The Antarctic Circumpolar Current and the Antarctic Polar Front

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Summary. A Sverdrup-type solution of the Circumpolar Current is constructed. It explains the southward shift of the current, but requires that the current is situated completely to the south of the maximal westerlies. The observations show, however, that winds and current almost coincide and that both, the wind belt and the current, show a shift to the south. A frictional model is used, which overcomes this discrepancy and allows the calculation of the transverse circulation of the current in full detail. The transverse circulation under different wind conditions is calculated and discussed and shows a strong dependence of the distribution and intensity of the various divergences and convergences on the wind. A new interpretation of the Antarctic Polar Front is given. It is regarded as a convergent or divergent phenomenon according to the wind conditions.

Der antarktische Zirkumpolarstrom und die antarktische Polarfront (Zusammenfassung). Obwohl ein ziemlich umfassendes Beobachtungsmaterial über den antarktischen Zirkumpolarstrom vorliegt, konnte er bisher nicht befriedigend theoretisch erklärt werden. Der Strom wurde stets als rein zonal aufgefaßt, bis Stommel zeigen konnte, daß die aus Südamerika und der Drake-Passage gebildete östliche Begrenzung die Anwendung von Sverdrups Theorie gestattet. Eine solche Lösung wird konstruiert und diskutiert; sie erklärt die Verlagerung des Stromes nach Süden, verlangt aber, daß der Strom vollständig südlich des Maximums der Westwinde liegt. Um diese Frage zu prüfen, wird die Position des Stromes nach dynamischen Berechnungen von Kort mit der Position der stärksten Westwinde nach H. Wexler und der Position der antarktischen Konvergenz rund um den antarktischen Kontinent verglichen. Es ergibt sich, daß der Windgürtel mit dem Strom nahezu zusammenfällt und daß die antarktische Konvergenz etwas südlich des Zentrums der Strömung liegt. Daraus muß geschlossen werden, daß eine Lösung ausschließlich nach Sverdrups Theorie auf den Zirkumpolarstrom nicht anwendbar ist. Von wesentlicher Bedeutung ist jedoch die Feststellung, daß nicht nur der Strom, sondern auch der Westwindgürtel eine Verlagerung nach S während ihres Fortschreitens nach E erfahren, eine Tatsache, die bisher unbeachtet geblieben ist.

Unter Berücksichtigung dieser Beobachtungsergebnisse wird eine Lösung für den Zirkumpolarstrom ermittelt, in der auch die Reibung berücksichtigt wird. In dieser Lösung fallen Strom und Westwindgürtel zusammen. Die Berücksichtigung der Reibung gestattet aber auch die Ermittlung der meridionalen und vertikalen Geschwindigkeiten in einem Schnitt senkrecht zur Richtung der Hauptströmung. Es kann gezeigt werden, daß die zonale Hauptströmung nahezu geostrophisch ist, während die Reibung eine entscheidende Rolle bei der Ausbildung der Querzirkulation spielt. Die Querzirkulation wird am Beispiel eines Discovery-Schnittes von Australien nach dem antarktischen Kontinent diskutiert und zeigt vollständige Übereinstimmung mit den aus der Wassermassenanalyse gewonnenen Vorstellungen.

Da die Querzirkulation maßgeblich von der Windverteilung beeinflußt wird, wird diese für drei verschiedene Windverteilungen ermittelt. Dabei zeigt sich, daß die Lage der verschiedenen Konvergenzen und Divergenzen an der Oberfläche wesentlich von der Windverteilung bestimmt ist. Da entlang der Wasserartengrenze zwischen antarktischem und subantarktischem Oberflächenwasser die Bewegungen je nach den Windverhältnissen konvergent oder divergent sind, ist es nicht mehr zulässig, diese Linie als antarktische Konvergenz zu bezeichnen, und der Name antarktische Polarfront wird eingeführt.

Bei schwach ausgeprägten Westwinden überwiegt die durch die Reibung bedingte Querzirkulation nahe dem Hauptstromstrich und führt zu einer leichten südwärts gerichteten Komponente der Strömung an der Oberfläche. Damit entsteht eine Divergenz an der linken Flanke und eine Konvergenz an der rechten Flanke des Stromes und die Zirkulation entspricht der von Sverdrup gegebenen Interpretation der Polarfront. Bei starken Westwinden in einer relativ nördlichen Position sind die Bewegungen südlich des Westwindgürtels und damit im Bereich der Polarfront divergent, ein Fall, der von Wexler beschrieben wurde und ihn zu einer Interpretation der Polarfront als divergentes Phänomen veranlaßte. Sind hingegen starke Westwinde in einer relativ südlichen Position vorhanden, so ist die Wasserbewegung nahe der Polarfront konvergent und die Bewegung des Tiefenwassers nach S besonders stark, ein Fall, wie ihn G. E. R. Deacon bei seiner Interpretation der Polarfront im Auge hat. Diese Behandlung der Querzirkulation im Bereich des antarktischen Zirkumpolarstromes unter verschiedenen Windverhältnissen ist damit geeignet, die unterschiedlichen Interpretationen der Polarfront, die als Spezialfälle ihre volle Gültigkeit behalten, zu einem gemeinsamen Bild zu vereinen.

Le courant antarctique circumpolaire et le front antarctique circumpolaire (Résumé). A l'aide de la théorie de Sverdrup on construit une solution du problème posé par le courant circumpolaire. Cette construction explique le déplacement vers le sud du courant, mais elle exige que le courant soit situé complètement au sud du maximum des vents d'ouest. Les observations nous montrent, cependant, que les vents et le courant coïncident à peu près et que tous les deux sont déplacés vers le sud. On se sert d'un modèle de friction qui fait évanouir cette discordance et permet de calculer en détail la circulation transversale du courant. Puis on calcule et discute la circulation transversale en fonction de diverses conditions du vent et on voit que la distribution et l'intensité des diverses divergences et convergences dépendent fortement du vent. Le front antarctique polaire ainsi reçoit une nouvelle interprétation qui permet de le considérer comme phénomène convergent ou divergent suivant les conditions du vent.

The Antarctic Circumpolar Current, flowing in a closed circle around the Antarctic continent, is certainly the most powerful current in the oceans. Since the work done by R. R. S. "Discovery II", which contributed so much to the knowledge of its structure, many attempts have been made to explain this current theoretically. G. E. R. Deacon [1937b], Sverdrup (H.U. Sverdrup, M.W. Johnson, R.H. Fleming [1946]), and V. G. Kort [1959] calculated the transports, the dynamic topographies, and the geostrophic currents, but discrepancies have occurred, when attempts have been made to explain these transports from wind data. K. Hidaka and M. Tsuchiya [1953] used exceptionally high values of 10^{10} g cm^{-1} sec^{-1} for the coefficient of lateral eddy viscosity and of $2 \cdot 10^3$ g cm^{-1} sec^{-1} for the coefficient of vertical eddy viscosity in order to explain the observed values of mass transport and slope of sea level. However, as pointed out by H. Stommel [1957], the observed distribution of properties in the current could not be maintained in the presence of such a strong turbulence. W. H. Munk and E. Palmen [1951] suggested that the friction could be applied to the current from the bottom of the ocean, caused by the large scale irregularities of the ocean bed under the current. But all these theories treat the current as a purely zonal phenomenon. Stommel [1957] was the first to point out that this zonal flow could be seriously affected by the existence of the quasiboundary formed by South America, the Antilles Arc, and Palmer Peninsula. In this case a Sverdrup-type solution would be possible with a longitudinal slope against the current, by which the wind stress is balanced. But it must be borne in mind that even if the main motion in the Circumpolar Current is almost zonal, a transverse circulation is superimposed on this zonal flow, which must be an essential feature of this current, and must have a strong influence on its dynamics, especially if one considers the enormous length of the current of about 20,000 km. This transverse circulation has been discussed by Sverdrup [1933], Sverdrup, Johnson, Fleming [1946] by means of an analysis of the distribution of properties in meridional sections across the current. This analysis indicates an equatorward flow in the surface layer under the influence of the west winds, a poleward flow of subsurface water and deep water, a northward flow of bottom water, as well as the sinking and northward spreading of the Antarctic intermediate water. Any appropriate model of the Antarctic Circumpolar Current must explain not only the main zonal motion but also the transverse motion in a meridional plain. Stommel [1957] includes such a transverse circulation in his model of the Circumpolar Current; this model, in fact, reflects the main features of Sverdrup's picture quite well, although this model is considered by Stommel only as a sketch.

1. A Sverdrup-Type Solution. As Stommel's model is so promising, it seems worthwhile to investigate it a little more closely, to derive numerical values for the parameters in question, and to test how far the zonal and meridional motions are described by it. The linearized stationary equations of a frictionless motion in the southern hemisphere, caused by a wind stress τ_0 at the surface, are

$$f\,M^y = -\frac{\partial P}{\partial x} + \tau_0{}^x \tag{1}$$

$$-f\,M^x = -\frac{\partial P}{\partial y} + \tau_0{}^y \tag{2}$$

when the x-axis points east and the y-axis north. M^x and M^y are the components of the mass transport and P the vertically integrated pressure. The equation of continuity is

$$\frac{\partial M^x}{\partial x} + \frac{\partial M^y}{\partial y} = 0. \qquad (3)$$

Introducing (1) and (2) into (3) gives with $\frac{\partial f}{\partial y} = -\beta$ the vorticity equation in the form

$$\beta M^y = \frac{\partial \tau_0^y}{\partial x} - \frac{\partial \tau_0^x}{\partial y}. \qquad (4)$$

This process leads to the simultaneous elimination of M^x and P, and M^y can be determined directly from the wind stress. Considering a pure zonal wind stress ($\tau_0^y = 0$), M^y is given by

$$M^y = -\frac{1}{\beta}\frac{\partial \tau_0^x}{\partial y} \qquad (5)$$

and P results from a simple integration of

$$\frac{\partial P}{\partial x} = \frac{f^2}{\beta}\frac{\partial}{\partial y}\left(\frac{\tau_0^x}{f}\right) = \tau_0^x + \frac{f}{\beta}\frac{\partial \tau_0^x}{\partial y}. \qquad (6)$$

