The Total Meridional Heat Flux and Its Oceanic and Atmospheric Partition

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ABSTRACT

Atmospheric meridional heat transport is inferred as a residual from the Earth Radiation Budget Experiment (ERBE) data and in situ oceanic estimates. Reversing the conventional approach of computing the ocean as an atmospheric model residual is done to permit calculation of a preliminary uncertainty estimate for the atmospheric flux. The structure of the ERBE errors is itself an important uncertainty. Total energy transport is almost indistinguishable from a hemispherically antisymmetric analytic function, despite the great asymmetry of the oceanic heat fluxes. ERBE data appear sufficiently noisy so that a considerable range of atmospheric transports remains possible: the maximum atmospheric value lies between 3 and 5 PW in the Northern Hemisphere, at one standard deviation, although the values are sensitive to the noise assumptions made here. The Northern Hemisphere ocean and atmosphere carry comparable poleward heat fluxes to about 28°N where the oceanic flux drops rapidly, but does not actually vanish until the oceanic surface area goes to zero. Within the estimated error bars, there is a remarkable antisymmetry about the equator of the combined ocean and atmospheric transports, despite the marked oceanic transport asymmetry.

1. Introduction

The partitioning and fluctuations in the net poleward transport of heat (energy, actually enthalpy; see Warren 1999) by the atmosphere and ocean are central elements in the description and understanding of climate and climate change. Over the last 25 yr, beginning probably with the work of Vonder Haar and Oort (1973), the estimated oceanic fraction increased from the essentially negligible contribution implied by Sverdrup et al. (1942), finally reaching about 50% of the total at Northern Hemisphere midlatitudes, as estimated by Trenberth and Solomon (1994). More recently (Trenberth and Caron 2001, hereafter TC01), one estimate of the northern atmospheric poleward heat transport has significantly increased, resulting in an apparent maximum of about 5 PW (Petawatts = 10^{15} W) proportionally reducing the oceanic fraction (see Fig. 1 from TC01). Because much of the flux in the atmosphere is in the form of the transport of latent heat, and because the ocean carries an equivalent amount of water, much of

the heat flux commonly assigned to the atmosphere is actually in a combined mode of both systems (e.g., Bryden and Imawaki 2001; R. X. Huang 2001, personal communication).

It may well be that the ocean is carrying as little as 10% of the net poleward heat transport at the midlatitudes. But 10% of 5 PW is 0.5 PW whose redistribution or change would correspond to a large climate shift. The area of the earth's surface poleward of 40° is 5.6×10^{13} m^{-2}. A shift in the oceanic heat transport, removing 0.5 PW, would correspond to an atmospheric radiative forcing change of about 9 W m^{-2}, larger than what is expected from doubled atmospheric CO_2. But it also seems highly desirable that any discussion of such numbers be done using realistic error estimates; otherwise, there is an unwarranted implied accuracy to the result. In particular, this paper began as an attempt simply to place error bars in Fig. 1.

Before proceeding, is helpful to obtain a rough estimate of the heat flux the ocean might carry. The meridional overturning circulation in the North Atlantic is about 15 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}). If we take a 15° temperature difference as representing the maximum average difference between the temperature of northward-moving warm water and southward-moving cold water in the subtropics, that is 225° Sv, or converting the units

