GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 22, PAGES 2797-2800, NOVEMBER 15, 1997

Northern boundary currents and adjacent recirculations off southwestern Australia

Gwyneth E. Hufford and Michael S. McCartney
Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Kathleen A. Donohue
School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii

Abstract. Full-depth hydrographic and velocity measurements along 115°E south of Australia (WHP section I9S) reveal an active northern boundary current regime within 200 - 300 km of the Australian continental shelf and an offshore recirculation regime within the South Australian Basin. In the upper ocean an oft-described westward-flowing northern boundary current, the Flinders Current, extends through the thermocline and the salinity minimum strata of Antarctic Intermediate Water, with an opposing eastward recirculation to its south. The new data shows that beneath the Flinders Current, an eastward-flowing deep northern boundary current transports water of subtropical Indian Ocean origin supplied by southward deep flow along the western continental slope of Australia in the Perth Basin. Between these northern boundary currents and the Antarctic Circumpolar Current, thermocline and deep geostrophic shears indicate weak recirculations, eastward at thermocline levels and westward in the deep water. Lowered Acoustic Doppler current profiler data reveal stronger organized recirculations to both the Flinders Current and the deep northern boundary current, with the westward deep recirculation exceeding the eastward transport of the deep northern boundary current and thus representing a net supply of deep water to the Perth Basin.

Introduction

The Indian Ocean and the sector of the Southern Ocean to its south have a complex system of basins and separating ridges that shape the regional deep circulation (Mantyla and Reid, 1995). The Indian Ocean has no northern sources for deep and bottom water, and the complex topography channels the meridional flow of deep and bottom waters from the Southern Ocean through several discrete passages. The easternmost of these is the Perth Basin between the west coast of Australia and the Broken Plateau (Figure 1). Through this passage deep and bottom waters from the South Australia Basin pass to the subtropical/tropical West Australia Basin and thence through fractures in the Ninetyeast Ridge to the Central Indian Basin (Warren, 1982). This northward net flow is the difference between the northward deep western boundary current (DWBC) pressed up against the eastern flank of the Broken Plateau and a southward deep flow in the eastern part of the Perth Basin (Toole and Warren, 1993; Robbins and Toole, 1997; and Talley and Baringer, 1995). In this note, we examine hydrographic and velocity measurements taken along 115°E (WHP section I9S). Between Australia and the Antarctic Circumpolar Current there is a net westward deep flow that is the difference between opposing eastward and westward flows in the South Australian Basin; these opposing flows link to the opposing northward and southward deep flows of the Perth Basin as diagramed in Figure 1a.

A section southward along 115°E from Australia across the Antarctic Circumpolar Current.

The dominant feature of the temperature[1] distribution along our 115°E section, Figure 2a, is the series of full water-column temperature fronts of the Antarctic Circumpolar Current (ACC) near 50°S, indicative of the ACC's geostrophic shear reaching the sea floor. North of the ACC fronts, flatness of isotherms indicates weak geostrophic shear across much of the South Australia Basin.

