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ABSTRACT

A base set of climatological heat and momentum flux fields has been calculated for the North Atlantic as part of a pilot study for a global climatology. The fields are qualitatively reasonable. Comparison with the fields of Isemer and Hasse (1987), which have been adjusted to match oceanographic constraints, indicates that the net heat loss in the base climatology is too low by between 10-30 W/m^2 over most of the North Atlantic basin if the constraints are representative of the long-term mean ocean heat transport. The deficit arises mainly as a result of differences between the latent heat flux fields, the shortwave fields are in very good agreement. The implied ocean heat transport at 24°N is 0.29 PW less that the lower limit on the hydrographic estimate (Bryden, 1993). Possible reasons for this discrepancy are discussed and at present it is not clear whether the problem lies in the calculation of the fluxes or in appropriate use of the hydrographic estimates as constraints.

KEYWORDS

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A PILOT HEAT AND MOMENTUM FLUX STUDY FOR THE NORTH ATLANTIC - BASE CLIMATOLOGY

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1. INTRODUCTION

Heat and momentum flux fields for the North Atlantic, determined from a large dataset of ship reports for the period 1980 - 91, are presented in this report. They have been calculated as part of a pilot study for a global flux climatology (Josey, 1995a) and the aim at this stage has been to produce a first set of climatological fields (subsequently termed the 'base' climatology) rather than a final product. In the next phase of the study, the fields will be refined to include recent additions to the ship dataset, corrections to several meteorological variables at the level of individual reports and a full objective analysis treatment.

The data source for the fields is detailed in the next section. This is followed by a description of the flux calculation scheme in Section 3. Climatological mean fields derived from the individual flux values are presented in section 4. Finally, the climatologically implied ocean heat transport in the North Atlantic is calculated and some conclusions are drawn following a comparison with direct hydrographic estimates.

2. DATA SOURCE

The ship reports used in this study are a subset of the global Comprehensive Ocean-Atmosphere Dataset (COADS) Release 1a (Woodruff et al., 1993) for the region (0 - 90° N, 100° W - 40° E) and time period 1980 - 1991. The full global set contains some 40 million reports of which about half lie in the region under consideration. Climatological heat flux fields have not previously been calculated using Release 1a. da Silva et al.(1994) have produced a global flux climatology covering the period 1945 - 1989, for which an earlier version (the 'interim product') of Release 1a was used for 1980 - 1989. However, Release 1a contains a significantly greater number of reports than the interim product (an increase of 30 - 40% in the mid-1980's) and so we expect improved spatial coverage and reduced sampling errors in our analysis for this period. Recent revisions and extensions to Release 1a which cover the period 1992 - 93 and January - May 1988 (Worley, S. personal communication) have not been included at this stage but will be in the next phase of the climatology.

3. SHIP REPORT CORRECTIONS AND FLUX DETERMINATION METHOD

3.1. Corrections to Reported Variables

Prior to calculating the fluxes, visual estimates of the wind speed have been corrected for biases arising from the use of the WMO Code 1100 wind scale as described below. Further corrections to the reported variables as discussed in Kent et al.(1993) will be included in the next phase of the climatology.

3.1.1. Beaufort Scale Correction

The visual estimates of wind speed reported in COADS 1a were originally calculated using the WMO Code 1100 Beaufort equivalent scale which is known to have systematic biases at both low and high wind speeds. A correction scheme for these biases proposed by da Silva et al (1994) has been used in this study. In the scheme, visual winds are corrected according to the following formula,

$$u_N = 0.787 u_O + 0.9547 u_O^{1/2}$$

where u_N and u_O are the corrected and uncorrected wind speeds at 20m.

Preliminary results from a comparison of several different scales using data from the Voluntary Observing Ships Special Observing Project for the North Atlantic (Kent, 1995) indicate that an alternative scheme proposed by Lindau (1995) gives better agreement between measured and estimated wind speed distributions than the da Silva scheme and, subject to the results of the ongoing evaluation study, it will be used in subsequent analyses.

