NOTES AND CORRESPONDENCE

On Meridional Heat Transports in the World Ocean

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ABSTRACT

Updated estimates of meridional heat transport in the Atlantic Ocean water body derived from the surface energy budget agree with the evaluation of hydrographic sections, annual mean northward transports being about 8 and 11 × 10^{14} W at 30°S and 25°N, respectively. For the World Ocean as a whole, a southward transport of 6 × 10^{14} W is obtained at 60°S. Concerning the satellite-derived net radiation at the top of the atmosphere, the five data sets published in the literature are adjusted to force a zero annual mean for the globe as a whole; the required adjustments are ± 10 W m^{-2} for the various sets. Even so, the required poleward heat transport in the atmosphere-ocean system obtained from the five data sets differs conspicuously, with a range of 20 × 10^{14} W at 30°N. This range may reflect observational errors and real interannual variability. The comfortable numerical agreement notwithstanding, plausible error tolerances far exceed the differences between the heat transport estimates derived by various independent methods.

1. Introduction

The role of the tropical oceans in the global heat budget was the topic of a recent article in this journal (Hastenrath, 1980; hereafter referred to as H). In that study, satellite measurements of net radiation at the top of the planet earth (Vonder Haar and Ellis, 1974; Gruber, 1978) indicated the required poleward heat transport in the atmosphere-ocean system as a whole. Meridional transports within the hydrosphere were calculated from the assessment of the surface oceanic heat budget based on long-term ship observations (Hastenrath and Lamb, 1978, 1979; Budyko, 1963; Wyrtki, 1965, 1966; Zillman, 1972; Aagaard and Greisman, 1975). The atmospheric meridional heat transport was inferred as a residual. Since H was accepted for publication, some additional estimates of oceanic heat transports, obtained by different methods, have appeared. The purpose of the present note is to provide a synopsis of these heat transport estimates. Results are discussed with reference to Tables 1 and 2 and Figs. 1-4, Figs. 1-3 being updated versions of Figs. 9-11 in H.

2. Atlantic Ocean

Inasmuch as annual mean oceanic meridional transports are obtained from the net oceanic heat gain (Hastenrath and Lamb, 1978, 1979) by integration starting in the Arctic basin, the heat transports in the North Atlantic are of foremost interest. In H, Aagaard and Greisman's (1975) data were adopted for the heat budget of the Arctic basin north of 66°N. For the zone 66-30°N in the Atlantic, Budyko's (1963) charts were used, in consistency with the data source for the midlatitudes of the other oceans. Lamb (1981) calculated the meridional heat transport in the Atlantic, also relying on Aagaard and Greisman's study for the Arctic, but using Bunker and Worthington's (1976) rather than Budyko's (1963) values for 70-30°N. He considers Budyko's (1963) charts deficient in the western portion of the band 40-50°N. Lamb's annual mean results for various latitude circles are summarized in Table 1. Bryden and Hall (1980) evaluated the oceanic heat transport across 25°N both from Bunker's (1976) assessment of the surface heat budget and directly from hydrographic sections (Fuglister, 1960; Niiler and Richardson, 1973). As shown in Table 1, they obtained almost identical numbers from the two independent methods. Wunsch (1980) calls this agreement fortuitous, and gives 24°N as the latitude of the section. Roemmich (1980) determined the oceanic heat transport at 24 and 36°N from hydrographic sections, as did Wunsch (1980) for these and other latitudes. They obtained similar values, which are also included in Table 1.

For the realm around 30-25°N a remarkable agreement is emerging from Table 1 between the estimates based on surface heat budget and hydrographic sections. It is furthermore noted that Behringer and Stommel's (1981) independent assessment of oceanic heat gain in the tropical North Atlantic based on subsurface data is consistent with evaluations of the surface heat budget (Hastenrath and Lamb, 1978). Concerning the midlatitude North Atlantic and particularly the zone 50-40°N (Lamb, 1981), Bunker's (1976) surface heat budget results are regarded as superior to Budyko's (1963) charts. Therefore, Lamb's (1981) value of oceanic heat transport across 30°N is substituted in this study for

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TABLE 1. Estimates of northward heat transport (10^{13} W) in the Atlantic Ocean. Derived (a) from surface heat budget and (b) from hydrographic sections.

