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A note on Sverdrup balance in the Southern Ocean

by D. James Baker, Jr.[1]

ABSTRACT

Three sets of recent data from the Southern Ocean, on mass transport through the Drake Passage (Whitworth *et al.*, 1982), on surface winds (Jenne *et al.*, 1971; Han and Lee, 1981) and on density (Gordon *et al.*, 1978) allow an instructive look at the dynamics of the Antarctic Circumpolar Current. These new data suggest that the simple Sverdrup balance of wind stress curl driving a poleward flow south of about 50S as first proposed by Stommel (1957) is consistent with the observed transport within experimental uncertainties. The wind data and the hydrographic data are consistent with the major effects of the wind stress curl occurring in the south Indian Ocean, a result in agreement with recent satellite measurements (Chelton *et al.*, 1981).

1. Introduction

The transport measurements made since 1975 in the Drake Passage (Nowlin *et al.*, 1977; Whitworth *et al.*, 1982) by the International Southern Ocean Studies program, when taken together with the wind data of Jenne *et al.* (1971) and Han and Lee (1981) and the hydrography of Gordon *et al.* (1978) allow us to estimate the terms in the time independent vorticity equation in the Southern Ocean. The estimation of terms is carried out here in the context first proposed by Stommel (1957) and later elaborated by Wyrtki (1960) and Veronis (1973).

Stommel notes that the latitude circles that pass through Drake Passage are blocked by the island arc to the east, and that nowhere in the circumpolar region is there a latitude with a deeper threshold than 1000 m. In addition, the wind stress curl changes sign from positive to negative at about 50S. These facts provide the geographic context for a Sverdrup balance between wind-stress curl and southward geostrophic transport over the circumpolar region. This southward flow can be balanced by northward western boundary currents, the largest of which lies just to the east of Argentina and is fed by the transport through the Drake Passage.

The hydrographic data then available confirmed the general tendency of the flow to follow such a pattern. Wyrtki (1960) showed that the data available at that

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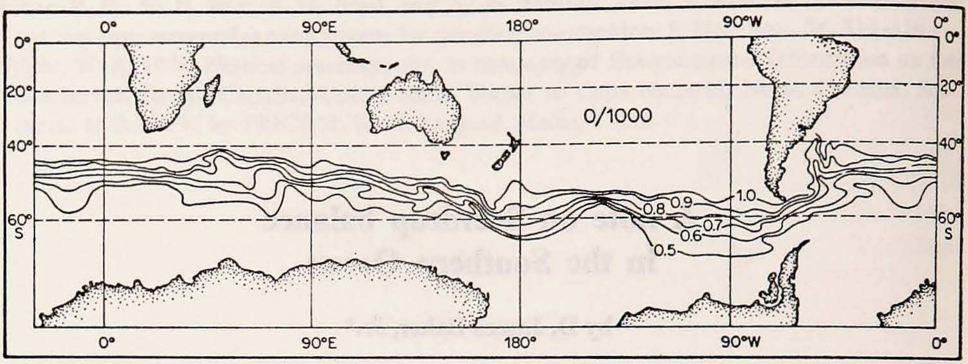

Figure 1. Dynamic topography relative to 1000 db of Gordon *et al.* (1978) replotted on a Mercator projection to illustrate southward flow in southeast Indian Ocean, and northward flow east of South America.

time was quantitatively consistent with a Sverdrup balance. The latest data set of Gordon *et al.* (1978) is replotted in Figure 1. Figure 2 shows a map of the curl of the wind stress as calculated by Taylor (1978).

2. The vorticity balance

The Sverdrup balance is (Sverdrup, 1947):

$$\beta V = \nabla x \tau/\rho$$

where V is the total meridional transport integrated from the bottom to the surface, β is the northward gradient of the Coriolis parameter, and τ is the wind stress at the surface. We will make two comparisons here: the open ocean meridional transport as predicted by the wind stress curl compared to the transport through Drake Passage (since almost all of that flow appears to flow north after leaving the Passage), and the mass transport compared with wind stress curl as a function of longitude at 55S.