3.2. Flux Calculation Scheme

Turbulent and radiative heat fluxes and the wind stress have been calculated using a version of the program BFORM (Taylor, 1995) that has been extended to include a treatment of the radiative terms. Stability and height corrections are included in the flux calculations using Monin - Obukhov similarity theory. The following platform dependent default heights for the wind and temperature sensors have been assumed for the calculations:

i.) Platform type (PT) code =0 - 5 (US Navy, merchant ship, foreign military, ocean station vessel, lightship, ship, 'deck' log or unknown). Sensor height = 20m.

ii.) PT = 6 - 8 (moored, drifting or ice buoy). Sensor height = 8m.

iii.) PT = 9 - 10 (manned ice station or oceanographic station). Sensor height = 20 m.

iv.) PT = 13 -14 (Coastal - Marine Automated Network or other coastal/island station). Sensor height = 10m.

v.) PT = 15. Fixed ocean platform. Sensor height = 80m.

Fluxes have been determined for each ship report for which the necessary basic variables are available and the full set of basic and diagnosed variables has been archived on Exabyte tape CL001. The choice of bulk formulae for the flux calculations is described in the following sections.

3.2.1. Wind Stress

The wind stress, τ, has been calculated using the bulk formula,

$$\tau = \rho c_D u^2$$

where ρ is the density of air; c_D, the stability dependent drag coefficient, and u the wind speed (corrected as described in 3.1.1. if based on a visual estimate). The drag coefficient scheme of Smith (1988) which is based on direct measurements of the wind stress at sea has been employed. However, in a recent study of wind stress measurements made in the Southern Ocean, Yelland and Taylor (1995) found neutral values of c_D at wind speeds above 6 m/s which were about 10% higher than those from previous open ocean studies and the revised formulation that they suggest may be employed in the next phase of the climatology.

3.2.2. Turbulent Heat Fluxes

The sensible and latent heat fluxes, Q_H and Q_E, have been calculated using the following bulk formulae,

$$Q_H = \rho c_p C_h u (T_s - T_a)$$

$$Q_E = \rho L C_e u (q_s - q_a)$$

where c_p is the specific heat of air at constant pressure; L, the latent heat of vaporisation; C_h and C_e, the stability dependent transfer coefficients for sensible and latent heat respectively; T_s, the sea surface temperature; T_a, the potential air temperature; q_s, 98% of the saturation specific humidity at sea surface temperature, and q_a the atmospheric specific humidity. Transfer coefficients for the turbulent heat flux have also been taken from Smith(1988). Recent work by Kent and Taylor (1995) suggests that the use of artificially increased transfer coefficients in many earlier studies, for example Oberhuber (1988), cannot be justified on the grounds of errors in ship reported variables or by a fair-weather bias.

3.2.3. Shortwave Flux

The net shortwave flux has been determined using two techniques, the first is employed in a sampling sense, returning a value for each report, the second makes use of monthly average quantities and returns the mean field.

The sampling estimate, Q_S, is obtained using the simple 'okta' model of Dobson and Smith (1988),

$$Q_S = (1-\alpha) Q_o \sin\theta (A_i + B_i \sin\theta)$$

where α is the albedo; Q_o, the solar constant taken to be 1368 W/m^2 (Frohlich and London, 1986) ; A_i and B_i, empirically determined coefficients for each category of reported total cloud amount in oktas (note that there are 10 categories in all, ranging from 0 - 9, with 9 being the code for 'sky obscured'); θ, the solar elevation, given by the following formula,

$$\sin\theta = \sin\phi_2 \sin\delta + \cos\phi_2 \cos\delta \cos h$$

with,

$$\delta = -23.5 \sin(80 - D)$$

$$h = 15(12 - t) - \phi_1$$

where δ is the declination; ϕ_1 and ϕ_2, the longitude and latitude; h, the hour angle; t, Greenwich Mean Time at the observing location and D, the Julian day.

Dobson and Smith (1988) have assessed the performance of estimates made with several different bulk formulae against time series of direct solar radiation measurements, covering periods of tens of years, from five weather ships in the North Atlantic and North Pacific. They find that the 'okta' model provides as good an estimate of the shortwave flux at a given time as more complicated models which include a dependence on cloud type. The main disadvantage with using this formula is that derived monthly means may be in error if there is a significant diurnal bias in the number of reports (see 4.1). However, even if it proves unsuitable for calculating monthly mean estimates, the formula will still be employed in future analyses in order to make the solar heating correction to reported air temperatures suggested by Kent et al.(1993).

