REVIEWS OF GEOPHYSICS AND SPACE PHYSICS, VOL. 21, NO. 5, PAGES 1131-1137, JUNE 1983
U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1979-1982

POLEWARD HEAT TRANSPORT BY THE OCEAN

Kirk Bryan

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton, NJ 08540

Introduction

Poleward heat transport and its relation to the thermohaline circulation of the World Ocean have long been neglected subjects, but a perceived need for a better understanding of the Earth's climate have given an impetus to studies of the ocean's role in the global heat balance. Oceanographers have a new appreciation of the existing hydrographic and geochemical data base, and ambitious plans are being made to measure new sections in all the major oceans. It is best to consider ocean heat transport in the context of fresh water, oxygen, silica and other geochemical transports. From the standpoint of climate, however, heat transport is of primary interest. To keep the scope of this review within manageable limits, attention will be restricted to this one aspect of a broader ocean transport problem. Research over the last four years has brought about some important changes in outlook. We will return to this point in the summary.

This review draws heavily on several summaries that have recently appeared (Bryden, 1982; Bryan, 1982a; Hastenrath, 1982; "CAGE Experiment: A Feasibility Study," Dobson et al. 1982). As these summaries indicate, poleward heat transport by ocean currents remains one of the most poorly understood elements of the global heat balance. Estimates based on several different principles all indicate that the poleward heat transport in the ocean is of comparable magnitude to poleward heat transport in the atmosphere, but the processes appear to be quite different. An important indicator of different mechanisms is the observation that the atmospheric heat transport is greatest where the atmospheric poleward temperature gradient is greatest, while the ocean transport appears to be a maximum at low latitudes where the north-south temperature gradients in the ocean are rather weak.

Heat Balance Methods

The requirement for poleward heat transport by the Earth's fluid envelope arises from the fact that the greater part of direct solar insolation is received in low latitudes, while back radiation to space is more evenly distributed over the globe. A steady state balance can only be maintained by a poleward energy transport. There are two heat balance methods

Paper number 3R0019.

Table 1: Sample northward heat transport estimates based on surface heat balance. Units are 10^{15}W.

Atlantic	Hastenrath (1980)	Hastenrath (1982)
25°N	1.6	1.1
Equator	1.4	1.0
25°S	1.2	0.7
Pacific and Indian		
25°N	1.1	1.1
Equator	-0.7	-0.7
25°S	-2.6	-2.6

that have been used to estimate the ocean component of the poleward energy transport. The oldest method is based on the heat balance of the ocean surface. Empirical formulas exist which allow the components of surface heat balance to be calculated from standard observations taken by surface shipping. Heat received or given off by the oceans can be estimated as a residual term. If this residual term is integrated with respect to longitude, an estimate of the total heat flux through the ocean surface at each latitude is obtained. Transport can then be found by summing up over latitude belts, starting at the poles. Long term heat balance requires that the net vertical heat flux over the entire World Ocean is zero.

Advances in data processing have allowed much more detailed heat balance calculations at the ocean surface to be carried out. The work of Bunker (1976), Hastenrath and Lamb (1977) and Weare et al. (1981) has much greater spatial resolution than previous studies, allowing an identification of regions of large amplitude heating and cooling with well known water mass features. The results in Table 1 sample the heat transport estimates made by Hastenrath (1980, 1982) based on surface heat balance calculations. Since new calculations are not available on a global basis, a combination of new and old estimates of surface heat balance is used. The transports are given in petawatts (1 PW = 10^{15}W). Curiously, heat transport appears to be poleward in the North Atlantic but equatorward in the South Atlantic. This asymmetry appears (Stommel, 1980) to be associated with the strong thermohaline circulation of the Atlantic. North Atlantic Deep Water (NADW) flows out of the Atlantic basin and is replaced by much warmer intermediate and surface waters. In Table 1 the heat transport of the Pacific and Indian Oceans have been lumped together because there is some evidence that the flow though in the Indonesian Archipelego may be greater than previously estimated (Godfrey and Golding, 1981).

