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COMMENTS ON SOUTHERN OCEAN NEAR-SURFACE CIRCULATION AND ITS VARIABILITY
(Invited paper)

by

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ABSTRACT

This literature review discusses the mean and variable surface-layer circulation of the Southern Ocean. The variable components are equal to or even more energetic than the mean circulation. Therefore circulation charts often do not present the significant currents that exist during specific periods.

1. INTRODUCTION

These comments are by no means meant to be a comprehensive review of Southern Ocean circulation. Rather, they are directed at aspects of ocean circulation that may be of use in predicting iceberg drift or that should be considered when planning the path to be followed when towing icebergs from Antarctica to regions north of the Southern Ocean.

2. LARGE-SCALE CIRCULATION

Surface geostrophic circulation relative to deep water has been determined by various authors, most recently by Gordon and others (1978). They show that the surface flow relative to the 1 000 dbar level is dominated by the Antarctic circumpolar current (ACC). The typical or characteristic geostrophic velocity of the ACC relative to 1 000 dbar is 10 cm/s, with an average direction towards the east. However, the ACC path is not totally zonal since large standing waves, with meridional amplitude of 1 500 km, are present. These waves are best associated with varying bottom depths, primarily those of the northern slope of the mid-ocean ridge.

The geostrophic shear within the water column presented by Gordon and others (1978) and Nowlin and others (1977) suggests that the surface geostrophic flow relative to 1 000 dbar is about half of that relative to 3 000 dbar. Thus the 0/1 000 dbar characteristic speeds may be doubled (to 20 cm/s) in order to yield the 0/3 000 dbar value, which (assuming the velocity at 3 000 dbar is near zero) should be closer to the absolute ACC climatic mean. The 0/1 000 dbar charts have the advantage of being continuous over the mid-ocean ridge, which has sections shallower than 3 km.

The ACC axis occurs near the ocean polar-front zone, separating Antarctic from sub-Antarctic surface-water masses, and so is linked to a relatively large meridional temperature gradient (both in the mean ocean and atmosphere thermal fields). The width of the ACC is similar to the width of the region experiencing the transition of water masses; it can usually be taken to be 200 to 300 km. but may extend over a band as much as 500 km in sections not overlying a sharp submarine topographic feature. More detailed study of the ACC in the Drake Passage by Nowlin and others (1977) indicates that the ACC is composed of a number of high-velocity filaments, separated by weaker currents. The mean speeds within the multi-axis reach 30 to 40 cm/s. Determination of geostrophic currents relative to deep levels for other parts of the circumpolar belt (Gordon 1975, Jacobs and Georgi 1977) suggests that a multi-axis ACC may be typical, though a principal axis can usually be identified.

The relative geostrophic surface current is not the total picture of surface circulation and perhaps not even the dominant component. Wyrtki and others (1976), in a survey of mean and eddy kinetic energy for the world ocean (50°S. to 60°N.) based on ship-drift data, show that the eddy energy is four to ten times above the mean kinetic energy. Thus the expected activity of the time-varying eddy or transient component may be at least twice as large as the mean velocity.

An additional factor not brought out by the relative geostrophic currents is the current component influencing the entire water column, i.e. the barotropic component. The magnitude of this component is only known where sufficiently long-term direct current measurements have been made.

3. BAROTROPIC COMPONENT

The International Southern Ocean Studies (ISOS) program is mainly focused on direct current measurements in the Drake Passage. These data have provided a more complete understanding of the total ACC and its variations. Comparison of the 0/3 000 dbar geostrophic flow with that of the geostrophic flow adjusted to mean current values as measured by the ISOS program at 2 700 m and a statistical study of the year-long current meter records, indicate that the barotropic component in the mean is 30 to 40% of the baroclinic component (Bryden and Pillsbury 1977, Nowlin and others 1977, Fandry and Pillsbury, in press). However, large variations in the barotropic component occur, probably associated with large-scale atmospheric forcing with periods of longer than 30 d, and to local forcing for shorter periods (Baker and others 1977, Baker, in press, Wearn and Baker, in preparation*). The barotropic component may vary by 100%, so the total transport through the Drake Passage, which would be roughly proportional to the surface currents, averages 139 x 10^6 m^3/s with variations of about 50 x 10^6 m^3/s.

Therefore, the characteristic surface current of the ACC, including the mean baroclinic and barotropic components, may be taken as 25 to 30 cm/s (assuming the Drake Passage measurements are typical of the whole circumpolar belt). Large-scale, long-period variations of the ACC may be taken as $\pm$ 10 cm/s.