The alternative approach is to make use of the formula proposed by Reed (1977) which is based on an analysis of weather ship and coastal station measurements, according to which the monthly mean net shortwave flux,

$$\overline{Q_S} = (1 - \alpha) Q_c [1 - 0.62\,\overline{n} + 0.0019\,\overline{\theta_N}]$$

where Q_c is the clear - sky solar radiation, $\overline{n}$ is the monthly mean fractional cloud cover and $\overline{\theta_N}$ is the monthly mean local noon solar elevation (which has been approximated by the local noon value on the middle day of the month as determined from the earlier formula for $\sin\theta$ with $\cos h$ set equal to 1; this approximation will be replaced by the average over all days in the month in the next phase of the climatology).

Dobson and Smith (1988) found that estimates of the long term mean insolation made at 3 marine stations using the Reed formula were accurate to within 12 W/m^2, while those determined using other bulk formulae were significantly worse, and for this reason we have adopted it for the current study. Values for the albedo for use with both the Reed formula and the 'okta' model have been taken from Payne (1972). For the clear sky radiation, we have made use of the expression suggested by Seckel and Beaudry (1973),

$$Q_c = a_0 + a_1\cos\Phi + b_1\sin\Phi + a_2\cos2\Phi + b_2\sin2\Phi$$

where,

$$\Phi = (360/365)(D - 21)$$

and the coefficients a_i, b_i depend on latitude as follows:

i.) Latitude 20° S to 40° N

$$a_o = -15.82 + 326.87\cos\phi_2$$
$$a_1 = 9.63 + 192.44\cos(\phi_2 + 90)$$
$$b_1 = -3.27 + 108.70\sin\phi_2$$
$$a_2 = -0.64 + 7.80\sin2(\phi_2 - 45)$$
$$b_2 = -0.50 + 14.42\cos2(\phi_2 - 5)$$

ii.) Latitude 40° N to 60° N

$$a_o = 342.61 - 1.97\phi_2 - 0.018\phi_2^{\ 2}$$
$$a_1 = 52.08 - 5.86\phi_2 + 0.043\phi_2^{\ 2}$$
$$b_1 = -4.80 + 2.46\phi_2 - 0.017\phi_2^{\ 2}$$
$$a_2 = 1.08 - 0.47\phi_2 + 0.011\phi_2^{\ 2}$$
$$b_2 = -38.79 + 2.43\phi_2 - 0.034\phi_2^{\ 2}$$

It has been assumed that the formulae for 40 - 60° N may be employed at latitudes up to 80° N . This assumption does not have a significant impact on the climatologically derived ocean heat transport (see 4.3) as the surface area of the ocean at high latitudes is relatively small but a more accurate treatment, possibly based on the Lumb (1964) formula, needs to be taken in the next phase. The method by which Seckel and Beaudry obtained their clear sky expression is not clearly documented in the literature but we have chosen to use it primarily because Reed employed it in deriving his formula.

Gilman and Garrett (1994) have commented that the Reed formula has been used inappropriately under conditions of low cloud cover, in which case the estimate of the mean incoming shortwave can become greater than the clear-sky value if $\overline{\theta}_N$ is sufficiently large. We follow their suggestion that the incoming shortwave be constrained to be less than or equal to Q_c, while noting that the impact of this constraint is likely to be low given the typically high cloud cover in the North Atlantic. Gilman and Garrett also suggested that attenuation of shortwave radiation by aerosols may cause a significant reduction in the surface insolation but we have not attempted to include a treatment of this effect at this stage as the climatological distribution of aerosols over the Atlantic is not well known.

3.2.5. Longwave Flux

Bulk formula parameterisations of the net longwave flux have been developed by considering the difference in the upwelling blackbody radiation from the sea surface and the downwelling component from the atmosphere. The performance of a number of bulk formulae (Brunt (1932); Anderson (1952); Berliand (1960); Efimova (1961); Swinbank (1963); Clark et al. (1974); Bunker (1976); Hastenrath & Lamb (1978)) has been assessed against direct measurements by Katsaros (1990) and more recently by Bignami et al (1995). Katsaros considered just the downwelling radiation using open ocean measurements from the GATE, JASIN, STREX, FASINEX and Tropic Heat II experiments. She found a similar degree of accuracy from most of the formulae, the mean error in the daily averaged downwelling flux was less than 6 W/m^2 with the exception of the Berliand, Bunker and Efimova estimates for which it was about 10 W/m^2.

