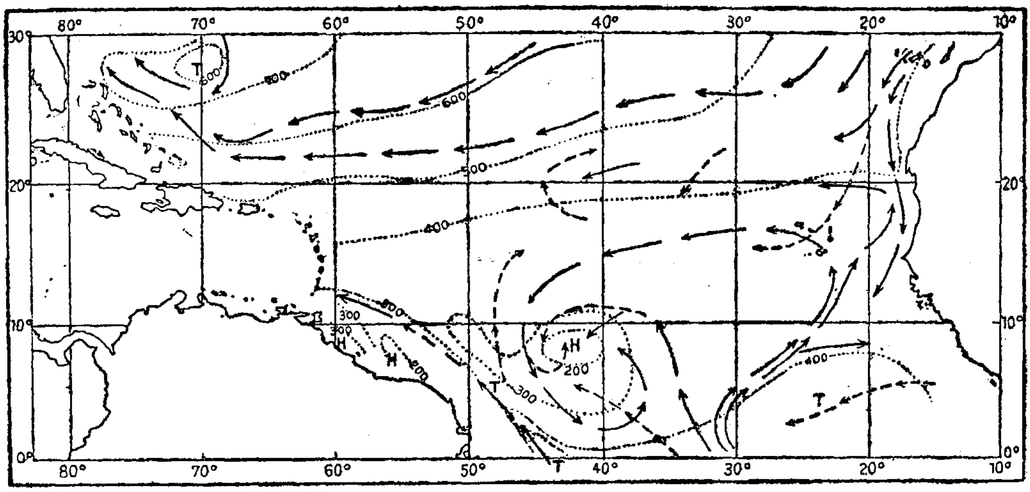

FIG. 2.

Topography of the Surface σ_t = 27 and currents, deduced from the salinity and oxygen content, according to Montgomery.

Thus the 27 Surface is found well under the depth considered by DEFANT for the equatorial and counter current. The latter is even lacking, in the proper sense; in its place, the water only moves south of theh 200 M. summit to the East, for a time, then in Long. 30° W., the water with low salinity (less than 35%) runs from the South Hemisphere to the region of Cape Verde Islands; the water of the North equatorial under current between Lat. 20° and 30° N. owes its particularly high salinity to the mixing with the Mediterranean sea water coming out of the straits of Gibraltar. From this and without regard to the South American coast, MONTGOMERY finds no signs, within the range of the chart, which militates in favour of a penetration of water particles into 27 Surface in a vertical direction, contrary to his supposition. The calculated dynamic velocities are certainly very low and reach only 1,7 cm./sec. in a section between Latitudes 8° and 29° N.

The σ_t = 26 Surface (Fig. 3) sinks to 200 m. from the surface of the sea in the region of the Canary Islands and still more before the Bahamas; the depth lines take an East West direction, as in the case of the 27 surface, and form a ridge extending from the Sierra Leone Coast towards Guiana, which is only slightly under the discontinuity layer of Fig. 1. Both the North and South equatorial currents have a high salt content on their outer side opposite the Equator but are poor in salt on their inner side. What it however particularly striking about Montgomery's chart is the vast extension of the counter current towards West where it originates close to the Antilles. It appears to MONTGOMERY as a 100 to 150 nautical miles broad strip with a high salinity (often referred to as the river in the sea) which inserts itself between the two low salinity sides of both equatorial currents.

MONTGOMERY is therefore forced to admit that there is a bending of the high salinity wing of the North equatorial current (Fig. 3) whereby its South wing would be cut off from the Caribbean Sea; it may be that the transfer of salt towards the counter current takes place within the Antilles bend or that the low salinity water is driven back into the Caribbean Sea. There is another possibility which MONTGOMERY himself does not appear to reject off hand, that in this region with such irregular bottom forms, vertical exchange movements are not out of the question. Finally it should be pointed out, that from the point of view of salt content, the low salinity side of the North equatorial current is fed

