JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. C6, PAGES 13,235–13,249, JUNE 15, 1999

Where do ocean eddy heat fluxes matter?

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Abstract. A quasi-global compilation of current meter and temperature records, along with some of the published literature, is used to assess the importance of the meridional eddy heat flux in the ocean circulation, and a comparison is made to a uniform global estimate from altimetric data. Eddy fluxes are found to be important, relative to estimated total heat fluxes, in western boundary current areas of all oceans. Eddy heat flux divergences are potentially important in many other locations, but the mooring coverage is inadequate to be more quantitative. The eddy heat flux in the Southern Ocean is of only modest magnitude compared with that in the western boundary currents, but because of the large circumpolar distance, the integrated flux is very important and probably dominant. All these results are generally consistent with independent estimates made from satellite altimeter variability, but the mooring coverage is not adequate to assess the apparent importance of eddy heat fluxes in the tropics as implied by the altimeter. With the exception of the extreme northeastern North Atlantic, where the local wind dominates the variability, there is no evidence for upgradient fluxes. Climate change models must apparently accurately model the eddy mean-flow interactions near western boundary currents, in the high-latitude North Atlantic, in the tropics, and in the Southern Ocean. One can infer that models describing other physical properties such as carbon or nutrients must also adequately represent the eddy contributions to those fluxes as well.

1. Introduction

Over the past 20 years, two distinct pictures of the ocean circulation have emerged. The first picture is basically the historical one, dating back at least 100 years, in which the circulation is regarded as large scale, fundamentally steady, and laminar. The second picture, which is much more recent, regards the circulation as fundamentally time dependent and turbulent. These two paradigms clash when one comes to discussions of observational strategies, or the likely skill of climate forecast models based upon the first picture.

Picture 2 emerged out of the discovery of the oceanic mesoscale activity in the early 1970s [see, e.g., *The MODE Group,* 1978] and has evolved with numerous current meter and float time series measurements since then. The most vivid expression of picture 2 is obtained from the global TOPEX/POSEIDON altimeter measurements [e.g., *Wunsch and Stammer*, 1998].

Oceanic kinetic energy is dominated by eddy time and space scales almost everywhere. Any visual depiction of the flow field at a point or averaged over a small region clearly shows that the "mean" flow is a very small fraction of the time variation. Indeed, the 11-year record of *Müller and Siedler* [1992] fails to produce a statistically significant mean. Taken literally, the existence of this intense variability suggests that the circulation has to be regarded as turbulent. That conclusion drives one to expensive observational and modeling strategies involving synoptic pictures of the entire global ocean. In contrast, the historical paradigm underlies almost all the successful theoretical, analytical treatments of the ocean circulation [e.g. *Pedlosky*, 1996]. An observational strategy based upon combining scalar field observations over decades is then workable. It also permits one to integrate extremely coarse resolution (e.g. 4°) models forward in time for 1000 years [see *Delworth*, 1997] and to claim they have skill.

Can one reconcile these two pictures? One possibility [*Wunsch*, 1981] is that the eddy field has no dynamical consequences. The eddies are then purely kinematic features with no physical importance beyond a local noise. Sampling the ocean would still be difficult, so as to avoid aliasing effects, but apart from producing a simple, possibly very small, downgradient flux of energy, momentum, and other properties, they would carry no significant quantities of heat, fresh water, or related quantities such as carbon or potential vorticity.

There is a large literature on eddies (see the somewhat dated reviews by *Wunsch*, 1981, *Robinson*, 1983 or *Holloway*, 1986] directed at understanding eddy variability in a huge variety of settings by differing instru-

Paper number 1999JC900062.
0148-0227/99/1999JC900062$09.00

ments. Many authors have previously discussed the eddy heat flux. Most discussions are of regional observations or models, exploring one or more local mechanism of eddy generation or interaction. In this present paper, we seek a more global description of the role of eddies: to understand whether any generalizations are possible that would permit a summary statement of their influence over the bulk of the ocean. Are they dynamically important, and if so, is their importance restricted to a few special regions requiring special care?

Stimuli for this present report are the synthesis of the altimetric data by *Stammer* [1998; hereinafter referred to as S98] into a global eddy heat flux estimate and the global current meter coverage obtained since the early 1970s reported by *Dickson* [1981] and *Wunsch* [1997; hereinafter referred to as W97]. The latter compilation was created to study the vertical mode partition of the motions generating altimetric sea surface signals. As such, it is believed to contain most (but not all) of the existing records from moorings with durations of at least 9 months, with a minimum of three instruments having a depth range spanning the main thermocline of the ocean, in water nominally greater than 4000 m (a few moorings violate the depth criterion). The three instrument minimum with measurement depths above, within, and below the main thermocline permits at least a crude separation of barotropic and baroclinic modes. Because of these restrictions, many current meter records were omitted. In particular, large numbers of single-instrument and shallow-water instruments have not been included. Use of altimetry in shallow water remains problematic (there is a variety of problems ranging from tidal aliases to geoid noise), and a major goal here, as in W97, is to determine the reliability or interpretability of the near-global coverage by the altimeter. Many of the results have been previously reported in the literature (see the reference list in W97, and the reviews noted above), but here a uniform computational procedure has been used, and we attempt to synthesize them into basin-wide maps to produce a global-scale context. Some results in the literature from moorings not re-analyzed here will however, be employed, particularly dealing with results from the tropics and the Southern Ocean.

The present results are far from definitive. A complete recomputation of eddy heat fluxes from moored devices will probably be worthwhile in a few years, when the recent World Ocean Circulation (WOCE) moored data have become fully available.

2. Altimeter Results

Using 4 years of surface geostrophic variability estimates from the TOPEX/POSEIDON spacecraft, *Stammer* [1998] calculated the meridional eddy heat (and salt) flux under the assumption that it occurs through the baroclinic instability of the large scale geostrophic fields. He produced charts of both the apparent eddy coefficient κ, of the net heat flux resulting from the product of κ (see Figure 1), and the mean meridional temperature gradient, assuming that the fluxes are always down gradient. A summary is that he finds strong meridional eddy fluxes in the western boundary current regions of all oceans, a strong flux in the tropics equatorward of about 15° latitude, and a comparatively weak flux in the Southern Ocean apart from the Agulhas Retroflection. The Southern Ocean result is perhaps surprising, given the general perception that the eddy flux is particularly important there.

When integrated zonally around the earth, the net altimeter-estimated eddy heat fluxes do not exceed about 0.3 PW or except in the Southern Ocean, around 20% of the mean meridional fluxes [*Macdonald and Wunsch*, 1996]. A 20% contribution is, however, a major element in climate; the apparent North Atlantic eddy heat flux divergence exceeds 0.5 PW between 5° and 18°N; and, as discussed below, the regional contributions to the fluxes and flux divergences are sometimes very large.

A number of assumptions have to be made in the altimetric calculations (the reader is referred to S98), and

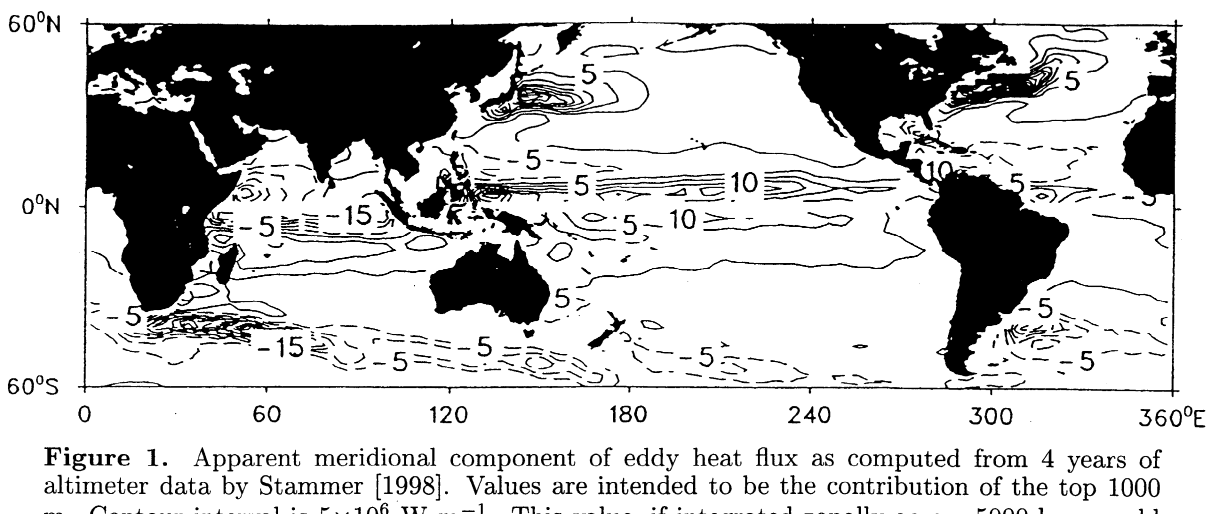


Figure 1. Apparent meridional component of eddy heat flux as computed from 4 years of altimeter data by Stammer [1998]. Values are intended to be the contribution of the top 1000 m. Contour interval is 5×10^{6} W m^{-1}. This value, if integrated zonally across 5000 km, would produce a meridional heat flux of 2.5×10^{13} W.

one of the purposes of this paper is to make estimates from the current meter/temperature records so as to determine the fluxes by a wholly independent method. In particular, we seek some understanding of the vertical structure of the eddy heat flux, a complementary study to that reported in W97.

3. Current Meter/Temperature Data

Figure 2a shows the distribution of available moorings, which is clearly focused in the North Atlantic Ocean. The data were all filtered to remove high-frequency variations; that is, energy was removed at periods shorter than 1 day in all records. Many records had been, filtered before the data reached us; in a small number of them, all energy at periods shorter than 40 hours had been removed. We will not distinguish these records from the others, as there is little energy between periods of 40 and 24 hours except near the equator. Since W97 was written, a few more records were obtained, including several in the equatorial Indian Ocean, two in the Southern Ocean near 65°S, and one 2-year record from 26°N, 70°W inexplicably missing from all the previous data sources. Not all current meter records are accompanied by temperature data, and hence there is not a one-to-one correspondence with the records in W97.