More recently, Bignami et al (1995) have used data from seven cruises in the Western Mediterranean over the period September 1989 to August 1992 to assess estimates of the net longwave flux (upwelling - downwelling) from the same set of bulk formulae. They find that all of the formulae (with the exception of that of Hastenrath & Lamb which is biased high by 36 W/m^2) underestimate the net longwave by 20 - 30 W/m^2. They suggest that the low bias is due to an overestimation of the amount of columnar water vapour in the atmosphere, resulting from the use of land-based bulk formula coefficients in a marine environment, and develop a corrected formula based on the Mediterranean observations which has a mean bias error of just 0.3 W/m ^{2}.

Of the earlier formulae, that of Clark. et al (1974) performs well in both the Katsaros and Bignami analyses and we have chosen to use it for our calculations. We have also examined the possibility that the results of Bignami et al are applicable to larger ocean basins and have used their formula to calculate parallel longwave estimates for each report. The two formulae are given below:

a.) Clark et al. (1974)

$$Q_L = \varepsilon\sigma_{SB}T_s^{\,4}(0.39 - 0.05e^{1/2})(1 - 0.69n^2) + 4\varepsilon\sigma_{SB}T_s^{\,3}(T_s - T_a)$$

b.) Bignami et al. (1995)

$$Q_L = \varepsilon\sigma_{SB}T_s^{\,4} - \sigma_{SB}T_a^{\,4}(0.653 + 0.00535e)(1 + 0.1762n^2)$$

where ε is the emittance of the sea surface, taken to be 0.98 ; σ_{SB}, the Stefan - Boltzmann constant, equal to 5.7 x 10^{-8} W m^{-2} K^{-4} ; e, the water vapour pressure; n, the fractional cloud cover and T_s and T_a are in degrees Kelvin.

(Note that the performance of the various longwave formulae is being assessed in an ongoing study using measurements from several cruises. Preliminary results from this study and a detailed review of the bulk parameterisations for the longwave may be found in Josey (1995c).)

4. CLIMATOLOGICAL FIELDS

In this section, climatological annual mean flux fields calculated from the individual flux estimates are presented. The filtering procedure used to remove outliers is described in 4.1 prior to a discussion of the fields in 4.2. A comparison of the climatologically implied ocean heat transport with direct hydrographic estimates is then given in 4.3.

4.1. Filter & Binning Procedure

Outliers have been removed from the set of fluxes prior to determining the mean fields using trimming flags that are included within Release 1a for the zonal and meridional wind speed, sea surface and air temperatures, humidity and sea level pressure. For Release 1a, a climatological analysis was used to determine smoothed medians and lower and upper median deviations (first and fifth sextile limits) for each month, variable and 2° x 2° box. A flag was then set for each of the basic variables in each report according to whether it lies within 2.8, 3.5 or 4.5 deviations (σ) from the median (Slutz et al.(1985) and 'stat' document - available from COADS internet site - for details). The 4.5 σ flag has been added to Release 1a (it was not present in earlier versions of COADS) in order to allow the effects of extreme climatic events to be included in derived mean fields and it is this flag that has been used to construct the filter in the current study. da Silva et al. (1994) had to make use of the more restrictive 3.5 σ flag in their study and imposed a stronger 2.8 σ constraint to reduce noise in climatologically ice covered regions. Our approach has been to use the 4.5 σ flag in order to retain as much information as possible. In subsequent analyses, the objective analysis scheme detailed in Josey (1995b) will be used to reduce noise in the raw fields.

The filter rules are summarised in Table 1 which shows the variables for which both the upper and lower deviation flags must lie within 4.5 σ in order for a given field to be accepted.