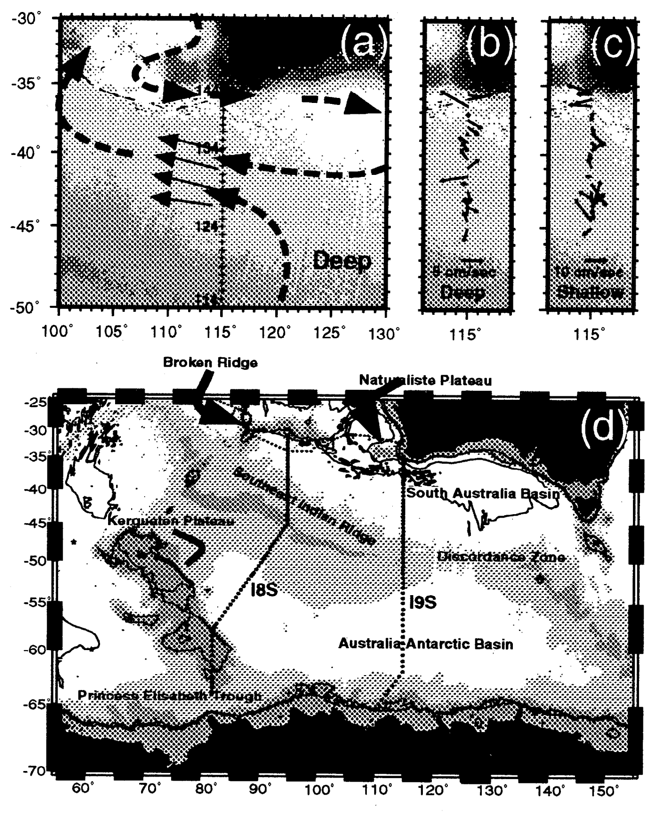

Figure 1. (a) the circulation scheme deduced from this analysis, stations 114 -146 are labeled along 115E. (b) - (c) diagrams of the depth averaged LADCP velocity vectors for the stations depicted in (a). 'Deep' and 'shallow' refer to water column below and above 1500 m. (d) a detailed view of the region.. The shaded topography indicates 3000 m and 4000 m depths while the contours indicate 200 m, 1000 m, 2000 m and 5000 m.

[1] All temperatures in this paper are potential temperatures referenced to zero pressure.