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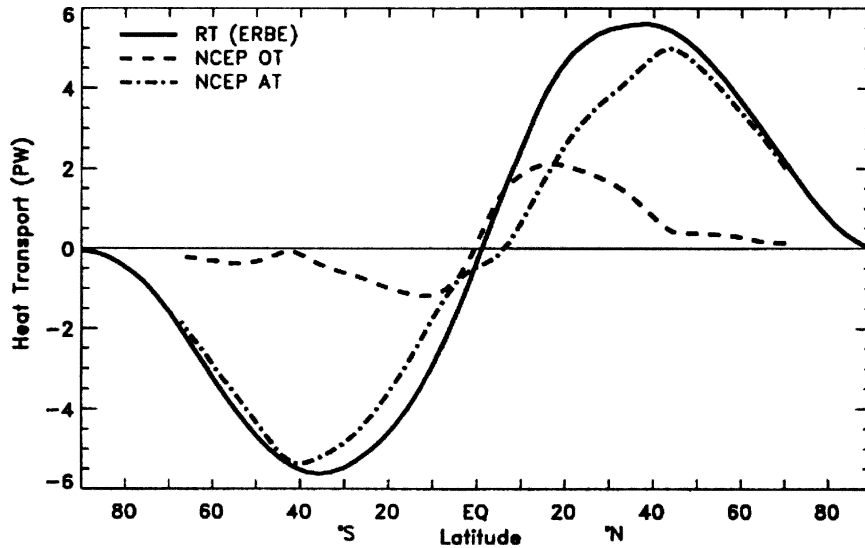E-mail: cwunsch@mit.edu

FIG. 1. Modified from TC01. Calculated total meridional heat transport, $\tilde{F}(\phi)$ (solid curve), from ERBE data; NCEP-based estimate of atmospheric contribution to total poleward transport (dashed–dot); and the oceanic residual (dashed). Note the hemispheric difference in the oceanic contribution, the near antisymmetry of the total, and the absence of error bars.

to Watts with a heat capacity of $c_p = 4.2 \times 10^3$ J m^{-3}, the result is about 0.9 PW. The Gulf Stream, in a horizontal gyre circulation, has a return flow with a smaller temperature difference. Part of the Gulf Stream circulation is accounted for in the meridional overturning. Taking the remainder as 15 Sv at a temperature drop of 5°, produces another 0.3 PW for a North Atlantic total of about 1.2 PW. The Pacific has a weaker meridional overturning, but a larger temperature drop in the much wider horizontal gyre, whose total might be another 1 PW. In this rough analysis, the Ekman component is included partially in both gyre and overturning circulations. Thus an upper bound on the oceanic flux of heat of $O(2$ PW) would appear to be about right. If the system is carrying significantly more than this value, the atmosphere must be doing it. An oceanic value much different from 2 PW at the midlatitudes implies a major change in the existing general circulation, and, in turn, would require a qualitative change in the wind system.

2. Total radiation to space

The most reliable estimates of the global radiation to and from space are believed to be from the Earth Radiation Budget Experiment (ERBE) and *Nimbus-7* satellite measurements (e.g., Bess and Smith 1993). TC01 rely on 3 yr of ERBE data. The average of 1987–89 (using the three complete years) of the net outgoing radiation, $\tilde{R}(\phi)$, as a function of latitude, ϕ (see online at http://www.cgd.ucar.edu/cas/catalog/satellite/erbe/

means.html) is shown in Fig. 2 as Watts per meter squared as a function of sampled latitude, $\phi_j, 1 \leq j \leq 72$. Also shown is the net outgoing radiation $\tilde{R}(\phi_j)a(\phi_j)$ when multiplied by the area occupied in each latitude band, $a(\phi_j)$. (Tildes are being used to denote observed or estimated quantities to distinguish them from their true values.) When summed from the South to the North Poles,

$$\tilde{F}(\phi_n) = \sum_{j=0}^{n} \tilde{R}(\phi_j)a(\phi_j), \tag{1}$$

balance fails at a level of about 6 W m^{-2} over the entire earth, summing to 3 PW at the North Pole. One can sum $\tilde{R}(\phi_j)a(\phi_j)$ from both Poles toward the equator (also displayed in Fig. 2), so that the residual results in an apparent transport jump there. This closure error can arise from either a random error, or a systematic one of about 6 W m^{-2}. This latter value is far larger than any plausible estimate of ongoing global warming.