In order to obtain a solution of this problem only the wind stress τ_0^x must be known as a function of latitude and the distribution of P along the eastern boundary of the ocean, that means along the west coast of South America. Wind stress data from the Ocean around Antarctica are still very meagre and uncertain. Hidaka [1951] uses a zonal wind stress distribution with a maximal wind stress of 0.7 at 40° S, which is extrapolated from Munk's data [1950] for the Pacific Ocean north of 20° S. In another paper Hidaka [1958] computes average wind stresses over all oceans, and these values show that the maximal wind stresses occur between 45° and 50° S and reach values above 1.0 g cm^{-1} sec^{-2}. Therefore the problem will be treated here with a simplified wind stress distribution, as shown in fig. 1. There are trade winds between the equator and 30° S, west winds between 30° and 60° S with a maximum of 1.0 g cm^{-1} sec^{-2} at 45° S and again weak east winds south of 60° S. The meridional transport component M^y is calculated from the β-effect according to (5). It shows equatorward

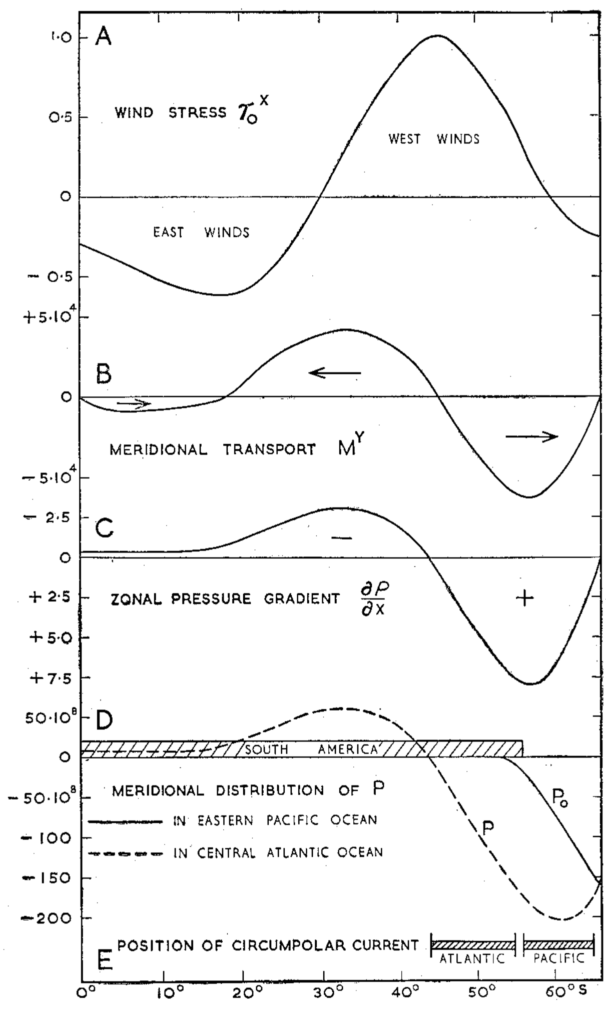

Fig. 1. Sverdrup-type solution for the Antarctic Circumpolar Current, showing distribution of zonal wind stress (A), meridional transport component (B), zonal pressure gradient (C), and distribution of the vertically integrated pressure (D)

motion north of the maximal westerlies and poleward motion south of them, fig. 1. The zonal pressure gradient is calculated from (6) and indicates north of the maximal westerlies a descent of the sea level in the direction of the wind and south of them an ascent of the sea level. In order to find the distribution of P somewhere in the ocean, it can be assumed that P_0 is constant along the coast of South America and that the whole meridional decrease of P_0 occurs off the Drake Passage, thus representing the Circumpolar Current. Calculating backwards from the west coast of South America over a distance $L = 20{,}000$ km the curve P in fig. 1 results, representing roughly the meridional distribution of P in the central South Atlantic Ocean. This curve cannot be valid north of about 30° S because of the influence of the land barriers formed by Australia and Africa. It shows, however, a considerable southward displacement of the Antarctic Circumpolar Current $\left(\text{which is here identified with } \frac{\partial P}{\partial y}\right)$ by about 10° of latitude during its progress to the E from the Atlantic Ocean to the Drake Passage.

This Sverdrup-type solution for the Circumpolar Current given here is identical with that sketched by Stommel [1957], figs. 26–28. The essential features of this solution are (i) the development of an anticyclonic gyral in each ocean to the north of the maximal westerlies, similar to that given by Munk [1950] for the North Pacific Ocean, (ii) the position of the Circumpolar Current entirely to the south of the maximal westerlies, and (iii) the southwards displacement of this current by about 10°. It also follows from this solution that the flow should be divergent at the position of the maximal westerlies, and such a divergence is in fact indicated in charts of the surface currents (see G. Schott [1942, 1943]).

Before discussing the agreement of this solution with the observations, the vertical structure of the current will be briefly investigated. The equations (1) to (3) written for velocities are

$$f\,v = -\frac{\partial p}{\partial x} - \frac{\partial \tau^x}{\partial z} \tag{7}$$

$$fu = \frac{\partial p}{\partial y} \tag{8}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{9}$$

where $\tau^x = \tau_0{}^x e^{-z/E}$ is the wind stress decreasing exponentially with depth z, and E is a measure for the depth of the Ekman layer. Introducing (7) and (8) into (9) with the condition $w = 0$ at $z = 0$ gives an equation for the vertical velocity w

$$w = \frac{\partial}{\partial y}\left(\frac{\tau^x - \tau_0{}^x}{f}\right) + \frac{\beta}{f^2}\int_0^z \frac{\partial p}{\partial x}\,dz. \tag{10}$$

The condition $w = 0$ at the bottom $z = B$ gives, if $e^{-B/E} \ll 1$, the relation

$$\frac{\partial}{\partial y}\left(\frac{\tau_0^x}{f}\right) = \frac{\beta}{f^2}\int_0^B \frac{\partial p}{\partial x}\,dz \tag{11}$$

which is identical with (6), as $P = \int_0^B p\,dz$. The pressure p is given by

$$p = \varrho_0 g h(x, y) + \int_0^z \varrho\,(x, y, z)\,g\,dz \tag{12}$$

where $h\,(x, y)$ is the topography of the sea surface. For the vertical distribution of ϱ the simple assumption

$$\varrho = \varrho_B - \Delta\varrho(x, y)\,e^{-z/D} \tag{13}$$

may be made, giving an exponential increase of density to the value ϱ_B at the bottom. The depth D is a measure of the depth at which the density difference between surface and bottom decreases to about 1/3, and indicates, therefore, approximately the position of the lower boundary of the discontinuity layer. Introducing (12) and (13) into (11) and using (6) the relation

$$\varrho_0 g B \frac{\partial h}{\partial x} - g D (B-D) \frac{\partial \Delta\varrho}{\partial x} = \frac{\partial P}{\partial x} \tag{14}$$

results, where $\frac{\partial P}{\partial x}$ is known from (6) as a function of y. For simplicity we will assume that $\frac{\partial h}{\partial x}$ and $\frac{\partial \Delta\varrho}{\partial x}$ show the same dependence on y as $\frac{\partial P}{\partial x}$. Thus, we can write

$$\frac{\partial h}{\partial x} = \frac{h_0}{L} G(y); \frac{\partial \Delta\varrho}{\partial x} = \frac{\Delta\varrho_0}{L} G(y); \frac{\partial P}{\partial x} = \left(\frac{\partial P}{\partial x}\right)_0 G(y)$$

and the relation (14) becomes

$$\varrho_0 g B h_0 - g D (B-D) \Delta\varrho_0 = \left(\frac{\partial P}{\partial x}\right)_0 L. \tag{15}$$

The numerical values are $\varrho_0 g = 10^3$ g cm^{-2} sec^{-1}, $B = 4 \cdot 10^5$ cm, $D = 5 \cdot 10^4$ cm, and $L = 20 \cdot 10^8$ cm. The maximal value of $\left(\frac{\partial P}{\partial x}\right)_0$ is 8 g cm^{-1} sec^{-2} according to equation (6) and fig. 1, and the difference of the sea level across the current can be taken from the presentation of the dynamical topography of the Circumpolar Current given by Deacon [1937b] as 120 cm. These values result in a density difference $\Delta\varrho_0 = 1.8 \cdot 10^{-3}$ across the current, which corresponds well to the observations. With the expression (13) for the density and (12) for the pressure distribution, the velocity components can now be written as

$$u = \frac{1}{f}\left(\varrho_0 g \frac{\partial h}{\partial y} - g D (1 - e^{-z/D}) \frac{\partial \Delta\varrho}{\partial y}\right) \tag{16}$$

$$v = \frac{1}{f}\left(\varrho_0 g \frac{\partial h}{\partial x} - g D (1 - e^{-z/D}) \frac{\partial \Delta\varrho}{\partial x} - \frac{\tau_0^x}{E} e^{-z/E}\right) \tag{17}$$

$$w = -\frac{\partial}{\partial y}\left[\frac{\tau_0^x}{f}(1 - e^{-z/E})\right] + \frac{\beta}{f^2}\left[\varrho_0 g \frac{\partial h}{\partial x} z - g D \frac{\partial \Delta\varrho}{\partial x} z + g D^2 \frac{\partial \Delta\varrho}{\partial x}(1 - e^{-z/D})\right]. \tag{18}$$

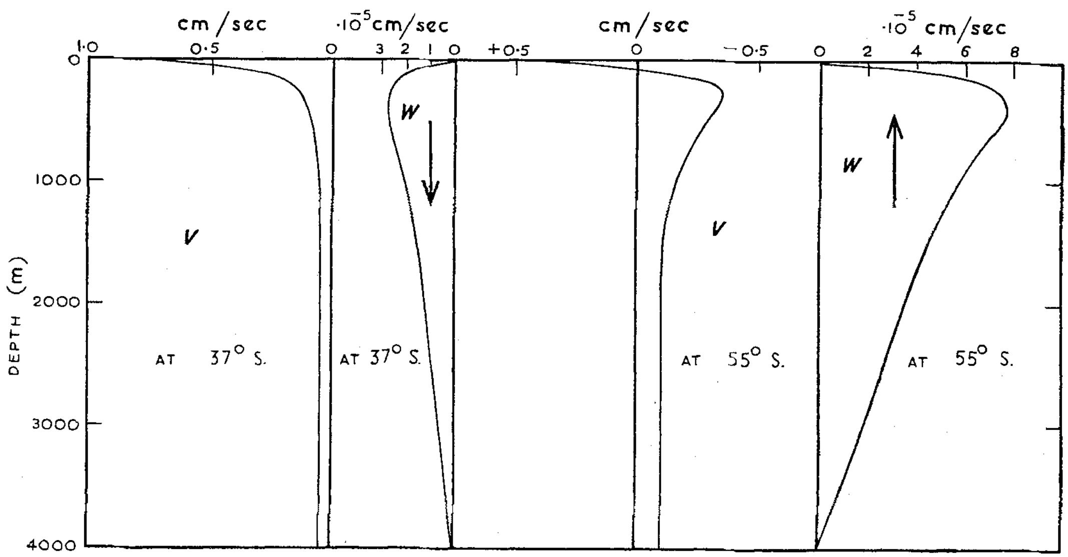

Fig. 2. Vertical distribution of the meridional (v) and vertical (w) velocity in a Sverdrup-type solution, for one position to the north (37° S) and one to the south (55° S) of the maximal westerlies