Vonder Haar and Oort (1973) introduced a new way to estimate the ocean heat transport indirectly. Essentially their method is based on using satellite measurements to find the total energy transport requirement for the Earth's fluid envelope. Then the heat transport of the atmosphere estimated from radiosonde data is taken out, leaving the heat transport by the oceans and polar pack ice as a residual term. Trenberth (1979) has extended their calculations to the Southern Hemisphere. Recently there has been considerable interest in the feasibility of applying this method to individual ocean basins. Results based on the work of Campbell (1981) and Dobson et al. (1982) are shown in Table 2. The Northern Hemisphere between 20°N and 60°N is divided into sectors corresponding to the Atlantic and Pacific Oceans, and the North American and Eurasian Continents. There is a sizeable net radiation loss over continents, but almost a net radiation balance over the oceans. Over land areas column I should balance the atmospheric heat flux divergence given for two data sources in columns II and III. Over North America there is a balance within 10 Wm^{-2}, but over Eurasia the discrepancy is 30 to 40 Wm^{-2}. In the North Atlantic the two sources of atmospheric heat flux divergence roughly correspond. Neglecting poleward heat transport at 60°N, a 25 Wm^{-2} atmospheric heat divergence over the North Atlantic would imply a poleward heat transport of 0.6 PW at 20°N. This may be compared with the heat transport estimates of about 1.0 PW shown in Fig. 1 for 20°N in the Atlantic. The North Pacific historical wind data in column II imply a northward heat flux of 1.1 PW, while the FGGE data in column III would require an equatorward heat flux at 20°N.

In Situ Measurements

A third method of estimating heat transport is by direct in situ measurements. Unfortunately, detailed current measurements across an entire ocean section do not exist. Hydrographic sections are available in a few places for geostrophic calculations. For a basin closed at one end, Jung (1956) showed that the heat transport is approximately

$$H = \iint_{-H}^{0} \rho c_p v \theta \, dz \, dx \qquad (1)$$

where ρ is the density, c_p is the specific heat at constant pressure, v the meridional

Table 2: A comparison of satellite derived annual net radiation with heat flux divergence from radiosonde winds for various sectors between 20°-60°N W/m^2. Over North America and Eurasia radiation and flux divergence should cancel, but errors in heat flux divergence are expected in areas of high topography.

Region 20°N - 60°N	I Annual Net Radiation Loss Campbell (1981)	II Atmospheric Heat Flux Divergence Oort (1982)	III European Center FGGE DATA (Dobson et al.1982)
N. America	+27	-20	-32
N. Atlantic	-2	26	30
Eurasia	+25	18	13
North Pacific	+1	26	-14

velocity and θ the potential temperature. Let v and θ be broken down into vertically averaged components and departures from a vertical average. We can then rewrite (1) as

$$H = \iint_{-H}^{0} \rho c_p \, (\bar{v}\bar{\theta} + v'\theta') \, dz \, dx \qquad (2)$$

The heat transport integral is now divided into a part which depends on a reference level, and a part which can be estimated from the density field and surface wind stress independent of the reference level.

In the original studies which used this method of decomposition of the heat transport integral, Bryan (1962) and Bennett (1978) evaluated $\bar{v}$ in the interior using the Sverdrup transport formula, and balancing the interior flow with the western boundary current. Although $\bar{\theta}$ is rather uniform in deep ocean areas it varies rapidly near lateral boundaries. Thus the estimate of $\bar{v}\,\bar{\theta}$ depended on a subjective estimate of western boundary layer width. New studies have circumvented this problem in several ways. Bryden and Hall (1980) and Hall and Bryden (1982) made their calculations at 25°N in the Atlantic using IGY data Fuglister (1960). In this east-west section much of the western boundary current is confined to the Florida Current whose transport has been measured (Niiler and Richardson, 1973). In the Florida Current the vertically averaged temperature, $\bar{\theta}$, is about 10°C warmer than $\bar{\theta}$ in the open ocean part of the section. Since $\bar{\theta}$ is rather uniform over most of the section, Bryden and Hall (1980) were able to estimate the total contribution of $\bar{v}\,\bar{\theta}$ as simply the transport of the Florida Current times 10°C. Hall and Bryden (1982) find that the positive (northward) contribution of $\bar{v}\,\bar{\theta}$ and the Ekman transport is offset by a negative contribution of the geostrophic component of $v'\theta'$. The net heat transport is northward, however, and Hall and Bryden (1982) estimate their error is ± 0.3 PW with the key assumption that the IGY section is representative. This error estimate for a single basin is considerably less than the ± 1.0 PW error estimate of Vonder Haar and Oort (1973) for total ocean heat transport in the Northern Hemisphere.

