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The wind-driven circulation in the Weddell–Enderby Basin*

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Abstract—The cyclonic wind pattern over the Weddell–Enderby Basin induces a southerly Sverdrup transport. With the Kerguelen Plateau as an eastern boundary at 70°E, the streamlines of Sverdrup transport are constructed from monthly averaged wind data on a 5° grid. The resulting cyclonic circulation can be categorized as a subpolar gyre, similar to the circulation pattern of the Norwegian–Greenland Sea. The maximum transport in the western boundary current over the continental slope east of the Antarctic Peninsula is $76 \times 10^6\ m^3\ s^{-1}$. Ship and iceberg drift, geostrophic transport calculation, and both direct and indirect near-bottom current information are supportive of a relatively strong current in the western margin of the basin. Comparison of the wind-driven Sverdrup transport to the 0/500-db baroclinic pattern is good west of 30°E though further to the east the comparison is poor. This may result from an imperfect eastern boundary or perhaps the 0/500-db baroclinic field provides an incomplete picture of the full wind-driven component, which is expected to be largely barotropic within the nearly homogeneous Weddell–Enderby water column.

INTRODUCTION

SIR GEORGE DEACON'S (1976, 1979) review of the ocean circulation characteristics east of the Antarctic Peninsula noted that SCHOTT (1912) and BRENNECKE (1918) commented on the occurrence at all depths of relatively warm, saline water immediately south of a zone at 60°S of colder, fresher, more polar waters. The structure reverses the larger-scale meridional gradients and appears in several atlas presentations (TOLSTIKOV, 1966; GORDON and GOLDBERG, 1970; CARMACK, 1977). For example, the thermohaline properties at 750 m (Fig. 1) indicate relatively warm, saline water south of colder, fresher water from 30°W to 20°E. East of 20°E the isopleths trend north–south, with the more typical zonal orientation being re-established further east.

Surface current drift charts (U.S. Hydrographic Office, 1957; TRESHNIKOV, 1964) and relative dynamic topography charts (TOLSTIKOV, 1966; GORDON, MOLINELLI and BAKER, 1978) all show a large cyclonic motion dominating the region east of the Antarctic Peninsula to the Greenwich meridian and often to 40°E. The nature of the eastern end of the circulation is not clear, though most studies indicate significant southward motion near 20 to 30°E. Following the schematic representation of wind-driven circulation of MUNK (1950), the cyclonic circulation of the waters may be considered to be a subpolar gyre. As such it is analogous to the circulation of the Norwegian–Greenland seas in the North Atlantic and to the Gulf of Alaska and Bering Sea in the North Pacific.

The object of this study is to determine the structure of the wind-driven circulation using Sverdrup dynamics and compare it to observations in the Weddell–Enderby Basin.

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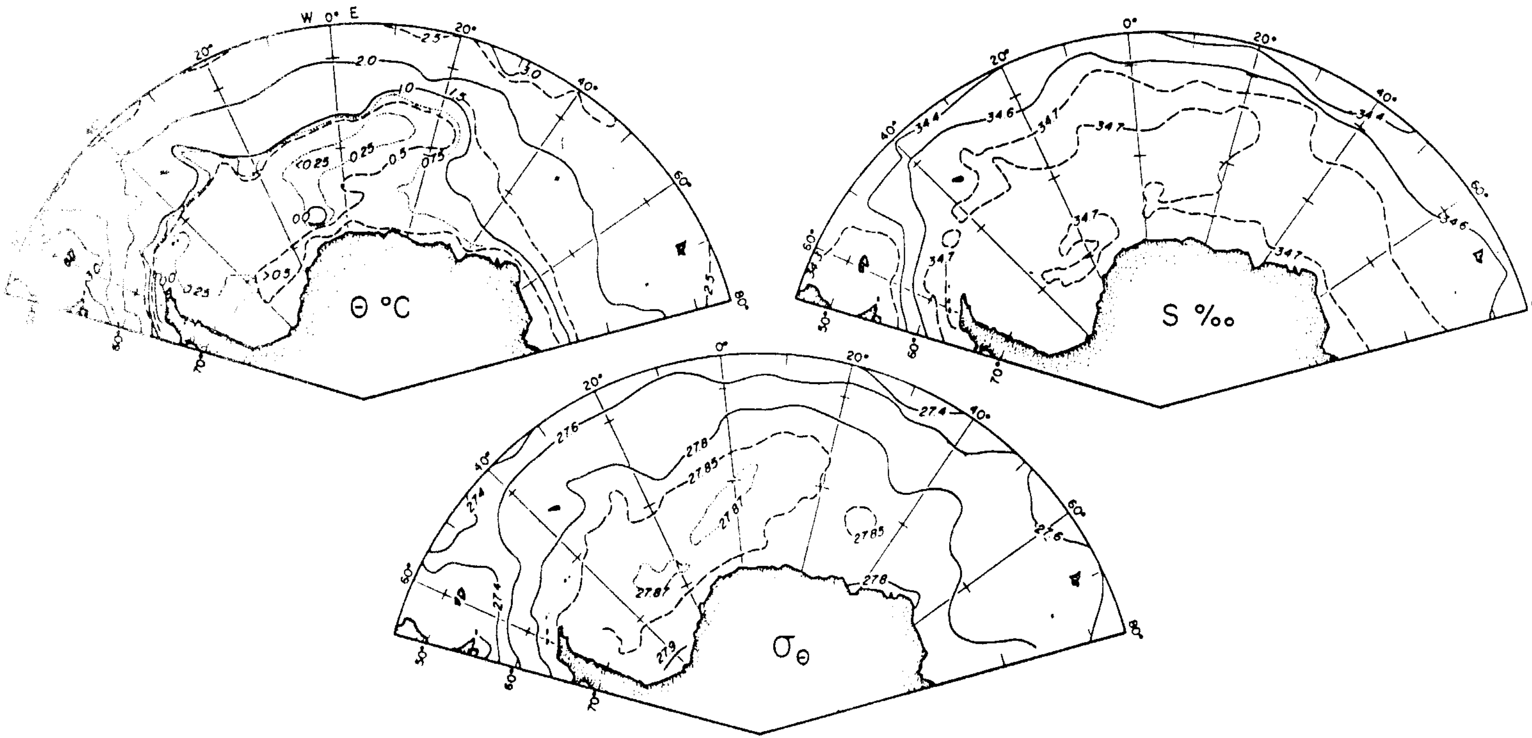