In the open ocean, between the ACC region and the Antarctic continental margins, the mean 0/1 000 dbar surface currents are very small, typically less than 2 cm/s, though somewhat higher speeds may be attained over the northern boundary of the Weddell-Enderby Basin and over the east wall of the Kerguelen Plateau (Carmack and Foster 1975, Gordon and others 1978). The low degree of baroclinicity is expected in the open ocean south of the ACC because of the nearly homogeneous water column. It is possible that the barotropic component may be the major component of the circulation. This is suggested in a study by Gordon and others (in press) in which the wind-driven Sverdrup transport for the Weddell-Enderby Basin (between the Antarctic Peninsula and Kerguelen Plateau) is presented. The wind-driven flow pattern does not compare well with the 0/500 dbar dynamic topography: the cyclonic gyre is much more developed in the Sverdrup streamlines than in the relative dynamic field. This is particularly evident in the western margin (over the slope adjacent to the Antarctic Peninsula) where the wind-driven circulation requires a significant western boundary current (although the mean surface current is only 3 to 5 m/s, the total transport may reach 76 x 10^6 m^3/s), but the 0/500 does not show a geostrophic western boundary current. Yet support for a western boundary current can be found in studies on iceberg drift (Swithinbank and others 1977, McClain 1978), deep current measurements (Carmack and Foster 1975, Foster and Middleton 1979), drift of ice-locked ships (e.g. S S *Endurance* and *Deutschland*), and sea-floor sediment forms (Hollister and Elder 1969).

Therefore, it is probable that charts of surface geostrophic currents relative to deep reference levels in the region south of the ACC may miss some important circulation features. However, if the barotropic component is indeed dominant for this region, it would not generate very large surface velocities due to its full water-column effect. Therefore, as Gordon and others (in press) point out, the wind-driven (barotropic) velocity away from the western boundary ranges typically from 0.3 to 1.7 cm/s, and from 3 to 5 cm/s within the western boundary current. As in the case of the ACC, the barotropic component south of the ACC may experience variations in association with atmospheric effects.

Over the continental margins of Antarctica, surface currents apparently are somewhat more vigorous than in the open ocean. The U.S. Navy Hydrographic Office publication (1957) indicates coastal currents directed towards the west (as part of the east wind drift) with speeds of 25 cm/s to as high as 50 cm/s (1.0 knot) and above in the Ross Sea and adjacent to Wilkes Land.

These estimates may be high in comparison to recent estimates based on the drift of icebergs (Swithinbank and others 1977, Tchernia 1977), current meter observations (Sverdrup 1953, Jacobs and others 1970, Foldvik and Kvinge 1974), ice-locked ships (Deacon 1937), and geostrophic velocities (Foster and Carmack 1976). Typical surface values of 5 to 10 cm/s are suggested.

It is possible that the coastal currents may be strongest over the shelf break, where a strong frontal zone is commonly found (Jacobs and others 1970, Gill 1973, Foster and Carmack 1976, Jacobs and others 1979), but this remains to be documented.

4. MESOSCALE TRANSIENTS

Vigorous transients, or eddy activity superimposed on the mean flow, are expected (Wyrtki and others 1976), and they are quite evident in the ISOS current-meter measurements in the Drake Passage (Pillsbury and others, in press), in the sea-surface temperature distribution as viewed from satellites (Legeckis 1977, 1978), in the ISOS mooring thermistor records (Sciremammano 1979) and in expendable bathythermograph (XBT)-hydrographic survey data (Mackintosh 1946, Gordon 1971, Patterson and Sievers 1976, Joyce and Patterson 1977). Savchenko and others (1978) document the existence of a large transient cyclonic eddy at 132°E. between 51 and 52°S.

These studies, and others, show that the velocities associated with the mesoscale activity attain values above the mean zonal current values discussed above. North-south velocities of over 30 cm/s are common (Joyce and Patterson 1977, Pillsbury and others, in press). The mesoscale features are depicted as meanders and eddies in the ACC-polar front with scales of less than 100 km, though satellite observations suggest larger (100-300 km) meanders (Legeckis 1977). The eddies move eastward with the mean larger-scale flow and hence require about one week to cross a meridian.

Lutjeharms and Baker (1979), in a survey of mesoscale activity in the entire Southern Ocean based on variations in dynamic height and isotherm topography, indicate that much transient motion occurs at scales below 300 km. These features are more common in the ACC band and may be related to topographic features. The most energetic mesoscale features are expected at scales below 100 km, perhaps at 60 km, which defines the local Rossby deformation radius.