The results here are far from robust: the records are fragmentary and not very long compared to the dominant time scales. Even with the 446 records employed, many of the results are semi-qualitative, only indicative, and subject to change if the data base is ever improved.

3.1. Covariances

We begin this study of the global eddy characteristics with a discussion of the apparent "eddy" heat fluxes (eddy is placed in quotation marks to indicate its use as a shorthand for variability about the record mean, whatever its dynamical cause).

The eddy heat flux vector $\mathbf{h}'$, is defined as

$$\mathbf{h}' = \left[\overline{u'\theta'},\ \overline{v'\theta'}\right] \tag{1}$$

where u', v' are the zonal and meridional velocity deviations from their temporal means. Corresponding correlation coefficients,

$$C_{u\theta} = \frac{\overline{u'\theta'}}{\sqrt{\overline{u'^2}\,\overline{\theta'^2}}},\ C_{v\theta} = \frac{\overline{v'\theta'}}{\sqrt{\overline{v'^2}\,\overline{\theta'^2}}}. \tag{2}$$

were computed for all instruments, but the latter are not displayed here (the raw global mean of $|C_{v\theta}|$ is 0.16). Given the available data, the conclusions drawn are, unfortunately, sensitive to the handling of the statistics.

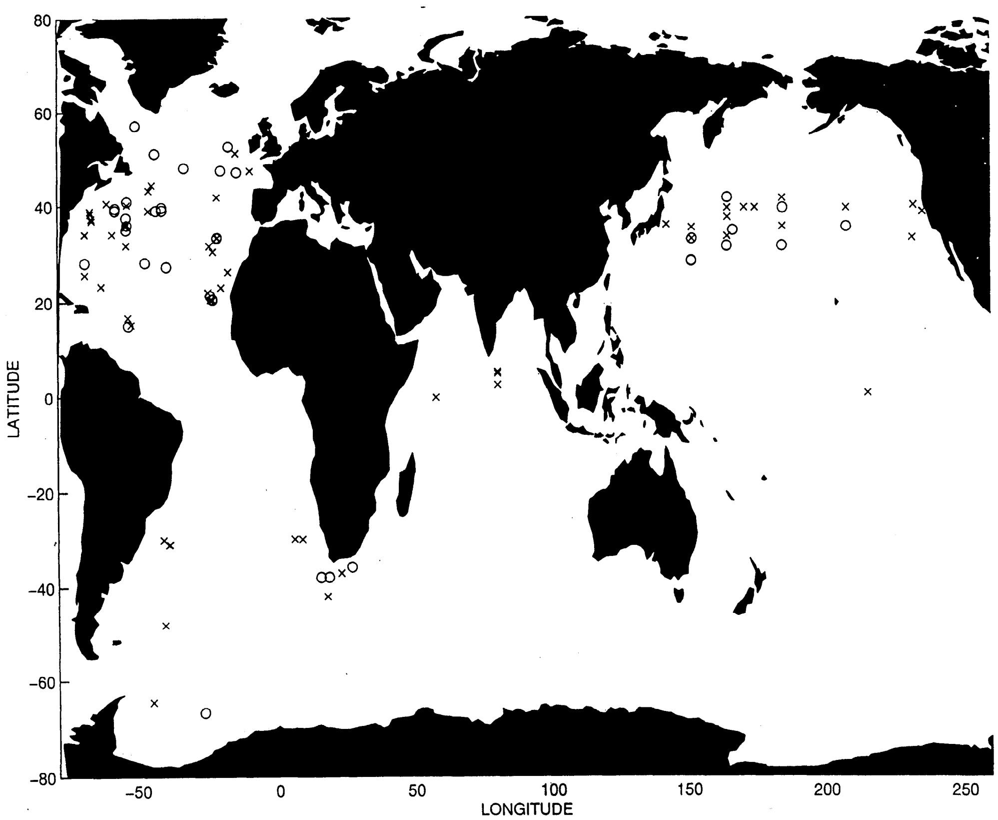


Figure 2a. Mooring positions used in this study; see *Wunsch* [1997] for a description of the selection criteria. Crosses indicate moorings where at least one instrument, somewhere in the vertical, had a meridional heat flux apparently significantly different from zero at 95% confidence; circles indicate moorings that did not.

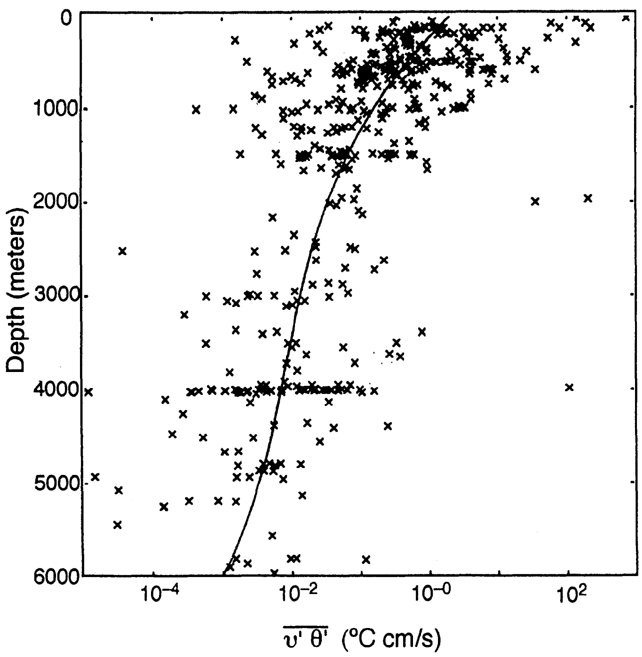


Figure 2b. Vertical profile of $log_{10}\left(\left|\overline{v'\theta'}\right|\right)$ for the entire global data set. A least squares fit of the first four Chebyshev polynomials is shown. No weighting was done. Despite outliers, the dominance of the upper ocean is apparent.

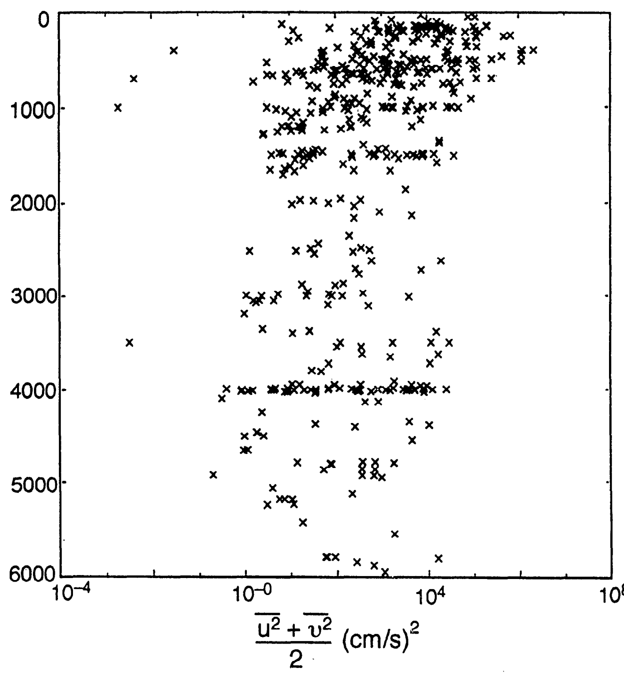


Figure 2c. The vertical profile of $log_{10}\left[\left(\overline{u'^2}+\overline{v'^2}\right)/2\right]$, which although weakly surface intensified, is much less so than is the eddy heat flux—presumably the result of the surface intensified mean temperature gradient. Actual profile is unreliable as a global average owing to the maldistribution of moorings around the world.

One wishes to understand the significance of apparent eddy heat fluxes, their sign and magnitude, with their physics directly dependent upon the inference that they represent quantitatively a climatological average (otherwise, they have no meaning).

The key issue is that the eddy heat fluxes are directly proportional to the correlation between velocity and temperature, and it is a standard result of elementary statistics that two processes that are rigorously not correlated necessarily always show finite sample correlations. Thus the interpretation of sample heat fluxes requires a discussion of the statistical significance of the results. Measured velocity and temperature fields in the ocean have "red" spectra or are, equivalently in the time domain, strongly autocorrelated. As discussed, for example, by *Jenkins and Watts* [1968, p. 340], two truly uncorrelated processes that are strongly autocorrelated tend to produce sample cross-correlations which are numerically very large (sometimes called the "Slutsky-Yule effect"). Previous authors [e.g., *Richman* et al., 1977; *Bryden*, 1979] have dealt with this problem by attempting to determine the number of degrees of freedom in the records by estimating a timescale for decorrelation of the individual records of v, θ.