In order to estimate the terms, we first consider the magnitude of the terms over the "open ocean" region, that is, over that area from east of 40W around eastward to 70W, thus not including the area where the flow goes through Drake Passage and turns north. Estimates are made for one latitude only, 55S. For transports across that latitude, we have:

$$V \cdot L = \frac{\overline{\nabla x \tau/\rho}}{\beta} \cdot L$$

where L is the distance along that latitude line (2.1×10^9 cm), and the bar denotes longitudinal averaging.

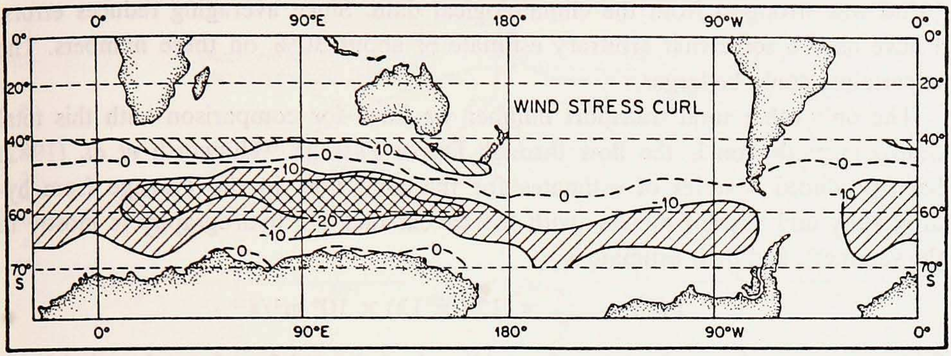

Figure 2. Wind stress curl calculated by Taylor (1978) using spherical coordinates from data of Jenne *et al.* (1971). Contour units are 10^{-9} dyne/cm³.

The wind stress measurements have been taken from two sources: the calculations made by Taylor (1978) who used the data of Jenne *et al.* (1971) to compute wind stress, wind stress curl (presented in Fig. 2), Sverdrup transport, and Ekman transport; and from the calculations of Han and Lee (1981). Taylor's calculations yield for the Sverdrup transport:

$$\frac{\overline{\nabla x \tau/\rho}}{\beta} \cdot L = -173 \times 10^6 \ \mathrm{m^3/s} \ ,$$

and for the Ekman transport:

$$\bar{V}_{ek} \cdot L = 26 \times 10^6 \ \mathrm{m^3/s} \ .$$

where a minus sign means transport to the south.

The Han and Lee data include climatological surface winds available up to 1974. To compensate for lack of a wind-speed frequency distribution, Han and Lee introduce a Gaussian distribution model in which the speed frequency can be estimated in terms of the mean and the variance. Bunker's (1976) drag coefficients were used. This estimate is probably closer to the truth, but if anything, the wind stress is underestimated in the far southern regions because of lack of data. The Han and Lee data yield:

$$\frac{\overline{\nabla x \tau/\rho}}{\beta} \cdot L = -(190 \pm 60) \times 10^6 \ \mathrm{m^3/s}$$

and

$$\bar{V}_{ek} \cdot L = (29 \pm 9) \times 10^6 \ \mathrm{m^3/s} \ .$$

The errors are difficult to estimate because of the sampling problem, but most authors assume that wind stress in the southern hemisphere has uncertainties of at least 50%; the recent FGGE data off Australia has shown even larger discrepancies (wind was stronger) from the climatological data. Since averaging reduces errors, I have used a somewhat arbitrary estimate of about 30% on these numbers. The uncertainty could be larger.

The only other total transport number we have for comparison with this total transport prediction is the flow through Drake Passage. Whitworth *et al.* (1982) have produced a series of estimates for the total flow in the Passage from hydrography and current meters (with the caveat that the hydrography is mostly in the summer), and their estimate is

$$T_{\text{Drake Passage}} = (127 \pm 12) \times 10^6 \text{ m}^3/\text{s}$$

Thus our comparison is between the predicted southward flow from the wind stress and the Drake Passage transport:

$$\frac{\nabla x \tau/\rho}{\beta} \cdot L \overset{?}{=} T_{\text{Drake Passage}}$$