Using the values of $\frac{\partial h}{\partial x}$ and $\frac{\partial \Delta \varrho}{\partial x}$, as determined above, the vertical distribution of v and w, which is independent of longitude, is shown in fig. 2 for one position north and another south of the maximal westerlies. The velocity distribution at 37° S shows equatorward motions throughout the whole water column, which are strengthened in the Ekman layer, and vertical downward motion in all depths with a maximum at the bottom of the Ekman layer. At 55° S the meridional component is polewards with a maximum just below the Ekman layer; the Ekman layer itself moves equatorwards. The vertical motion is ascending at all depths. It must be noted, that the meridional component of velocity does not vanish at the bottom, because $\varrho_0 h_0 - \Delta \varrho_0 D \neq 0$ and consequently also the zonal motion reaches to the bottom without changing its direction.

The total transport of this model current would be 160 million m³/sec, which is greater than the usually assumed value of 120 million m³/sec and indicates that the average value of the wind stress must be less than 1.0 at the position of the maximal westerlies.

2. Comparison with the Observations. This concept of the Circumpolar Current, obtained as a Sverdrup-type solution of the circulation, explains very well the features of this current, listed below, but there are certain consequences of the solution, which do not seem to agree with the observations and must be investigated more closely. The features explained by the theory are:

1. Mass transports, sea level difference and density gradient across the current are explained quantitatively, and are in agreement with the observations.
2. The theory explains the southward shift of the current.
3. It gives upwelling to the south and sinking to the north of the maximal westerlies.
4. It gives a general northward flow in the Ekman layer under the whole west wind belt.
5. It shows a southward flow of sub-surface and deep water in the range of the current.
6. It shows a northward flow in the whole water column to the north of the maximal westerlies, and this can be taken as indicative of the northward spreading of intermediate water.
7. It shows that the zonal flow reaches to the bottom, even if only with very small velocities, and can, therefore, be influenced by the bottom topography.
8. All deep water and bottom water must be supplied from the western margin of the current, i.e. from the Atlantic Ocean.
9. Even the eddy in the Weddell Sea is indicated in the topography of the sea level shown in fig. 1 for the Atlantic Ocean section.

The consequences which must be investigated more closely are:

1. The Circumpolar Current would have to be situated completely to the south of the maximal westerlies.
2. If the Antarctic Convergence is considered as a line separating ascending motion to the south from descending motion to the north of it, it would have to coincide with the belt of maximal westerlies and to be situated at the northern flank of the current.
3. This solution gives no mechanism which would allow deep water from the Indian and Pacific Oceans to penetrate southwards. But a more detailed solution, including the influence of the land barriers formed by Africa and Australia, might show that such a flow is possible in deep western boundary currents.

In order to check the first two consequences of this model the positions of the current, of the belt of maximal westerlies, and of the Antarctic convergence must be compared. A chart of the mass transports in the Antarctic Circumpolar Current has recently been drawn by Kort [1959]. It is more comprehensive than the map given by Sverdrup (Sverdrup, Johnson, Fleming, [1946], fig. 163) because the more recent "Discovery" sections have been included as well as the Russian observations. Kort's chart shows that the pure circular flow of the Circumpolar Current occurs between the transport lines 0 and 14, each representing 10 million m³/sec. In order to avoid disturbances at the boundaries of the current, the position of the transport lines 2 and 12 has been determined for every 10° of longitude and is plotted in fig. 3 together with the transport line 7, representing the centre of the current. This map of the position of the Circumpolar Current shows that the current shifts northwards in the Atlantic Ocean, but reaches its northernmost position only in the Indian Ocean at 60^0 E, and from there it flows southwards, reaching its southernmost position south of New Zealand. From there it is bent again a little to the north before approaching the Drake Passage. There is no sign of a regular shift of the current towards the south during its flow from the Atlantic Ocean to the Drake Passage.

The position of the maximum westerly winds has recently been mapped by Wexler [1959] and was calculated from average sea level barometric pressure data. It is also represented in fig. 3 and shows a southward shift of the belt of maximal westerlies from between 40^0 to 45^0 in the central South Atlantic Ocean to between 55^0 and 60^0 in the eastern South Pacific Ocean. This shift of the maximal westerlies is a very remarkable feature and until now has not been related to the shift of the Circumpolar Current towards the south. In all treatments of the current the west winds have been considered to be purely zonal.

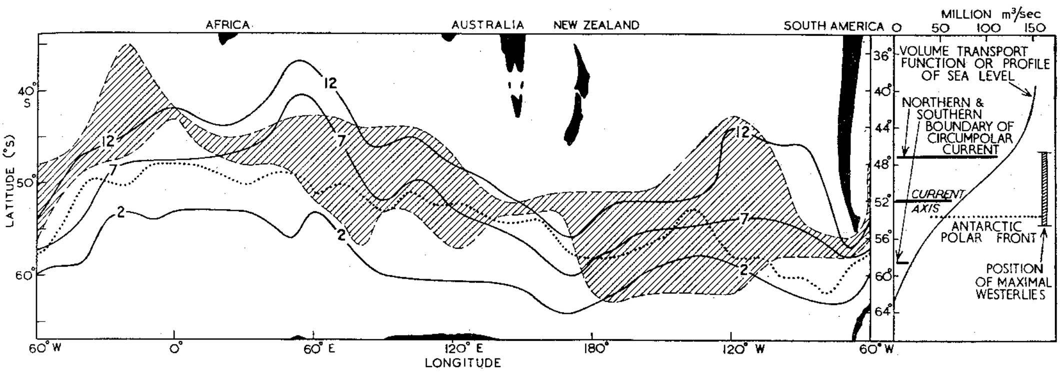

Fig. 3. Position of the Antarctic Circumpolar Current, indicated by means of the transport lines of 20, 70, and 120 million m^3/sec relative to the Antarctic continent after Kort [1959]. Heavy lines: position of the belt of maximal westerlies after Wexler [1959], broken lines and shaded area: position of the Antarctic Polar Front (Antarctic convergence, after Mackintosh [1946]), dotted line: the diagram on the right margin shows the average positions of these features

To complete the picture the position of the Antarctic convergence, according to Mackintosh [1946], has been entered on fig. 3. This position of the temperature front has been confirmed by more recent data and bathythermograph sections as shown by Wexler [1959]. On the right margin of fig. 3 the average positions of the Circumpolar Current, of the belt of maximal westerlies, and of the Antarctic Polar Front have been drawn, and conclusions about their relative positions can now be drawn. It can clearly be seen that the centre of the west wind belt almost coincides with the current axis or with the maximal meridional gradient of the sea level. Eighty million m^3/sec flow south of the centre of the west wind belt and 60 million m^3/sec to the north of it. The Antarctic Polar Front is situated to the south of the current axis and clearly lies south of the maximal westerlies. Consequently it must be concluded that a simple Sverdrup-type solution for the Antarctic Circumpolar Current, requiring the current to be entirely to the south of the maximal westerlies, cannot describe the current satisfactorily, although it explains many of the features of the current.

Any theory to explain the Circumpolar Current must show the current coinciding approximately with the west wind belt and the Antarctic Polar Front being situated south of the current axis. The concept of the west wind belt being purely zonal must be rejected, because this belt also shows a southward shift. However, this shift, which coincides with that of the current, no longer requires the compensation of the wind stress in a zonal pressure gradient, which is a main feature of the Sverdrup-type solution and causes the southward shift of the current. There will, however, be a zonal pressure gradient, which is a necessity in a non-zonal circulation, and in which a part of the wind stress is compensated, but another part of the wind stress will be compensated by friction.

3. A Solution with Friction. When discussing the Antarctic Circumpolar Current, Sverdrup (Sverdrup, Johnson, Fleming, [1946], p. 621) points out, that this current cannot be explained without taking friction into account. In order to establish a frictional model of the current, which should be as simple as possible, friction is taken as proportional to the velocity. The linearized stationary equations (1) and (2) for the mass transport can then be written in the form

$$f\, M^y + r\, M^x = -\frac{\partial P}{\partial x} + \tau^x \tag{19}$$

$$-f\, M^x + r\, M^y = -\frac{\partial P}{\partial y} + \tau^y \tag{20}$$

where r is the friction coefficient. Again only a zonal wind stress will be considered ($\tau^y = 0$). Elimination of M^x and M^y from (19) and (20) gives

$$(f^2 + r^2)\, M^x = -r\frac{\partial P}{\partial x} + r\tau^x + f\frac{\partial P}{\partial y} \tag{21}$$

$$(f^2 + r^2)\, M^y = -f\frac{\partial P}{\partial x} + f\tau^x - r\frac{\partial P}{\partial y}. \tag{22}$$

Since r^2 is small compared to f^2 the introduction of (21) and (22) into the equation of continuity (3), gives the following differential equation for P:

$$r\left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2}\right) + \beta\left(\frac{\partial P}{\partial x} + \frac{2\,r}{f}\frac{\partial P}{\partial y}\right) = f\frac{\partial \tau^x}{\partial y} + \beta\tau^x + r\frac{\partial \tau^x}{\partial x}. \tag{23}$$

Similar differential equations can also be obtained for M^x and M^y:

$$r\left(\frac{\partial^2 M^x}{\partial x^2} + \frac{\partial^2 M^x}{\partial y^2}\right) + \beta\frac{\partial M^x}{\partial x} = \frac{\partial^2 \tau^x}{\partial y^2} \tag{24}$$

$$r\left(\frac{\partial^2 M^y}{\partial x^2} + \frac{\partial^2 M^y}{\partial y^2}\right) + \beta\frac{\partial M^y}{\partial x} = -\frac{\partial^2 \tau^x}{\partial x \partial y}. \tag{25}$$

In the frictionless case, discussed in section 1, the distributions of pressure and of the components of the mass transport result from simple integrations, while differential equations have to be solved, when friction is taken into account.