(*submitted for publication as "Bottom pressure measurements across the Antarctic circumpolar current and their relation to the wind".)

5. CONCLUSION

The mean geostrophic currents at the sea surface relative to a deep reference level would underestimate the absolute mean surface current by about a third. Superimposed on the total mean current are the velocity variations associated with transient motions. These are substantially more vigorous than the mean velocity and are as active in the meridional component as they are in the zonal direction. Variations in meridional velocity would have typical time scales of one week.

It is noted that non-geostrophic motion also is present, notably the tidal and, in the surface layer, the wind effects. Tidal currents with a diurnal or semi-diurnal time scale may be a dominant element in the velocity spectra, but, in view of their high frequency (relative to the time scale of significant iceberg drift), they are best regarded as high-frequency noise. Net wind-induced Ekman drift may amount to 1 to 3 cm/s (Taylor and others, in press), being larger when the wind is greatest. However, during high-wind periods, the direct influence of wind on icebergs may be as or more significant, depending on iceberg shape (above and below the water line), as the ocean response to the wind.

The mesoscale transients are the significant feature in Southern Ocean circulation which can be used to traverse the ACC during iceberg towing. The distribution of mesoscale variations are best monitored by remote sensing (sea-surface infra-red emission and altimeter measurements from satellite) and moorings for measurement of currents. In addition, the most active connection from the coastal east wind drift to the ACC may be by way of the western boundary current off the Antarctic Peninsula, east of the Kerguelen Plateau, and possibly near the Balleny Islands.

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DISCUSSION FOLLOWING INVITED PAPER

G. de Q. ROBIN: Do you have any comments yourself on this paper?

E.G. JOSBERGER: I slid many of them in while I was reading it, but I do have some general comments. Success or failure [of an iceberg towing project] will depend more on advanced knowledge of oceanographic factors and conditions than on anything else. More detailed knowledge is needed on the direction and speed of eddies and other elements. When we have this more detailed knowledge, we can develop an algorithm and a computer program that would suggest the best routing for a tow.

P.D. KILLWORTH: I would like to stress two aspects of ocean dynamics of direct relevance to towing plans. First, I wish to support Gordon's comments on eddying motions in the circumpolar current. Eddies are found all round the current, with small horizontal scales (50-60 km) and high velocities (30-50 cm sec^{-1}). Although modellers can now simulate such eddies numerically, their prediction remains elusive. Attempts to tow an iceberg through the current is likely to encounter several periods in which the eddy current is not just against the direction of tow, but actually somewhat faster! Although it is reasonable to expect monitoring of such eddies by satellite-carried radar altimeters in the next decade, the degree of randomness in their motion and the low manoeuvrability of a towed iceberg make it unlikely that it will be possible to optimise the towing route.

Second, I would like to discuss effects of convection (large-scale thermal and/or saline-driven vertical motions). It was suggested that if there is sufficient turbulence beneath an iceberg (as might be the case during towing, for example) then melting under a berg could be as important as melting at the side (as discussed by H.E. Huppert later in the meeting). Some confirmation of this was given by the experiments of D.S. Russell-Head in Melbourne. Evidence of the effectiveness of convection (albeit on sea ice, not bergs) for removal of ice is given in D.G. Martinson, P.D. Killworth and A.L. Gordon (submitted to the Journal of Physical Oceanography). If the berg is forced to remain in southern waters for long, a sizeable amount may be lost by convection in addition to the loss due to melting in more northern waters.

ROBIN: If you are towing an iceberg through the Antarctic convergence, the melt rates in the warmer water north of the convergence will be a more important factor than melting in the convergence.

KILLWORTH: Melting in the convergence will be a minor factor, <u>if</u> you ever get out of the convergence!

ROBIN: The effect will be rather small compared to later.

H.E. HUPPERT: The argument in your paper is a little inconsistent. The melt rate is a property of changes in sea-water temperature. Fresh melt water comes out of the berg and produces a stratification and this would make the water under the iceberg more stable, since the stratification tends to inhibit convection. Therefore, the amount of melting is less than you imply.

KILLWORTH: Satellite photographs of the Weddell gyre show, about every other year, a polynya — about one million square kilometers of open ice-free water drifting west. Why does the ice disappear from this area? The only heat source available is by convection of warm deep water from below and we have a model to explain how this might happen. Deep convection could happen if an iceberg were stationary for a matter of weeks.

HUPPERT: The polynya is in sea ice, not freshwater ice down to 200 to 250 m; this is a dif-

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