Stommel and Csanady (1980) have developed a valuable constraint on the heat and fresh water balance of the ocean. They point out that in the case of simple overturning in the meridional-vertical plane the ratio of heat transport and fresh water transport is simply proportional to the slope of the prevailing temperature-salinity curve. This simple model appears to be useful at higher latitudes and water mass properties can thus provide a check on independent estimates of the heat and water balance over the oceans. The idea may be very useful for making simple models of oceans in the geologic past.

Wunsch (1978) has introduced a novel diagnostic method for determining $\bar{v}$ from hydrographic sections using inverse theory. Consider the volume enclosed between two east-west sections across an ocean basin. In subsurface density surfaces water mass properties should be

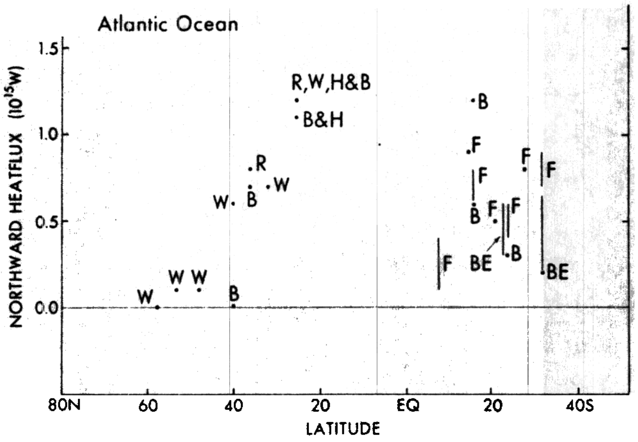

Fig. 1. *In situ* measurements of poleward heat transport by ocean currents based on IGY and *Meteor* data. B (Bryan, 1962), BE (Bennett, 1978), B & H (Bryden and Hall, 1980), F (Fu,1981), H & B (Hall and Bryden, 1982), R (Roemmich, 1980), W (Wunsch, 1980).

approximately conserved. Fluxes of water mass properties in or out of the density surfaces depend on $\bar{v}$ and v' along the intersection of the density surface with the east-west sections. Let the total flux of some property by the v' component be denoted by γ_i where the index i denotes a particular density interval. For conservation within each interval the total flux integral due to v' must balance that due to $\bar{v}$. Summing up the contributions of $\bar{v}$ for each pair of hydrographic stations along the two sections we obtain,

$$\sum_{j=1}^{J} a_{ij}\,\bar{v}_j = \gamma_i \qquad (3)$$

where the index j denotes the station pairs. A set of equations like (3) can be written for different properties in each i-th density interval. Generally, the index J, indicating the total number of station pairs greatly exceeds the number of conservation relations. Increasing the number of equations by choosing smaller density intervals is counterproductive, because the number of entirely independent equations, K, depends on the data and cannot be artificially increased.

Inverse theory or quadratic programming provides a formal method for dealing with an under-determined system of this kind. It provides a criterion for selection of one solution from the large number that satisfy the constraints imposed. For example, the selection criterion might be that the variance of the solution minus some reasonable first guess solution be a minimum. Different constraints may also be given various weights depending on physical considerations. The formal method of selecting solutions for $\bar{v}$ has been criticized by Stommel and Veronis (1981) and Luyten and Stommel (1982) who show that the inverse method as applied by Wunsch (1978) can give nonphysical results for certain configurations of bottom topography.

Heat transport results in the Atlantic based on IGY data and Meteor data (Wüst and Defant, 1936) are shown in Fig. 1 and Table 3. Inverse theory has been used in the studies carried out by Wunsch (1980), Roemmich (1980), and Fu (1981). At 25°N inverse theory predicts the same transport found by Niiler and Richardson (1973). Since the hydrographic data are the same as that used by Hall and Bryden (1982) the heat transport estimates must also correspond. The water mass properties of the North Atlantic (Fuglister, 1960) indicate that the outflow of deep cold water must be partially compensated by the inflow from the south of warmer surface waters. The heat transport calculations showing northward heat flux in the South as well as the North Atlantic are consistent with this picture of the thermohaline circulation. In the South Atlantic the shelf at the western boundary tends to be very narrow north of Argentina. This reduces the sensitivity to the $\bar{v}\,\bar{\theta}$ term and part of the scatter is due to the use of Meteor and IGY data taken at different seasons. In spite of this scatter the overall pattern in Fig. 1 is consistent with an inflow of heat in the South Atlantic, augmented by heating near the equator, and finally depleted by strong cooling in the higher latitudes of the North Atlantic.