Define the autocovariance and cross covariance of any two zero-mean wide-sense stationary time series $x(t)$, $y(t)$ as

$$R_{xx}(\tau) = < x(t)\, x(t+\tau) >,$$
$$R_{xy}(\tau) = < x(t) y(t+\tau) >, ..., \tau = 0, 1, ... \qquad (3)$$

where the bracket denotes an ensemble average. Then it is not hard to show [e.g., *Jenkins and Watts*, 1968, p.338] that the variance of a sample cross covariance at zero lag, $\tilde{R}_{xy}(\tau = 0)$, from M samples, is

$$< \left[\tilde{R}_{xy}(0) - R_{xy}(0)\right]^2 > = \frac{1}{M} \sum_{r=-\infty}^{\infty} R_{xx}(r)\, R_{yy}(r), \qquad (4)$$

which permits computation of the variance and confidence limits for such quantities as the sample averages $\overline{v'\theta'} = \tilde{R}_{v\theta}(0)$. The difficulty is that R_{xx}, etc., are not known and usually can only be estimated from the data itself, from expressions such as

$$\tilde{R}_{xx}(\tau) = \frac{1}{M} \sum_{t=1}^{M} x(t)\, x(t+\tau), \; 0 \le \tau \le M-1, \qquad (5)$$

where a unit time step is being used. As $\tau \to M$, $\tilde{R}_{xx}(\tau)$ becomes unstable owing to a lack of data and it is desirable to avoid using $\tilde{R}_{xx}(\tau)$ for large values of τ. Often, an integral timescale

$$\tilde{T}_1 = \frac{1}{\tilde{R}_{xx}(0)} \sum_{\tau=0}^{\infty} \tilde{R}_{xx}(\tau) \approx \frac{1}{\tilde{R}_{xx}(0)} \sum_{\tau=0}^{\tau_0} \tilde{R}_{xx}(\tau), \qquad (6)$$

is used, where τ_0 is defined as the time lag, as best one determine it, where $\tilde{R}_{xx}(\tau_0) = 0$. For autocovariance functions of longitudinal velocities in homogeneous turbulence, the autocovariance remains zero for $\tau > \tau_0$. One then reduces from M to $M/\tilde{T}_1$ the degrees of freedom in a test of significance of a cross-correlation coefficient. This calculation is sensible and often produces reasonable results. The difficulty is that it can grossly overestimate the number of degrees of freedom if there are true long-lag autocorrelations present.

Jenkins and Watts [1968] suggest "prewhitening" the time series prior to calculating the cross-correlation coefficient. Consider an example. Figure 3 shows a power density spectrum for a not-untypical 2-year record from mooring 25 at 156 m in the North Pacific Ocean. The spectrum is quite "red" out to periods of about 100 days becoming, characteristically of many such records, nearly white at longer periods. The temperature spectral estimate at this instrument is very similar and is not shown. The raw records produce an apparent correlation $C_{v\theta} = -0.71$. The records were whitened by applying an order 5 prediction error filter [see, e.g., *Ljung*, 1995; *Box and Jenkins*, 1978]. The correlation is changed to $C_{v\theta} = +0.06$, suggesting that the true correlation is zero, and hence one might conclude that the eddy heat flux is indistinguishable from zero.

Use of pre-whitened time series is, however, based upon the assumption that the physics of the variability remains uniform over the entire frequency interval of the spectrum. For the present example, the implication is that the higher-energy, low-frequency, nearly white spectral region represents the same physical process as the high-frequency, lower-energy (per unit frequency band) region of the power law behavior of the spectrum. Prewhitening raises the number of degrees of freedom to a value close to the record length in days M; but it seems doubtful that the "white band" and the "power law band" represent the same physics; computing a correlation coefficient as if they did may be combining apples and oranges.

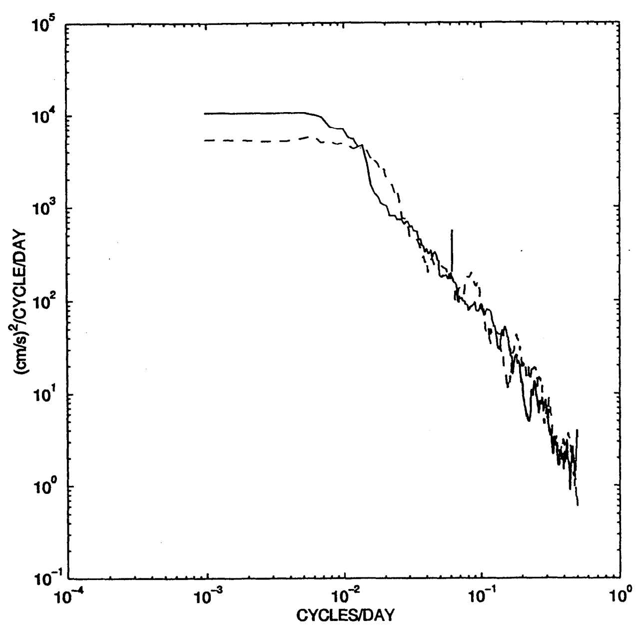


Figure 3. Spectral density estimate for the two components of horizontal velocity (meridional component is dashed) on the 2-year-long record at 35°N, 171°W97, 156 m in the North Pacific. The spectra are computed using D. Thompson's multitaper algorithm; see *Percival and Walden* [1993]. An approximate mean 95% confidence interval is shown

We will thus use the raw (unwhitened) correlation coefficients to discuss significance. The standard error of the covariance is computed from (4) using the entire sample autocovariance; this is a rough measure but should at least semiquantitatively reflect the actual uncertainty.

A full description of the physics requires an analysis of the second-moment contributions by frequency band, including the underlying spectral densities and their cospectra and quadrature spectra. The resulting volume of numbers would swamp the reader and we confine ourselves to these integrated (across frequency bands) summary conclusions. It is worth mentioning, however, that the dominant timescales of the variance in the records is always in the mesoscale range (for example, see Figure 15 of W97 or *Stammer* [1997]).

3.2. Mooring Motion Errors

As noted in W97, there are some moorings carrying pressure sensors in strong flows, where it is apparent that the mooring underwent large vertical excursions as it is dragged down by the current. *Hogg* [1991] has described a method for systematically correcting the measurements for mooring motion, essentially by employing estimates of the pressure/temperature relationship from the moored data itself. Experience with the method (N. Hogg, personal communication, 1998) is that the corrections for second moments of temperature and velocity are only significant on moorings in extreme environments, such as the Gulf Stream. To understand the extent to which the present results are likely to be contaminated by mooring motion biases, two moorings near the Gulf Stream for which the corrections had been made (N. Hogg, personal communication, 1998) were analyzed in both the corrected and uncorrected forms with the results shown in Table 1.

There is little difference between the corrected and uncorrected estimates. On mooring 57, the uppermost instrument shows a substantial change in both components, while on mooring 58, only the meridional component of the second instrument is substantially modified. However, all of the shifts lie within 1 standard deviation of the estimated uncertainty, and although this error is not explicitly included in $\sigma_{v\theta}$, $\sigma_{u\theta}$, in mapping and analyzing the results, we are unlikely to seriously bias the results as long as the existing uncertainty estimates are used.

3.3. Global Summary Statistics

The 105 moorings depicted in Figure 2a carry 446 instruments with both temperature and velocity. Of

Table 1. Covariances Uncorrected and Corrected for Two moorings near Gulf Stream

Depth (m)	$\overline{u\theta}$	$\overline{u\theta}_c$	$\sigma_{u\theta}$	$\overline{v\theta}$	$\overline{v\theta}_c$	$\sigma_{v\theta}$
			Mooring 57			
499	34.4	47.4	12	21.2	16.9	10.6
1007	1.9	1.9	1.0	2.3	2.3	1.1
1510	0.50	0.50	0.2	0.5	0.5	0.3
3997	0.08	0.08	0.03	0.04	0.04	0.04
			Mooring 58			
247	35.3	35.3	7.4	4.6	4.6	5.3
500	16.0	16.6	3.6	2.5	5.2	2.6
1008	1.2	1.2	0.3	-0.05	-0.05	0.2
1516	0.3	0.3	0.09	-0.004	-0.004	0.06
3995	0.06	0.06	0.02	-0.002	-0.002	0.01

Mooring 57 is at 40.1°N, 54.7°W; mooring 58 is at 40.9°N, 54.7°W. Relevant data for the two moorings are given by *Wunsch* [1997, Table 1]. For each instrument, a depth is shown, and the standard errors of the estimates $\sigma_{u\theta}$, $\sigma_{v\theta}$ are also displayed. Subscript c denotes the mooring-motion corrected values.

this number, a fraction were deployed so close to the bottom that the temperature records are dominated by the least-count noise. Of the 105 moorings, 98 of them have at least one instrument for which $\left|\overline{v'\theta'}\right| > \sigma_{v\theta}$, but only 66 have one or more instruments such that $\left|\overline{v'\theta'}\right| > 2\sigma_{v\theta}$. With Gaussian statistics, the latter would approximate a test of significance at 95% confidence. Thus about 2/3 of the moorings show an eddy heat flux on at least one instrument that is statistically distinguishable from zero at this confidence level, and these are indicated with a cross on Figure 2a. By the same measure, 107 instruments have an apparent nonzero zonal eddy heat flux at 95% confidence.

On any given mooring, the vertical profile of $\overline{v'\theta'}$ tends to vary strongly with depth. Figure 2b displays the entire set of $\left|\overline{v'\theta'}\right|$ as a function of depth, irrespective of significance, sign or location, as well as a smoothed vertical fit. Clearly the large upper ocean fluctuations of v', θ' dominate the profiles, but in some cases, the weaker fluctuations in these variables at great depth produce statistically significant heat fluxes while the large upper ocean values fail to be distinguishable from zero. For comparison, the entire global set of kinetic energies, $(\overline{u'^2} + \overline{v'^2})/2$, is displayed in Figure 2c, and although nonuniform and widely scattered, it does not show the same degree of surface intensification as does the meridional eddy temperature flux. Qualitatively, at least, the assumption in S98 and of previous authors that significant eddy heat fluxes are confined to the top 1000 m, is confirmed.