Fig. 1. Potential temperature, salinity, and sigma-θ distribution at 750 m for the Weddell Enderby Basin and region immediately to the north. The Southern Ocean Atlas data set (GORDON and MOLINELLI, in preparation) was used.

The Weddell–Enderby Basin is defined as the basin between the Antarctic Peninsula and the Kerguelen Plateau and between Antarctica and a series of ridges running roughly northeast from the northern tip of the Antarctica Peninsula to the Crozet Plateau. It is called the Atlantic–Indian–Antarctic Basin on the U.S. Navy Hydrographic Office world map of 1961. The use of the name Weddell–Enderby Basin reflects the name given to the two abyssal plains that comprise the flat, deep sections (HEEZEN and THARP, 1977). The Weddell Sea is the large embayment occupying the south western corner of the Weddell–Enderby Basin.

SVERDRUP TRANSPORT

The mean wind field over the Weddell–Enderby Basin is cyclonic (Fig. 2). The wind field adjacent to the east side of the Antarctic Peninsula is consistently from south to north (SCHWERDTFEGER, 1979). The ocean circulation pattern induced by this wind may be calculated following the dynamics presented by SVERDRUP (1947). Continuity and vorticity considerations require the divergent Ekman drift of the surface water to induce a general poleward transport within the water column. The motion is compensated by an intense, equatorially directed transport in the western boundary region.

The Sverdrup transport relation is derived from the steady state vertical component of the vorticity equation, neglecting the inertia terms and all friction except the wind stress

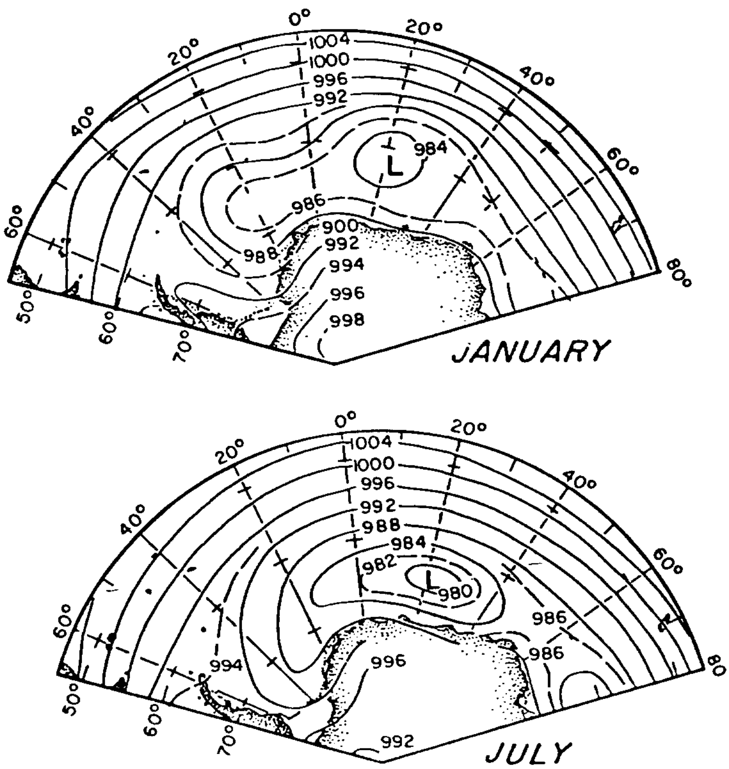

Fig. 2. Sea-level atmospheric pressure for January and July, taken from Figs 8 and 72 of TALJAARD *et al.* (1969); values in millibars.