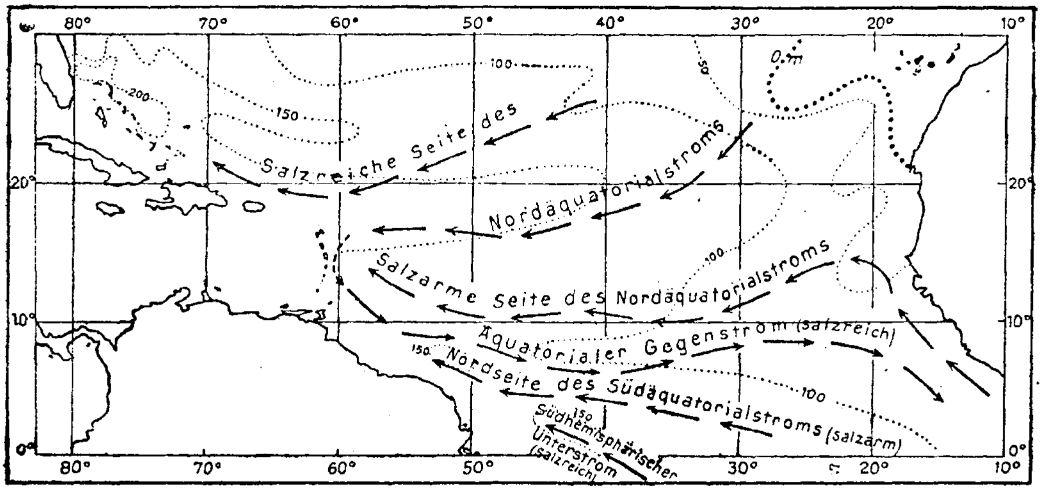

FIG. 3.
The $\sigma_t = 26$ *Surface according to Montgomery.*

by the African coastal water and that the counter current, at least in depths of 50 to 100 m. does not reach the coast directly there but only meets it further south; the upper surface current, according to SCHUMACHER, would really run concurrently only during the months from October to December.

B. — THE CAUSES OF THE COUNTER CURRENT.

4). *Sverdrup's and Defant's interpretation.* — It may be noted from the above considerations, that as regards the counter current, we have to deal with a phenomenon which is in no way uncertain but quite constant and well defined and the cause of which requires just as clear an explanation. We know that chiefly on the basis of a laboratory experiment which was not particularly conclusive (Krümmel 1911, p. 475), the counter current was looked upon as a compensating current which carried back the water thrown westward by the equatorial currents. We also that H.U. SVERDRUP and A. DEFANT have rejected this notion and considered the counter current as a gradient current resulting from gravitation as expressed in Fig. 1. On the strength of observations made aboard the "Carnegie" in the Pacific Ocean, H.U. SVERDRUP (1932-34) comes next to his new conception: here appears in the tropics an almost homogeneous superficial layer, which is separated by a discontinuity layer from the heavier depth water. The discontinuity layer shows two bulges with a hollow between after the fashion indicated in Fig. 1. Then, as a result of the isostasy prevaling in a sea with stationary movements, the upper surface of the sea reproduces these irregularities (very much exaggerated in Fig. 1.) in the opposite direction while very strongly lessening them) so that it shows a hollow at the Equator, a second one in the North hemisphere with a bulge between the two. DEFANT (1935-1936) (15) studied the same phenomenon on the occasion of extensive observations in the Atlantic Ocean; these and the distribution of salinity already referred to have led him to evolve the current and circulation schema reproduced in Fig. 1. This periodical (1937 pp. 174-184, 6 tables) gave a detailed report on this subject, it will therefore be sufficient to refer to the main points.

Owing to the deflecting force resulting from the earth's rotation, the whole of the currents formed by the S.E. trade wind driven water move towards the left in the south hemisphere at a right angle to the wind, but towards the right after crossing the Equator.

(15) A. DEFANT. — *The equatorial current.* — Report of Proceedings of the Prussian Academy of Science., Physics, Mathematics. Class XXVIII, Berlin, pp. 450-472, 12 Fig.

(V.W. Ekman) (16). The subtropical convergences and the zone of calms act as a solid wall which prevents the water flowing off so that the latter rises against it. Therefore a channel originates along the Equator on the south equatorial current (Fig. 1); its North-east declivity forms a ridge which runs obliquely across the ocean, then sinks down further north to a second hollow, after which it rises again on the other side in the region of the North-equatorial current. The pressure gradient corresponding to the counter current originates on the side of the said ridge which slants down towards the calm zone between Lat. 5° and 10° N. and the action of which is substantially reinforced by the limited isostatic ascent of the discontinuity layer which is found underneath.