Field Name	Variables for Which 4.5 σ Flags Must Be Satisfied
T_s	T_s
T_a	T_a
T_{dew}	T_{dew}
P	P
u_o , u_N	u_z , u_m
u_{10} , u_* , τ, Q_H , 10/L	u_z , u_m, T_a , T_s
Q_E	u_z , u_m, T_a , T_s , T_{dew}
Q_L	T_a , T_s , T_{dew}

Table 1. 4.5 σ Flags That Must Be Satisfied For The Given Fields to be Accepted

Here, T_{dew} is the dewpoint temperature; P, the pressure; u_z, the zonal wind speed; u_m, the meridional wind speed; u_{10}, the wind speed at 10m; u_*, the friction velocity and L, the Monin - Obukhov length in metres.

In addition to these climatological filters, the cloud cover observation is not included in the calculation of the mean if it is set to 9 (the code for sky obscured or observation not possible).

Using the filter described above, $1^\circ \times 1^\circ$ mean fields for the basic variables and derived fluxes were calculated for each month in the period 1980 - 91 (excepting April 1980 and February, March and August 1985 which were excluded from the analysis due to a pstar processing problem that has now been rectified). The mean fluxes have been determined by the sampling method (i.e. averaging over individual flux values) as opposed to the classical method (calculating the mean fluxes from the monthly mean meteorological variables). The decision to use the sampling method was based on an earlier study (Josey et al., 1995) which showed that correlations between meteorological variables, particularly during the passage of mid-latitude storms, can lead to the classical mean latent heat flux being biased high by up to 15%. The individual monthly fields were then binned by month of the year and averaged over to produce climatological monthly means for the whole period. Finally, an average over the latter fields was taken to give the climatological annual mean fields presented in the next section.

The possibility of a diurnal bias in the number of reported observations (suggested by the analysis of the shortwave fields to be discussed in 4.2.2) has been investigated using data for January 1986 for the whole of the North Atlantic binned by the hour (reported as GMT) at which the report was made. The number of observations peaks at the reporting hours 0000,0600,1200 and 1800 hr, as expected, dropping to about 15% of the maxima at the mid-point of each 6-hour interval, and just 1-2% at other times. The total number of reports, together with the number of observations N(x), for several of the met variables and diagnosed fluxes in one hour intervals about the reporting hours are given in Table 2 (note that the number of sensible heat flux estimates, not tabulated, is the same as that for the latent heat flux).

Time	Total	N(u)	N(Ta)	N(Td)	$N(Q_S)$	$N(Q_L)$	$N(Q_E)$
0000	20175	19669	19754	11330	17439	8857	9423
0600	20356	19766	19863	11479	17566	8941	9563
1200	23012	22384	22334	12997	20751	10754	10944
1800	22394	21695	21617	12403	19840	10163	10451

Table 2. Total Number of Observations and Frequencies of Particular Fields in One Hour Intervals About Specified Times

A bias towards reporting at 1200 and 1800 is obvious, there being a reduction of 12 % in the total number of reports at 0000 relative to 1200. This pattern is also seen in the number of reported met variables and diagnosed fluxes. For the shortwave flux the reduction is 16 % and this will clearly lead to the monthly mean being an overestimate if it is calculated as a simple sampling mean from all available values with no correction for the diurnal bias. This can be avoided if the Reed (1977) formula is used. Diurnal variations in the other components of the heat flux are obviously not as dramatic as that in the shortwave but it may be necessary in subsequent analyses to correct these terms for the reporting bias, possibly by forming climatological six-hour mean fields which would then be combined to give the overall mean.

4.2. Climatological Annual Mean Fields

4.2.1. Meteorological Variables

Raw climatological annual mean fields for the reported meteorological variables are shown in Fig.1 and corresponding frequency distributions in Fig.2. Note that the fields have not been corrected for seasonal variations in the area sampled, hence at latitudes north of 60° N they are likely to become increasingly summer-biased. The main features of each field are discussed briefly below.