In order to obtain a solution characteristic of the Circumpolar Current, a wind stress of the form

$$\tau^x = \tau_0 \cos k\,(y - \alpha x) \tag{26}$$

will be assumed showing a gradual linear southward shift of the position of the maximal westerlies, as found by Wexler [1959], and represented in fig. 3. Entering this wind distribution into equation (23) it is evident that P must also be of the form

$$P = P\,(y + \alpha x) = P(\zeta) \tag{27}$$

and consequently equation (23) becomes

$$r\,(1 + \alpha^2)\frac{\partial^2 P}{\partial \zeta^2} + \beta\left(\alpha + \frac{2\,r}{f}\right)\frac{\partial P}{\partial \zeta} = (f + \alpha r)\frac{\partial \tau^x}{\partial \zeta} + \beta\tau^x. \tag{28}$$

The solution of this equation is of the form

$$P = A \sin k\zeta + B \cos k\zeta. \tag{29}$$

Using numerical values $\tau_0 = 0.8$ g cm^{-1} sec^{-2}, $f = 10^{-4}$ sec^{-1}, $\beta = 1.6 \cdot 10^{-13}$ cm^{-1} sec^{-1}, $r = 10^{-6}$ sec^{-1}, $\alpha = 1/20 = 0.05$ corresponding to a southward shift of the wind belt by 1000 km along a distance of 20,000 km, and $k = 10^{-8}$ cm^{-1} corresponding to a width of the wind belt of about 30 degrees of latitude, it follows that $A = 6.65 \cdot 10^9$ and $B = 1.28 \cdot 10^9$. With the expression (29) for P the distribution of M^x and M^y can be calculated from (21) and (22). It can be seen that M^x is completely determined by the term $f\frac{\partial P}{\partial y}$, because the two other terms are less than 1/100 of this term. Consequently, the zonal motion can be considered as almost geostrophic. The conditions are completely different in the case of the meridional

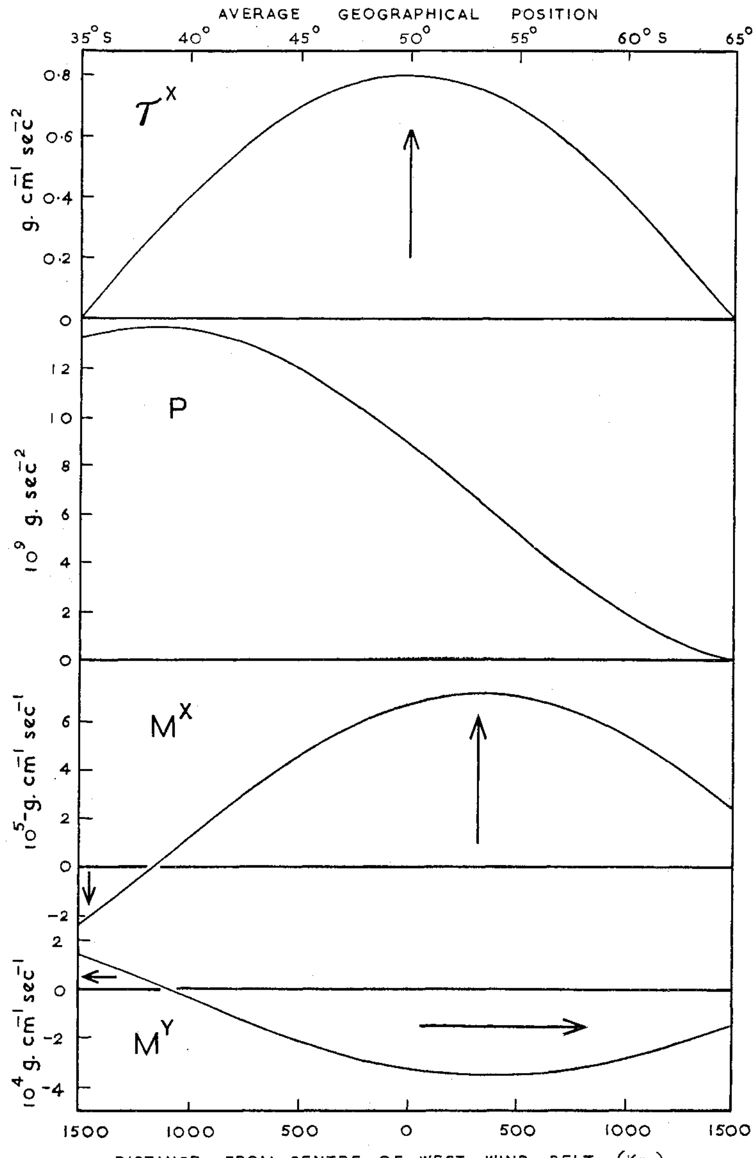

Fig. 4. Solution for the Antarctic Circumpolar Current taking friction into account, showing meridional distribution of zonal wind stress (τ^x), of vertically integrated pressure (P), of zonal (M^x) and meridional (M^y) component of mass transport relative to the centre of the west wind belt

motion, where all three right hand terms in equation (22) are of almost the same order and have to be taken into account.

In fig. 4 the meridional distributions of the wind stress τ^x, of the pressure P and of the components of the mass transport M^x and M^y are shown relative to the centre of the west wind belt. With these values a total transport of the Circumpolar Current of 140 million m³/sec results. The centre of the current, that means, the maximal zonal velocity, occurs a little to the south of the position of the maximal westerlies, which is in accordance with the observations, see fig. 3. The meridional motion is to the south, and indicates the southward transport of water required to produce the southward shift of the whole current. In the Ekman layer, however, the flow is to the north. As the current in the Atlantic Ocean is completely to the north of 55° S and off the Drake Passage completely to the south of 55° S, the total meridional transport across 55° S must be equal to the total zonal transport of the current. There is a zonal pressure gradient, which is α times that of the meridional gradient. In the northernmost part of the west wind belt, transports to the west and to the north occur, and the sea level shows a small northward slope. Such a slope is, in fact, indicated in the profiles of isobaric surfaces across the Circumpolar Current, shown by Sverdrup (Sverdrup, Johnson, Fleming [1946], fig. 162). On the other hand, this effect might result from neglecting the homogeneous solution of equation (28). It is only by means of the homogeneous solution that boundary conditions can be taken into account. Such boundary conditions must in any case arise, when the influence of the coast line of South America and also that of the other continents is considered in establishing a more detailed solution. The consideration of boundary conditions in connection with the solution of the homogeneous equation would then result in a Sverdrup-type solution, in which zonal pressure gradients appear. But such a solution would be of importance only in the northern portions of the Circumpolar Current and would form the connection with the solution for the subtropical gyral.

From this application of a simple frictional theory to the Circumpolar Current, it can be concluded, that the current practically coincides with the centre of the west wind belt, and that its southward shift is due to the southward shift of the whole wind system. The relative position of current and west wind belt is in full agreement with the observations, fig. 3. This shows that a pure Sverdrup-type solution, in which the Circumpolar Current has to be situated completely to the south of the maximal westerlies, cannot be applied, but that friction has to be taken into account, resulting in a general coincidence of current and west wind belt. But as the current reaches down to the bottom, the topography can influence its position in certain places, causing deviations from the general trend of the current, as shown by Sverdrup (Sverdrup, Johnson, Fleming [1946], p. 616).

4. The Transverse Circulation. In order to get information about the vertical structure of the current in the frictional case, the equations for the velocity components have to be investigated, and with friction proportional to velocity the equations corresponding to (19) and (20) are:

$$f\varrho v + r\varrho u = -\frac{\partial p}{\partial x} - \frac{\partial \tau^x}{\partial z} \tag{30}$$

$$-f\varrho u + r\varrho v = -\frac{\partial p}{\partial y} - \frac{\partial \tau^y}{\partial z}. \tag{31}$$

The equation of continuity is used in the form

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{32}$$

and the pressure p is given by

$$p = \varrho_0 g h + \int_0^z \varrho g \, dz \tag{33}$$

where h is the topography of the sea surface. It has been demonstrated that the Circumpolar Current shows the same shift to the south along its eastward flow as the west wind belt.

Therefore, it is no restriction of generality, if the co-ordinate system is turned by a small angle, so that the x-axis coincides with the isobars. This angle is equivalent to the value α, indicating the southward shift in section 3, equation (26), and amounts to 2.9 degrees. Consequently all derivatives with regard to x vanish, $\frac{\partial p}{\partial x} = 0$ and $\frac{\partial u}{\partial x} = 0$. With this, and assuming a wind stress in the x-direction only, $\tau^y = 0$, equations (30) to (32) simplify to

$$f\varrho v + r\varrho u = -\frac{\partial \tau^x}{\partial z} \tag{34}$$

$$-f\varrho u + r\varrho v = -\frac{\partial p}{\partial y} \tag{35}$$

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \tag{36}$$

With the natural boundary conditions $w = 0$ at $z = 0$, and $z = B$, where B is the depth of the ocean, equation (36) is transformed into the statement

$$\frac{\partial}{\partial y}\int_0^B v\,dz = 0$$

and because $v = 0$ at the Antarctic continent, it follows that

$$\int_0^B v\,dz = 0. \tag{37}$$

As we are not interested primarily in the zonal components of velocity, u will be eliminated between (34) and (35) giving an equation for v

$$(f^2 + r^2)\,\varrho v = -f\frac{\partial \tau^x}{\partial z} - r\frac{\partial p}{\partial y}. \tag{38}$$

With the condition (37) a relation between the wind stress and the meridional pressure distribution results from (38):

$$\int_0^B \frac{\partial p}{\partial y}\,dz = \frac{f}{r}\,\tau_0^x \tag{39}$$

where τ_0^x is the zonal wind stress component at the surface.