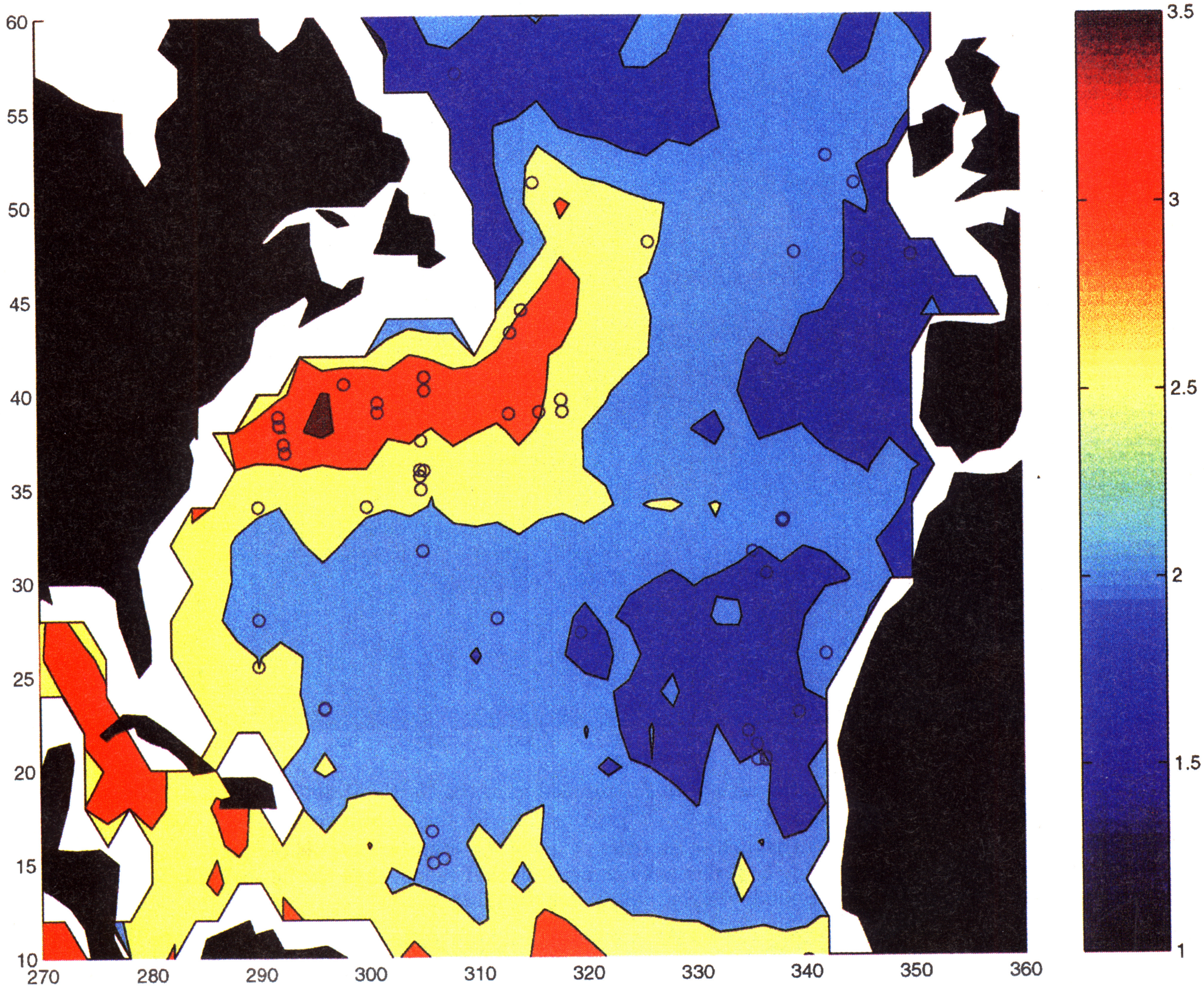
The zero-order description of the motions used in W97 was of a sum of uncoupled linear dynamical modes of a flat-bottom ocean. This description is a useful first approximation, but it is important to recognize that if it were strictly correct, $\overline{v'\theta'}$ would vanish identically, with the two fields being in temporal quadrature. It is thus only the deviations from perfect adherence to the linear dynamical picture, many of which are described in W97, that produce nonzero results here. In particular, attention was called in W97 to the tendency at many moorings for there to be apparent phase locking between the modes; this and other effects generate finite values of $\overline{v'\theta'}$.

4. Eddy Heat Flux: Meridional Component

Although zonal eddy temperature fluxes $\overline{u'\theta'}$ are reported here, our focus is on the meridional component $\overline{v'\theta'}$. The latter, as an element of the control of the bulk transfer of heat from equator to pole which so dominates the climate system, has received much more attention than the zonal elements. The $\overline{u'\theta'}$ are surely important in maintaining the zonal gradients in observed climate states, but estimates of the heat flux divergences as a function of longitude in the ocean are much less highly developed than the meridional ones, and a fuller discussion of the zonal heat flux divergence budget is postponed.

4.1. North Atlantic Ocean

The North Atlantic is the only ocean basin with coverage that begins to be even close to adequate. Note that even here, in any given depth range, many moorings lack any instrument at all. Plate 1 superimposes the mooring positions on the contours of $log_{10}(KE)$, where KE is the kinetic energy, estimated from four years of TOPEX/POSEIDON data [*Stammer*, 1998]. The axis of the Gulf Stream variability maximum will be shown on subsequent charts so as to fix the moorings relative to the Gulf Stream variability.



Atlantic [see *Stammer,* 1997; and *Wunsch,* 1997]. An assumption of horizontal isotropy was made, which probably overestimates the energy in the Gulf Stream region. The axis of highest variability is indicated on later plots for reference. Mooring positions are shown as circles.

4.1.1. Top 300 m. Plate 2 displays contours of $\overline{v'\theta'}$ from all instruments in the top 300 m of ocean as well as the vector $\mathbf{h}' = \left[\overline{\mathbf{u}'\theta'}, \overline{\mathbf{v}'\theta'}\right]$. Here and in other depth ranges, where more than one instrument per mooring lay within the particular depth range, their values were averaged. The charts were made by a simple objective mapping technique using an uncorrelated error given by the estimated standard error for the particular covariance value and a Gaussian field covariance with 5° radius. The spatial heterogeneity of the $\overline{v'\theta'}$ field renders the maps only semiquantitative and subject to spatial biases. Although the confidence limits on the arrows are not indicated, they are accounted for in mapping the $\overline{v'\theta'}$ contours.

The units of the results are degrees Celsius per centimeter per second and need some context to be interpreted. Suppose the mapped value is representative of the entire 300 m depth range; then 1°C cm s^{-1} would produce a flux value of 12×10^6 W m^{-1} which can be compared directly to Figure 1. If it was also representative of a 5000 km width ocean basin, a mapped value of 1°C cm s^{-1} would produce 6×10^{13}W of heat flux, or 0.06 PW. The maximum value observed, of about 2°C cm s^{-1}, has a strong regional importance.

The next question is whether such values are of any importance to the general circulation. *Macdonald and Wunsch* [1996] estimated the total oceanic heat flux across 36°N as 1 ± 0.3 PW. Thus the eddy heat flux in the top 300 m of the North Atlantic appears to be a comparatively unimportant contribution to the total meridional value.

To examine the values in another way, if the meridional flux of 2°C cm s^{-1} just north of the Gulf Stream near 50°W is typical of a longitude band of about 10°, then the net heat flux over the top 300 m is about 0.01 PW, being exported to the north. If this heat flux is transferred to the atmosphere over a region 500 km in longitude, and 200 km north-south (very roughly

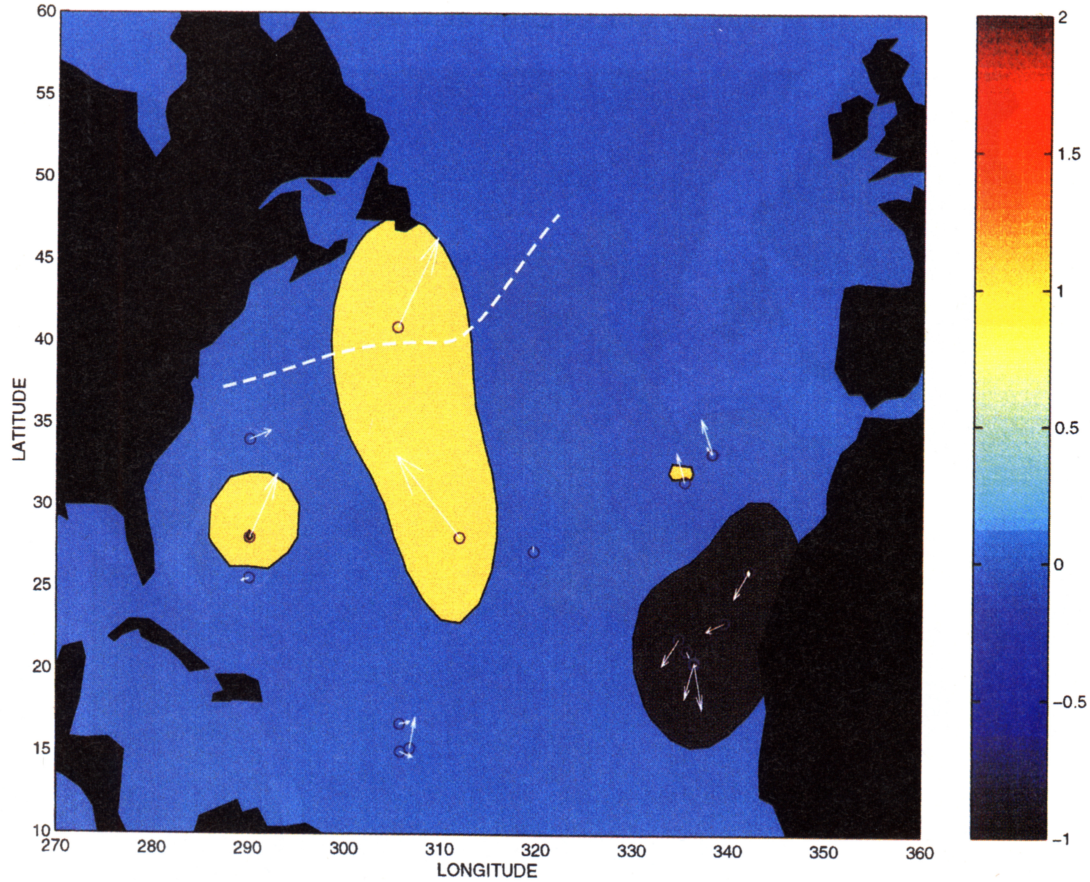


Plate 2. Contours of $\overline{v'\theta'}$ in °C cm s^{-1} in the top 300 m of the North Atlantic Ocean. Arrows depict the eddy heat flux vector $\mathbf{h}' = \left[\overline{u'\theta'}, \overline{v'\theta'}\right]$ except that for the mooring near 42° N, 305° E, $\overline{u'\theta'}$ was divided by a factor of 10 before plotting to make the other arrows visible (that is, for this particular mooring the eddy heat flux is much more strongly zonal than the figure indicates). Dashed line is the axis of the maximum variability seen in Plate 1.