The dry bulb and sea surface temperature fields have a very similar spatial variation, with the difference between the two lying in the range 0-1.5° C over much of the basin. Notable exceptions to this are the Gulf Stream and Norwegian Sea, where the sea is up to 4° C warmer than the air, and the Grand Banks and upwelling regions off the coasts of West Africa and Venezuela, where it is up to 2° C cooler. The temperature distributions are bimodal and there is a sharp cut off above 30° C in each. The dewpoint temperature field has a broadly similar spatial variation to the dry bulb, although there is a noticeable region of dry air off the coast of North-West Africa. The pressure field exhibits the well-known Azores High - Iceland Low dipole structure. Wind fields obtained using both the old WMO 1100 and da Silva et al. (1994) scales for visual winds are shown in Figs. 1f-g and 2f-g. The latter field is somewhat stronger, although the difference between the two scales will have been moderated by the high proportion of anemometer winds. The annual mean cloud cover field shows that the fractional cloud cover is greater than 5/8 virtually everywhere north of 35° N and only drops below 3/8 in the Mediterranean and Red Seas and along narrow coastal strips. Hence, the Gilman and Garrett (1994) modification of the Reed shortwave formula under conditions of low cloud cover is unlikely to have a significant impact over much of the open ocean. Finally, note that the Inter-Tropical Convergence Zone is evident as a band of relatively high cloud cover at 5° N.

4.2.2. Air - Sea Fluxes

Climatological annual mean fields, in both raw and contoured format, together with histograms of the various air - sea fluxes are shown in Figs. 3 - 5. The sign convention followed is to treat the individual components of the heat flux as being positive according to the dominant transport direction i.e. the latent, sensible and longwave fluxes are positive for heat loss by the ocean to the atmosphere while the shortwave is positive for heat gain by the ocean. When formulating the net heat flux this inconsistency has been removed by subtracting the sum of the latent, sensible and longwave fluxes from the shortwave. Hence, the net heat flux is positive for a heat gain by the ocean and negative for a heat loss.

The latent heat flux field has the expected features : a band of strong heat loss of up to 230 W/m^2 over the Gulf Stream, a broader region of less intense heat loss, up to 140 W/m^2, under the Trade Wind belt and very weak heat loss or slight heat gain over the Grand Banks region. Comparison with the corresponding field reported by Isemer and Hasse (1987), which was adjusted to match oceanographic constraints, indicates that the new field typically has a heat loss of order 30 W/m^2 less than the adjusted values over most of the basin.

The main region of sensible heat flux loss is also over the Gulf Stream with peak values of 40 - 50 W/m^2, with a second region occurring over the Norwegian Sea (note that the field in this region is probably biased towards summer values). Heat loss in the latter area has been recognised as being due to very cold air being advected from the neighbouring continent Bunker (1976). In comparison, the adjusted Isemer and Hasse (1987) field is again higher over most of the basin, although the difference is now only of order 10 W/m^2.

The longwave field calculated using the recent Bignami et al (1995) bulk formula has 10 - 20 W/m^2 greater heat loss than that obtained with the Clark et al (1974) parameterisation over much of the North Atlantic. The Clark derived field is in best agreement with that found by Isemer and Hasse (1987) who made use of the formula of Efimova (1961) which, it should be noted, performed poorly in both the Katsaros (1990) and Bignami et al (1995) analyses of cruise data. Similar spatial features are observed in both fields, local maxima over the Gulf Stream, where the sea - air temperature difference peaks, and in a zonal band extending westward from the coast of NW Africa, where the air is relatively dry. A minimum is seen under the ITCZ where the downwelling component is increased due to the enhanced cloud cover. It is noticeable that the overall variation is relatively small, in the range 50 - 80 W/m^2 or 30 - 60 W/m^2 over much of the basin depending on the choice of formula.

The shortwave fields obtained with both the Dobson and Smith (1988) and Reed (1977) formulae are in fairly good agreement in the heavily sampled mid-latitude region. However, the Dobson & Smith field becomes increasingly noisy and biased high relative to the Reed field in the more poorly sampled tropics. The cause of the increase in noise is the diurnal variation in sampling frequency discussed in Section 4.1., which in a poorly sampled region leads to a bias of the mean towards high daytime estimates of the shortwave. Thus, it is clear that care needs to be taken when calculating sampling mean shortwave fields to allow for such diurnal variations. The field obtained with the Reed formula, which makes use of monthly mean cloud cover, is much smoother and is found to be in good agreement with that of Isemer and Hasse (1987), although this is not surprising as they made use of a slightly modified version of the formula. It is primarily zonal, with peak values in the range 220 - 240 W/m^2 between 10^o - 20^o N, dropping to 200 W/m^2 under the influence of the ITCZ just north of the equator. (A contoured version of the Dobson & Smith shortwave field has not been shown because the high level of noise obscures the contouring).