The ERBE data and its errors have been well studied and analyzed (e.g., Barkstrom et al. 1989; Rieland and Raschke 1991; Bess and Smith 1993; Kiehl and Trenberth 1997). The latter conclude that the errors in the ERBE data are the equivalent of $\sigma_n = 7.8$ W m^{-2}, which is apparently interpreted as uncorrelated (white) noise over each ERBE pixel of 2.5° × 2.5°, most of it deriving from sampling problems at the diurnal frequency. Other estimates are approximately the same. A 3-yr average would reduce the standard error to
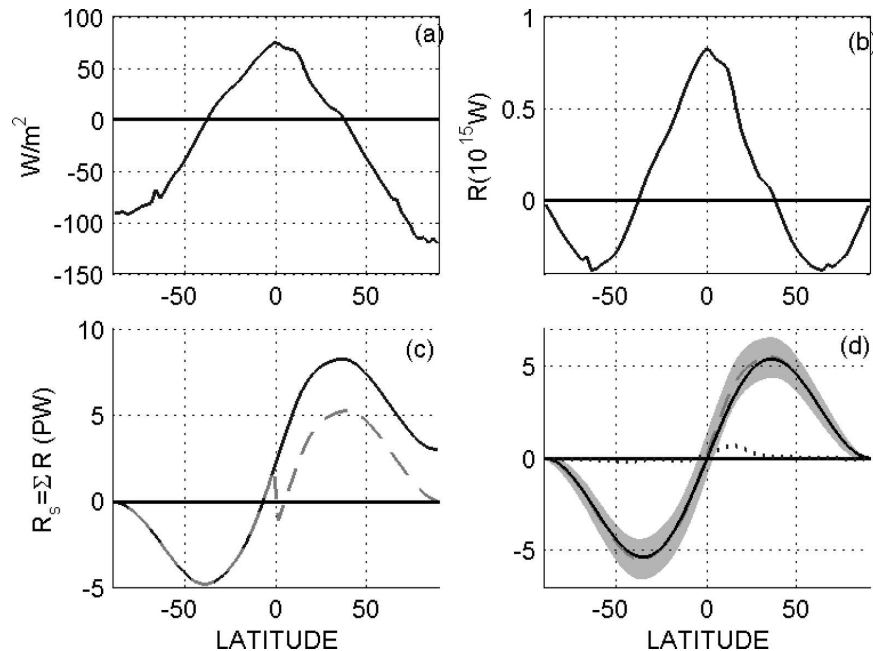
FIG. 2. (a) Direct average of the net incoming (positive values) radiation from ERBE observations 1987–89. The data are provided (NCAR) as zonal averages in latitudinal bands of 2.5°. (b) The same data multiplied by the area in each latitude band. (c) The accumulating sum of the values in (b) from 90°S to the North Pole, and which should sum to zero if the measurements were perfect (solid). Actual imbalance is the global equivalent of about 6 W m^{-2} of warming. Dashed curve shows the same values summed southward from 90°N to 0° demonstrating the error accumulation at the equator. (d) The inferred net radiative transport (dashed) as calculated from the prior estimate [solid curve, from Stone (1978)] along with its standard error as the shaded band. Dotted line shows the deviation required by the ERBE data from the prior, given the particular error estimates assumed to lie within the data.

$7.8/\sqrt{2} = 5.5$W m^{-2}. On the other hand, a closure failure owing to a random summation over each pixel, supposed independent measurements, each with an error variance of σ_n^2, would give an expected summation error of $1728^{1/2}\sigma_n$, where 1728 is the number of 2.5° squares on a sphere. If the 3-PW closure error were solely due to the random summation, we would have, $\sigma_n = 1904$ W m^{-2}, assigning an average area of 3.8×10^{10} m^2 to 2.5° × 2.5° squares, and which is impossibly large. Either the dominant global error is systematic, or the supposed random error is strongly correlated over large distances, or most likely, some combination of these errors. Unfortunately, the nature of the error is important to what follows. That large-scale correlated errors exist is strongly suggested by Figs. 8 and 9 of Bess and Smith (1993) showing large-scale, large differences in the estimated outgoing longwave radiation between the National Oceanic and Atmospheric Administration (NOAA) *NOAA-9,* ERBE, and *Nimbus-7* satellites. Here it will be arbitrarily assumed that there is a random error of 5.5 W m^{-2} in each 2.5° latitude band around the earth, uncorrelated with the error in any other band. This value might be a considerable overestimate of the effect of the random error, and if it should later be shown that it is too large, the following calculation is easily redone. [A reviewer has suggested that the so-called Clouds and the Earth's Radiant Energy System (CERES) instrument on the Tropical Rainfall Measuring Mission (TRMM) satellite (Wielicki et al. 1996) would provide a better estimate. But the TRMM version of CERES does not provide global coverage. Later versions of CERES do extend to high latitudes, but an error analysis of these more recent data is not yet available. Diurnal sampling problems remain.] What follows is intended primarily as a straw man calculation that perhaps will lead eventually to a more convincing set of values.