Introducing p according to (33), the following expression for h is obtained:

$$\varrho_0 g B\frac{\partial h}{\partial y} = \frac{f}{r}\,\tau_0^x - \int_0^B\int_0^z g\,\frac{\partial \varrho}{\partial y}\,dz\,dz. \tag{40}$$

This equation states that for a given (observed) distribution of the density ϱ the elevation of the sea surface h can be calculated, if the wind stress τ_0^x is known. Thus the topography of the sea surface is no longer a free parameter, but is determined by the distribution of mass and the wind stress at the surface. This allows its calculation along a meridional section with primary motion in a zonal direction, and finally the calculation of the meridional and vertical movements in the plane formed by this section. If the topography of the sea surface is calculated from (40) the velocity components can be found from the equations

$$(f^2 + r^2)\,\varrho u = f\frac{\partial p}{\partial y} - r\frac{\partial \tau^x}{\partial z} \tag{41}$$

$$(f^2 + r^2)\,\varrho v = -f\frac{\partial \tau^x}{\partial z} - rg\varrho_0\frac{\partial h}{\partial y} - rg\int_0^z \frac{\partial \varrho}{\partial y}\,dz \tag{42}$$

$$w = \int_0^z \frac{\partial v}{\partial y} dz. \tag{43}$$

The zonal component u of the velocity is practically given by the term $f \frac{\partial p}{\partial y}$ because the term $r \frac{\partial \tau^x}{\partial z}$ is usually much smaller. This indicates that the zonal component of the motion is almost geostrophic.

For a presentation of the transverse circulation in a meridional plane it is convenient to use a stream function, which can be introduced because of equation (36). With

$$w = \frac{\partial \varphi}{\partial y} \qquad v = -\frac{\partial \varphi}{\partial z} \tag{44}$$

the stream function φ is given by

$$\varphi = -\int_0^z v \, dz. \tag{45}$$

Introducing v from (38) and h from (40) φ can be calculated from

$$(f^2 + r^2)\,\varrho\varphi = f\,\tau^x - rg\varrho_0\,(B - z)\frac{\partial h}{\partial y} + rg\int_B^z\int_0^z \frac{\partial \varrho}{\partial y} dz\, dz. \tag{46}$$

For practical calculations the dependence of τ^x on z must be known, and according to Ekman's formula it is assumed to decrease exponentially as

$$\tau^x = \tau_0{}^x\, e^{-z/E} \tag{47}$$

where $\tau_0{}^x$ is the wind stress at the sea surface and E the depth of the Ekman layer. The topography of the sea level can be calculated from the integrated form of equation (40)

$$h = \int_0^y \left(\frac{f\,\tau_0^x}{\varrho_0 g B r} - \frac{1}{\varrho_0 B}\int_0^B\int_0^z \frac{\partial \varrho}{\partial y} dz\, dz\right) dy \tag{48}$$

where $\frac{g}{\varrho_0}\int_0^B\int_0^z \frac{\partial \varrho}{\partial y} dz\, dz = \frac{\partial Q}{\partial y}$ is identical with Jakhelln's function, and can be easily determined from hydrographic data.

The method developed here allows the calculation of the transverse motion in a plane perpendicular to the main motion. The application of Bjerknes' theory gives only the geostrophic currents perpendicular to the hydrographic section. As friction is neglected, no conclusions about the transverse circulation are possible. But also, if friction is taken into account, the main motion is almost geostrophic, as shown above, and is an equilibrium between pressure gradients and Coriolis accelerations. Consequently, friction does not play an important rôle in the balance of the primary motion. On the other hand, friction must be decisive for the development of the secondary motion; this is the motion in a plane, perpendicular to the primary motion, and includes vertical motions and cross components to the main motion. Therefore, the method developed above of calculating the transverse motion taking friction into account can be considered as an extension of Bjerknes' theory.

An application of this method will be demonstrated, using a hydrographic section from Cape Leeuwin, West Australia, to the Antarctic continent, taken by the "Discovery" in May 1932. This section has been discussed by Deacon [1937a] by means of a water mass analysis and by Sverdrup (Sverdrup, Johnson, Fleming [1946]) who calculated the shape of the isobaric surfaces relative to 4000 meters and the zonal components of the geostrophic motion. The first step is the calculation of the topography of the sea surface according to (48). The second term on the right hand side can be calculated from hydrographic data and represents the effect of the distribution of density. It is shown in fig. 5 by the curve marked $\frac{1}{g\,B}(Q-Q_0)$. This curve would give the shape of the sea surface, if no winds were to act and condition (37) were fulfilled. The corresponding meridional circulation is shown in fig. 7. Another curve in fig. 5, marked h^*, gives the topography of the sea surface relative to 4000 decibar. It would now be possible to calculate the topography for a given wind distribution, but as our knowledge about the average wind stresses in Antarctic waters is still meagre, it is more convenient to calculate the wind stress distribution for a given topography of the sea surface. The effect of completely different wind distributions will be discussed in the next section. In order to arrive at a topography of the sea surface, which might best correspond to average conditions, it is assumed that a slow uniform flow of bottom water to the north takes place. With this assumption the layer of no meridional motion is found between 2500 and 3000 m depth. The resulting shape of the sea level is given in fig. 5 by curve h which lies below the curve marked h^*, because of the higher position of the motionless layer. The difference between the curves h and $\frac{1}{g\,B}(Q-Q_0)$ is the effect of the winds on the topography. The wind stress corresponding to the topography h is also given in fig. 5 and shows a distribution very similar to the average wind conditions. Between 38° S and 62° S are west winds, to the north and south of this belt weak east winds. The only anomaly of this distribution is the concentration of the strongest winds in a narrow band, while the climatological data usually give a much smoother distribution.

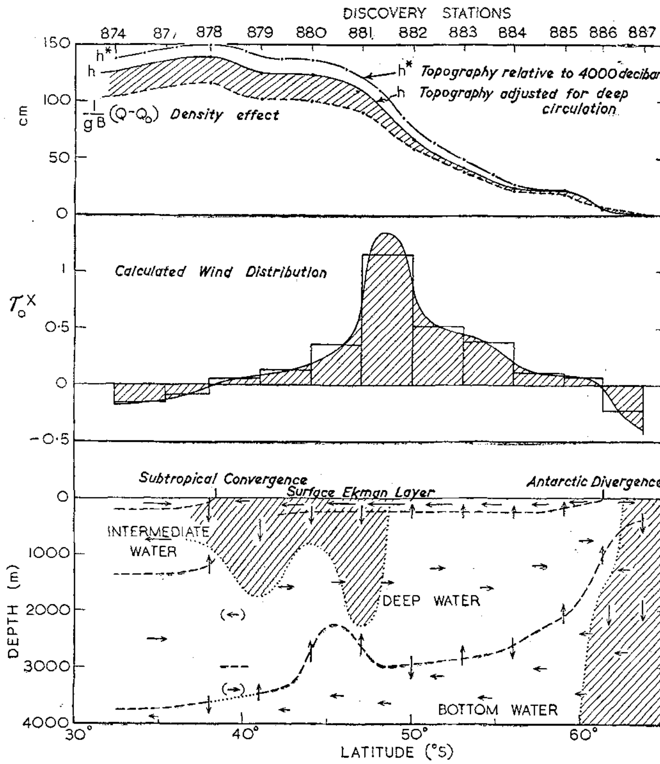

Fig. 5. Topography of the sea surface (h), wind stress distribution (τ^x_0) and transverse circulation in a "Discovery" section from Cape Leeuwin, West Australia, to Antarctica. Areas with prevailing sinking motion are hatched

After the topography h of the sea surface has been established, there is no difficulty in calculating the function φ according to (46) with the assumed stress distribution (47). It is, however, advisable to start the integration from the bottom, in order to attain a higher accuracy in the deeper layers, because the term $f\tau^x$ becomes important only close to the surface. The constants used for this example are: $B = 4000$ m, $\varrho g = 10^3$ g cm^{-2} sec^{-2}, $r = 10^{-6}$ sec^{-1}, $E = 100$ m.

The function φ, representing the secondary circulation in a plane perpendicular to the main motion, is given in fig. 6. For comparison, the distribution of salinity in the same section is shown in the lower part of fig. 6, in which the positions of the temperature maxima and minima are also entered. The figure shows that the strongest meridional flow occurs in the Ekman layer between stations Di 881 and Di 882, where the meridional velocity exceeds 1 cm/sec. To the north of this position the motion is descending, and this area coincides with the sinking of the intermediate water, characterized by the salinity minimum. The descending