exerted at the sea surface:

$$M_y = \frac{\text{curl}_z\, \tau}{\beta}, \tag{1}$$

where M_y is the Sverdrup transport (total wind-driven mass transport within the water column): τ is the wind stress acting on the sea surface: β is the meridional gradient of the Coriolis parameter f (where $f = 2\omega \sin \theta$: ω is the angular velocity of the earth's rotation and θ is latitude).

A particular problem in the application of equation (1) to the Southern Ocean is that it does not include the effects of sea-floor topography. For application to low latitudes this is not a problem because the wind-driven circulation attenuates before the sea floor is reached, as the wind-driven circulation is compensated by the density field. Density compensation may not be achieved in the Southern Ocean where the water column is nearly homogeneous.

The sea-floor interaction introduces two factors (WELANDER, 1959): (1) bottom stress, which removes vorticity introduced by the wind field, and (2) bottom slope, which adds additional vorticity terms. The effects of bottom stress are difficult to determine, but are usually considered negligible in the uniform depth model (WELANDER, 1968). This is particularly valid in the case of the nearly homogeneous water column of the Weddell–Enderby Basin, in which, by the very nature of deep-reaching currents, the mean speed in the water column is small. Current speeds associated with the Sverdrup transport in the Weddell–Enderby Basin (Figs 3 and 4) range from less than 0.3 to 1.7 cm s^{-1}. Thus, if the ocean response were totally barotropic, bottom currents would be of the order of 1 cm s^{-1} and the effect of bottom stress would be minimal. Any baroclinic adjustment would further reduce bottom stress.

The effects of bottom slope can be considered a modification of β:

$$M_y = \frac{\text{curl}_z\, \tau}{\beta - \dfrac{f}{H}\dfrac{\partial H}{\partial y}}, \tag{2}$$

where H is depth. The mean slope of the ridge marking the northern boundary of the Weddell–Enderby Basin (determined from the chart of HEEZEN, THARP and BENTLEY, 1972) is approximately 3×10^{-3}, so $(f/H)(\partial H/\partial y) = 7{\cdot}5 \times 10^{-13}$, about seven times larger than β. In this case the ridge slope will severely limit meridional transport, which is induced by the curl of the wind stress allowing the simplifying approximation of zero cross-ridge Sverdrup transport.

Two cases are presented: first, equation (1) is used to determine the pattern of the Sverdrup transport for the flat floor Weddell–Enderby Basin without a northern ridge: then the pattern is modified by the introduction of the northern ridge as an effective northern boundary.

WIND STRESS DATA

Application of equation (1) requires knowledge of the spatial distribution of the wind stress. Monthly averaged surface geostrophic wind for the southern hemisphere has been presented in map form at 5° latitude by 5° longitude grid points by JENNE, CRUTCHER, VAN

LOON and TALJAARD (1971). The geostrophic relation for sea-level winds is only an approximation. Over land the approximation is poor, as frictional forces attenuate the geostrophic wind speed and induce significant down pressure wind gradient. Over the ocean the approximation is considered to be generally good. The real wind magnitude may be between 70 and 100% of the geostrophic and the angular difference less than 20% (FOFONOFF and DOBSON, 1963: AAGAARD, 1969, 1970: HASSE and WAGNER, 1971).

TAYLOR, GORDON and MOLINELLI (1978) using the drag coefficient suggested by BROCKS and KRUGERMEYER (1972) and the wind values of JENNE *et al.* (1971) determined the wind stress acting on the Weddell–Enderby waters. In calculating the curl, spherical coordinates, as suggested by NEUMANN (1955), are used to account for convergence of longitude. Admittedly, the wind data set for the Southern Ocean is not ideal, but it is not apt to improve significantly in the immediate future. In addition the wind data set may underestimate the actual wind stress curl for two reasons: (1) the use of multi-year monthly data would not fully represent high-wind events, which may dominate the wind stress values, due to the non-linear relation of stress to wind: (2) SAUNDERS (1976) pointed out that use of a coarse grid would yield lower wind stress curl than would a fine grid. However, the data do warrant at least preliminary evaluation of the Sverdrup transport pattern within the Weddell–Enderby Basin.