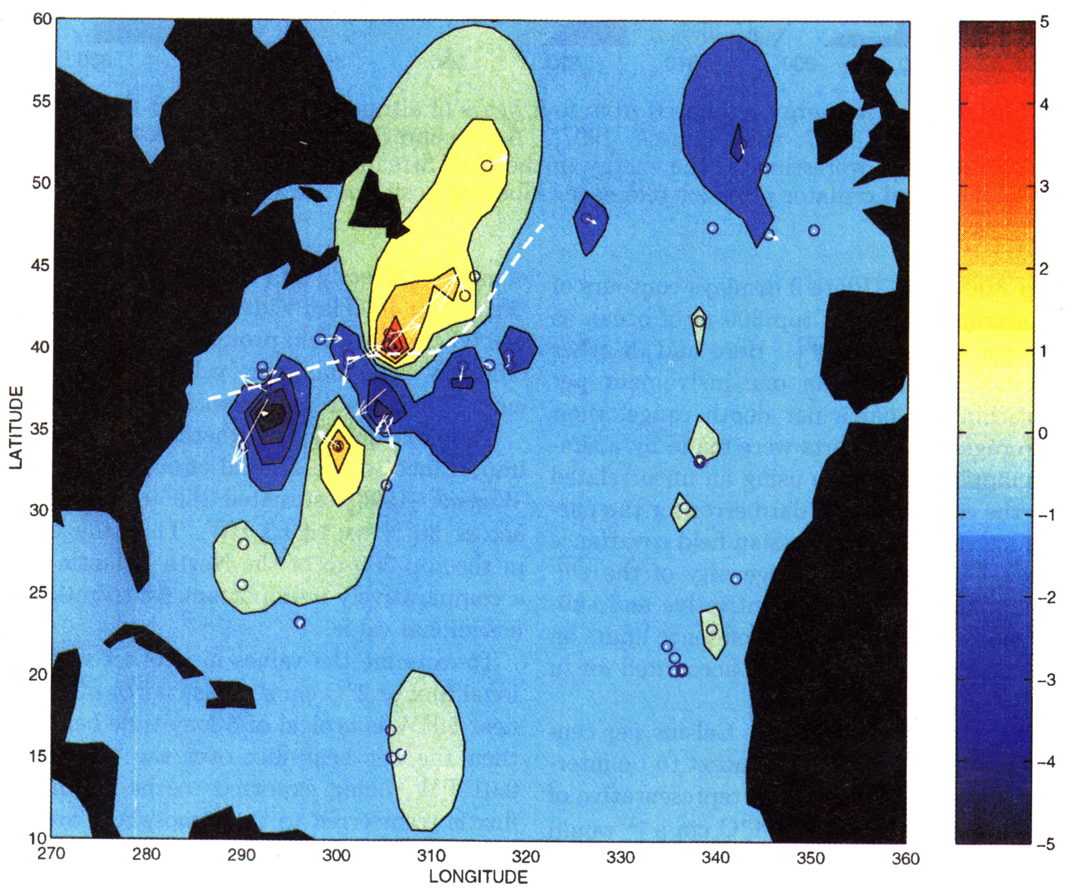


Plate 3. Values of $\mathbf{h}' = \left[\overline{u'\theta'}, \overline{v'\theta'}\right]$ and contours of $\overline{v'\theta'}$ in °C cm s^{-1} spanning the thermocline (301-900 m).

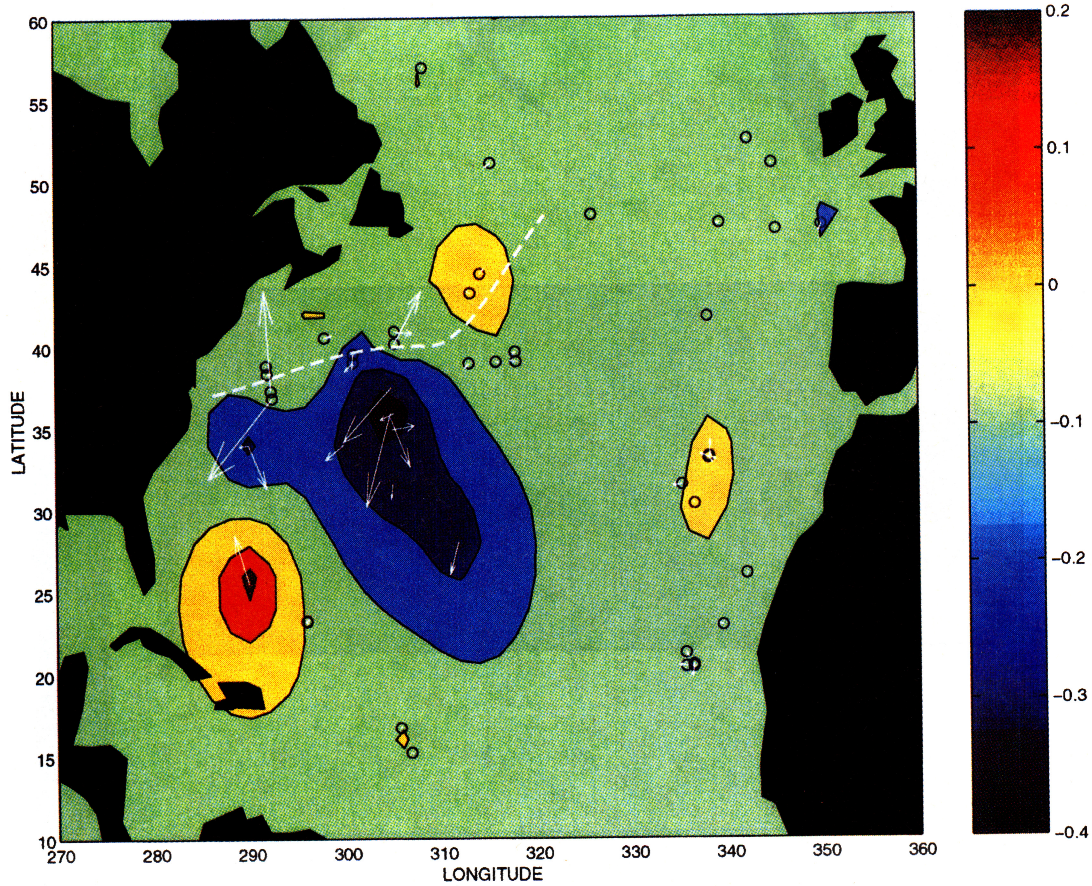


Plate 4. Same as Plate 2 except for depth range of 901-4000 m.

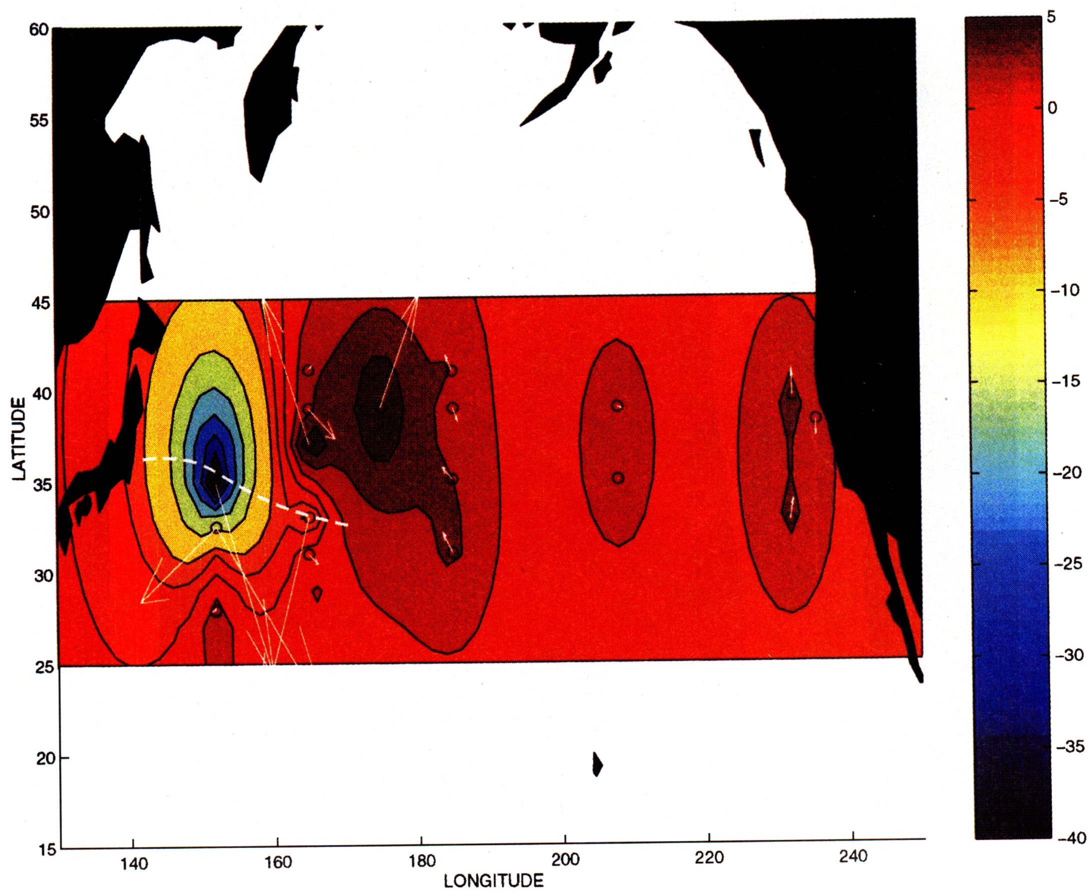


Plate 5. Eddy heat flux vector $\mathbf{h}'$ and contours of $\overline{v'\theta'}$ for the North Pacific in the depth range of 1-300 m. Dashed line is apparent axis of the maximum Kuroshio variability.