Unfortunately, only a small number of new results are available for other parts of the World Ocean. In the North Pacific suitable hydrographic data is not available, but a unique estimate of the role of mesoscale eddies has recently been made by Bernstein and White (1982). Making use of ship-of-opportunity data the authors have estimated the poleward heat transport in the Kuroshio Extension region. According to the authors the mesoscale eddy contribution would be approximately 0.3 PW poleward at 30°N. Bennett (1978) made estimates for the South Pacific using the Scorpio sections at 28°S and 43°S. His estimates are compared with very recent estimates based on inverse theory by Wunsch et al (1983) in Table 4. The new transport estimates for the South Pacific are surprisingly low, almost an order of magnitude less than the Atlantic fluxes shown in Fig. 1. This comparison suggests that there is no direct relation between the size of an ocean and its poleward heat transport. Wunsch et al. (1983) explains the weak heat transport in terms of the meridional circulation of the South Pacific. According to the authors a northward flow of very cold deep water is compensated by the outflow of intermediate water of only slighly higher temperature. From an examination of the salinity balance, the authors feel that they can exclude the possibility of a large flow north of Australia as suggested by Godfrey and Golding (1981).

Georgi and Toole (1982) in a pioneering study have examined the eastward transport of heat through meridional sections across the Antarctic Circumpolar Current. In the Drake Passage direct measurements are available. For two other sections running from Africa to Antarctica and from New Zealand to Antarctica, the authors were forced to select reference levels somewhat subjectively. The heat transport values of this study correspond to a reference level at the bottom. A selection of a reference level at 2500 decibars reduces the magnitude of the heat exchanges between the ocean basis by approximately 33%. The main result is that a net gain of 0.6 PW occurs in the Indian Ocean sector of the World Ocean, and the heat is lost in almost equal proportions to the Pacific and Atlantic sectors.

De Szoeke and Levine (1981) have devised an ingenious method for estimating poleward heat transport in the Southern Ocean. The authors find a path surrounding the Antarctic Continent along which the vertically averaged temperature is a constant. The heat transport normal to such a line is given by an expression similar to (2),

$$H = \oint\int_{-H}^{0} \rho c_p\, \underline{n}\, (\underline{\bar{v}}\;\bar{\theta} + v'\theta')\, dz\, dS \qquad (4)$$

n is the unit vector normal to the path pointing southward. By continuity the first term in the integral vanishes, and the second term can be evaluated from the interpolated density field and a knowledge of the wind stress. An un-

Table 3: Northward heat transport by ocean currents. A summary of estimates from Bryden (1982). In some cases more than one estimate is available due to different methods of analysis or different data sets for the same section.

	Latitude	x 10^{15}W	Reference
North Atlantic			
	59°N	-0.0	Wunsch (1980)
	53°	+0.1	Wunsch (1980)
	48°	+0.1	Wunsch (1980)
	40°	-0.0	Bryan (1962)
		0.6	Wunsch (1980)
	36°	0.7	Bryan (1962)
		0.8	Roemmich (1980)
	32°	0.7	Wunsch (1980)
	25°	1.1	Bryden and Hall (1980)
		1.2	Roemmich (1980)
			Wunsch (1980)
			Hall and Bryden (1982)
South Atlantic			
		0.2,0.7	Bennett (1978)
		0.7,0.9	Fu (1981)
	28°	0.8,0.8	Fu (1981)
	24°	0.3	Bryan (1962)
		0.3,0.5,0.6	Bennett (1978)
		0.4, 0.6	Fu (1981)
	15°	0.9, 0.9	Fu (1981)
	8°	0.1,0.2,0.4,0.4	Fu (1981)
South Indian			
	32°S	0.5,0.6,1.6,1.6,1.8	Bennett (1978)
North Pacific			
	32°N	-1.1	Bryan (1962)
South Pacific			
		-1.0,0.3,0.4	Bennett (1978)
		-0.1	
	28°	-1.2,-0.6,-0.2	Bennett (1978)