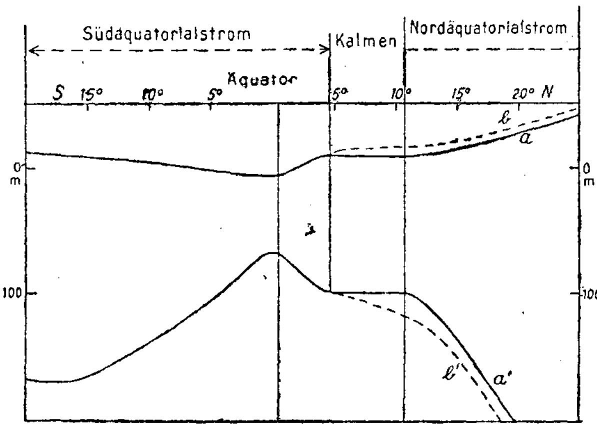

Fig. 4.
Possibilities for the course of the discontinuity layer and the surface of the sea.

But this does not yet provide a full answer to the question of the origin of the equatorial counter current; such is the view point expressed by Sverdrup (14) in a later work in which he states that a proper explanation of the counter current is not possible "as we have not a sufficient knowledge of the sea dynamics or of the factors which govern the distribution of density". In fact, the two well established dynamic requirements: an equatorial hollow in the south equatorial current and a rise in the North equatorial current are also supposed to be fulfilled, if, for instance, there is no current running in the calm zone and consequently the sea surface is horizontal. (Fig. 4a); of course, if it is admitted, that the calm zone water may be moving slowly westward in consequence of lateral friction, a slight ascent is even conceivable in this region (Fig. 4, part b). The existence of a slope is therefore quite consistent with the distribution of currents, but it is in no way a dynamic necessity which supposes that all other possibilities are excluded, which also Sverdrup and Defant have in no way stated.

5). *Explanation of the counter-current given by R.B. Montgomery and E. Palmén.* — Considerations of a similar kind have been brought forward by Montgomery and Palmén (17) (1940) when coming back to the explanation of the counter current as a compensating current, which explanation, moreover, is not inconsistent with the above, but, on the contrary, is complementary to it. As early as 1906, V.W. Ekman (16) (see this review p. 535) had pointed out that the counter current is a compensating current produced by a rising of the water on the western side of the ocean. In order to obtain a rough estimate, the two

(16) V.W. Ekman. — *Contribution to the theory of Sea Currents.* — Annalen der Hydrographie, pp. 423-430, 472-484, 527-540, 566-583, 38 Fig., 1 Table.

(17) R.B. Montgomery and E. Palmén. — *Contribution to the question of the equatorial counter current, Sears Foundation.* — Journal of Marine Research III, N° 2, pages 112 to 133, 9 Fig.

collaborators conjointly with EKMAN proceed from an evaluation of the wind transverse strain according to the formula :

$$\tau = 0{,}0025\ \rho\ w^2$$

(ρ = air density, w = wind velocity)

which has been confirmed by a whole series of various works, for the N.E. trade wind on 0,72 dyne section and for the S.E. trade wind on 1,19 dyne per square cm. If, for purposes of a rough estimate the covering layer is limited to a thickness of 100 m. and if the deflecting force is overlooked for a moment, a rising of 24 cm. should take place on the American side for an ocean width of round about 4000 km. this rising being offset by the wind impulse in the trade wind zone. On the other hand, in the calm zone, the declivity of the water surface can resolve itself into a downward current, due partly to an acceleration partly to an overcoming of the friction. The latter part is by far the more important and raises the question of where the impediments to water movements must be chiefly looked for. MONTGOMERY and PALMÉN weigh the various possibilities of friction on the bottom and on the discontinuity layer, but have to reject such a notion as it would imply quite unlikely values both of the wind velocity and of the exchange; they come to the conclusion that it is probably the lateral friction which plays the main part in the case of the counter current. This would moreover be in keeping, with the phenomena of turbulence which we often observed on its edges, such as ripples for instance.