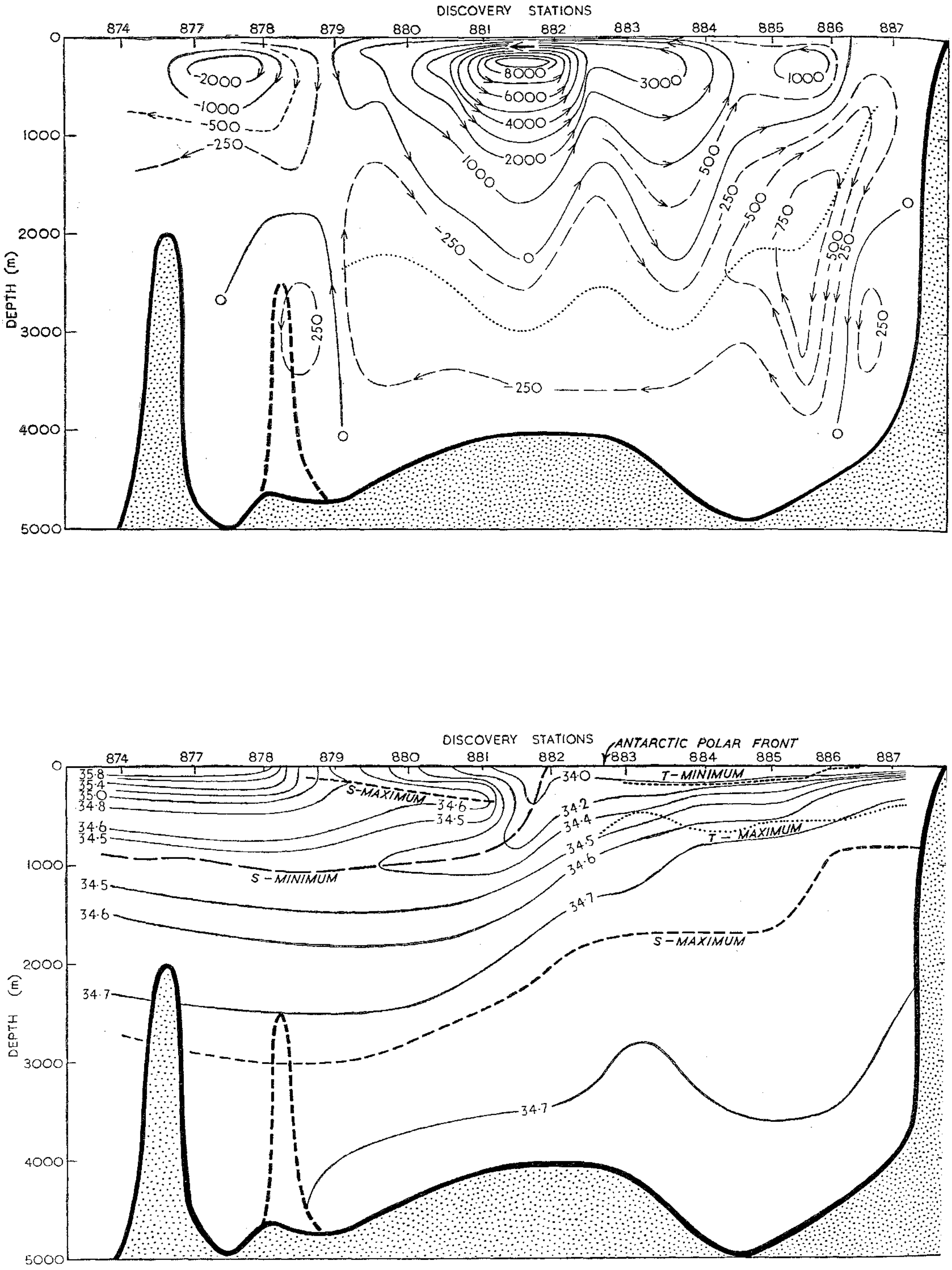

Fig. 6. "Discovery" section from Cape Leeuwin, West Australia, to Antarctica. Upper part: stream lines of the transverse circulation (dotted line shows position of the layer of no meridional motion) Lower part: distribution of salinity and positions of temperature and salinity maxima and minima

motion reaches a velocity of $20 \cdot 10^{-5}$ cm/sec equal to about 5 m per month. Below the depth of the Ekman layer and down to 2500 m depth the motion is polewards and generally ascending. In these depths the deep salinity maximum and the temperature maximum spread to the south. The velocities are below 0.1 cm/sec. Between Stations Di 882 and Di 886 the motion through the bottom of the Ekman layer is ascending, reaching values up to $5 \cdot 10^{-5}$ cm/sec. In this range the motion in the Ekman layer is northwards and in the lower part of the Ekman layer there is a temperature minimum, extending northwards. Parts of the water ascending between Stations Di 886 and Di 887 flow polewards and sink at the Antarctic continent. The sinking velocity is $8 \cdot 10^{-5}$ cm/sec, but most of the sinking water passes over into the ascending deep water and returns with it to higher levels. Only a small fraction of the sinking water reaches depths below 3000 m and spreads northwards. The velocity of this bottom flow is 0.01 cm/sec. North of Station Di 879 the surface flow is polewards, forming a convergence at the position of this station, from which a subsurface salinity maximum spreads polewards. It ends very abruptly at the position, where the intermediate water sinks. Between Stations Di 878 and Di 874 the flow is equatorwards underneath the Ekman layer with velocities of about 0.02 cm/sec, indicating the flow of the intermediate water. There is, however, no obvious connection between the sinking of the intermediate water between Stations Di 881 and Di 882 and its equatorward spreading beneath Stations Di 878 and Di 874. Probably this connection is effected under other wind conditions, and this will be discussed in the next section.

An irregularity is found in the deep flow between Stations Di 878 and Di 879, and is probably due to the submarine elevation rising west of the section to less than 2500 m depth. The densities of the water in these depths are higher to the north than to the south of this elevation, suggesting a connection with higher proportions of the sea bed to the southwest of it. This elevation is shown in fig. 6 by a dashed line.

The meridional components of velocity seem on first sight to be rather small, but when relating them to a width of the ocean of 10,000 km, the following transports are found in the different branches of the circulation:

Ekman layer below maximal west winds: 9.6 million m^3/sec north.
Ekman layer between Stations Di 877 and Di 878: 2.7 million m^3/sec south.
Intermediate Water below Station Di 877: 2.0 million m^3/sec north.
Deep Water below Station Di 884: 2.2 million m^3/sec south.
Bottom Water below Station Di 882: 0.3 million m^3/sec north.

A schematic picture of the water mass structure and of the circulation is given in the lower part of fig. 5. It shows the spreading of the main water masses and the vertical motions across their boundary surfaces. The areas with prevailing sinking motion are hatched. Between the Antarctic divergence in the south and the Subtropical convergence in the north the flow in the Ekman layer is northwards. This flow causes upwelling motion to the south of the maximal westerlies, and sinking motion to the north. The neutral point between these two motions coincides approximately with the boundary of the Antarctic and Sub-Antarctic surface water, and indicates the position of the Antarctic Polar Front, which will be discussed in section 6. The flow of the deep water is polewards and generally ascending. This flow is strengthened by parts of the water descending north of the Polar Front. Bottom water sinks at the antarctic continent, but only a small portion spreads northwards at the bottom. The larger part of the sinking water ascends again underneath the Antarctic divergence. The flow across the interface between deep and bottom water is irregular. The total zonal transport of the Circumpolar Current across this section is 95 million m^3/sec.

5. The Influence of Various Wind Conditions. In the preceding section the transverse circulation of the Circumpolar Current which has been discussed assuming a very delicate balance between winds, pressure distribution and circulation, represents the average conditions. But this will be the exception rather than the rule, and the transverse circulation will develop quite differently under various wind distributions. G. Veronis and Stommel [1956] have investigated the response of a stratified ocean to variable wind stresses. These investigations show that the ocean in mid-latitudes responds barotrophically to periods of the order of months and baroclinically only to periods of several years. Thus, shorter variations of the wind stress – of the order of weeks and months – change the topography of the sea level and the mass transports, but not the distribution of density, that is the structure of mass.

In the further treatment we shall not investigate the non-stationary case, but we shall investigate the stationary circulation pattern, which corresponds to different wind distributions but the same distribution of mass because from repeated sections across the Circumpolar Current it is known that the structure of mass is of a surprising zonal uniformity, and shows only very small seasonal changes. Further it will be assumed that the condition of the continuity of mass is valid in the form

$$\int v \, dz = 0 \tag{37}$$

thus excluding for this study the possibility of an adjustment of the circulation in the zonal direction. We do, however, not generally deny this possibility.

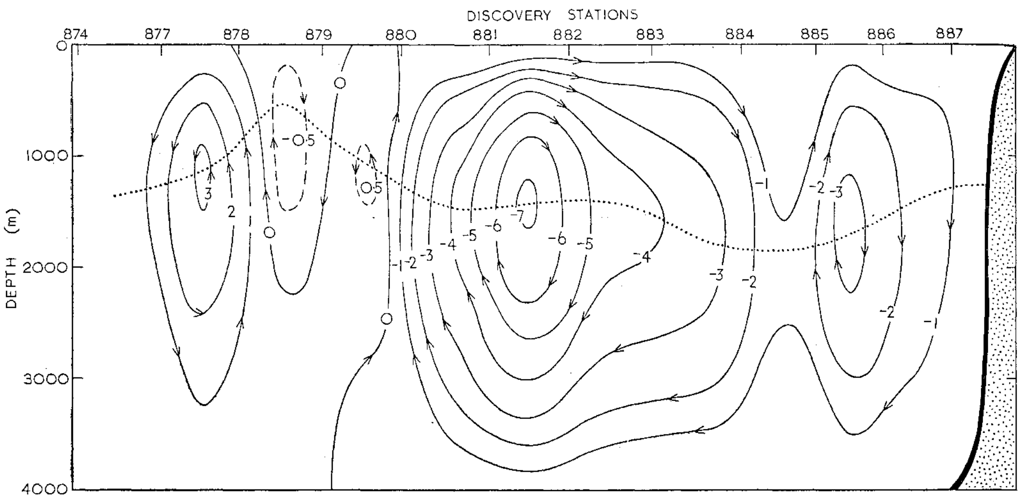

Fig. 7. Stream lines of the transverse circulation along the "Discovery" section from Australia to Antarctica, when no winds are blowing. Dotted line gives the layer of no meridional motion

Three different wind stress distributions will be used in conjunction with the distribution of mass observed along the "Discovery" section treated above, (i) no winds at all, (ii) the west wind belt in a southerly position, and (iii) the west wind belt in a northerly position.

If no winds are blowing, the topography of the sea surface is determined completely by the second term on the right hand side of equation (48), that is by the density effect. The shape of the sea surface is given by the curve marked "density effect" in the upper part of fig. 5. The corresponding transverse circulation is given in fig. 7 and shows a well-developed layer of no meridional motion in depths of about 1500 m. Above this layer the meridional motion follows the surface slope; below it the flow is in the opposite direction. Thus, in the range of the strongest zonal current, the flow is polewards, forming a divergence at the position of Station Di 880 and a convergence along the right flank of the current between Stations Di 883 and Di 884. This circulation pattern with zero or weak winds will be important for the discussion of the Antarctic Polar Front in the next section, because in the case of this flow pattern, the boundary between antarctic and Sub-Antarctic surface water along the right flank of the main current is intensified. To the north of Station Di 880 the flow pattern is irregular, but shows prevailing equatorward motions in depths between 500 and 1500 m, where the intermediate water spreads north. The flow in the deep and bottom layer underneath the Circumpolar Current is northwards.