It remains to remove the integrated error, whether systematic or random. Carissimo et al. (1985) conclude that earlier satellite measurements had a random error of about 8 W m^{-2}, and discuss several ad hoc corrections to remove the systematic error, bringing the implied $\tilde{F}$ to zero at the Poles.

To proceed, instead assume a prior value for the total

transport given by Stone (1978) for the total energy transport, $F(\phi)$, in the approximate form [his Eq. (17)]:

$$F(\phi) = \int_{-\pi/2}^{\phi} R(\phi)a(\phi)\, d\phi$$

$$= \frac{\pi a^2 S}{4}(-0.319)(\sin^3\phi - \sin\phi)$$

$$= E_0(\sin^3\phi - \sin\phi). \tag{2}$$

Here $E_0 = -14$ PW where $S = 1360$ W m^{-2} is the solar constant and a $= 6.3 \times 10^6$ m^{-2} is the radius of the earth; the numerical factor, -0.319, arises from the spherical harmonic expansion coefficients for insolation and albedo. Equation (2) assumes insolation and earth emission as functions of latitude appropriate to a finite obliquity earth, and is a plausible starting point. In practice, the even simpler model of an earth without seasons discussed by Stone (1978) proves almost as accurate.

The finite obliquity prior curve, which is independent of the ERBE data, is used to "predict" the ERBE values that are then used to adjust the prior, under the assumption that $\langle[\tilde{F}(\phi) - F(\phi)]^2\rangle = 25$. That is, an adjustment in each latitude band is permitted under the assumption that the difference between the prior and the correct value has a standard deviation of 5, which is very conservative (brackets denote expected value). In addition, the error variance is set to zero at $\phi = \pm\pi/2$, as $F = 0$ there to a very high accuracy. The model is being used as only a very weak prior, apart from the insistence on zero transport at the two Poles. In effect, the data are being used only to determine the latitude-by-latitude deviation from the prior, with the cumulative error over the globe being downweighted relative to the unbiased prior. This procedure can be regarded as a Bayesian one, or as an application of minimum variance estimation (Wunsch 1996). The large variance assigned to the prior corresponds to a very broad probability density for it. In the result shown in Fig. 2, the adjustments are rather slight, but not unexpected given the data noise level. The Stone (1978) model, despite its simplicity, proves unexpectedly consistent with the data. Error bars shown were computed from the standard expressions for minimum variance estimation [Wunsch 1996, see Eq. (3.6.22)] and represent a combination of the a priori confidence in the theoretical curve and the data errors. The only noticeable adjustment to the prior is a slight *increase* in value in the region of maximum Northern Hemisphere oceanic transport and a very weak, southward, enhancement in the Southern Hemisphere. Note that if the prior is given

greater weight, by reducing its uncertainty, these features nearly disappear. One must, however, resist the temptation to redo the calculation with a much smaller prior error on the model—doing so violates the assumption of independence of the prior variance with the actual data, an independence that is required to use the expressions for the error in the final estimate. With an entirely new set of radiation measurements, one would be entitled to reduce the prior error variance.