Paper number 97GL02278.
0094-8534/97/97GL-02278$05.00

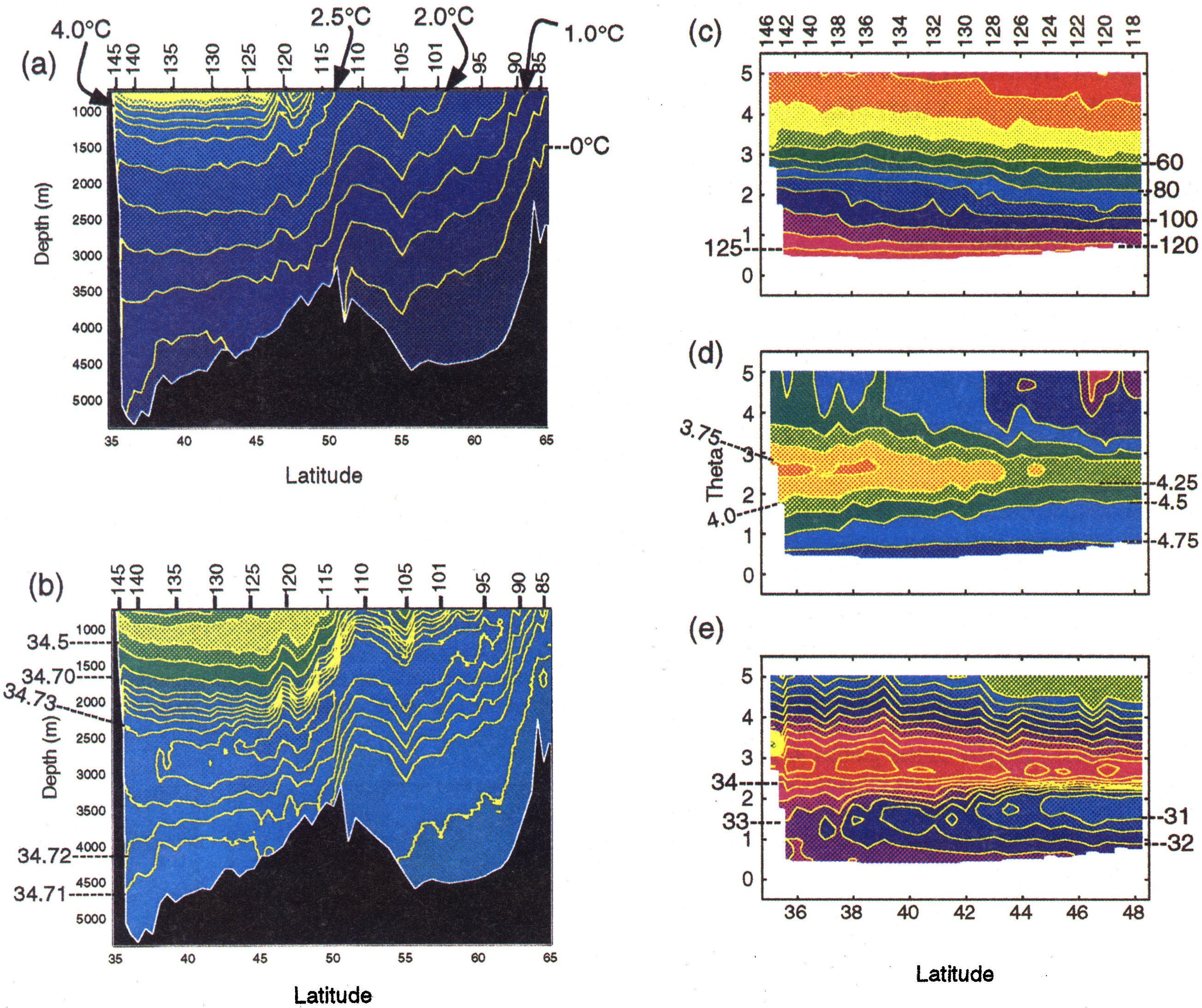

Figure 2. (a)-(b) contour sections of I9S properties plotted against pressure; (a) potential temperature, (b) salinity. (c)-(e) are nutrient sections south of southwestern Australia along I9S across the South Australia Basin, plotted against potential temperature; (c) silicate, (d) oxygen, (e) nitrate. The ACC salinity maximum is greater than 34.75. The nitrate maximum at 38S is greater than 35μmol/kg.

All but the coldest isotherms rise northwards across a 200 km wide boundary regime against the continental slope of Australia. The other panels of Figure 2 show salinity, oxygen, nitrate and silicate sections, which reveal a number of water mass core layers with northern boundary regime signals: a weakened nitrate minimum layer in the 1.0°C - 1.5°C range, a weakened salinity maximum layer near 1.5°C, a strengthened oxygen minimum layer near 2.5°C and essentially coincident with a strengthened nitrate maximum, and a weakened salinity minimum layer at the base of the thermocline near 4°C (the Antarctic Intermediate Water, AAIW). The whole northern boundary regime water column colder than 2.5°C has elevated silicate compared to deep waters to the south.

The near-bottom and deep isopycnal maps by Mantyla and Reid (1995) point us to the Perth Basin as a source region for the enhanced subtropical deep-water influences. East-west sections across the Perth Basin near 32°S (Toole and Warren, 1993; Robbins and Toole, 1997; and Talley and Baringer, 1995) show a strong ACC deep-water influence in the northward flowing DWBC at the Broken Plateau, while the southward flow off western Australia has a strong subtropical deep-water influence. Our interpretation is that this southward flow along the eastern boundary of the Perth Basin turns the corner at southwestern Australia to supply a deep northern boundary current (DNBC) flowing eastward through the 115°E section.

At thermocline levels the northward rise of isotherms in the boundary regime indicates the westward-flowing Flinders Current (Bye, 1972) relative to an underlying reference level, this Current is believed to extend to the AAIW depth. Below the AAIW, the northward rise of isotherms indicates monotonic geostrophic shear down to about 3500 m. However, the core layers described above indicate a transition from westward-flowing Flinders Current to eastward-flowing DNBC. The transition lies somewhere above the nitrate maximum and oxygen maximum and all deeper waters are moving eastward in the DNBC. The reversal of isotherm slope in the boundary regime, Figure 2a, below 3500 m (about 1.1°C) indicates that the DNBC achieves maximum eastward velocity at this level. The near bottom eastward flow is unlikely to reverse to westward because the high silicate of the abyssal waters also indicates a subtropical influence.

Consistent with this, the coldest bottom waters of the South Australia Basin are not in the DNBC, but are found to its south, delineated by the 0.5°C contour in Figure 2a. In detail, the coldest waters, < 0.45°C, are found clustered at stations 132 - 136 near 38°S - 41°S. At 115°E this cold patch is cutoff from the cold waters of the Australian-Antarctic Basin by the damming effect of the Southeast Indian Ridge. To the west this damming effect increases as the crest of the Ridge rises steadily to outcrop at Amsterdam Island (near 78°E, 38°S). To the east of our section water as cold as 0.4°C seeps into the South Australia Basin from the Australian-Antarctic Basin through the fissures of the Antarctic Discordance Zone (Mantyla and Reid, 1995). This is the coldest water entering the South Australia Basin, and we thus expect that the cold patch south of the DNBC along the 115°E section represents westward flow.