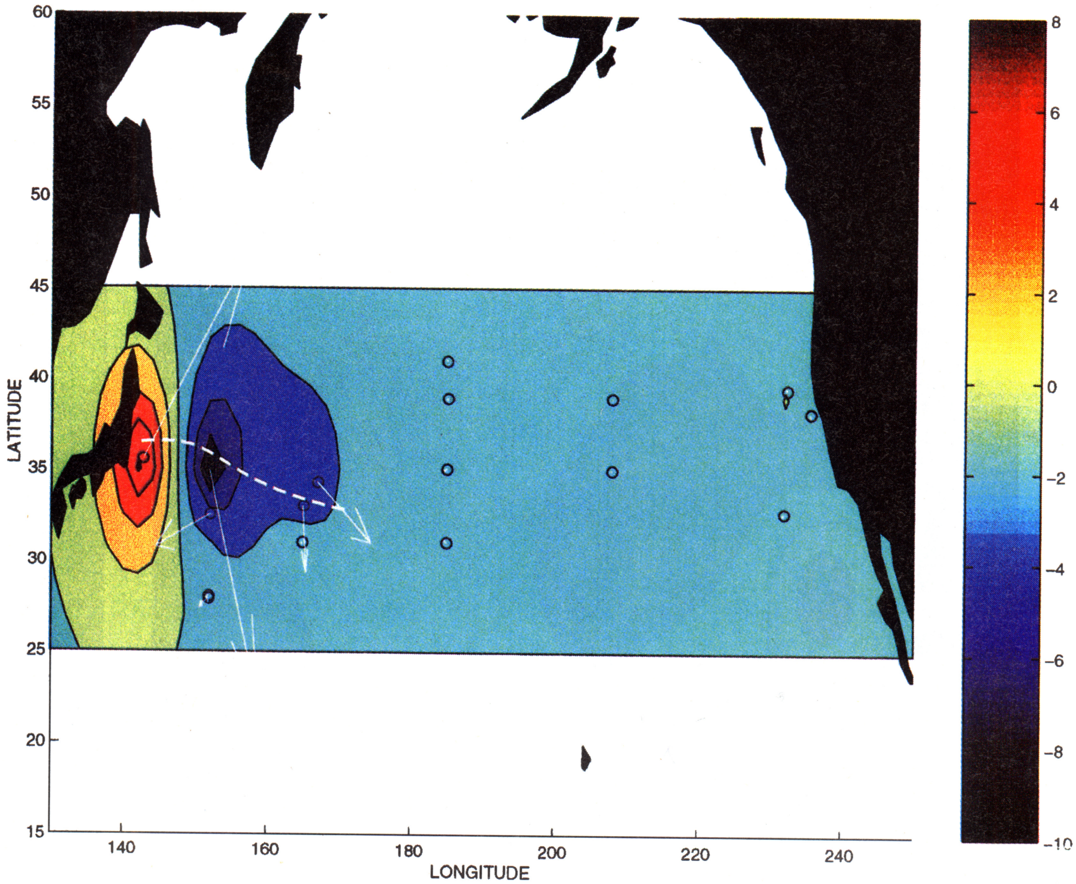


Plate 6. Same as Figure 8, except the thermocline range of 301-900 m.

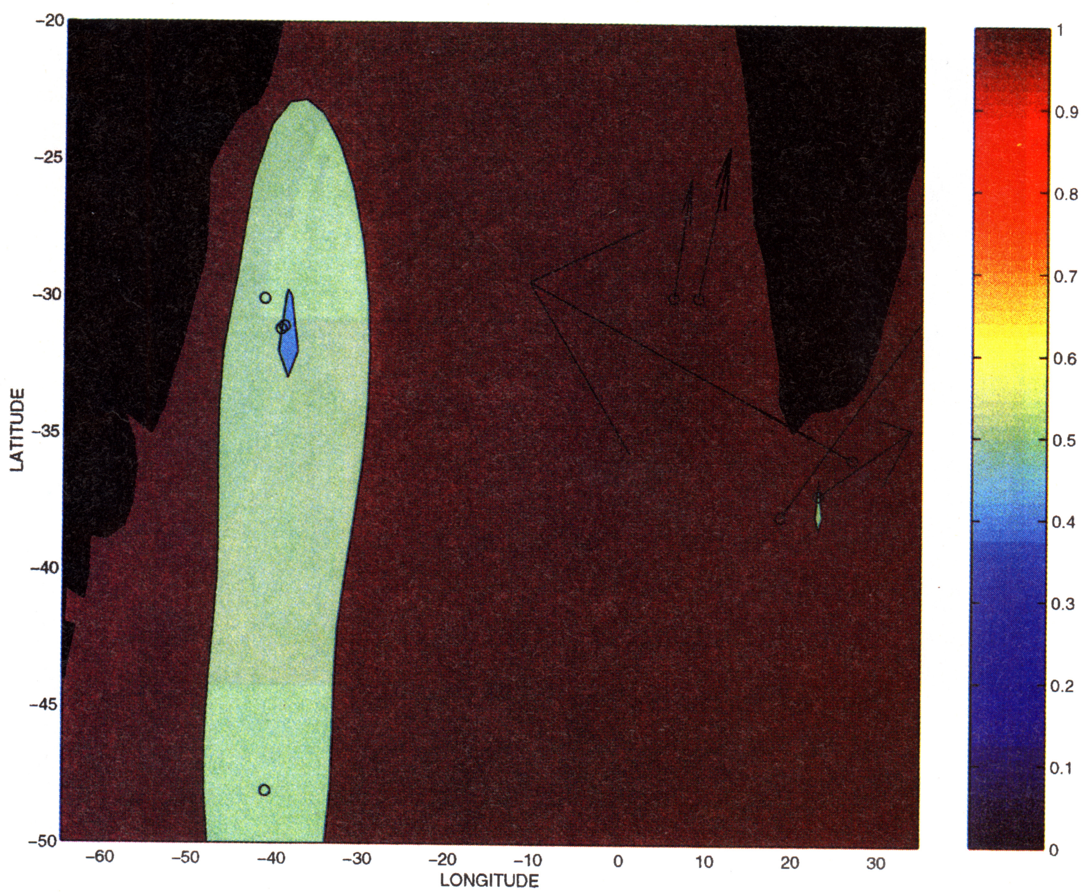


Plate 7. South Atlantic and Agulhas values of $\mathbf{h}'$ and contours of $\overline{v'\theta'}$ in the depth range of 301-900 m. Indicated interior contour value has no significance because of the minimal data coverage. The maximum zonal flux values are about $\pm 9°$ C cm s^{-1}. In the Brazil Basin, both flux components are very small.

the area lying between the Gulf Stream and the Grand Banks), the heat flux would be about 100 W m^{-2}, a very large value, e.g. compared to the net greenhouse gas increase forcing of about 9 W m^{-2} and even large compared to the total climatological values in this region [e.g., *Isemer et al.*, 1989].

Plate 2 when compared, e.g. to the *Levitus and Boyer* [1994] temperature climatology at 150 m, shows that all of the meridional flux vectors in this depth range are downgradient. With the limited available coverage, there is no indication of any upgradient flux regions. Mapped values in the eastern Atlantic are southward, but still downgradient. These approach 1°C cm s^{-1}, which integrates to a value that is small compared to the *Macdonald and Wunsch* [1996] estimate of 0.9±0.3 PW at 24°N but whose divergence is again not necessarily negligible.

(Estimates were made but are not displayed here of the lateral eddy-diffusion coefficient,

$$K = \frac{\overline{v'\theta'}}{\partial\bar{\theta}/\partial y}, \tag{7}$$

where $\partial\bar{\theta}/\partial y$ is the climatological meridional temperature gradient for all estimates here of $\overline{v'\theta'}$. These proved very noisy, and in the North Atlantic, estimates made from the *Levitus and Boyer* [1994] and *Fukumori et al.* [1991] climatologies differed considerably in numerical value, and sometimes in sign (see below). The values estimated were roughly consistent with those of *Stammer* [1998], but for present purposes, $\overline{v'\theta'}$ is the more fundamental number.)

4.1.2. 300-900 m. This depth range is rather large and inhomogeneous in its physics but is chosen to reflect, as well as possible, the motions of the main thermocline. The results are depicted in Plate 3. Coverage is somewhat improved relative to the level above, and the maximum absolute values obtained are up to 5°C cm s^{-1}. If integrated over 600m vertically, 1°C cm s^{-1} produces about 24×10^6 W m^{-1} and if integrated zonally over 5000 km, one has about 0.12 PW. The maximum values seen in the vicinity of the Gulf Stream would represent more than 0.5 PW if they were representative of the entire ocean width. The eddy heat flux divergence, with a general flux outward on both sides, in the Gulf Stream region is clearly very important. In the northeast Atlantic near 50°N, the values near 3 cm s^{-1}°C, southward, would produce over a longitude of 2500 km about 0.2 PW—about 1/3 the total value estimated by *Macdonald and Wunsch* [1996] of 0.6±0.4 PW.