		Latitude												
		60°N	36°N	30°N	24–25°N	0	8°S	15–16°S	21°S	24°S	28°S	30°S	32°S	60°S
Hastenrath (1980)	a	26		155	157	144						115		106
Lamb (1981)	a	28		107	113	102								
Bryden and Hall (1980)	a				111									
	b				110									
Roemmich (1981)	b		80		120									
Wunsch (1980)	b		75		120									
Bennett (1978)	b									65			68	
Fu (1981, METEOR)	b						42	86	54		83			
Fu (1981, IGY)	b						18	73		54			77	
This paper	a	26		107	110	98						69		60

the figure of H; the new values of northward heat transport are thus smaller by about 47 × 10^{13} W.

Values for all latitude circles of the tropical and South Atlantic to 60°S are decreased accordingly. Thus the value for 30°S is changed from 115 to 69 × 10^{13} W. This number agrees very closely with Bennett's (1978) results for 24 and 32°S (Table 1) based on the evaluation of hydrographic sections (Fuglister, 1960; Wüst and Defant, 1936).

Fu (1981) applied the inverse method used by Wunsch (1980) and Roemmich (1980) to the observations of the METEOR and IGY Expeditions in the South Atlantic (Fuglister, 1960; Wüst and Defant, 1936). He evaluated the meridional heat transports across various latitudes, with reference to the 2000 and 4000 db surfaces. The reference level makes a difference for the IGY observations, but matters little for the METEOR data set. The arithmetic mean of his results for the two reference levels is also listed in Table 1. Fu's numbers for 32 and 28°S agree reasonably well with the present and Bennett's (1978) results. Fu's relative minimum at 24 and 21°S appears startling, and his values for 8°S are much smaller than expected from the surface heat budget. Fu (1981) considers his errors as largest for this section.

3. World Ocean

The altered values of northward heat transport in the Atlantic between 60°N and 60°S, as shown in Table 1 [comparing the present results with those of Hastenrath (1980)] and Figs. 1 and 2, also affect the picture for the World Ocean as a whole. The corresponding new values are plotted in Figs. 1 and 3. For the Northern Hemisphere these amount to a smaller poleward transport, but a larger value for the Southern Hemisphere. For 60°S in particular (Table 2), the southward transport changes from 13 × 10^{13} W in H to 65 × 10^{13} W. The former value, in H, was found compatible with a required transport of the order of 10–20 × 10^{13} W as estimated from Zillman's (1972) heat budget maps for the Southern Ocean. However, in his recent study of the Southern Ocean heat budget Gordon (1981) obtained a required oceanic heat transport across 60°S of 54 × 10^{13} W, which would agree closely with the value of 65 × 10^{13} W arrived at here.

Referring to the early analysis of a hydrographic section by Bryan (1962), Wunsch (1980) suggests the possibility of an equatorward heat transport at 32°N in the Pacific Ocean. For the World Ocean as a whole, this would entail a considerably larger southward heat transport across 60°S than obtained above. However, in the light of the surface heat budget characteristics of the North Pacific, a southward heat transport across 32°N does not appear plausible. Also, the scale and configuration of the Pacific may be unfavorable for the evaluation of meridional transports from hydrographic sections.

Errors in transport estimates derived from the surface heat budget are discussed in H and in Lamb (1981). Concerning errors in the evaluation from hydrographic sections, Bryden and Hall (1980) propose a tolerance of ±30 × 10^{13} W for their meridional heat transport value at 25°N of 110 × 10^{13} W. However, the error margin does evidently not account for variability on the seasonal, interannual and longer time scales. This reservation regarding the temporal sampling applies to the hydrographic section approach in general (Bennett, 1978; Wunsch, 1980; Roemmich, 1980).

4. Atmosphere–ocean system

The discussion thus far has been confined to the evaluation of meridional heat transport in the ocean

TABLE 2. Estimates of southward heat transport (10^{13} W) across 60°S in the World Ocean as a whole.