WIND DRIVEN CIRCULATION

To determine the total Sverdrup transport pattern it is necessary to integrate local Sverdrup transport values from an eastern boundary, where there is assumed to be no zonal transport. This is difficult for a circumpolar ocean where no eastern boundary in the formal sense is found. However, there are significant submarine meridional barriers that can provide an eastern boundary for much of the water column.

For the purpose of studying the Sverdrup transport of the Weddell–Enderby Basin, 70°E is taken as the eastern boundary. The meridian marks the approximate western side of the Kerguelen Plateau and is an effective eastern boundary below 1000-m depth. In the upper kilometer cross-plateau advection does occur though it is apparent that enhanced meridional motion is present (see the 0/1000-db dynamic topography presented by GORDON, MOLINELLI and BAKER, 1978). Even within the narrow 2000-m deep gap separating the Kerguelen Plateau from the Antarctic margin, there is not significant zonal transport (JACOBS and GEORGI, 1977). This is further suggested by the trajectory of iceberg drift within the westward coastal current approaching Kerguelen Plateau from the east (TCHERNIA, 1977). The icebergs are diverted to the north over the east side of the plateau analagous to the northward transport of icebergs along the east coast of the Antarctic Peninsula (SWITHINBANK, MCCLAIN and LITTLE, 1977). It is possible that the Kerguelen Plateau separates subpolar gyres associated with the deep basins to both the east and west.

The western boundary of the Weddell–Enderby Basin is taken as the continental slope of the Antarctic Peninsula near 50°W south of 60°S and the South Sandwich Ridge north of 60°S. For the no-ridge case, the northern boundary is taken where the curl is zero, near 50°S. The ridge forms the northern boundary in the second case. The southern boundary is taken as the continental margin of Antarctica. The vorticity effects of the southern boundary are neglected. Accumulated M_y values which, because of continuity requirements, represent transport streamlines, are contoured. The no-ridge Sverdrup transport

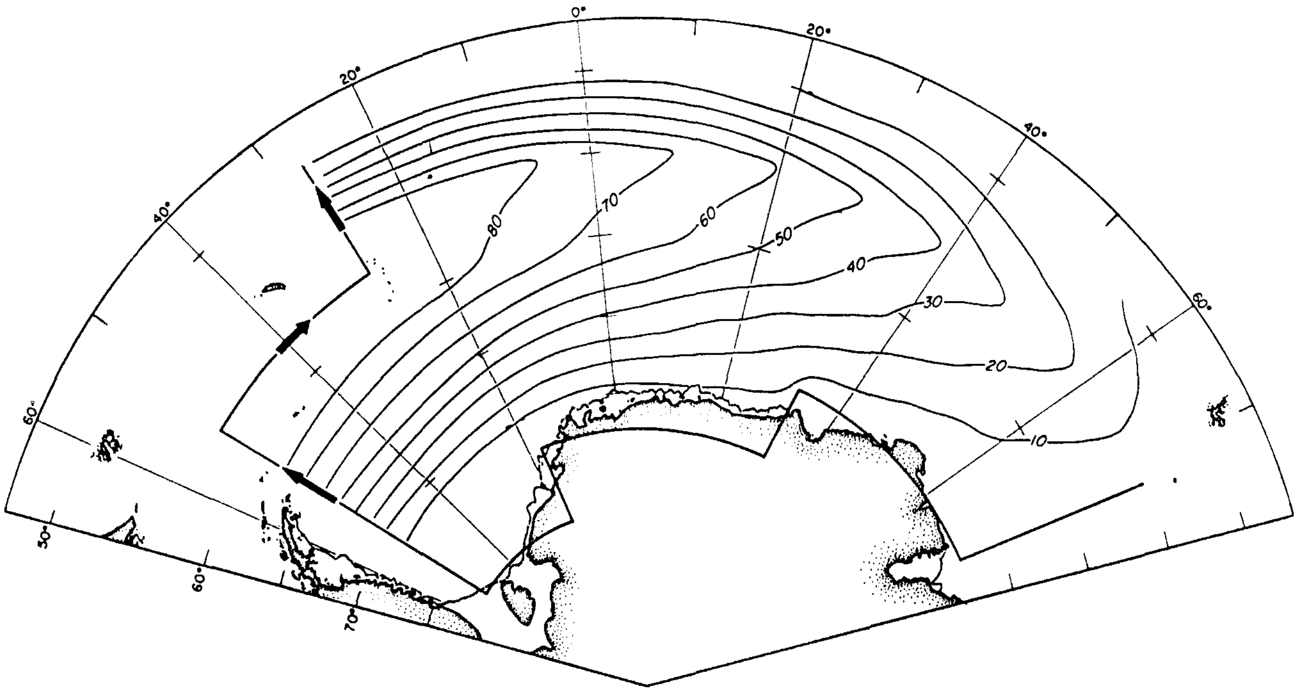

Fig. 3. Sverdrup transport streamlines for the area bounded by the heavy line. The northern boundary is taken where the Sverdrup transport is zero, at the maximum westerlies. Streamlines are in 10^6 m^3 s^{-1}. The arrows at the western boundary indicate the sense of the western boundary current.