Both the prior and the data are consistent—within errors bars—with a near-perfect hemispherical antisymmetry in the net flux that is remarkable, and that is briefly discussed at the end. Notice that the total flux maximum could be as high as 6.4 PW at 36°N or as low as 4.1 PW.

3. Separation into atmospheric and oceanic components

The combined ocean and atmospheric system has to carry the estimated poleward total heat transport at each latitude (the combined system is the true "global conveyor," not the ocean alone). How much is oceanic and how much is atmospheric? Oort and Vonder Haar (1976), TC01, and others, have calculated the atmospheric heat transport from atmospheric forecast models, and attributed the residual to the ocean. The most recent such calculation is that of TC01 who used both the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses and is what led to Fig. 1. Their discussion of problems in the reanalyses is not completely reassuring. Both reanalyses leave regional residuals that imply heat transports by the continents, but it is unclear how large a component it is. TC01 confine their calculation to the oceanic portion alone. The NCEP–NCAR reanalysis was corrupted by a 180° longitude error in the insertion of Southern Hemisphere "bogus" data, and other apparently systematic problems occur, but the magnitude of the resulting error is not stipulated. None of the atmospheric reanalyses are provided with an error bar, and quantitative estimates of global systematic errors are lacking, although the TC01 discussion shows that they certainly exist. (Bryden and Imawaki 2001, provide a good summary of the atmospheric model error problem.) It is not possible to assign an uncertainty to the model reanalysis computation in any straightforward fashion. Trenberth et al. (2001) report annual mean standard deviations in the atmospheric reanalyses of about 15 W m^{-2} over the extratropical oceans, which if

TABLE 1. Oceanic estimates of meridional heat flux with one standard deviation errors.

Lat	Value (PW)	Std error (PW)	Source	Comment
47°N	0.6	0.1	Ganachaud and Wunsch (2003)	Global inversion
24°N	1.8	0.3	Ganachaud and Wunsch (2003)	"
19°S	−0.8	0.6	Ganachaud and Wunsch (2003)	"
30°S	−0.6	0.3	Ganachaud and Wunsch (2003)	"
9°N	1.2	0.7	Wunsch (1984); Wijffels et al. (1996)	Combined estimate
12°N	2.2	0.6	Stammer et al. (2004)	Scaled up
90°S–90°N	0	0		By assumption

it is a spatial white noise random error, is a negligible contribution to present uncertainty.

A number of oceanic estimates of meridional heat flux have, however, appeared in recent years, and are accompanied by an error estimate. Here the principle is invoked that error bars should *always* be used, even if subject to later change. Of necessity, the most common procedure will now be reversed: that is, *the atmospheric transport will be computed as the residual of the oceanic one* relative to the estimated total value. The purpose of this approach is to take advantage of the availability of error estimates from both the oceanic and net radiation estimates, thus enabling provisional error bars for the atmospheric component. The systematic errors in the oceanic estimates are believed to be small, as they are based primarily upon simple geotrophic balance; the main errors are likely primarily random sampling ones (Ganachaud 2003).

The central results used are those of Ganachaud and Wunsch (2003) from a self-consistent global inverse calculation using only recent hydrographic sections (Table 1). Error estimates for the Ganachaud and Wunsh (2003) values are taken directly from their results. The available data permit calculations of this type only at the latitudes shown. In general (Ganachaud 2003), all error bars are believed dominated by the low-frequency temporal variability relative to the long-term mean flux. Few other global estimates are available. Wunsch (1984) produced Atlantic values at 8°N–8°S from a linear programming maximum and minimum, and thus obtained a range, one that will be nonetheless equated to a one standard deviation error—partially compensating for other hidden uncertainties. These are combined (error variances added) with the Wijffels et al. (1996) estimate for the North Pacific at 10°N of 0.7 ± 0.5 PW with the combination assigned to 9°N. Most oceanic estimates suggest that there is a Northern Hemisphere maximum in oceanic heat flux at about 15°N, but this latitude was not sampled during the World Ocean Circulation Experiment (WOCE), which provided the data used by Ganachaud and Wunsch (2003). Other estimates now exist of the oceanic heat

flux across latitude lines in a variety of basins (see, e.g., Bryden and Imawaki 2001), but these are often based only upon regional data, and do not span a complete longitude range. The contribution from the small mass flux of less than the 1-Sv mass flux (Roach et al. 1995) at near-zero temperature through the Bering Strait is neglected. Values and assigned uncertainties are listed in Table 1.