Hastenrath (1980)	13	Trenberth (1979)	100
Zillmann (1972)	10–20	Gordon (1981)	54
		This paper	65

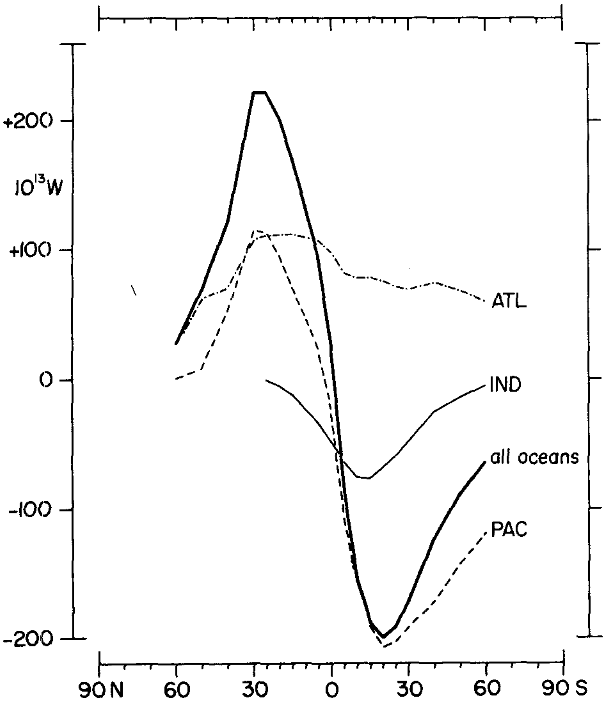

FIG. 1. Annual mean meridional heat transport within the oceans: Pacific (dashed), Atlantic (dash-dotted), Indian Ocean (thin solid), and all oceans combined (heavy solid). Northward transport positive, units in 10^{13} W [sources: Hastenrath (1980) and Budyko (1963) for 30–60°S and 30–66°N in the Pacific; Aagaard and Greisman (1975) for 66–90°N; and Lamb (1981) for 30–66°N in the Atlantic].

from the surface heat budget and hydrographic sections. Alternatively, Oort and Vonder Haar (1976) inferred the hydrospheric heat transport in the Northern Hemisphere as a residual, based on satellite measurements of net radiation at the top of the atmosphere and independent estimates of the atmospheric heat transport. Drawing on Stone's (1978) adjustment of the satellite data published by Ellis and Vonder Haar (1976), Trenberth (1979) applied the same procedure to the Southern Hemisphere. The results of Oort and Vonder Haar (1976) and Trenberth (1979) are also plotted in Fig. 3 for convenient reference. The shortcomings of this approach are related to the combined uncertainties in planetary net radiation and atmospheric heat budget. Estimates of the latter are least satisfactory for the Southern Hemisphere. Trenberth's (1979) value of southward directed oceanic heat transport across 60°S of 100 × 10^{13} W far exceeds both Gordon's (1981) result and the present estimate.

In fact, the uncertainties in satellite measurements of net radiation at the top of the atmosphere merit attention. In the global annual average this term is expected to be close to zero, but satellite observations yield sizeable imbalances. Thus from a one-year data set Gruber (1978) obtained a global integral of about -10 W m^{-2}. For the data published by Vonder Haar and Ellis (1974) the figure is about $+8$ W m^{-2}. It is remarkable that Ellis and Vonder Haar (1976) arrived at an imbalance as small as -0.01 W m^{-2} for a subset of 29 months contained in the aforementioned larger data compilation. The imbalance in the data published by Jacobowitz *et al.* (1979) is about $+6$ W m^{-2}. Their data for the year July 1975–June 1976 (H. Jacobowitz, personal communication, 1981) were used here.

An adjustment uniform with latitude was applied to the four data sets so as to achieve a zero global