The sign of the meridional heat flux in this depth range relative to the temperature gradient $\partial\theta/\partial y$ is more problematic. The strong southward values at 70°W and 55°W near the Gulf Stream would appear, according to the Levitus and Boyer climatology, to be upgradient. Near-synoptic hydrographic sections in this area [see, e.g., *Fukumori et al.*, 1991, Figures 46 and 52] show however, a weak reversal of the thermal gradient south of the Gulf Stream front and thus the simplest interpretation is that these fluxes too, are downgradient (as suggested earlier by *Bryden* [1982].

4.1.3. Upgradient Flux. In the northeast Atlantic, west and southwest of the British Isles, both the Levitus and Boyer climatology and Figure 60 of *Fukumori et al.* [1991] show the mapped isotherms trending nearly north-south here. In some of the records, the heat flux vector $\mathbf{h}'$ appears to be dominantly zonal and upgradient in this region, although one wishes for more data. *Marshall and Shutts* [1981] have emphasized that an upgradient eddy flux does not *per se,* mean that the mean thermal gradient is being sharpened. Rather, and in direct analogy to the energy flux vector [see *Longuet-Higgins*, 1964], only the divergent part of $\mathbf{h}'$ could do so. The coverage is far too poor for us to separate the rotational and irrotational parts of $\mathbf{h}'$. This region is, however, one which *Stammer and Wunsch* [1999] identified as having an eddy field dominated by local wind variability, a rare occurrence in the ocean. If it is accepted that the eddy field is dominantly wind driven as opposed to generated by baroclinic instability, then an upgradient, divergent flux is definitely possible, if still unproven.

4.1.4. The Tropics. *Fu et al.* [1982] concluded that there was no evidence in their records (those near 15°N, 300°E) for the release of energy through baroclinic instability of the North Equatorial Current as had been proposed by *Gill et al.* [1974]. Their conclusion was based upon the complex, spatially varying structure and apparent point-wise insignificance of $\overline{v'\theta'}$ in their results which are visible in both Plates 2 and 3. In a study related to this one, C. Wunsch [A summary of global baroclinic variability, unpublished manuscript, 1998] concluded that the *Fu* et al. [1982] records are most likely not representative of the true mean conditions in this region, which with hindsight is an unsurprising result given the comparatively short records from one specific year. (*Stammer and Wunsch* [1999] describe real interannual changes in eddy kinetic energy in some locations.) Few other tropical mooring results appear to exist. Weisberg and Weingartner [1988] reported that a mooring deployed at 6°N near 28°W for nine months produced an eddy heat flux indistinguishable from zero.

4.1.5. 900-4000 m. Here the numerical magnitudes of the eddy heat fluxes (Plate 4) are much reduced and apart from an isolated mooring near 24°N, 290°E, are generally insignificant except in the immediate vicinity of the Gulf Stream. These latter values are probably of local importance in the heat budget, but do not significantly contribute to the total heat transport

4.2. North Pacific

In the North Pacific, the limited spatial coverage is a major hindrance.

Plate 5 and Plate 6 show the values of $< v'\theta' >$ for two depth ranges 1-300 and 300-900 m. The interior values in the upper 300 m are generally weakly positive (poleward), with a strong southward flux on the edge of the Kuroshio, reminiscent of the Gulf Stream behavior. Across the main thermocline, most of the interior shows extremely weak fluxes with significant values only near the Kuroshio, diverging to the north and south. Because of the limited mooring coverage, no conclusions should be drawn about the detailed structure there.

4.3. South Atlantic and Agulhas Region

Although there are some records from the Brazil Basin in the South Atlantic, these were obtained from a complex topographic regime [see W97], the fluxes are extremely weak, and we will omit a discussion of the results. In the Agulhas region in the top 300 m (not shown), the flux is primarily zonal, with a northward component, $\overline{v'\theta'}$ approaching 3 °C cm s^{-1} on a mooring near 22°E. Across the thermocline, 301-900 m, there is a generally northward flux in all the Southern Ocean moorings (Plate 7). Below that the fluxes are very weak.

4.4. Southern Ocean

The Southern Ocean is widely regarded as one region where eddy heat fluxes are of first-order importance (see the reviews by *Nowlin and Klinck* [1986] and *Gordon and Owens* [1987]). It is thus slightly surprising to see that the map in S98 of apparent eddy heat flux shows comparatively modest values, particularly near the axis of the polar fronts. Of the present collection of records analyzed, only two moorings (97 and 98) are in the Southern Ocean, and these are at the very high latitudes of 64.5, 66.6°S (Figure 1). Only the western mooring shows a statistically significant, northward, meridional heat flux.

Bryden [1979] analyzed a number of records from the Drake Passage, with results which are often quoted as supporting the importance of eddies in the region of the polar front. These records were not made part of the compilation because of the instrument placement and water depth considerations, but Bryden's results are nonetheless useful here. *Sciremammano* [1980] extended *Bryden's* [1979] analysis and warned that the number of degrees of freedom assumed by Bryden appeared to be much too large. The Drake Passage instruments were all quite deep (shallowest at 1020 m); of the eight records analyzed, only three produced an apparently statistically significant correlation between v', θ' and directed poleward. At 2700 m, *Bryden* [1979] found a mean covariance $< v'\theta' >= 6.7 \times 10^3$J m^{-13} s^{-1}. If this value is assigned to a water column depth of 3500m (the approximate Drake Passage depth), it produces 1.8×10^7W m^{-1} (Stammer's [1998] value outside the Drake Passage is closer to 5×10^6 W m^{-1}); if this high value were assumed to apply over the entire 20,000 km longitudinal band around Antarctica, the corresponding eddy heat flux would be 0.75 PW poleward. *Bryden and Heath* [1985] described the results from moorings set southeast of New Zealand where the eddy energy was considerably higher than in the Drake Passage. In contrast to the Drake Passage, however, the $< v'\theta' >$ were of variable sign and generally of small magnitude, and the authors concluded that the eddy heat flux was indeterminate. Stammer's altimetric values integrate to less than 0.3 PW and his result suggests the high eddy fluxes are confined primarily to the region south of Australia and New Zealand.

The Drake Passage results are not directly testable against the altimetric values. South of New Zealand the current meters gave an indeterminate flux, while the altimeter produces values that are not particularly large in absolute terms but that integrate to a finite and important value, because they are unidirectional and occupy a large zonal sector. Because the point values are comparatively small, the current meters have difficulty in determining a statistically stable average value. There is thus no conflict between the current meters and the altimeter. The latter suggests that the Drake Passage results are not representative of the Southern Ocean as a whole and the net eddy heat flux is probably closer to Stammer's[1998] 0.28 PW than the 0.75 PW implied by the Drake Passage results. *deSzoeke and Levine* [1981] calculated a poleward, large-scale mean geostrophic heat flux of order 0±0.25 PW with an equatorward Ekman contribution of about 0.15 PW. Their calculation is consistent with the entire poleward heat flux being carried by the eddies alone at a rate of about 0.4±0.3 PW, although they describe the error estimate as "notional." *Gordon and Owens* [1987] produce budgets requiring about 0.5 PW poleward. S. Rintoul [private communication, 1997] has suggested that the correct values are considerably lower—this being a region dominated by oceanic warming from the atmosphere.

In the Southern Ocean therefore, the altimetric estimates, the current meter estimates, and estimates based upon air sea transfer studies are entirely consistent: the eddy flux per unit area is modest compared to midlatitude western basin values. The integrated value is, however, very important in, and probably dominates, the high-latitude Southern Ocean heat budget.

4.5. The Equator and the Tropics

The near-equatorial zone is not easily described from the altimetric data directly, i.e, without use of an assimilated general circulation model, because of the breakdown of geostrophy there. It has thus not been studied here apart from a few moorings selected simply for a rough comparison. The result in W97 was, as has been known for a long time, that the low mode approximation generally breaks down right on and near the equator itself, because of the rich mixture of high modes. To my knowledge, no mooring on the equator has ever been adequately instrumented to study the flow field over the full water column. Nonetheless, a summary few words are perhaps in order concerning previous results.

The Atlantic results have already been mentioned above. *Bryden and Brady* [1989] discussed the upper 250 m of the tropical Pacific from two triangular arrays on and near the equator. At 110°W, they found a southward flux of about 2×10^7 W m^{-1} on and north of the equator, a numerical value roughly consistent with the values determined by S98 just off the equator (although the asymmetry is not apparent in his results). At their southern mooring, south of the equator, the meridional heat flux was essentially zero. Farther west at 152°W, the net flux was much weaker at all positions. Much of the North Pacific upper oceanic layers is dominated by shear instabilities of the surface currents, but the net heat flux associated with them is expected to be small [*Philander*, 1990, p.97], a result consistent with observations [e.g., *Qiao and Weisberg*, 1998] showing that the waves, as expected from theory, are dominated by barotropic rather than baroclinic instabilities and are latitudinally confined. The *Bryden and Brady* [1989] records are comparatively short and limited to the upper ocean; one anticipates a strong dependence on El Niño-Southern Oscillation cycle in this region.

A large literature exists [e.g., *Eriksen*, 1985] on deeper observations in the tropics. These data are generally interpreted, at lowest order, as linear wave motions, whose velocity and temperature fluctuations tend to be in quadrature. Theory, however, [e.g., *Holton*, 1975, 1983] shows a wealth of dynamical interactions possible here, many related to critical layer phenomena.

The tropical region is complex and awaits a full water column observational data base. Discretion suggests saying little more about the near-equatorial region until a much more comprehensive and specific analysis can be carried out.