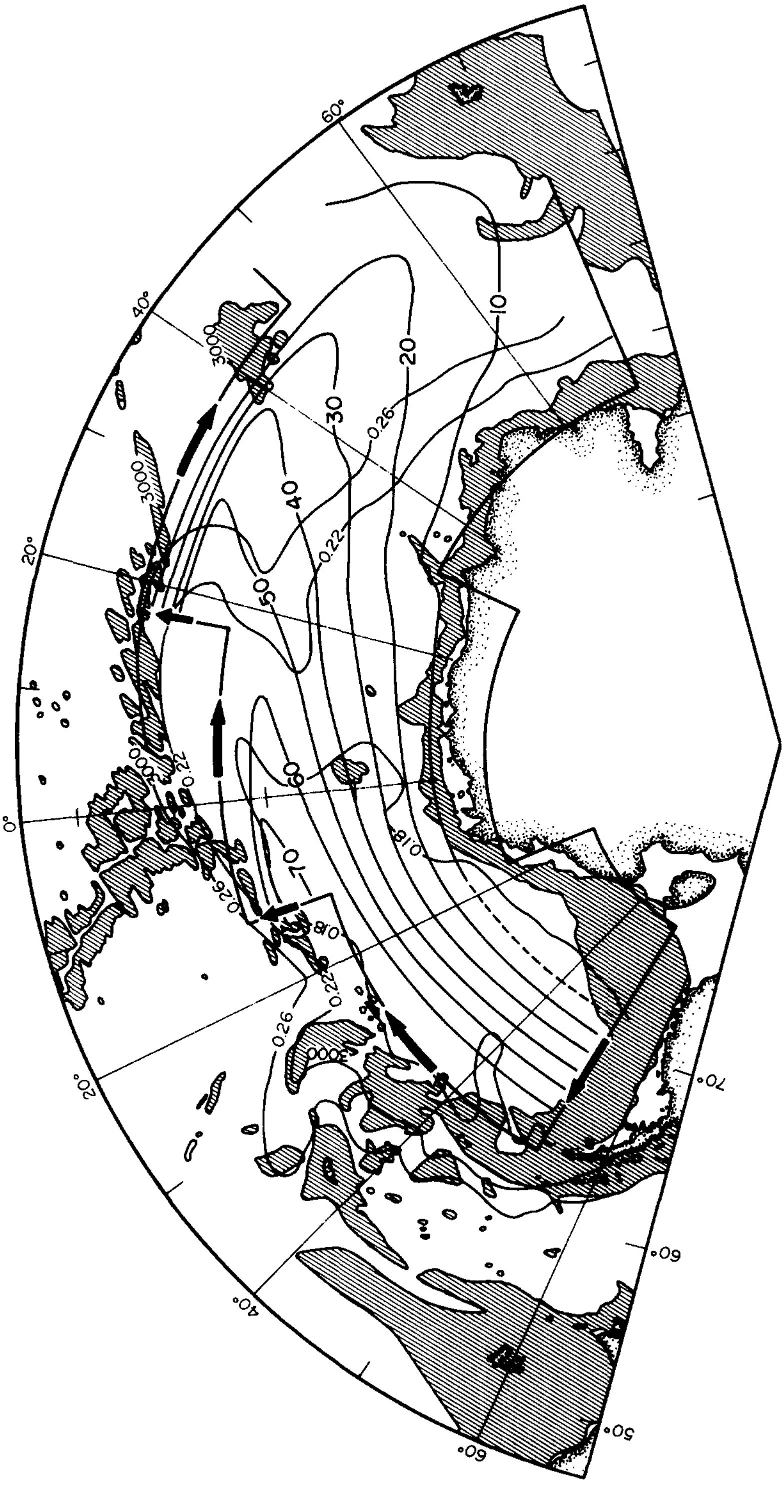

Fig. 4. Sverdrup transport streamlines for the area bounded by the heavy line. The northern boundary is taken to approximate the ridge system forming the northern boundary of the Weddell–Enderby Basin. The hatched area represents less than 3000-m sonic depth (Heezen, Tharp and Bentley, 1972). The 0.18, 0.22, 0.26 dynamic meter isopleths of the 0/500-dB dynamic topography (Fig. 5) are shown to aid comparison.

streamlines (Fig. 3) show a large-scale cyclonic circulation with the axis near 55°S and maximum western boundary transport of 85×10^6 m^3 s^{-1}.