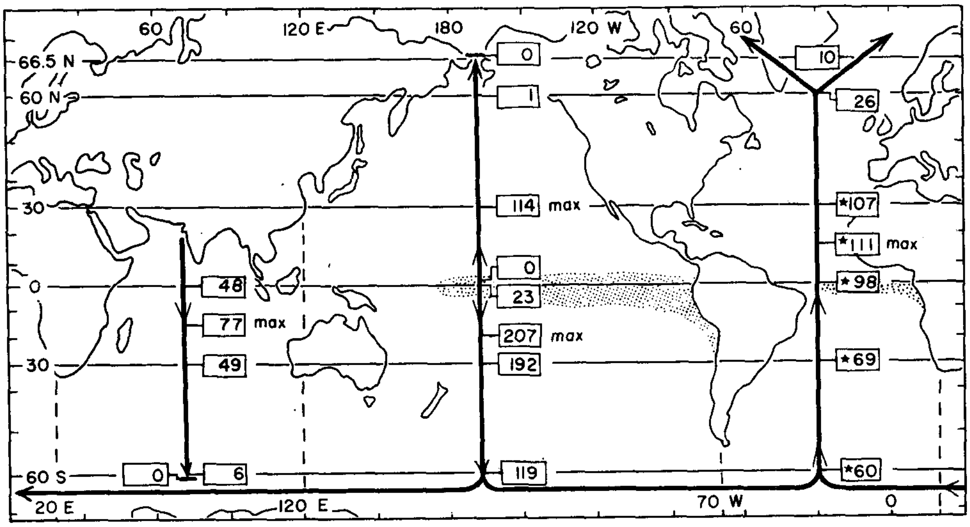

FIG. 2. Map scheme of annual mean meridional heat transport within the oceans (from Fig. 1). Heavy cross bar denotes latitude of zero, and max that of maximum meridional transport, with numbers indicating amounts in units of 10^{13} W. Stippling marks areas with $Q_{vo} > +50$ W m^{-2}, and broken lines show the meridians used as boundaries between oceans in the high southern latitudes. Asterisks indicate the numbers that differ from Fig. 10 in Hastenrath (1980).

annual mean. The required meridional heat transports in the atmosphere-ocean system corresponding to these adjusted net radiation values are compared in Fig. 4. Despite the adjustment for global balance, the maximum of required transport in midlatitudes differs considerably between the four curves. These differences may be due to a combination of observation errors and real interannual variability. The estimate of maximum multi-annual mean poleward heat transport around 30°N derived from satellite measurements seems hardly better than ~100 × 10^{13} W.

In an effort at improving estimates, the four curves in Fig. 4 were averaged. The resultant curve of the required meridional heat transport in the atmosphere-ocean system is plotted in Fig. 3. The difference between this curve and the plot of oceanic heat transport represents an estimate of the heat transport within the atmosphere. The curve of atmospheric heat transport differs from that in Fig. 11 of H, in part because of the altered oceanic transport figures, but particularly because the average of the four curves of Fig. 4 is used as reference in Fig. 3, rather than Gruber's (1978) satellite measurements. In Fig. 3, the hydrosphere accounts for 40 and 46% of the total poleward transport at 30°N and 20°S, respectively. These percentages also differ from Fig. 11 in H. Uncertainties are directly related to observation errors and real interannual variability of net radiation at the top of the atmosphere.

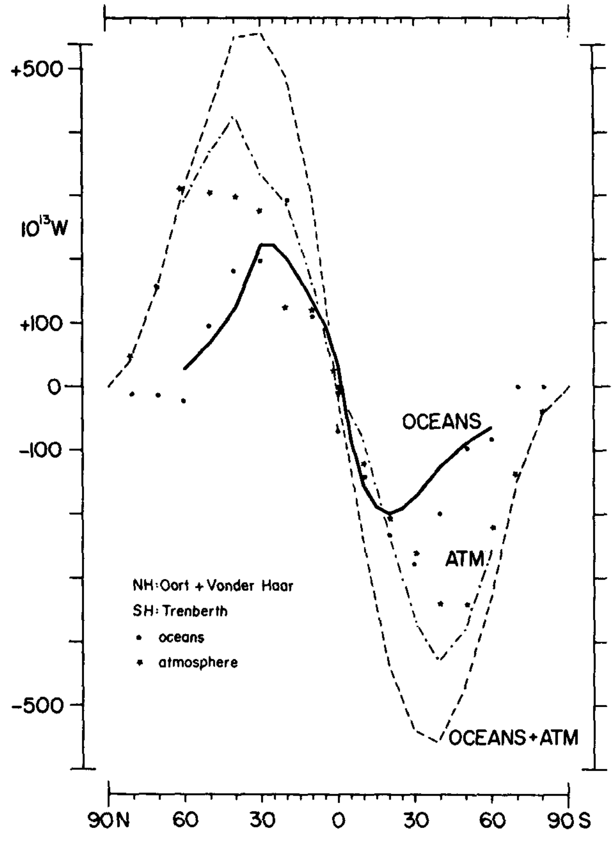

FIG. 3. Annual mean meridional heat transport within the atmosphere-ocean system (dashed line—average of the four curves in Fig. 4), within the oceans (solid line—from Fig. 1), and within the atmosphere (dash-dotted line—residual). Estimates by Oort and Vonder Haar (1976) for the Northern Hemisphere and by Trenberth (1979) for the Southern Hemisphere are entered as dots and stars for ocean and atmosphere, respectively. Northward transport positive, units in 10^{13} W.

