GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.3, PAGES 353-356, FEBRUARY 1, 1999

Atlantic Ocean baroclinic heat flux at 24 to 26° N

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Abstract. The spatially varying, interior geostrophic baroclinic heat flux component of the total meridional oceanic heat flux near 24°N in the Atlantic Ocean is examined using four transatlantic hydrographic sections including the October 1957 DISCOVERY II IGY section, the September 1981 ATLANTIS section, the August 1992 HESPERIDES section, the February 1998 RONALD H. BROWN section and the 1982 Levitus and the Lozier, Owens, Curry climatologies. The 1992 section is complemented by shorter western boundary sections obtained concurrently during the Trident cruise. We find an average southward baroclinic heat flux of 0.9 ± 0.3 PW with an annual cycle amplitude of ± 0.3 PW. More than 90% of the annual cycle is captured within 30° of the western boundary.

Introduction

Total meridional oceanic heat flux plays a crucial role in the energy balance of the sea-air system. At northern mid-latitudes the ocean transports nearly half the energy needed to balance the energy deficit at the top of the polar atmosphere. Near 24.5°N in the Atlantic Ocean, several studies have estimated similar meridional oceanic heat flux values, a nearly invariant 1.2 PW (1 PW = 10^{15} W) northward [*Bryden and Hall*, 1980; *Hall and Bryden*, 1982; *Roemmich and Wunsch*, 1985; *Rintoul and Wunsch*, 1991]. Several of these studies [e.g. *Bryden and Hall*, 1980; *Hall and Bryden*, 1982] have decomposed total meridional oceanic heat flux into components that can be estimated from hydrographic, surface wind and Florida Current transport data. In particular, the baroclinic heat flux (BHF) is given by

$$Q = \int_L \int_D \rho c_p \theta' v' dz dx \qquad (1)$$

where D is the depth, ρ is the density, c_p is the specific heat capacity of sea water, and θ', v' are deviations from the locally vertically averaged temperature and geostrophic velocity respectively. The limit of integration, L, is the horizontal dimension extending from the eastern boundary to the Bahamas Island Chain. The BHF in the Straits of Florida can be computed separately *Hall and Bryden* [1982].

Paper number 1998GL900323.
0094-8276/99/1998GL900323$05.00

BHF has been estimated from hydrographic data collected along 24.5°N. Typical values of this component of meridional oceanic heat flux are of the order 0.8 PW to the south [*Fillenbaum et al.*, 1997], thereby requiring considerable northward heat flux by the other meridional oceanic heat flux components to account for the net northward heat flux at this latitude. Herein, we use historical and more recent, average and quasi-synoptic data to estimate the effect on BHF values from (1) using different hydrographic climatologies; (2) slight changes in the locations of quasi-synoptic sections; and (3) the annual cycle. Our overall objective is to provide a measure of the robustness of earlier BHF estimates.

Data Analysis

The full basin sections along 24.5°N used in the study include the four transatlantic sections from October 1957, September 1981, August 1992 and February 1998 shown in Fig. 1 [*Hall and Bryden*, 1982; *Roemmich and Wunsch*, 1985; *Parrilla et al.*, 1994] In addition, data collected along nominally 26.5°N and 22.5°N extending only to the Mid-Atlantic Ridge during the 1992 Trident cruise are used [*Marchese and Gordon*, 1995]. The Trident cruise included shorter sections in the western Atlantic taken within a month of the August 1992 HESPERIDES transatlantic section (Figure 1). Both the 26.5°N and 22.5°N 1992 transects were designed to estimate the effect that slight changes in the location of the western portion of a heat flux section had on the overall estimates of heat flux.

The October 1957 hydrographic data were collected using discrete bottle samples, while the other cruises used continuously sampling conductivity, temperature,

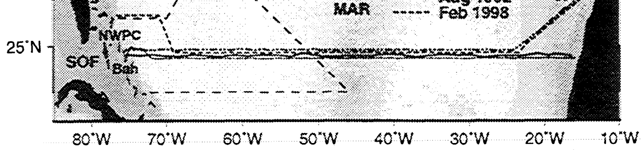

Figure 1. Station locations for CTD data from the 26.5°N and 22.5°N 1992 sections, the October 1957 section, the September 1981 section, the August 1992 section, and the February 1998 section (see legend). Locations described in text include the Strait of Florida (SOF), the Northwest Providence Channel (NWPC), the Bahamas Island Chain (Bah), the Mid-Atlantic Ridge (MAR) and the Canary Islands (CI).

depth (CTD) sensors. The October 1957 section was occupied at a relatively coarse resolution, as well as the 26.5°N and 22.5°N 1992 Trident sections (Table 1). Table 1 The September 1981, August 1992 and February 1998 sections have an eddy resolving resolution along the entire transect.