In the case of a northern boundary the altered transport streamlines (Fig. 4) reduce the transport to 76×10^6 m^3 s^{-1}. The axis of the cyclonic gyre is shifted to the south with a southwest–northeast orientation. The eastward transport formed over the northern boundary, which feeds the interior Sverdrup transport, is consistent with the occurrence of the cold, ice-laden, krill-rich band of water observed near 55 to 60°S (MACKINTOSH, 1972). It is also shown by the geostrophic calculations of CARMACK and FOSTER (1975).

EVERSON and VERONIS (1975) determined Sverdrup transport for the world ocean without bottom topography between 65°N and 65°S. The eastern boundary for the Southern Ocean is taken at the Drake Passage, producing an enormous western boundary current off the east coast of Antarctic Peninsula (300×10^6 m^3 s^{-1}). However, adjusting their value in proportion to the ratio of the longitudinal width of the Weddell–Enderby Basin to the full circumpolar belt would yield 100×10^6 m^3 s^{-1} which is approximately the value presented above. This implies that a series of subpolar gyres in the basins around Antarctica might be expected.

BYE and VERONIS (1979) point out that the magnitude of the western boundary current transport would be much reduced were a linear friction coefficient for the whole basin and the aspect ratio of the meridional to latitudinal width (L/M) taken into account. The aspect ratio for the Weddell–Enderby Basin is 3.4, a relatively large aspect ratio, similar to the Agulhas system ratio (BYE and VERONIS, 1979, Table 2). The modified transport with a basin-wide friction coefficient of 2×10^{-6} s^{-1} may amount to only 60% of the zero-friction case (based on the large aspect ratio basins given in Bye and Veronis' Table 2). Therefore the western boundary current transport of 76×10^6 m^3 s^{-1} represents an upper limit, with a possible lower limit of 46×10^6 m^3 s^{-1} when the Bye and Veronis considerations are taken into account. However, as noted above, use of a more detailed wind field could yield higher transport.

WESTERN BOUNDARY CURRENT

The Sverdrup transport requires a significant compensating western boundary current over the continental margin east of Antarctic Peninsula (specifically over the continental slope and rise) and adjacent to the South Sandwich Arch. Field data clearly attest to its presence: (1) drift of icebergs (SWITHINBANK *et al.*, 1977); (2) drift of sea-ice-locked ships (SHACKLETON, 1919; BRENNECKE, 1921) and buoys (ACKLEY, 1979); (3) indirect methods, such as bottom seawater temperature, salinity, oxygen (GORDON, 1974; CARMACK, 1977), and interpretation of bottom photographs (HOLLISTER and ELDER, 1969); and (4) direct observation of currents and geostrophic calculations (CARMACK and FOSTER, 1975; FOSTER and MIDDLETON, 1979).

The width of the western boundary current can be approximated using WELANDER's (1968) method, in which he derived an expression for the width of a western boundary current for a homogeneous ocean of variable depth. The equation is

$$\gamma = \frac{[\mu/2f\rho]^{\frac{1}{2}} f}{\left[H\beta - f\dfrac{\partial H}{\partial y} \right]}, \tag{3}$$

in which γ is the width and μ a coefficient of viscosity. Assuming $H\beta \gg f(\partial H/\partial y)$ and tuning μ so as to yield a Gulf Stream width of 200 km (using values of f and β appropriate for 35°N) results in a western boundary current width of 225 km at 65°S. At 65°S, where the western boundary current transport is 60×10^6 m^3 s^{-1}, for H of 3500 m and a 225-km wide current, the depth averaged velocity is 7.6 cm s^{-1}. This agrees well with the 5 cm s^{-1} mean drift speed of the sea-ice field confining the *Endurance* (SHACKLETON, 1919) which drifted in a curved path approximately over the continental slope and rise from 76°25'S, 30°W to 69°05'S, 51°31'W from 18 January to 27 October, 1915 before being crushed in the ice. The value is determined from the map provided by SHACKLETON (1919) using a smooth curved mean drift path.

The value also agrees well with the drift of the *Deutschland*, while she was ice-locked from 8 March to 26 November, 1912 following a 1665-km path approximately parallel to the *Endurance* path but 225 km to the east (still within the predicted western boundary current) with a mean drift of 7.3 cm s^{-1} (determined by drawing a smooth curve over the drift map given by BRENNECKE, 1921). The average of ship drift given in Table A, page 212 of BRENNECKE's (1921) account is greater than 7.3 cm s^{-1}, however Brennecke included all the fine-scale drift track features and hence contained transient and wind event features in addition to the mean drift.