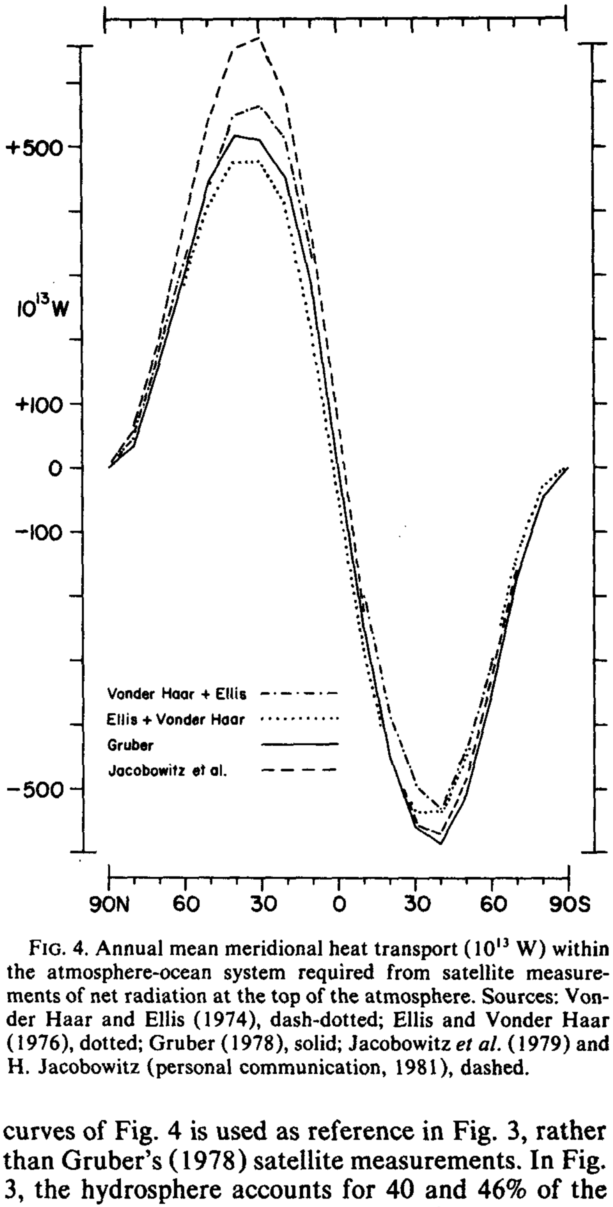

FIG. 4. Annual mean meridional heat transport (10^{13} W) within the atmosphere-ocean system required from satellite measurements of net radiation at the top of the atmosphere. Sources: Vonder Haar and Ellis (1974), dash-dotted; Ellis and Vonder Haar (1976), dotted; Gruber (1978), solid; Jacobowitz *et al.* (1979) and H. Jacobowitz (personal communication, 1981), dashed.

Upon completion of this study, a paper by Stephens *et al.* (1981) appeared that contains annual mean values of net radiation at the top of the atmosphere for 10° latitude zones derived from 48 months of satellite measurements. This set possesses a global imbalance of +9 W m^{-2}. As for the four profiles displayed in Fig. 4, an adjustment uniform with latitude was applied to achieve a zero global annual mean, and then the required meridional heat transport in the atmosphere-ocean system corresponding to these adjusted net radiation values was calculated. The resulting meridional profile is within drafting accuracy almost identical to the average of

TABLE 3. Annual mean northward heat transport (10^{13} W) within the atmosphere. O + R 71: Oort and Rasmusson (1971, p. 127–135, layer 1012.5 to 75 mb); O + V 76: Oort and Vonder Haar (1976, layer 1012.5 to 75 mb); T 79: Trenberth (1979); Fig. 3: present study, Fig. 3; H 82: computed from net radiation at the top of the atmosphere [$\mathrm{SWLW}\,{\uparrow\!\downarrow}_{\mathrm{top}}$] in Fig. 3, and values of surface net radiation [$\mathrm{SWLW}\,{\uparrow\!\downarrow}_{\mathrm{sfc}}$], and sensible Q_s and latent heat flux Q_e at the surface [Budyko (1974, p. 219); Sellers (1965, p. 5, 103)].