For the preliminary geostrophic transport estimates we are reporting here we have chosen for a reference level a level-of-no-motion (LNM) at 1500 db. This LNM gives weak eastward flow in the northward intensified oxygen minimum and nitrate maximum, and stronger deep eastward flow in the deeper water-masses of the system, consistent with these waters invading the South Australia Basin from the subtropics. The LNM simultaneously leads to the westward flow of the Flinders Current penetrating through the salinity minimum of the AAIW, Figure 2b. Using this LNM we have estimated the bulk transport of upper-ocean and deep flow for each station pair accumulated southward from Australia (Figure 3). We have not continued these estimates southward to and across the ACC: such a LNM is clearly inappropriate there as this current is believed to be eastward-flowing from top to bottom. We do not report details of transports for different water-mass layers; additional work will be needed to firm up reference-level selections and resolve differences with transports estimated from lowered acoustic Doppler current profiler (LADCP) data described below.

The 1500 db LNM yields a DNBC with estimated transport below 1500 db of 19 Sv (1 Sverdrup = 1 Sv = $10^6 m^3 s^{-1}$) towards the east, and a Flinders Current with estimated transport above 1500 m of 20 Sv towards the west (Figure 3). To the south the geostrophic transports fluctuate but accumulate small net flows: an upper-ocean eastward transport of 5 Sv in opposition to the Flinders Current, and a deep westward flow of 6 Sv in opposition to the DNBC flow. In both cases these represent recirculations of the northern boundary currents, albeit weak ones. Included on Figure 3 are estimates of transport below 3500 db, the approximate Southeast Indian Ridge crest height at this longitude: the net flow north of the Ridge is an *eastward* 4-5 Sv. This is problematic for the deep flow, for overall there must be *westward* net deep flow through this section to provide the net northward deep flow through the Perth Basin, since the Ridge is shallower than 3500 db westward from this section. To change the sign of this net flow to westward would require shifting the LNM below 1800 db, and would result in the DNBC transporting the northward intensified oxygen minimum and nitrate maximum the "wrong way." Clearly a reference level choice more sophisticated than a fixed LNM is needed: as a guide to that choice we consider a more direct transport estimate from lowered acoustic Doppler current profiler (LADCP) data.

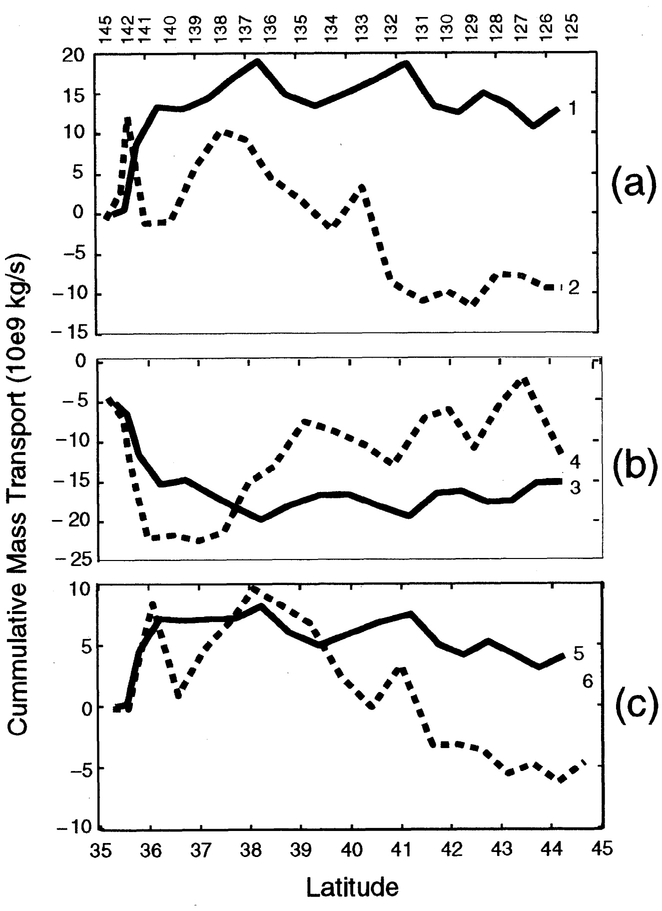

Figure 3. Transports for the northern part of I9S accumulated southwards from Australia across the south Australia Basin. The solid curves indicate geostrophic estimates using a 1500 m reference level. The dotted curves represent vertical and meridional integrals of the LADCP velocity profiles. (a) water column below 1500 m, (b) above 1500 m, (c) below 3500 m.