To obtain the structure defining the Northern Hemisphere maximum, we use the global-state estimate of the ocean by Stammer et al. (2004). At 24°N, their Northern Hemisphere value is lower than the Ganachaud and Wunsch (2003) value by a factor of about 1.2 (attributed primarily to a lack of resolution in the western boundary currents, and the omission of the purely diffusive component), and comparably reduced compared to other North Atlantic–only values. We multiply the Stammer et al. (2004) value at 12°N (the apparent latitude of maximum Northern Hemisphere oceanic heat flux) by the same factor, and use double the uncertainty value at 24°N as ±0.6 PW. Values and estimated uncertainties are simply interpolated, linearly, between the data points. The resulting oceanic heat flux estimate with error estimates is shown in Fig. 3 using linear interpolation between the estimated values, both for the flux and the error estimates. It qualitatively resembles many such previously published curves.

As a comparison to these estimates, in Fig. 3 the zonally integrated annual mean values from bulk formulas of Grist and Josey (2003) summed from 90°N are shown. These numbers are not independent of the Ganachaud and Wunsch (2003) results as they were adjusted to be consistent with geostrophic calculations across the same zonal hydrographic lines [but not the specific Ganachaud and Wunsch (2003) solution]. Their interpolation is quite different from the linear one used here. The error band shown for the Grist and Josey (2003) result was computed by S. Josey (2004, personal communication) from the standard deviations of the underlying estimates—a lower limit on the uncertainty. Within the error limits shown, the Grist and Josey
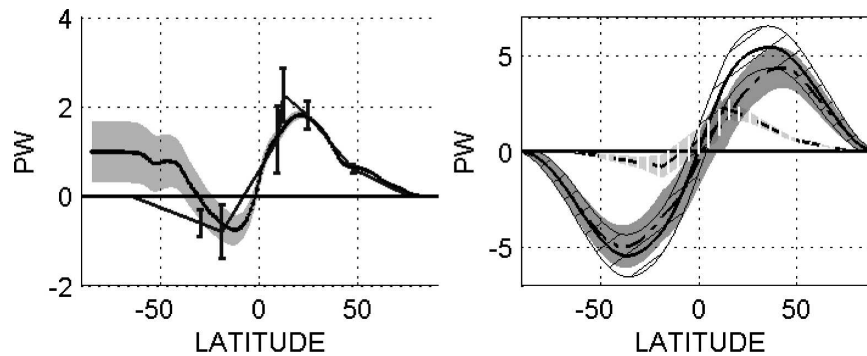
FIG. 3. (left) Dots with error bars are oceanic heat flux computed from direct ocean measurements (Table 1). Thin line indicates the linearly interpolated values. Thick line with shaded band is the Grist and Josey (2003) annual mean zonally summed total from bulk formula calculations adjusted to the direct measurements, summed from the North Pole. Error bar is by S. Josey (2004, personal communication). (right) Atmospheric residual heat flux (dash–dot, with shaded error band) computed by linear interpolation of oceanic values. The error bar is the sum of that from ERBE and that from the oceanic values and assumed to be independent. The dashed line with vertical hatching is again the direct ocean calculations with linear interpolation and the estimated standard error band. The solid curve and hatched error band are a repetition of the total curve and its estimated error from Fig. 2d.

(2003) values are consistent with those being used here, except that poleward of the most southerly zonal section, they only required closure at the southern boundary at a level of 2 W m^{-2}, or about 1-PW net imbalance as seen in the figure. That the uncertainty assigned is a lower limit can be understood by noting that the bulk formula estimate uncertainty cannot be smaller than that of the inverse calculations used to adjust it.