Latitude	O + V 76	T 79	O + R 71	Fig. 3	H 82
90°N	0				0
80°N	+50				+41
70°N	+160		+136		+151
60°N	+310		+277	+292	+280
50°N	+310		+310	+390	+357
40°N	+300		+344	+428	+420
30°N	+280		+282	+334	+384
20°N	+110		+137	+283	+308
10°N	+100		+105	+162	+168
0	+20	−17	+89	−3	+23
10°S		−123	−190	−6	−132
20°S		−209		−234	−307
30°S		−258		−367	−439
40°S		−335		−433	−479
50°S		−344		−384	−424
60°S		−201		−262	−323
70°S		−145			−169
80°S		−48			−51
90°S		0			0

the four sets of Fig. 4, as plotted in Fig. 3; a difference as large as 10–13 × 10^{13} W was found only at four of the latitudes.

The annual mean meridional heat transport in the atmosphere obtained as a residual between the two other curves in Fig. 3, is compared in Table 3 with various other sources. The columns O + V 76, O + R 71, and T 79 are based on aerological observations. The column H 82 was obtained from evaluation of the heat budget equation of an atmospheric column, using the net radiation at the top of the atmosphere $\mathrm{SWLW}\,{\uparrow\!\downarrow}_{\mathrm{sfc}}$ in Fig. 3, and values of surface net radiation $\mathrm{SWLW}\,{\uparrow\!\downarrow}_{\mathrm{sfc}}$, sensible Q_s, and latent heat flux Q_e at the surface published by Budyko (1974, p. 219) and Sellers (1965, pp. 5, 103). In fact, for annual mean conditions, the divergence of the total vertically integrated transport of sensible heat c_pT, geopotential energy gz, and latent heat Lq, namely

$$\mathrm{div}(c_pT + gz + Lq) = \mathrm{SWLW}\,{\uparrow\!\downarrow}_{\mathrm{top}} - \mathrm{SWLW}\,{\uparrow\!\downarrow}_{\mathrm{sfc}} + Q_s + Q_e\,. \quad (1)$$

Integration of $\mathrm{div}(c_pT + gz + Lq)$ with latitude yields the required meridional heat transport within the atmosphere listed in column H 82 of Table 3.

Table 3 shows that the present results (Fig. 3) agree broadly with the calculations of Oort and Rasmusson (1971, pp. 127–135) for the Northern Hemisphere midlatitudes, where transports are largest and the radiosonde network is most plentiful. In addition, the atmospheric transport curve of Fig. 3 is in good agreement with the column H 82 for most latitudes of both hemispheres. Given the values of the three right-hand terms of Eq. (1) from Budyko (1974) and Sellers (1965), the required atmospheric meridional heat transport (column H 82) would depend only on the latitudinal pattern of $\mathrm{SWLW}\,{\uparrow\!\downarrow}_{\mathrm{top}}$. This in turn would affect the results of Fig. 3 in the same way. Thus the indirect assessment of atmospheric meridional heat transport presented in Fig. 3 is compatible with the results of two other independent approaches.

In order to appreciate typical error tolerances, consider zero heat transport across the equator and a systematic error in, say, the satellite-derived net radiation at the top of the atmosphere of about 10 W m^{-2}, a number mentioned above. This would correspond to an error in the heat transport across 30°N of the order of 100 × 10^{13} W. Similar considerations apply for the atmospheric and hydrospheric domains of the system separately.

5. Conclusion

This note has shown that the available estimates of meridional heat transport in the Atlantic Ocean water body obtained independently from the surface heat budget and from hydrographic sections (Tables 1, 2, Fig. 3) agree remarkably closely. Moreover, the meridional heat transport in the global atmosphere derived here as a residual from the evaluation of the oceanic heat budget and satellite measurements of net radiation at the top of the atmosphere, is similar to independent estimates from aerological observations and from published calculations of the surface heat budget. However, as pointed out in H and in Wunsch (1980), plausible error tolerances far exceed the differences between heat transport estimates derived by various independent methods.

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