The pattern of the transverse circulation at an extremely southerly position of the west wind belt – wind maximum in 56° S – is shown in fig. 8. Under the west wind belt the flow is

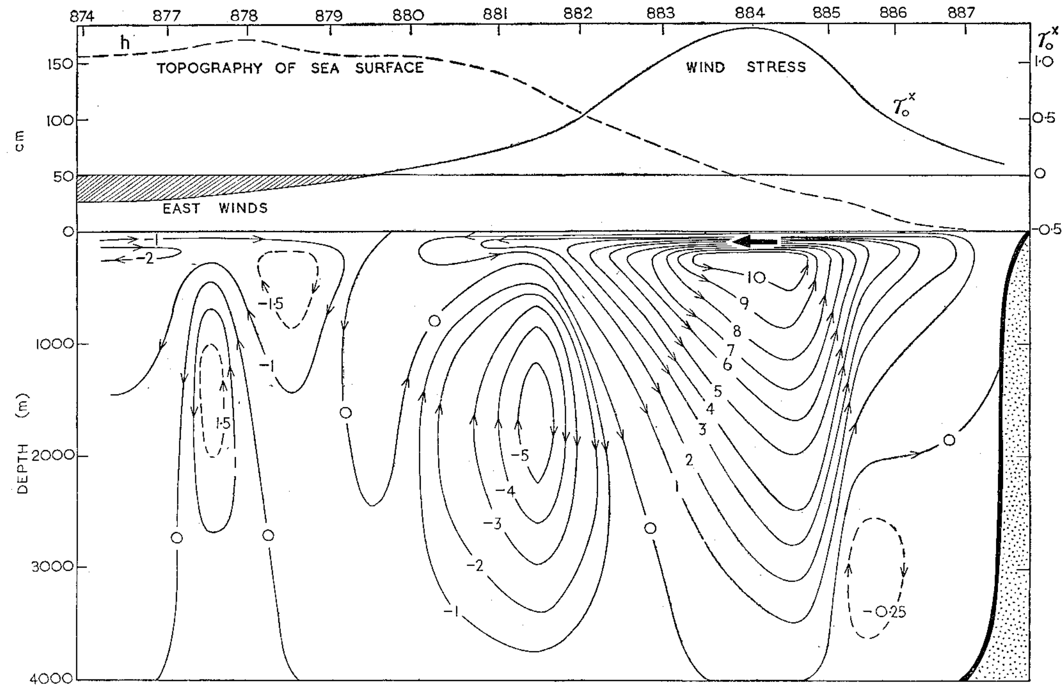

Fig. 8. Stream lines of the transverse circulation along the "Discovery" section from Australia to Antarctica, at a southerly position of the west wind belt. Wind stress distribution and topography of the sea surface are given in the upper part

northwards within the Ekman layer with a divergence south of the main current, reaching right to the Antarctic continent. The convergence to the north of the main current enables Antarctic surface water to sink along the position of the Antarctic Polar Front, which in this case is a convergence. Underneath the Ekman layer the flow is polewards. No layer of zero meridional motion is formed. North of Station Di 880 the flow is polewards in the Ekman layer and northwards in depths between 500 and 1500 m, indicating the northward spreading of the intermediate water.

The third case to investigate is the pattern of the transverse circulation at a northerly position of the west wind belt – 43° S in fig. 9. The flow in the Ekman layer under the west wind belt is again north. In the range of the main current, which lies in this case south of the maximal westerlies, the motion is divergent. Consequently, ascending movements occur in the range of the Antarctic Polar Front, which indicates the water mass boundary between the Antarctic and Sub-Antarctic surface water. Underneath the Ekman layer the flow is polewards and ascending, thus carrying deep water into a position below the Antarctic divergence. This divergence is developed between Stations Di 884 and Di 885; south of it the surface flow is polewards under the east winds. Sinking occurs along the Antarctic continent or along the ice edge. South of Station Di 882 a layer of no meridional motion is developed in about 2000 m depth, through which bottom water ascends into the range of the deep water. It must, however, be borne in mind that no individual water particle would complete the circuit around one of the stream lines because of the small velocities involved, and because the wind pattern and consequently the circulation pattern would change before even a fraction of the circuit could be completed. Therefore, it is not likely that sinking of surface water down to the very bottom occurs at the Antarctic continent, but it can be assumed that under certain conditions – well developed east wind along the Antarctic continent – descending motion prevails for a while. In this example the descending motion between Station Di 887 and the Antarctic continent would have a velocity of $12 \cdot 10^{-5}$ cm/sec, which would result in a vertical

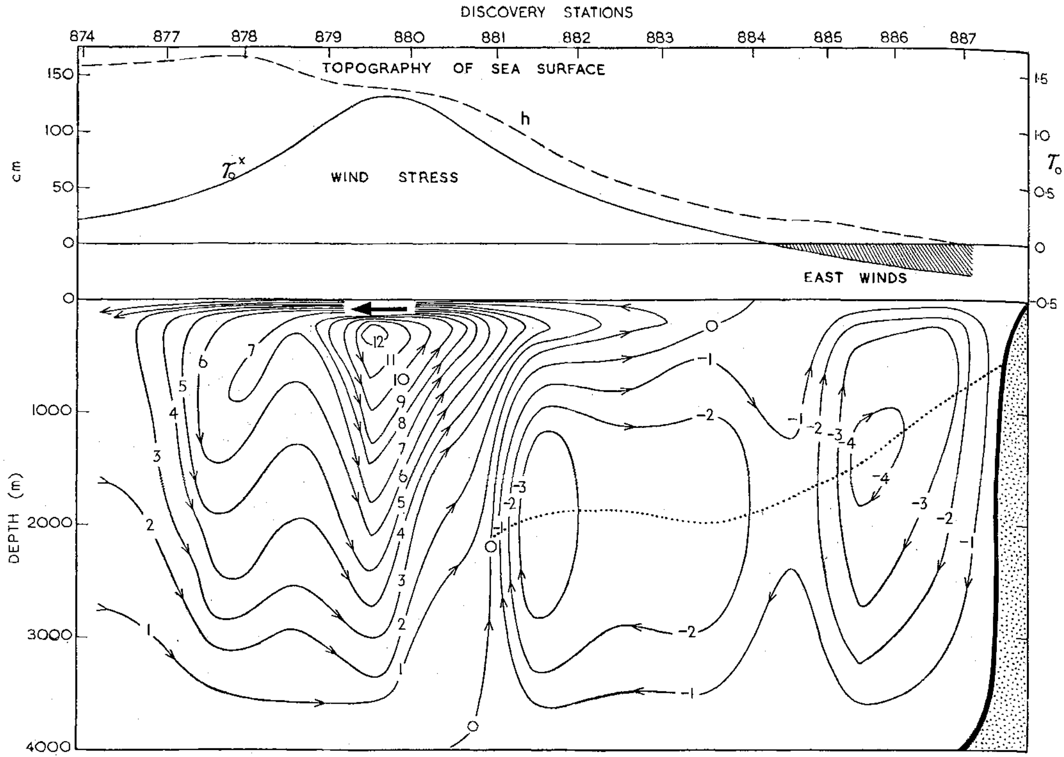

Fig. 9. Stream lines of the transverse circulation along the "Discovery" section from Australia to Antarctica, at a northerly position of the west wind belt. Wind stress distribution and topography of the sea surface are given in the upper part. The dotted line shows the layer of no meridional motion

displacement of a particle by only 3 m during one month, an effect, which would not even be observable.

A comparison of all these cases shows that the positions of the surface divergences and convergences associated with the Ekman drift current vary considerably. Thus, at the position of the boundary between antarctic and sub-antarctic surface water, ascending motion occurs when the west wind belt is shifted northwards, and descending motion when the west winds are south of their normal position or when the winds are weak. The Antarctic divergence is strongly developed when the west wind belt is north of its normal position and east winds blow along the Antarctic continent. The flow in the deep water is always polewards, but it is strengthened underneath the west wind belt and corresponds also directly to its strength. A northward flow of intermediate water takes place in depths between 500 and 1500 m when the west wind belt is displaced to the south or when the winds are weak. This discussion of the transverse circulation in the range of the Circumpolar Current shows clearly that the main features and the different branches of the circulation are quite differently developed under various wind conditions. Consequently, only the consideration of the influence of different wind stress distributions can lead to an understanding of certain phenomena.

6. The Antarctic Polar Front. Around the Antarctic continent a well developed front is usually formed at the boundary between the Antarctic surface water and the Sub-Antarctic surface water, indicated at the surface by a discontinuity in temperature. The position of this line has been carefully determined and charted by Mackintosh [1946], it is usually called the Antarctic convergence and its position is shown in fig. 3. Along this line the Antarctic surface water because of its higher density is thought to sink underneath the Sub-Antarctic surface water, forming the antarctic intermediate water, which spreads northwards and is characterized by a salinity minimum. But Deacon ([1933], p. 221) pointed out that the Antarctic intermediate water has its origin in a region of intense mixing just north of this front. The fact that the sinking of the intermediate water, indicated by a downward bend of the isohalines, occurs north of the position of the temperature front can be seen on many of the "Discovery" sections presented by Deacon [1937a]. The salinity section, given in the lower part of fig. 6, shows this situation clearly but it shows also that the salinity maximum extending southwards from the Subtropical convergence, ends very abruptly when coming into the range of descending motions between Stations Di 881 and Di 882. This indicates a very strong mixing in this area where the zonal flow of the Circumpolar Current is strongest.

After more detailed data on the structure of this temperature front became available from bathythermograph observations Wexler [1959] was able to demonstrate the existence of cold cores just to the south of the position of the strongest surface temperature gradient, indicating ascending motion. He concluded that this front is a divergent phenomenon. There can be no doubt about the fact that with strong west winds the drift current within the Ekman layer is divergent to the south of the maximal westerlies, thus causing upwelling. On the bottom of the Ekman layer, in depths of about 100 m, a very well-developed temperature minimum exists at the bottom of the Antarctic surface water (see fig. 6, lower part). If the Ekman layer is divergent due to the action of winds, patches of this water can rise to the surface, or at least near to it, producing the temperature pattern observed by Wexler. But this divergence neither explains the existence of a sharp temperature front, nor the formation and sinking of intermediate water to the north of this front.

If one considers a pure Ekman drift current in the surface layer, flowing under the influence of a west wind belt, the meridional motion is divergent to the south of the maximal westerlies and convergent to the north of them. This would explain the observations of upwelling to the south of the maximal westerlies, discussed by Wexler, and the sinking of intermediate water to the north of them. But there would be no reason at all for the formation of a temperature front at the neutral point between ascending and descending motion.

The formation of a strong water mass boundary, from here on called the Antarctic Polar Front, can, however, only be explained by converging motions, and Sverdrup (Sverdrup, Johnson, Fleming [1946], p. 618) pointed out that the observed southerly component of the zonal flow just to the north of the front must be associated with its development. An inspection of charts of the surface currents, as drawn by Schott [1942, 1943], shows that the eastward surface flow between the Subtropical convergence and the Antarctic Polar Front is divergent, thus having a northerly component in its northern, and a southerly component in its southern part. The reason for this divergence is not yet quite clear, but it might be associated with a divergence of the mass transport, situated near the centre of the west wind belt, which appears in the Sverdrup-type solution, given by Stommel [1957] and discussed in section 1. This southward component of the surface flow just to the north of the Antarctic Polar Front leads Sverdrup to the conclusion that a weak thermohaline circulation might be developed which carries the light sub-antarctic surface water to the south, where it converges with the northward flowing Antarctic surface water.