Unpublished topographical charts of the Atlantic Ocean Surface, drawn up by DEFANT on the basis of the "Meteor's" observations and which MONTGOMERY and PALMÉN had occasion to examine confirm these interpretations. In the North equatorial current region, the depth lines of the 100-db surface run almost West-East and show a North South surface declivity. Such is not the case with the sea surface: the contour lines run from North-North East to South-South West, and the sea surface rises from East South East to West-North West; so that the current would flow upwards on the sea surface! As regards forces affecting the North equatorial current, friction being unimportant in relation to the wind, deflecting force and declivity can be left out of account so that the schema of Fig. 5 A is available.

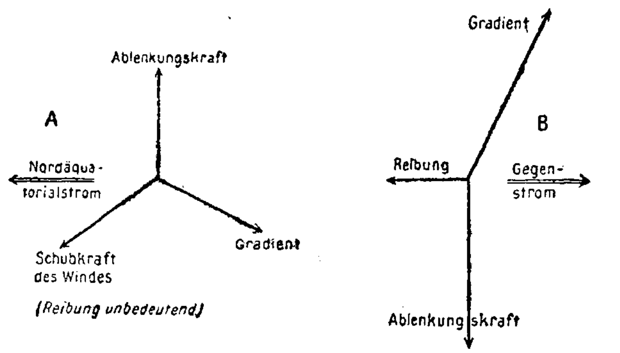

FIG. 5.

Force Equilibrium : A *in the North equatorial current.*
B *in the Counter current.*
according to Montgomery and Palmén.

A *Deflecting force*
North equatorial current
Gradient
Wind impulse
(friction being left out of account)

B *Gradient*
Friction
counter-current
deflecting force.

On the other hand as regards the counter current (Fig. 5 B) the wind impulse subsides and corresponds to an equilibrium between the declivity deflecting force and friction, similarly to Gulderg-Mahn schema for calculating the wind from gradient and friction. Of course ths relations are such, that on account of the considerable velocity of the counter current, the component of the gradient which counterbalances the deflecting force, is by far greater than that which contributes to overcome friction. But as observations go to show various irregularities due to internal and other waves, the longitudinal component of declivity does not effer uniform values. The two Authors find a way out by stating that in this respect they are only interested in observations made in the vicinity of the Equator where the transverse declivity disappears. Here in fact on the sea surface is found a declivity of about 20 dynamic decimeters (Fig. 6: the stations lie between Latitude 1°8' South and Latitude 1°8' North, (see the above mentioned evaluation). The longitudinal section drawn up by DEFANT (1935) (15) through the counter currents suggests something of the kind because he shows just as the topographical chart of the discontinuity layer does that the latter sank considerably from Africa to America; for isostatic reasons, the surface must therefore move up in the same direction.

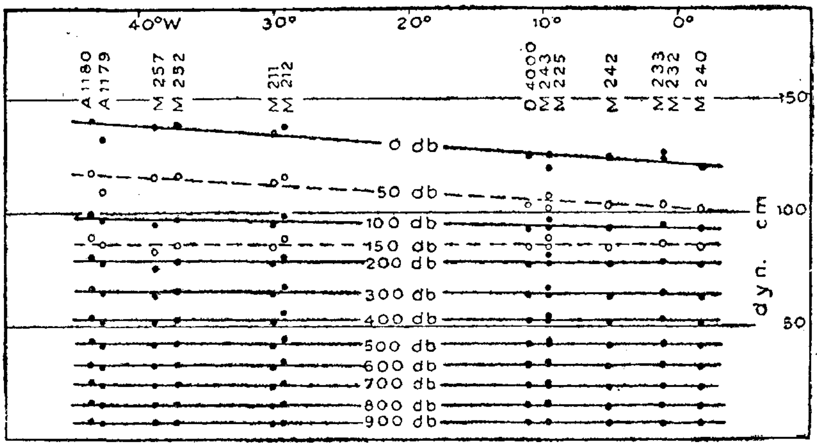

FIG. 6.

Section of isobars surfaces in the Atlantic Ocean, along the Equator, according to Montgomery and Palmén.