The 1982 *Levitus* [1982] and the *Lozier et al.* [1995] (LOC, hereafter) climatologies are used. The Levitus 1982 climatology was generated by objectively mapping available hydrographic, CTD and mechanical and expendable bathythermograph profiles at discrete depths with temperature and salinity distributions computed separately. Data are available on a one degree latitude/longitude grid. Below 1000m only annual averaged values are available. Above 1000m seasonal values of salinity and monthly values of temperature are available. Considerable smoothing was required to achieve this resolution (e.g., at 30°N, the data are smoothed over 15 degrees in both latitude and longitude). The LOC climatology was generated by averaging only hydrographic and CTD data along isopycnal surfaces into one degree latitude/longitude squares, thus preserving the temperature-salinity relation in their fields. No horizontal smoothing other than that inherent on the one degree averaging was applied, hence this climatology contains numerous gaps in the 1 degree grid where no data are available. In order to reduce the number of data gaps a bimonthly climatology was created that assured that a data point could be found at least every two degrees. All data were interpolated onto the same standard depths as the Levitus 1982 climatology.

Results

The values for the BHF estimated from the four transatlantic transects are given in Table 1. The initial three transatlantic occupations show a decrease through time in the southward interior BHF, followed by a dramatic increase in southward BHF in February 1998. The BHF accumulated away from the western boundary shows that most of the difference occurs to the west of 50°W, where the variability is the highest (Figure 2). Peaks in BHF (e.g. a peak at 66°W in August 1992) represent an accumulation of positive heat flux (i.e., an increase in the relative amount of warm water flowing northward on top of cold water flowing southward), followed by an accumulation of negative heat flux. These peaks represent eddies and recirculations (*Johns et al.* [1996]). The transects resolve the peaks which have similar spatial scales of about 500 km. Thus, the estimates of total BHF from the synoptic sections are not aliased because of inadequate resolution.

Table 1 and Figure 2 also show the two annual mean climatologies. As described previously, the Levitus 1982 climatology has been smoothed considerably in space. The smoothing is manifest by the absence of mesoscale features. Close to the western boundary (within 3°), this smoothing may have reduced the northward BHF which is the result of the northward flow of the Antilles Current above the southward Deep Western Boundary Current, leading to a slight overestimate of the net southward BHF. The northward BHF next to the Bahamas Island Chain typically has values between +0.7 to +1.5 PW northward, but the Levitus annual mean only includes about +0.2 PW (Figure 2). The Levitus 1982 climatology only includes the October 1957 transect, in addition to other data collected earlier and hence tends towards a similar structure for BHF. The LOC climatology only includes the October 1957 and September 1981 sections. While maintaining more mesoscale features, the LOC tends towards a structure similar to the September 1981 section.

The 26.5°N and 22.5°N 1992 data provide a measure of the differences caused by small (order of degrees) changes in the location of a portion of the transatlantic section (see Figure 1 for station locations). Using the eastern portion of the August 1992 HESPERIDES section with the 26.5°N and 22.5°N 1992 sections results in a BHF of -0.9 PW using the 22.5°N section and -1.0 PW using the 26.5°N section compared to -0.7 PW using the 24.5°N August 1992 section (Table 1). As before, the differences are due to differences in the mesoscale features found along the western boundaries (not shown) since patching together non-synoptic sections induces an error on the order of the eddy variability. Using only these sections, the differences suggest an uncertainty in BHF estimates of the order of 0.1-0.2 PW (standard deviation).

Table 1. Interior baroclinic heat flux estimates at 24°N/26°N

	Lat. (°N)	1957	1981	1992	1998	Levitus 1982	LOC	Trident (22.5°N) 1992	Trident (26.5°N) 1992
Date		Oct 6-12	Aug 12-Sep 6	Jul 20-Aug 16	Jan 23-Feb 24			Aug 5-31	Aug 5-31
Ship		*Discovery II*	*Atlantis 109*	*Hesperides*	*Brown*			*Baldrige*	*Baldrige*
Spacing (km)		166±42	71±31	61±12	55±23			126±88	78±41
Eddy noise (PW)		0.27	0.33	0.26	0.24		0.23	0.19	0.24
Hall and Bryden [1982]	24.5	-0.93							
Molinari et al. [1990]	26.5					-0.84			
Fillenbaum et al. [1996]	26.5	-0.88	-0.78			-0.99			
This study	24.5	-0.90	-0.81	-0.71	-1.16	-0.99	-0.75		

Baroclinic heat flux for several different sections and annual mean climatologies. Units are given in PW (1 PW = 10^{15}W). "Eddy noise" is determined by the standard deviation of the difference between the local BHF and the Levitus 1982 BHF (see text).