ACKLEY (1979) presented drift data of ice-locked buoys in the region 70 to 75°S, 50 to 60°W. The buoys drifted northward at 1.7 to 8.8 cm s^{-1}.

FOSTER and MIDDLETON (1979) presented a year-long current meter record 50 m off the sea floor (4504 m) at 66°29.3'S, 41°02.6'W. The mean current was 1.31 cm s^{-1} with a compass heading of 6°. However, the mooring position was 450 km east of the continental slope adjacent to the Antarctic Peninsula, well to the east of the predicted western boundary current, which may account for the much smaller speed.

An estimate of the total transport of water out of the Weddell Sea was presented by CARMACK and FOSTER (1975), using current meter referenced geostrophic calculations. They found a total (nearly barotropic) transport of 96.9×10^6 m^3 s^{-1}, about 20×10^6 m^3 s^{-1} above the maximum flux within the Sverdrup transport patttern given in Fig. 4 (with a northern boundary). While the five current meter moorings reported by Carmack and Foster span a time period of only 96 to 354 h and hence cannot be considered a climatic mean, their results suggest that the vigor of the Weddell subpolar gyre determined from climatic wind data is not unreasonable.

Field data clearly support the presence of a northward-directed current in the western margin of the Weddell–Enderby Basin at approximately the speed and transport determined using Sverdrup dynamics. However the predicted width of the western boundary current may be somewhat less than observed, though more detailed field data and more sophisticated modelling are required for further comparison.

COMPARISON TO DYNAMIC TOPOGRAPHY

The shape or structure of the Sverdrup transport pattern can be compared with relative baroclinic dynamic topography determined from hydrographic data. Dynamic topography of the Weddell gyre is included in the circumpolar charts of GORDON *et al.* (1978). The 0/1000, 1000/2500, and 2500/4000-db charts show weak cyclonic motion with characteristic velocity of the surface relative to 1000 db south of 60°S of only 0.4 cm s^{-1}. East of 20 to 30°E a general southerly flow marks what may be taken as the eastern boundary of the Weddell gyre.

A more detailed dynamic chart of the sea surface relative to the 500-db level is given in Fig. 5. Comparison with the Sverdrup transport pattern (Fig. 4) shows some similarities and some differences (three isopleths of Fig. 5 are placed in Fig. 4 to aid comparison).

A. *Similarities*

(1) Strong eastward flow associated with the ridge system extending northeast from the tip of the Antarctic Peninsula.

(2) General cyclonic circulation west of 30°E.

B. *Differences*

(1) The cyclonic trough in the 0/500-db pattern occurs near 70°S in the western region of the Weddell–Enderby Basin, rather than between 60 and 65°S as suggested by the Sverdrup transport: however deeper layers do show better compliance with the Sverdrup pattern (see 1000/2500 and 2500/4000-db charts of GORDON *et al.*, 1978).

(2) The baroclinic field of the upper 500 m shows southerly and easterly motion between 60 and 65°S and 0 and 30°E and also between 55 and 65°S east of 30°E, where, as the Sverdrup transport indicates, flow is towards the southwest.

(3) The 0/500-db baroclinic pattern shows no western boundary current.

The differences between dynamic topography and the Sverdrup transport presented may have a number of causes. It would be easy to ascribe them to insufficient wind data, but we doubt if this is the chief cause. Nor would detailed introduction of bottom slope be of aid because the major discrepancy in the south eastern regions of the Weddell–Enderby Basin occurs over flat topography. The application of equation (2) with measured bottom slope (HEEZEN *et al.*, 1972) in the vicinity of the 'counter-Sverdrup' 0/500-db baroclinic flow east of the Greenwich meridian indicates that the bottom slope is insufficient to induce such a deviation. The three primary reasons for differences are believed to be: (1) The baroclinic field represented by the 0/500-db pattern does not fully resolve the wind-driven transport, which would primarily be a barotropic circulation. The possibility is further supported by the lack of a western boundary current in the 0/500-db pattern, even though field observations indicate significant northward current in the western margin of the basin. (2) The 0/500-db baroclinic field may include circulation due to non-wind factors, notably thermohaline alterations of the water column, usually considered as significant both along the continental margins of Antarctica and in the open sea, and (3) The imperfect eastern boundary invalidates the application of simple Sverdrup dynamics to the Weddell–Enderby Basin.