LADCP-based boundary current transport estimates

Direct-velocity measurements made at each station using a LADCP complement the geostrophic velocity estimation from geostrophic shear and water mass-based inferred flow directions and LNM's. The LADCP system used was a 153-kHz broadband self-contained ADCP mounted on the rosette. Details regarding the instrument and data processing may be found in Hacker et al. (1996) and Fischer and Visbeck (1993).

The alternate accumulated transport curves in Figure 3 are constructed from the LADCP vector velocities, Figure 1, by integrating the cross-track component above and below 1500 db and assigning the sum of the two half-distances to adjacent stations as the width over which the depth-integral speed acts. In the LADCP transport estimates of Figure 3 the Flinders Current appears narrower and peaks at about 22 Sv compared to the geostrophic estimate of 20 Sv. The DNBC transport is more structured and peaks at about 11 Sv compared to 19 Sv for the geostrophic estimate. In both cases the LADCP estimates of the boundary current transport are impacted by a strong westward barotropic flow at station 140 (see vectors in Figure 1); this westward flow does not have associated water-mass signals in the property sections (Figure 2).

South of these northern boundary currents, where the geostrophic estimates indicate a small net accumulated transport in weak recirculation flows, the LADCP estimates show organized accumulation of transport. In the upper ocean the westward 22 Sv transport of the Flinders Current is opposed by a compact eastward recirculation of 14 Sv between 37°S and 40°S, with some additional structure farther south that accumulates little additional transport. In the deep water the eastward 11 Sv transport of the DNBC is opposed by a larger amplitude westward transport of 20 Sv, mostly through the 7 stations between 38°S and 42°S. We inferred above that a westward flow is required at these same stations because of the occurrence there of the coldest bottom water in the South Australia Basin. Additional support for this westward flow regime is found in the property distributions of Figure 2: the various core layers have one extreme in the DNBC and the other extreme in the ACC, with the station group 131 - 136 spanning the westward flow regime characterized by values intermediate between these extremes. The transport curve below 3500 m shows the section having a net *westward* flow of 4-5 Sv, this "fixes" the defect so evident in the LNM-based geostrophic estimate by providing a source for deep water to flow towards the Perth Basin. Robbins and Toole (1997 and personal communication) quantified the net deep northward flow in the Perth Basin as about 5 Sv (their layer 7, below about 3000 m in the Perth Basin), a reasonably good match.

Conclusions and Discussion

We have identified a deep-reaching northern boundary current shear signature, a shear that reverses below 3500 m. Property distributions and LADCP measurements both suggest that the upper ocean part of the shear distribution corresponds to a westward-flowing Flinders Current (Bye, 1972) extending vertically through the thermocline and the AAIW to a flow reversal near the upper deep water. At deeper levels the shear corresponds to an eastward-flowing DNBC intensifying downwards to the shear reversal at 3500 m then weakening somewhat with depth below that. The water-masses in this DNBC are similar to the water flowing south near the coast of western Australia suggesting that the southward flow transits the rather complicated topography of the southwestern corner of Australia to turn eastward into the South Australia Basin, Figure 1.

Offshore of the northern boundary regime the geostrophic estimates indicate weak recirculations of both the Flinders Current (Bye, 1972) and the DNBC. The LADCP data suggests that these recirculations are more intense than the geostrophic estimates. A net deep westward flow is a regional budgetary requirement for supplying deep water to the Perth Basin. The LADCP estimates provide the necessary net westward deep flow, as well as regional consistency with water mass distributions. The geostrophic estimates based on a simple fixed level-of-no-motion cannot do both simultaneously.