The numbers yield:

$$(190 \pm 60) \times 10^6 \text{ m}^3/\text{s} \overset{?}{=} (127 \pm 12) \times 10^6 \text{ m}^3\text{s} \; .$$

The Sverdrup transport is larger, but in view of the uncertainties, it is just possible to say that the data could be consistent with the simple Sverdrup model as proposed by Stommel. The smaller northward transports at other topographic features such as the Kerguelen Plateau and the Campbell Plateau-Macquarie Ridge in the course of the Antarctic Circumpolar Current, when added to the Drake Passage transport, would undoubtedly reduce the difference between these two numbers, but total transport data are not available. Other terms, neglected in the Sverdrup balance, such as bottom friction, bottom stretching and nonlinear effects, could also contribute, and probably in the direction to reduce the difference, but that is not certain.

Since the hydrographic data do not yield total transports, it is not possible to make a comparison with the predicted Sverdrup transport. However, we can make a mass balance consistency check. For example, we expect that the observed geostrophic flow relative to 3000 db integrated over the open ocean region should be equal to the geostrophic flow relative to 3000 db in the Drake Passage. From the Gordon *et al.* (1978) data I calculate that at 55S:

$$\bar{V}_{\text{geo, }0/3000} \cdot L = -(113 \pm 20) \times 10^6 \text{ m}^3/\text{s} \; .$$

The baroclinic transport through Drake Passage relative to 3000 db is (Whitworth *et al.*, 1982)

$$T_{\text{Drake Passage}} = (103 \pm 13) \times 10^6 \text{ m}^3/\text{s} \; .$$

The agreement of these numbers is encouraging confirmation of internal consistency in mass balance which must accompany the integrated vorticity balance.

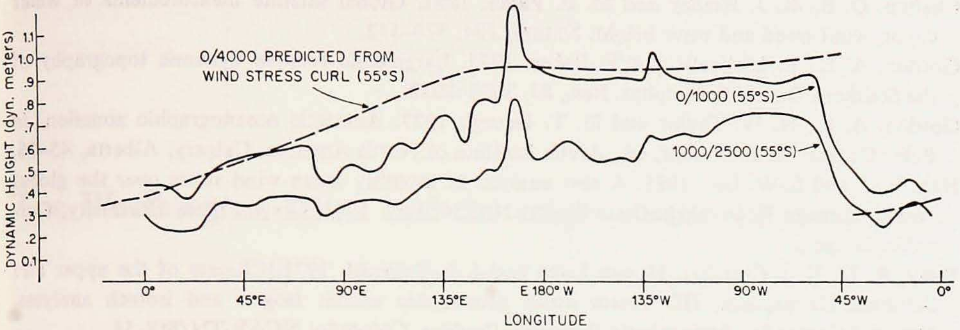

Figure 3. Dynamic height at 55S as a function of longitude from data of Gordon *et al.* (1978) and predicted dynamic height from wind stress curl data of Taylor (1978) integrated eastward from 45W.

The longitudinal distribution of wind stress curl shows interesting similarity to the observed geostrophic flow. Figure 3 shows the integrated wind stress curl plotted together with the dynamic height at 55S. The integration was begun at 45W and continued eastward around the entire latitude circle. It is clear from both the curl distribution (Fig. 2) and from this figure that the major driving occurs in the Indian Ocean. Gordon *et al.* (1977) noted this effect, and the recent paper of Chelton *et al.* (1981) confirms the strong wind stress in the south Indian Ocean. The Chelton data are from a global satellite (Seasat) analysis, and thus are not subject to the previous spatial sampling errors due to ship tracks concentrated on supply lines.

3. Conclusions

The best data available are still highly uncertain, but mass transport is consistent between the southward open ocean geostrophic flow and the transport in Drake Passage. This southward transport is consistent with a Sverdrup balance. The predicted southward transport from the wind stress curl is larger than, but, within the uncertainties, consistent with the transport in Drake Passage. Further refinements on the Sverdrup balance such as bottom friction, bottom stretching, nonlinear effects, and time dependence, will not be testable until better data sets are available. In view of the remoteness of the region, such data may require satellite measured winds, satellite altimetry, and arrays of drifting buoys.

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