In any case, the behavior of the oceanic heat flux curve is consistent with conventional belief, and having a strong asymmetry across the equator. The most rapid divergence occurs between the Northern Hemisphere flux maximum and about 48°N (i.e., across the midlatitude storm belt). Residual flux of heat into the Nordic/Bering Seas is comparatively modest (despite the implications in some papers that the Nordic Seas dominate the oceanic heat budget).

An atmospheric residual is then computed by subtracting the linearly interpolated oceanic values from the best-fit ERBE results (Fig. 3), with the ERBE and oceanic errors assumed to be independent. The atmospheric residual curve is qualitatively similar to those previously published. A Northern Hemisphere maximum value at 36°N lies between 5.2 and 3.0 PW, essentially spanning the range of estimates from that of Oort and Vonder Haar (1976) to that of TC01. The available data do not distinguish these values. The Southern Hemisphere maximum is at about 39°S and lies in the range −4.0 to −6.7 PW at one standard deviation. In the absence of uncertainty estimates for the atmospheric model values, it is not possible to do a quantitative comparison with the results obtained here.

4. Discussion

Qualitatively, the results are very similar to those of TC01, the major exception being the more gradual reduction in oceanic heat transport at high northern latitudes. Within the substantial error bars, the results are elsewhere indistinguishable, and it is the error bars themselves that are the primary new result here.

The biggest issue with the ERBE data concerns their error structure, and in particular the separation between systematic and spatially correlated stochastic components. But under the present, primarily illustrative, assumptions, approximate estimates of the net radiation to space can be made. As anticipated by the rough scale analysis, the oceanic component reaches a maximum value of somewhat less than 2 PW at low Northern Hemisphere latitudes. Depending upon the error bars, the northward oceanic heat flux remains comparable to that of the atmosphere to about 25°N, but declines rapidly thereafter as heat is lost to the atmosphere, and the fraction of oceanic area is much reduced. The value of the maximum contribution of the atmosphere to the total meridional heat flux remains uncertain by about 2 PW, and this uncertainty is important in any test of the realism of climate models.

As discussed in many papers, the weakness of the oceanic transport in the Southern Hemisphere is something of an artifact: the South Atlantic transport is equatorward, thus reducing the contribution to the total poleward flux. Despite this hemispheric asymmetry, the combined ocean–atmosphere transports are remarkably latitude antisymmetric (Fig. 3) within the es-

timated errors. Why and how this antisymmetry is maintained by the combined system, given the large difference between the oceanic flux contribution in the two hemispheres, is not so clear. Stone (1978) discusses elements of the contributions and rationalizes the structure in terms of negative feedbacks among competing transport mechanisms. Whatever the mechanism, it suggests that if the oceanic heat flux weakens, as some discussions of climate change have proposed, that the atmospheric flux would compensate, although precisely how it would so compensate is less clear. The combined system is, as noted above, the true global conveyor of enthalpy.

The error estimates used here remain less than satisfactory. Systematic errors in ERBE have been accommodated by assuming that the prior estimate is an accurate one. Random error has been assumed to decorrelate between $2.5°$ latitude bands at about 5.5 W m^{-2} for the 3-yr zonal average data. Ocean estimates are probably dominated by interannual variability, but the only systematic study was that of Ganachaud (2003) using a model, and then only for the North Atlantic Ocean. Because of the scaling argument, the oceanic transports are not likely to very much exceed the values given here, but their overall accuracy, and thus the errors in the atmospheric residual are still poorly known.

An additional source of error, not explicitly accounted for here, is the interannual variability in ocean heat storage. Stammer et al. (2004) noted that there can be a decadal-average discrepancy in ocean heat flux on the order of 0.5 PW owing to heat storage changes. Much of this difference is presumably involved in the interannual ocean transport fluctuations discussed by Ganachaud (2003). It could appear in the atmospheric fields, but the atmospheric model-derived interannual variability (Trenberth et al. 2001) is very small.

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