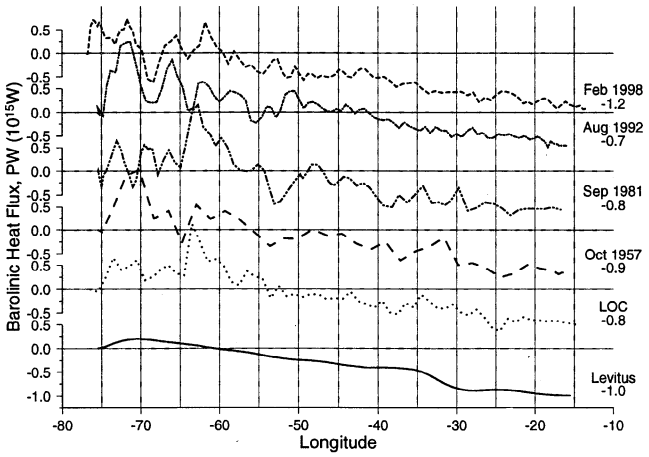

Figure 2. Cumulative southward baroclinic heat flux integrated from the western boundary for the February 1998, the August 1992, the September 1981, the October 1957 sections, and the Lozier, Owens and Curry and the Levitus 1982 annual mean climatologies (see Figure 1 for locations). Final BHF is listed to the left of each curve. Note each curve is offset by 1.25 PW.

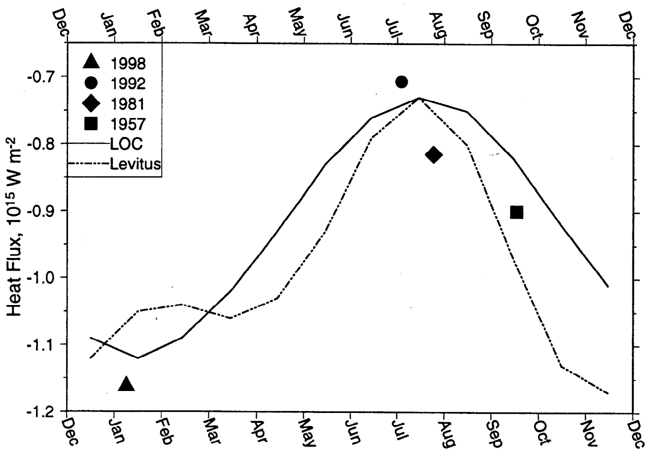

Figure 3. Annual harmonic of baroclinic heat flux for the Lozier, Owens and Curry climatology (solid line) and annual and semi-annual harmonics for the Levitus 1982 climatology (dashed line) are plotted. Baroclinic heat flux for the full basin synoptic sections are shown including the February 1998 (triangle symbol), the August 1992 (circular symbol), the September 1981 (diamond symbol), and the October 1957 (square symbol) sections. The BHF is plotted at the median dates for the transatlantic cruises. Note the data are plotted twice to emphasize the annual cycle.

A simple estimate of the possible error induced by aliasing the mesoscale eddy field can be obtained by comparing the synoptic transatlantic sections with the highly smoothed Levitus climatology. Since the Levitus climatology has effectively removed all the mesoscale features, the differences between the Levitus BHF as a function of longitude and the synoptic section BHF is a measure of the eddies. This difference for each section results in a mean of about 0.24 PW (Table 1). Note this is essentially the same as the eddy error estimated in Hall and Bryden (0.25 PW) by decomposing the BHF further into a horizontal average $v'\theta'(z)$ and local deviations, $v''\theta''(x,z)$, which they suggest represent eddy fluxes. They found that the local deviations had a very small basin wide integral. They concluded that the standard deviation was a better estimate of the eddy flux error, and suggest an error of 0.24 PW.

Other sources of "error" or variability in mean BHF values include time dependent fluxes such as the annual cycle. *Molinari et al.* [1990] estimated mean monthly values of BHF at 26.5°N using the *Levitus* [1982] climatology. A similar calculation was performed here for 24.5°N and the monthly BHF estimates are fit with an annual and semi-annual harmonic. The resulting curve is plotted in Figure 3. These values, as expected, are only slightly different from the *Molinari et al.* [1990] results and show the same peak to peak range of 0.5 PW. A similar annual cycle is obtained performing an analogous computation on the LOC data (Figure 3). Only the annual harmonic is used for the LOC bi-monthly climatology due to the limited data. The four synoptic cruise BHF values provide strong, essentially independent (i.e. the Levitus climatology only includes the October 1957 data) support for the existence of an annual cycle in BHF (Figure 3). Both climatologies appear consistent with observed BHF values. Thus, even with large spatial smoothing, the Levitus 1982 can replicate the seasonal cycle.