CONCLUSIONS

The differences between the Sverdrup streamlines and the baroclinic field of the upper 500 m suggest caution in accepting the validity of Sverdrup dynamics for the Weddell–Enderby Basin, particularly in view of the imperfect eastern boundary. Hence these results must be considered preliminary. With this in mind we suggest that the climatic wind field over the Weddell–Enderby Basin induces a rather vigorous Sverdrup transport pattern. The maximum western boundary current transport is over 76×10^6 m^3 s^{-1}. Velocities associated with the Sverdrup and western boundary transport may be relatively small (as also suggested by the limited field data) due to the deep-reaching effect of the wind field in the nearly homogeneous water column of the Weddell–Enderby Basin. The expected large

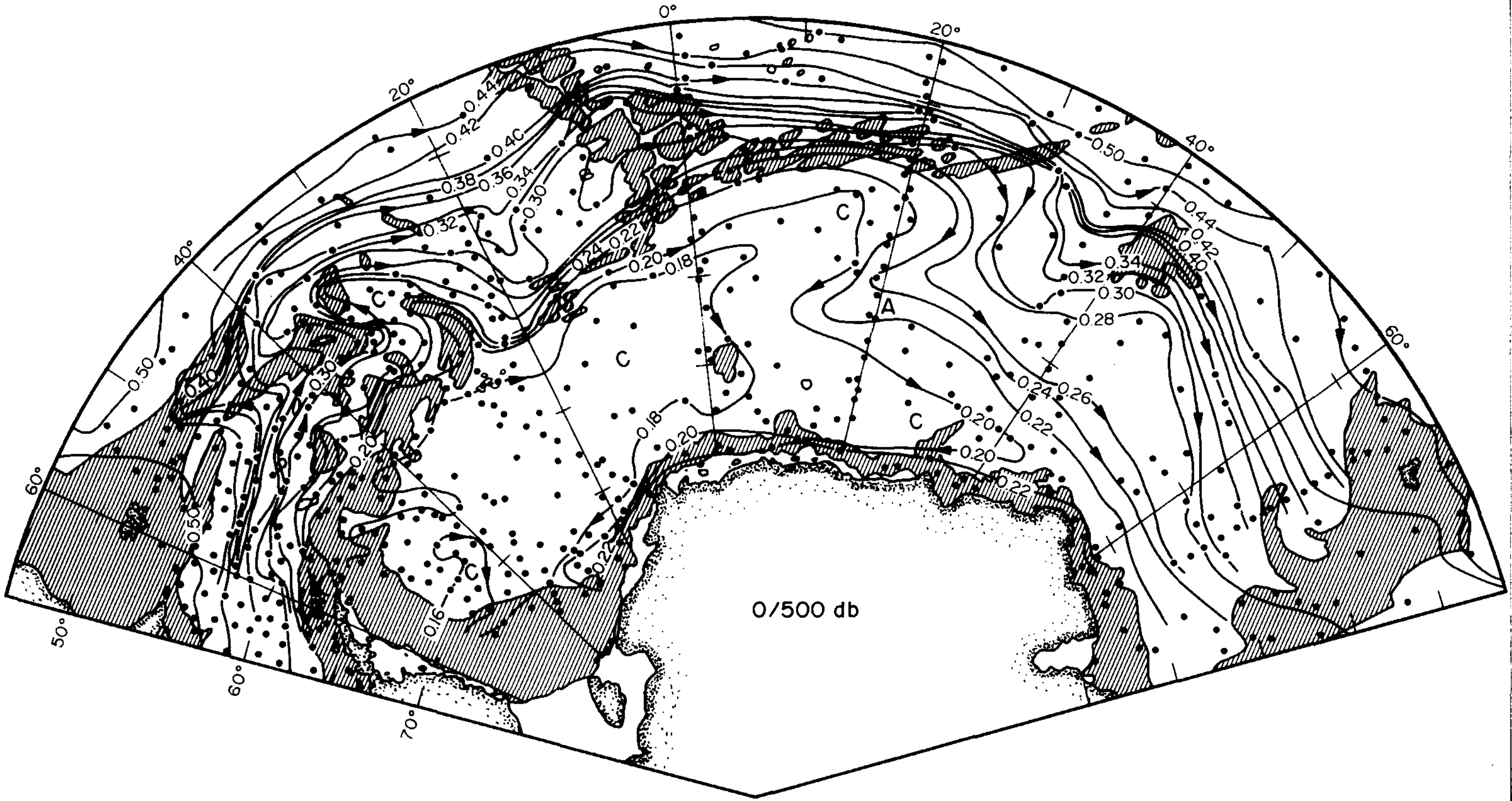

Fig. 5. Dynamic topography of the sea surface relative to 500 db. The Southern Ocean Atlas data set is used (GORDON and MOLINELLI, in preparation): the station positions are indicated by dots. C, center of cyclonic flow: A, anticyclonic center.

barotropic response makes comparison with the baroclinic field of the upper layers particularly difficult. This demonstrates the need for long-term direct current and sea-level observation within the Weddell-Enderby Basin to study the pattern of the circulation and structure of the western boundary current.

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