certainty of the calculation is due to the fact that the density field must be compiled from non-synoptic data. The authors estimate that the geostrophic component of the heat transport across a path corresponding to $\bar{\theta}$ equal to 1.3°C. The path lies in a zone between 50-60°S. The estimated geostrophic heat transport is zero with an uncertainty of ± 0.23 PW. In agreement with a model study of Bryan and Lewis (1979) the Ekman component of the heat transport is equatorward. By elimination the authors conclude that the contribution of mesoscale eddies must play (Bryden, 1979; Sciremammano, 1980) a key role in poleward heat transport to the waters surrounding the Antarctic Continent.

Models

The most difficult problems in climate will require a hierarchy of ocean-atmosphere coupled models of increasing complexity. For poleward heat transport to be properly partitioned between the atmosphere and ocean both components of the model will have to be carefully designed. In an interesting study Miller et al. (1982) examined ocean heat transport implied by a solution of an atmospheric general circulation model with sea surface temperature specified. The atmospheric model is numerically integrated over several seasonal cycles. Next the method which Vonder Haar and Oort (1973) applied to real data is applied to the model. The authors find that the atmospheric model is not in perfect equilibrium. There is a net flux into the ocean which averaged out to 4 Wm^{-2}. Miller et al. (1982) make a somewhat *ad hoc* adjustment of incoming radiation to obtain a balance. This adjustment has the effect of reducing the heating at low latitudes. Heat transport is calculated for each ocean basin. The results for the Atlantic are in qualitative agreement with Fig. 1. At 25°N the computed northward heat transport is higher than that of Hall and Bryden's, but within their 33% error estimate.

Seasonal variations in heat transport have been examined in a recent analysis by Bryan (1982b) of the Bryan and Lewis (1979) model. Interesting differences are found between the Atlantic and Pacific. In the Atlantic the thermohaline circulation dominates, and seasonal changes due to winds are relatively small. Seasonal changes in heat transport are predicted by the model to be less than 50% of the annual mean. In the Equatorial Pacific, how-

Table 4: *In situ* measurements of northward heat flux (10^{15}W) using *Scorpio* data.

South Pacific Heat Flux

Latitude	Low Estimate	High Estimate	Error
28°S	Wunsch et al. (1983)		
	-0.14	-0.05	± 0.22
	Bennett (1978)		
		-0.05	
43°S	Wunsch et al. (1983)		
		+ 0.13	± 0.35
	Bennett (1978)		
		+ 0.4	

ever, the effect of seasonal wind variations dominate the model heat transport. The model predicts that the heat transport would reverse over a wide span of latitudes. The major cause of the reversal is the strengthening of the Northern Hemisphere trades in the period December through February. Seasonal changes in the north-south component of the wind stress are found to oppose the effect of the zonal wind component, but the effect is smaller.

To build a model useful for studying transient tracers, Sarmiento and Bryan (1982) have developed the concept of "robust diagnostic model." Instead of attempting to calculate the ocean circulation directly from the observed density field using the equations of motion, a more complete model including the conservation equations for temperature and salinity is used. The conservation equations include an extra term which represents a Newtonian damping towards observed water mass properties. The damping time constant is an adjustable parameter. The robustness of the model lies in its ability to adjust the observed data to be compatible with the constraints of the model. It is found that the most reasonable heat transport estimates relative to *in situ* measurements were obtained by forcing the model to observations only below the thermocline and at the surface.

Meehl et al. (1982) have tested the ocean component of global joint ocean-atmosphere model with 5°x5° latitude and longitude resolution. The model is very similar to that used by Bryan and Lewis (1979). The boundary conditions are also similar except that the semi-annual variation of temperature and wind stress is included. The model heat transport is twice that of the standard case of Bryan and Lewis (1979) in the Northern Hemisphere and nearly five times as great in the Southern Hemisphere. The authors conclude that the semi-annual mode in the boundary conditions intensifies the thermohaline circulation in their model. Perhaps over-looked is the fact the vertical mixing of temperature and salinity in the Meehl et al. (1982) is over three times the upper ocean mixing used by Bryan and Lewis (1979). Further tests of the models are needed to clarify the role of vertical mixing on the intensity of the thermohaline circulation.