As noted above most of the spatial variability in BHF is introduced to the west of 55°W. Annual cycles using only the first and second harmonics of Levitus 1982 data are fit to the cumulative BHF values at representative longitudes in Figure 4 to ascertain if temporal variability is similarly located. A large proportion of the annual cycle in BHF at the eastern end of the section is caused by BHF variability along the western boundary. By 45°W more than 90% of the full basin annual cycle is captured.

A long time-series of short hydrographic sections has been obtained along the western boundary along 26.5°N [*Vaughan and Molinari*, 1997]. Seasonal averages of cumulative values of BHF integrated out to 72.5°W qualitatively support the climatological annual cycle. Two January-February cruises give an average BHF of +0.3 PW while five June-August cruises give an average BHF of +0.7 PW, consistent both with positive BHF in the west and increased northward BHF in the summer found using the climatological data. These values are higher than that seen from the Levitus data near the western boundary.

Conclusion

In summary we find:

- Mesoscale variability, largest west of the Mid-Atlantic Ridge, creates an uncertainty in BHF of about 0.26 PW (standard deviation);

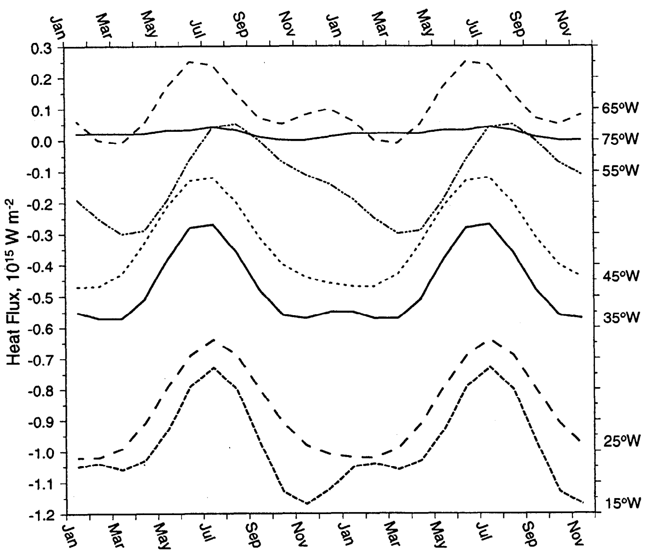

Figure 4. Annual harmonic of baroclinic heat flux for the Levitus 1982 climatology at 24.5°N integrated from the western boundary to various longitudes. Note the data are plotted twice to emphasize the annual cycle. No offset is applied to the data; BHF generally becomes increasingly negative as the integration proceeds from the western boundary. By 75°W very little BHF has been accumulated and by 65°W the positive BHF of the Antilles Current/Deep Western Boundary Current is apparent.

- Although uncertainties are large, the synoptic cruises support the existence of an annual cycle in BHF estimated from the climatologies with maximum southward transport in winter and maximum northward transport in summer;
- Errors in mean annual BHF from inadequate sampling of the annual cycle can be as large as 0.22 PW (0.5 PW peak to peak difference)
- and 90% of the annual cycle in interior BHF is established by conditions within 30° of the western boundary.

Comparing the BHF values from the synoptic sections and the two climatologies provides a measure of the mean annual BHF and the uncertainty in this estimate. These estimates suggest a mean annual southward BHF of -0.90 PW and about $\pm$ 0.3 PW uncertainty. The uncertainty estimate is based on the differences between the climatologies and the four synoptic sections. *Molinari et al.* [1990] using the Levitus climatology demonstrate that throughout the year the northward Ekman and barotropic transports are sufficiently large to result in a net northward heat flux that sums to the typical 1.2 PW total northward heat flux value. *Bryden and Hall* [1980] give an uncertainty in total meridional heat flux of about 0.3 PW, with a total of 0.24 from errors in the interior BHF. Our estimate for the uncertainty in BHF including the annual cycle, raises the uncertainty on the total heat flux to $\pm$ 0.4 PW. The variability of the BHF shown here raises some interesting questions about how quickly the oceans mass field responds to seasonal forcing and should provide a benchmark for models to simulate.

Acknowledgments. This research was sponsored in part by the National Oceanic and Atmospheric Administration Office of Global Programs and the Office of Oceanic and Atmospheric Research .

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(Received September 15, 1998 ; revised December 18, 1998; accepted December 22, 1998.)