Simple Sverdrup wind-driven circulation theory for the upper ocean (e.g. Veronis, 1973) and Stommel-Arons upwelling-driven abyssal circulation theory for the deep ocean (e.g. Veronis, 1976 & 1978) may provide explanations for the Flinders Current and DNBC, respectively. Australia represents the eastern boundary for both the upper and deep Indian Ocean (e.g. Welander, 1959). This boundary jumps from the west coast of Australia, at 115-120°E north of 35°S, to the west coast of Tasmania at 145°E for 35-45°S. Since subtropical gyre wind forcing extends this far south, a small anticyclonic gyre is indicated for the oceanic region south of Australia and west of Tasmania. The Flinders Current becomes the necessary patch that receives the equatorward wind-driven flow and carries it westward to join the rest of the southern Indian Ocean subtropical gyre circulation west of 120°E. Similarly, though with much greater complexity because of the multiple basins and boundaries of the deep ocean, upwelling-driven poleward interior flow experiences the same shift of eastern boundary; the DNBC becomes the required patch that supplies a source of lower latitude waters for the deep southward interior circulation west of Australia. These are, of course, very simple theoretical frameworks for circulation patterns, and indeed, the surprising strength of the northern boundary currents and the recirculations to their south may point to different physical processes than linear interior dynamics with zonal boundary currents that merely satisfy interior circulation budget constraints.

Acknowledgments. Thanks to all the participants of the first WHP leg of R/V Knorr's WOCE expedition to the Indian Ocean, but particularly to Tom Whitworth, Eric Firing Joe Jennings and Marshall Swartz for their valuable contributions to a successful cruise. The hydrographic work was supported by NSF grantOCE-9413167 and the LADCP work by NSF grant OCE-9413172. This is WHOI contribution number 9507, SOEST contribution number 4512, and U.S. WOCE contribution number 540.

References

Bye, J. A. T., Oceanic circulation south of Australia, in *Antarctic Oceanology II: The Australian-New Zealand Sector, Antarctic Res. Ser.*, vol. 19, edited by D.E. Hayes, AGU, Washington, D.C., 95-100, 1972.

Fischer, J., and M. Visbeck, Deep velocity profiling with self-contained ADCPs, *Journal of Atmospheric and Oceanic Technology,* 10, 764-773, 1993.

Hacker, P., E. Firing, W. D. Wilson and R. Molinari, Direct observations of the current structure east of the Bahamas, *Geophysical Research Letters*, 23, 1127-1130, 1996.

Mantyla, A. W., and J. L. Reid, On the origins of deep and bottom waters of the Indian Ocean. *Journal of Geophysical Research,* 100, 2417-2439, 1995.

Robbins, P. E., and J. M. Toole, The dissolved Silica Budget as a constraint on the meridional overturning Circulation of the Indian Ocean. *Deep-Sea Research,* 44, 879-906, 1997.

Talley, L., and M. Baringer, Preliminary results from a WHP section in the Central Indian Ocean. *International WOCE Newsletter*, 21, 35-38, 1995.

Toole, J. M., and B. A. Warren, A hydrographic section across the subtropical South Indian Ocean. *Deep-Sea Research.*, Part I, 40, 1973-2019, 1993.

Warren, B. A., The deep water of the Central Indian Basin, *Journal of Marine Research,* 40, supplement, 823-860, 1982.

Veronis, G., Model of World Ocean Circulation: I. Wind-driven, two-layer, *Deep-Sea Research,* 31, 228-288, 1973.

Veronis, G., Model of World Ocean Circulation: II. Thermally-driven, two-layer, *Deep-Sea Research,* 34, 199-216, 1976.

Veronis, G., Model of World Ocean Circulation: III. Thermally and wind-driven, *Deep-Sea Research,* 36, 1-44, 1978.

Welander, P., On the Vertically Integrated Mass Transport in the Oceans, in *The Atmosphere and the Sea in Motion*, edited by B. Bolin, pp. 95-101, Oxford University Press, 1959.

G. E. Hufford and M. S. McCartney, Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543. (email: ghufford@whoi.edu; mmccartney@whoi.edu)

K. Donohue School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, HI 96822 (email: kathyd@soest.hawaii.edu)

(received April 11, 1997; revised July 10; accepted July 30, 1997)