Summary

The period since the last IUGG has seen a great surge of interest in the heat transport problem. Existing data has been re-analyzed to provide new estimates of poleward heat transport in the Atlantic and South Pacific. The past four years has seen a significant change in prospective. Previously heat transport estimates based on a combination of satellite data, and atmospheric radiosonde data appeared to be the most reliable standard with which to compare model results. New *in situ* estimates of heat flux based on hydrographic data, some of which are based on inverse theory provide new insight on the errors involved. For favorable east-west sections the errors in estimates of poleward heat transport from oceanographic methods appear to be no larger than those for indirect heat balance methods and have the obvious advantage of providing information on mechanisms of heat transport. Ambitious plans are being made to make more high quality, coast to coast, east-west hydrographic sections. An obvious gap exists in the North Pacific Ocean. In the next four years we can confidently expect that a first order description of the role of ocean currents in a global heat balance will emerge.

Acknowledgements. The author is very grateful to Harry Bryden for making material available for this review. The assistance of Elizabeth Williams and Martha Jackson in preparing the manuscript is gratefully acknowledged.

References

Bennett, A.F., Poleward heat fluxes in Southern Hemisphere oceans, *J. Phys. Oceanogr.*, *8*, 785-798, 1978.

Bernstein, R.L., and W.B. White, Meridional eddy heat flux in the Kuroshio Extension Current, *J. Phys. Oceanogr.*, *12*, 154-159, 1982.

Bryan, K., Measurements of meridional heat transport by ocean currents, *J. Geophys. Res.* *67*, 3403-3414, 1962.

Bryan, K., Poleward heat transport by the ocean: observations and models, *Ann. Rev. Earth Planet. Sci.*, *10*, 15-38, 1982a.

Bryan, K., Seasonal variation in meridional overturning and poleward heat transport in the Atlantic and Pacific Oceans: A model study, *J. Mar. Res.*, 40 (Supl. Vol.) 39-53, 1982b.

Bryan, K. and L.J. Lewis, A water mass model of the World Ocean, *J. Geophys. Res.*, 84(C5) 2503-2517, 1979.

Bryden, H.L., Poleward heat flux and conversion of available potential energy in Drake Passage, *J. Mar. Res.*, *37*, 1-22, 1979.

Bryden, H.L., Ocean heat transport, Papers of the JSC/CCCO Meeting on Time Series of Ocean Measurements, Tokyo, May, 1981, World Climate Program, Publ. 21, IOC, Paris, WMO, Geneva, 1982.

Bryden, H.L., and M.M. Hall, Heat transport by currents across 25°N latitude in the Atlantic Ocean. *Science*, *207*, 884-886, 1980.

Bunker, A., Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean, *Mon. Weather Rev.*, *104*, 1122-1140, 1976.

Campbell, G.G., Energy transport within the earth's atmosphere-ocean system from a climate point of view, Ph.D. Thesis, Colorado State University, Fort Collins, CO., 1981.

De Szoeke, R.A. and M.D. Levine. The advective flux of heat by mean geostrophic motions in the Southern Ocean, *Deep-Sea Res.* *28*, 1057-1085, 1981.

Dobson, F., F.P. Bretherton, D.M. Burridge, J. Crease, E.B. Kraus, and T.H. Vonder Haar, *The 'Cage' Experiment*: *A Feasibility Study*, World Climate Program, *22*, World Meteor. Org. Geneva, 95 pp. 1982.

Fu, L.L., The general circulation and meridional heat transport of the subtropical South Atlantic determined by inverse methods, *J. Phys. Oceanogr.*, *11*, 1171-1193, 1981.

Fuglister, F.C., *Atlantic Ocean Atlas of Temperature and Salinity Profiles and Data from the International Geophysical Year of 1957-58*, Woods Hole Oceanographic Inst., *Atlas Series 1*, 209 pp, 1960.

Georgi, D.T., and J.M. Toole, The Antarctic Circumpolar Current and the oceanic heat and fresh water budgets, *J. Mar. Res.*, (Vol.40, Suppl.), 183-197, 1982.

Godfrey, J.S., and T.J. Golding, The Sverdrup relation in the Indian Ocean, and the effect of the Pacific. Indian Ocean through-flow on Indian Ocean circulation and on the East Australian Current, *J. Phys. Oceanogr.*, *11*, (6): 771-79, 1981.