The sea surface in the region of equatorial currents should therefore be imagined somewhat in the way indicated in Fig. 7 schema: in the shape of waves, but at the same time rising westward. Underneath the discontinuity layer, the declivity of the isobars surfaces in the longitudinal direction is very small, the probability is that it is practically nil. It was found that the lateral exchange amounted to 7.10^7 cm.$^{-1}$ g. sec.$^{-1}$, which agrees with a previous estimate made by MONTGOMERY (18) (p. 246) which gave 4.10^7.

To sum up, it may be stated that, according to MONTGOMERY-PALMÉN views, the equatorial counter-current does not seem to be the result of the field of pressure and masses shown in Fig. 1. The hydrodynamic calculation of a current, according to BJERKNES and SANDSTRÖM, which it should not be forgotten is only applicable to: 1° invariable temporal conditions and 2° when dealing with a frictionless movement, offers no explanation as to the relation between cause and effect, that being generally the case with mathematic calculations. As a rule, the position in this: the distribution of density is known through a series of measurements, from which the current can then be calculated; but the relation from cause to effect may be reversed. For instance, G. WÜST (1924) (19) calculates the current in the Florida Channel from the field of forces and finds himself in agreement with Pillsbury's measurements. Still, no one can question that in this case it is a narrow space compressed current which, under the influence of the earth's rotation, bends the surface of equal density,

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(18) R.B. MONTGOMERY. — *Attempted determination of the vertical and lateral exchange at the depth of the discontinuity layer in the equatorial Atlantic Ocean.* (Annalen der Hydrographie, pp. 242-246, 5 Fig.).

(19) G. WÜST. — *Florida and Antilles Current.* — Hydrodynamic investigations — Published by the Institut für Meereskunde, N.F.A., Pamphlet 12, Berlin 1924, 48 pages, 6 figures, 1 Table.

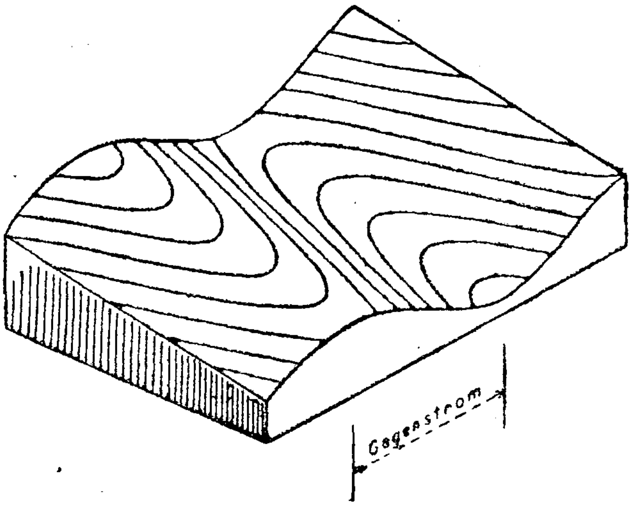

FIG. 7.
Schematic transverse illustration of the tropical Atlantic Ocean surface.

so that the current is the cause and the bending is the effect. Conversely, it is not unlikely that, in the long course of the Gulf Stream the differences in density between subtropical and polar waters take care of the crossing of the North Atlantic Ocean, whereby, according to EKMAN (1931) (20) the wind may cause the differences in density to press against the narrow strip occupied by the North Atlantic Current.

But if the distinction between cause and effect is carried to the extent of seeking the source of energy of the current, it is found in the declivity along the counter current which is also a consequence of the wind. Although the longitudinal component of the declivity is so small in relation to the transverse component that it can presumably be left out of account in the dynamic calculation, it is however evidently essential for the progress of the counter current; which supports, in this case, an opinion expressed by C.G. ROSSBY (21) (1936, see also DEFANT's report 1937, p. 62 (7)). In this sense, according to MONTGOMERY and PALMÉN, the Counter-current is both a compensating current and a gradient current, as EKMAN had already stated in 1906.

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(20) V.W. EKMAN. — *The Gulf Stream problem.* — Gerl. Beiträge zur Geographie XXXIII, Copenhagen, Vol. II, pp. 335-364, 3 Fig.

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