5. Discussion and Conclusions

Apart from the tropical region where we have too few data to draw any conclusions, the current meter results generally confirm the inferences from altimetric measurements: eddy heat fluxes are quite small in the oceanic interior, rising to values significant when compared to the total values in the western boundary current areas. Again, "eddy" here is used to denote the variability, with no particular dynamics implied. The eddy heat flux across the Antarctic Circumpolar Current is weak, as seen both in the altimetry and the results south of New Zealand from *Bryden and Heath* [1985], in contrast to the Drake Passage results of *Bryden* [1979]. Because of the long zonal extent of the Southern Ocean, *Stammer's* [1998] integrated value of about 0.28 PW poleward near 40°S, is actually larger than the integrated values at 40°N where there is a particularly intense eddy heat flux. The large integration distance in the Southern Ocean more than compensates the generally small values of $\overline{v'\theta'}$ there. In the region of the Northern Hemisphere western boundary currents, the eddy heat flux divergence is of major importance, even though the basin-wide totals are comparatively modest. Stammer's results show that the eddy contribution is important equatorward of about 15° latitude, but we have not been able to directly confirm his inference.

For purposes of modeling the ocean circulation and climate, the eddy contribution appears relatively unimportant throughout much of the ocean interior, contributing 1% of the net meridional flux. In contrast, adequate representation or parameterization of the eddy flux appears essential for an adequate computation of air-sea flux at lowest order in the vicinity of the strong western boundary currents. Parameterization efforts may be most effective in the Southern Ocean, although regional interaction with topography, not examined here, may lead to quantitative deviations from simple schemes.

The present results by no means exhaust the available observational data but should be viewed as a first-attempt at a global compilation. More records will become available from the WOCE observations of the past several years and, along with the records not meeting our very specific selection procedures, should eventually permit a more complete story to be told.

A discussion of how models handle eddy heat fluxes is a major undertaking in its own right. Some of the relevant issues are summarized by *Bryan* [1986], *Böning and Bryan* [1996], and *Fanning and Weaver* [1997]. In general terms, models that are intended to compute oceanic heat transfers under changed atmospheric conditions (climate change) can probably largely neglect the ocean interior eddy fields. Models must, however, accurately compute the interaction of the western boundary currents, the tropical current system, and the Antarctic fronts with their neighboring eddy fields (even if much of that interaction is simply movement of the meandering jet). The wind-driven eddy motions of the northeastern North Atlantic appear to represent a different physical process. Eddy heat flux divergences appear to be of first-order importance to the overall heat balance of the ocean in many regions. For climate change modeling, one must have confidence that modifications in both the eddy fluxes and in the eddy-mean flow interactions are being properly represented. There is also every reason to believe that eddy flux contributions to the movement of other scalar properties such as carbon or nutrients are equally likely to be important.

Acknowledgments. This work was supported in part by grant NAG5-3724 of the National Aeronautics and Space Administration. Contribution to the World Ocean Circulation Experiment.

References

Böning, C. W., and F. O. Bryan, Large-scale transport processes in high-resolution models, in *The Warmwatersphere of the North Atlantic Ocean,* edited by W. Krauss, pp. 91-128. Gebrüder Borntraeger, Berlin, 1996.

Box, G. E. P., and G. M. Jenkins, *Time Series Analysis, Forecasting and Control*, 575 pp., Holden-Day, San Francisco, 1978.

Bryan, K., Poleward buoyancy transport in the ocean and mesoscale eddies. *J. Phys. Oceanogr., 16,* 927-933, 1986.

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

Bryden, H. L., Sources of eddy energy in the Gulf Stream recirculation region, *J. Mar. Res.*, 40, 1047-1068, 1982.

Bryden, H. L., and E. C. Brady, Eddy momentum and heat fluxes and their effects on the circulation of the equatorial Pacific Ocean, *J. Mar. Res., 47*, 55-79, 1989.

Bryden, H. L., and R. A. Heath, Energetic eddies at the northern edge of the Antarctic Circumpolar Current in the southwest Pacific, *Progr. Oceanogr., 14*, 65-87, 1985.

Delworth, T. L., North Atlantic interannual variability in a coupled ocean-atmosphere model, *J. Clim.,9*, 2356-2375, 1997.

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.

Dickson, R. R., Flow statistics from long-term current-meter moorings. The global data-set in January 1989. World Ocean Circulation Experiment, 35 pp. plus numerous tables, *Publ. WCRP-30, WMO/TD 337*, World Clim. Res. Program, Geneva, 1981.

Eriksen, C. C., Moored observations of deep low-frequency motions in the Central Pacific Ocean: vertical structure and interpretation as equatorial waves, *J. Phys. Oceanogr., 15*, 1085-1113, 1985.

Fanning, A. F., and A. J. Weaver, A horizontal resolution and parameter sensitivity study of heat transport in an idealized coupled climate model. *J. Clim., 10*, 2466-2478, 1997.

Fu, L.-L., T. Keffer, P. Niiler, and C. Wunsch, Observations of mesoscale variability in the western North Atlantic: A comparative study, *J. Mar. Res., 40*, 809-848, 1982.

Fukumori, I., F. Martel and C. Wunsch, The hydrography of the North Atlantic in the early 1980's. An atlas. *Prog. Oceanogr., 27*, 1-110, 1991.

Gill, A. E., J. S. A. Green, and A. J. Simmons, Energy partition in the large-scale ocean circulation and the production of mid-ocean eddies. *Deep-Sea Res., 21*, 499-528, 1974.

Gordon, A. L., and W. B. Owens, Polar oceans. *Rev. Geophys.,25*, 227-233, 1987.

Hogg, N. G., Mooring motion corrections revisited. *J. Atmos. Oceanic. Techno., 8,* 289-295, 1991.

Holloway, G., Eddies, waves, circulation and mixing: statistical geofluid mechanics. *Ann. Rev. Fluid Mech., 18*, 91-147, 1986.

Holton, J., *The Dynamic Meteorology of the Stratosphere and Mesosphere,* 218 pp., Am. Meteor. Soc., Boston, 1975.

Holton, J., The stratosphere and its links to the troposphere, in *Large-Scale Dynamical Processes in the Atmosphere,* edited by B. J. Hoskins and R. P. Pearce, pp. 277-303, Academic, London, 1983.

Isemer, H. J. Willebrand and L. Hasse, Fine adjustment of large scale air-sea energy flux parameterizations by direct estimates of ocean heat transport. *J. Clim., 2*, 1173-1184, 1989.

Jenkins, G. M. and D. G. Watts, *Spectral Analysis and Its Applications,* 525 pp.,. Holden-Day, San Francisco, 1968.

Levitus, S. and T. P. Boyer. World Ocean Atlas 1994, vol. 4: Temperature, *NOAA Atlas NESDIS 4*, U. S. Gov. Print. Off., Washington D. C., 117 pp., 1994.

Ljung, L., *System Identification Toolbox: Manual.* The Mathworks, Sherborn, Mass, 1995.

Longuet-Higgins, M. S., On group velocity and energy flux in planetary wave motions. *Deep-Sea Res., 11* , 35-42, 1964.

Macdonald, A. and C. Wunsch, The global ocean circulation and heat flux. *Nature, 382*, 436-439, 1996.

Marshall, J., and G. Shutts, A note on rotational and divergent eddy fluxes. *J. Phys. Oceanogr., 11*, 1677-1680, 1981.

MODE Group, The, The Mid-ocean dynamics experiment, *Deep-Sea Res., 25*, 859-910, 1978.

Müller, T. J., and G. Siedler, Multi-year current time series in the eastern North Atlantic Ocean. *J. Mar. Res., 50*, 63-98, 1992.

Nowlin, W. D., Jr. and J. M. Klinck, The physics of the Antarctic Circumpolar Current. *Rev. Geophys., 24*, 469-492, 1986.

Pedlosky, J., *Ocean Circulation Theory,* 453 pp., Springer-Verlag, Berlin, 1996.

Percival, D. B. and A. T. Walden, *Spectral Analysis for Physical Applications. Multitaper and Conventional Univariate Techniques*, 583 pp., Cambridge Univ. Press, Cambridge, 1993.

Philander, S. G., *El Niño, La Niña, and the Southern Oscillation*, 289 pp., Academic, San Diego, Calif., 1990.

Qiao, L. and R. H. Weisberg, Tropical instability wave energetics: observations from the tropical instability wave experiment, *J. Phys. Oceanogr., 28*, 345-360, 1998.

Richman, J., C. Wunsch and N. Hogg, Space and time scales of meso-scale motion in the western North Atlantic. *Rev. Geophys., 15,* 385-420, 1977.

Robinson, A. R. (ed.), *Eddies in Marine Science,* 609 pp., Springer-Verlag, Berlin, 1983.

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

Stammer, D., Global characteristics of ocean variability from regional TOPEX/POSEIDON altimeter measurements. *J. Phys. Oceanogr.*, *27*, 1743-1769, 1997.

Stammer, D., On eddy characteristics, eddy mixing and mean flow properties. *J. Phys. Oceanogr.*, *28*, 727-739, 1998.

Stammer, D. and C. Wunsch, Temporal changes in eddy energy of the oceans. *Deep-Sea Res., 46*,77-108, 1999.

Weisberg, R. H. and T. J. Weingartner, Instability waves in the equatorial Atlantic. *J. Phys. Oceanogr., 18*, 1641-1657, 1988.

Wunsch, C., Low frequency variability of the sea, in *Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel*, edited by B. A. Warren and C. Wunsch, pp. 342-374, The MIT Press, Cambridge, Mass., 1981.

Wunsch, C., The vertical partition of horizontal kinetic energy and the spectrum of global variability. *J. Phys. Oceanogr.*, *27*, 1770-1794, 1997.

Wunsch, C. and D. Stammer, Satellite altimetry, the marine geoid and the oceanic general circulation. *Annu. Rev. Earth Planet. Sci.*, *26*, 219-254, 1998.

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(Received January 30, 1998; revised November 16, 1998; accepted February 17, 1999.)