Hall, M.M., and H.L. Bryden, Direct estimates and mechanisms of ocean heat transport, *Deep-Sea Res.*, *29*, 339-360, 1982.

Hastenrath, S., Heat budget of tropical ocean and atmosphere, *J. Phys. Oceanogr.*, *10*, 157-170, 1980

Hastenrath, S., On meridional heat transports in the World Ocean, *J. Phys. Oceanogr.*, *12*, 922-927, 1982.

Hastenrath, S. and P. Lamb, *Climatic Atlas of the Tropical Atlantic and Eastern Pacific Oceans*, Madison: University of Wisconsin Press, 105 pp, 1977.

Jung, G.H., Energy transport by air and sea. Section XIV of *The Dynamic North*, Book I, published by Technical Assistant to Chief of Naval Operations for Polar Projects, 19 pp, 1956.

Luyten, J. and H. Stommel, Recirculation reconsidered. *J. Mar. Res.*, *40*, (Suppl. Vol.) 407-426, 1982.

Meehl, G.A., W.M. Washington, and A.J. Semtner, Experiments with a global ocean model driven by observed atmospheric forcing, *J. Phys. Oceanogr.*, *12*, 301-312, 1982.

Miller, J.R., G.L. Russell, and L-C Tsang, Annual oceanic heat transports computed from an atmospheric model, *Dyn. Atmos. Oceans*, 1982, in press.

Niiler, P.P., and W.S. Richardson, Seasonal variability of the Florida Current, *J. Mar. Res.*, *31*, 144-167, 1973.

Oort, A.H., *Global Atmosphere Circulation Statistics, 1958-1973*, NOAA Prof. Paper, *14*, U.S. Gov't. Printing Office, Washington, DC, 323 pp, 1982.

Roemmich, D., Estimation of meridional heat flux in the North Atlantic by inverse methods, *J. Phys. Ocean.*, *10*, 1972-83, 1980.

Sarmiento, J.L., and K. Bryan, An ocean transport model for the North Atlantic. *J. Geophys. Res.*, 87(C1), 394-408, 1982.

Sciremammano, F. Jr., The nature of the poleward heat flux due to low-frequency current fluctuations in the Drake Passage, *J. Phys. Oceanogr.*, *10*, 843-852, 1980.

Stommel, H., Asymmetry of interoceanic freshwater and heat fluxes, *Proc. Nat. Acad. Sci. USA*, 77(5) 2377-2381, 1980.

Stommel, H., and G.T. Csanady, Relation between the T-S curve and global heat and atmospheric water transports, *J. Geophys. Res.*, *85*, (C1) 495-501, 1980.

Stommel, H., and G. Veronis, Variational inverse method for study of ocean circulation, *Deep Sea Res.*, *28A*, 1147-1160, 1981.

Trenberth, K.E., Mean annual poleward energy transports by the oceans in the southern hemisphere, *Dyn. Atmos. Oceans*, *4*, 57-64, 1979.

Vonder Haar, T.H., and A. Oort, New estimate of annual poleward energy transport by northern hemisphere oceans, *J. Phys. Oceanogr.* *3*, 169-172, 1973.

Weare, B., P.T. Strub, and M.D. Samuel, Annual mean surface heat fluxes in the tropical Pacific Ocean, *J. Phys. Oceanogr.*, *11*, 705-717, 1981.

Wunsch, C., Meridional heat flux of the North Atlantic Ocean, *Proc. Nat. Acad. of Sciences, USA*, *77*, 5043-5047, 1980.

Wunsch, C., The North Atlantic general circulation west of 50°W determined by inverse methods, *Rev. Geophys. and Space Phys.*, *16*, 583-620, 1978.

Wunsch, C., D. Hu, and B. Grant, Mass, heat, salt and nutrient fluxes in the South Pacific Ocean, *J. Phys. Oceanogr.*, (in press) 1983.

Wüst, G., and A. Defant, *Scientific Results of the German Atlantic of the Research Vessel "Meteor" 1925-27*, *6*, Atlas, Walter de Gruyter, Berlin Leipzig, 1936.

(Received October 29, 1982;
accepted January 6, 1983.)