Another explanation of this meridional circulation, used by Sverdrup for the interpretation of the Polar Front, has been given by K. Wyrtki [1960a] taking frictional effects into account. In the frictional case the motion is no longer purely geostrophic but has a down-slope component. During periods of weak west winds the down-slope component of the velocity will be stronger than the northward drift current velocity, thus resulting in a divergence to the north of the strongest meridional pressure gradient and in a convergence to the south of it. This down-slope surface flow is certainly conditioned by the distribution of mass and by the topography of the sea surface, as observed in sections across the Circumpolar Current, but it is effected by friction. When interpreting the Antarctic Polar Front Sverdrup called this circulation thermohaline, but it seems to be advisable to restrict the use of the term thermohaline somewhat, rather than to use it for any type of transverse circulation associated with a certain distribution of mass.

The transverse circulation within the Circumpolar Current under the influence of different wind distributions, as discussed in the previous section, will now enable us to relate the various diverging interpretations of the Polar Front to these wind patterns. Anticipating the result of this discussion, it can be said that all three interpretations are valid, but apply at different times, depending on the wind conditions. Consequently, they will be jointly used for the explanation of the Antarctic Polar Front and of the related transverse circulation.

In the case of weak west winds, fig. 10A, the Ekman drift current will have a northward component on both sides of the main current. But in the range of the strongest meridional pressure gradient, corresponding to the axis of the main zonal current, the surface flow will be southwards, thus forming a convergence to the south of the main current and a divergence to the north. This convergence will intensify the Polar Front, and both Antarctic and Sub-

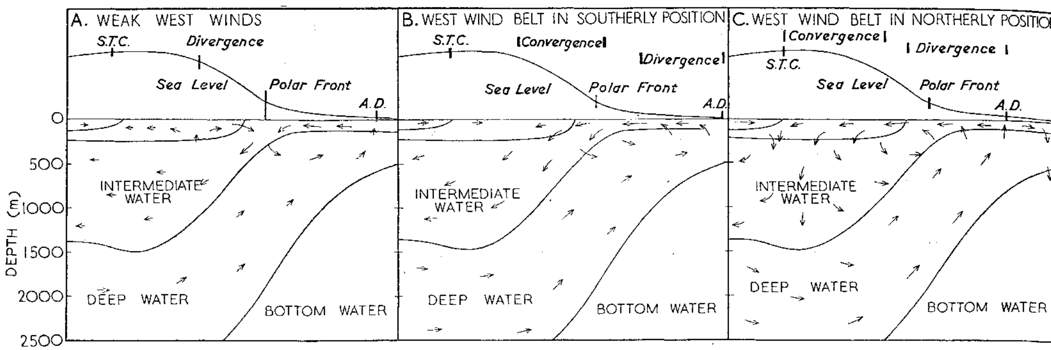

Fig. 10. Schematic presentations of the transverse circulation in the range of the Circumpolar Current at different wind conditions. Upper part: topography of sea level and positions of convergences and divergences. Subtropical Convergence (S.T.C.), Antarctic Divergence (A.D.). Lower part: transverse circulation and boundaries of main water masses

Antarctic surface water can mix and sink at this position. The northward-flowing Antarctic surface water will cause an ascent of deep water and the formation of the Antarctic divergence near the ice edge. The poleward flow of deep water and the equatorward flow of intermediate water will be weak, and the Subtropical convergence will not be very pronounced. This circulation pattern corresponds best to the interpretation given by Sverdrup [1934] and Wyrtki [1960a] and is based on a consideration of the transverse circulation near the centre of the main zonal current. The consequence of this explanation is that the Polar Front has to be situated slightly to the south of the centre of the Circumpolar Current, and this is in full agreement with the observations, as shown in fig. 3. A diagram giving G.E.K. vectors along a section across the Circumpolar Current along 20° E (B. Maximov [1959]) shows clearly that the meridional components of the motion are southwards between 49° and 51° S, where the temperature diagram indicates the Antarctic Polar Front, thus confirming the interpretation given above of this front. To the north as well as to the south of this belt, the meridional components of the motion are north. There is a convergence at 51° S near the position of the Polar Front and a divergence at 49° S.

If the west winds are strongly developed and in a southerly position, a circulation pattern results as sketched in fig. 10B. In this case, a convergence develops north of the maximal westerlies and a divergence to the south of them, extending right to the ice edge. The neutral point between ascending and descending motion will be situated south of the position of the Polar Front, which must move slowly north, but stays in the range of sinking motion. In this case chiefly ntarctic Asurface water will sink near the Polar Front, while the Sub-Antarctic surface water is just driven northward by the winds. The strong divergence south of the maximal westerlies draws up considerable amounts of deep water, which flows polewards underneath the Circumpolar Current and ascends south of it. The Subtropical convergence will be weakly developed. This is the circulation pattern, which Deacon [1937a] uses for the interpretation of the Polar Front. There is no doubt about the fact that the circumpolar west winds cause this ascent of deep water, and further north the sinking of intermediate water, and maintain the strong baroclinity of the ocean underneath. The implications of this wind system on the deep circulation in the ocean have been discussed by Wyrtki [1960b] showing that even the flow of deep water has to be explained by the action of the winds. The submarine waterfall, mentioned by Deacon to illustrate the downward sliding of Antarctic surface water over the steep ascent of the warm deep water, is certainly most strongly developed at this southerly position of the west wind belt.

At a northerly position of the west wind belt (fig. 10C) the system of a divergence and a convergence in the surface flow will also be shifted to the north. Consequently, the Polar Front must come in the range of divergent motion, and water from the bottom of the Ekman layer, where a temperature minimum is found, can ascend. This circulation pattern is that discussed by Wexler [1959] when he gives evidence of ascending motion just to the south of the Polar Front. At a northerly position of the west wind belt, east winds will develop near the Antarctic continent, causing a departure of the Antarctic divergence from the ice edge and poleward movements of the surface water. A weak convergence will develop along the ice edge in this case, as described by G. Koopmann [1953]. The poleward flow and the ascending motion in the deep water will be comparatively strong, while the northward flow of intermediate water is interrupted. The northerly position of the convergence in the Ekman layer will also condition an intensification of the Subtropical convergence.

The discussion of these three cases demonstrates, how the various approaches towards an interpretation of the Antarctic Polar Front can be combined into one general picture, taking the variability of the wind field into account. There are, however, some problems in connection with the development of the Polar Front, which cannot yet be solved, and the main question seems to be, whether the Circumpolar Current is a single straight current, or whether it is an eddy system, similar to the Gulf Stream south of Newfoundland, or even a multiple current. Such a structure seems to be indicated in bathythermograph sections which, as Wexler [1959] points out, show a streakiness of the flow. In this connection, however, the question arises whether or not the Polar Front is a continuous line, or whether it disappears after a certain length and is formed again at another position, as seems to be the case with the Gulf Stream front (W. S. von Arx, D. F. Bumpus and W. S. Richardson [1955]). To decide about this question, a two-dimensional pattern of the temperature distribution at the surface must be obtained, and this is probably only possible by the use of airborn radiation thermometers. These few remarks demonstrate, however, that there are many more problems to be solved in connection with the Circumpolar Current.

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Hydrochemische Untersuchungen im Maracaibo-See

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Zusammenfassung. Nach einer kurzen Beschreibung der Geographie des Maracaibo-Sees werden die Ursachen, die den Salzgehalt des Sees beeinflussen, abgehandelt. Die chemische Untersuchung des Seewassers an fünf verschiedenen, weit voneinander entfernten Punkten ergibt, daß der Salzgehalt von S nach N stetig zunimmt. Im Zentrum des Sees finden sich überraschenderweise ein ziemlich hoher Salzgehalt und darüber hinaus reichlich Ammoniak und Schwefelwasserstoff. Die Anwesenheit dieser beiden Substanzen läßt an ein Massensterben von maritimen Lebewesen in dieser Gegend denken. Es werden frühere Untersuchungen bestätigt, nach denen zur Zeit der Zufluß an Süßwasser die Verdampfung übertrifft. Wegen des hohen Salzgehaltes kommt eine Verwendung des Seewassers als Trinkwasser oder auch für industrielle und landwirtschaftliche Zwecke nicht in Frage. Der Salzgehalt hat eine verstärkte Korrosion der im See errichteten Kunstbauten (Bohrtürme, Pumpstationen usw.) zur Folge, da er darüber hinaus noch die Entwicklung von das Baumaterial angreifenden Bohrwürmern begünstigt.

Hydrochemical investigations in Lake Maracaibo (Summary). After a concise description of the geography of Lake Maracaibo the causes are discussed which are influencing the salinity of the lake's water. The chemical analysis of five water samples taken at five different widely spaced places of the lake shows that the salinity is increasing from south to north. The central region of the lake is characterized by rather high a salinity – what is surprising – and, in addition, by a high contents of ammonia and hydrogen sulphide. The presence of these two substances suggests the death in masses of the maritime living beings at this region. Former investigations according to which the inflow of fresh water exceeds evaporation are verified. Owing to the high salinity the water of the lake is not suitable to be used as drinking water or for industrial or agricultural purposes. The high corrosion the technical constructions (boring towers, pumping stations etc.) in the lake are subject to, is likewise due to the high salinity which, in addition, advances the propagation of wood worms spoiling the building material.

Recherches hydrochimiques dans le Lac Maracaibo (Résumé). Après avoir donné une description concise de la géographie du Lac Maracaibo, on discute les causes qui influencent la salinité de l'eau du Lac. Les analyses chimiques de cinq échantillons de l'eau, pris à grands espaces à cinq endroits différents du lac, nous montrent que la salinité s'accroit d'une manière suivie en allant du sud au nord. La région centrale du lac est caractérisée par une hauteur assez frappante de salinité et, de plus, par une grande teneur en ammoniaque et en hydrogène sulfuré. La présence de ces deux substances semble indiquer que les êtres maritimes ayant vécu à cet endroit ont succombé en masses. Des recherches antérieures selon lesquelles l'afflux des eaux douces excède l'évaporation, se vérifient. La haute salinité ne permet pas d'utiliser l'eau du lac pour les besoins des hommes ni pour les besoins de l'industrie ou de l'agriculture. Elle est également la cause d'une forte corrosion des bâtiments industriels (p.e. tours de sondage, stations d'épuisement etc.) et, de plus, elle contribue à augmenter la propagation des vers du bois qui endommagent les matériaux de construction.