The wind stress field is shown for completeness but as the calculated values are scalar as opposed to vector averages it is a little misleading. Maxima under the main westerly wind belt between 45 - 65^o N and under the Trades between 10 - 20^o N are evident with the former region dominant. However, if vector averages are taken the strength of the two gyres should become more equal as found by Isemer and Hasse (1987).

The net heat flux has been calculated using the Reed shortwave fields with both the Bignami and the Clark longwave fields. For both fields the main area of heat loss is a band extending north-eastward from the Gulf Stream to the Norwegian Sea, with peak values of about 200 W/m^2. Over much of the mid-latitude ocean there is very little net heat transfer, while the main heat gain region is in the sub-tropics. The heat loss regions are noticeably broader and more intense if the Bignami formula for the longwave is used. The primary difference between the base climatology net heat flux fields and the adjusted field presented by Isemer and Hasse (1987) is that in the latter analysis the line of zero net heat flux lies further to the south (mainly because of the difference in the latent heat flux fields) and encompasses a significantly greater fraction of the ocean surface.

4.3. Zonal Mean Variation

The zonal mean variation of each of the air - sea heat fluxes has been calculated by averaging over 1^o strips, see Fig. 6. For the turbulent terms, the latent heat flux dominates over most of the North Atlantic, averaging between 100 and 120 W/m^2 from the equator to 40^o N. However, the sensible heat loss becomes more important towards higher latitudes as the latent heat flux declines and the Bowen ratio tends towards 1 at 80^o N. The roughly constant value of the zonal mean latent heat flux loss from 10 - 40^o N, reflects the fact that the broad region of secondary heat loss under the Trade Winds is as important in terms of overall heat transfer as the narrower region of primary heat loss over the Gulf Stream. The longwave flux estimates show little zonal variation north of 30° N although there is a slight reduction at lower latitudes. The difference between the Bignami et al and Clark et al values also decreases towards the equator. The zonal mean shortwave flux calculated with the Reed formula exhibits a smooth poleward decline with the exception of a local minimum due to the ITCZ at 5° N. A transition from net heat gain to loss between 33° and 35° N (depending on the longwave estimate used) is evident in the net heat flux curves. The net heat loss per 1° strip has also been calculated (this takes into account variations in basin width with latitude) and is shown in Fig. 7. The difference between the net heat flux calculated with the Bignami and Clark schemes is seen to be about 0.01 PW / 1° strip and this results in a strong divergence between the derived ocean heat transport obtained with the two formulae which is discussed in the next section.

4.4. Implied Ocean Heat Transport

The climatologically implied ocean heat transport as a function of latitude may be calculated by integrating the heat loss over successive zonal strips, provided the transport across a particular latitude is known and the assumption is made that there is no net heat storage in the ocean on the decadal timescale covered by the climatology. Aagaard and Greisman (1975) have suggested that the poleward heat transport across 80° N is 0.1 PW based on the results of a heat budget analysis for the Arctic Ocean and we take this value as a northern boundary condition for the heat transport calculation. Isemer and Hasse (1987) made use of the same constraint but applied it at 65° N, which was the northern limit of their climatology. However, their choice does not appear to be appropriate if one considers the details of the Aagaard and Greisman analysis.

The implied heat transport has been calculated using net heat flux estimates obtained with both the Bignami and Clark longwave formulae, it is shown in Fig. 8. Also shown are direct hydrographic estimates at 24° N (Bryden, 1993) and 60° N (Bacon, 1995) and the implied heat transport obtained by Isemer and Hasse (1987) before they adjusted it to match the oceanographic constraints. All three inferred heat transport curves are in fairly good agreement with the direct estimate at 60° N, with the Bignami based one perhaps slightly high. However, the Bignami and Clark curves diverge rapidly thereafter to the extent that the Clark based estimate reverses sign at 20° N and implies a southward heat transport of 0.8 PW across the equator. In contrast, the transport obtained with the Bignami formula is more reasonable, reaching a peak value of 0.92 PW at 32° N and then falling to 0.81 PW at 24° N which, however, is still 0.29 PW less than the lower limit on the hydrographic estimate. There are several possible reasons for the remaining difference:

i.) Errors in ship reports of the dew point temperature, may result in the latent heat flux being underestimated by up to 10 W/m^2 (Kent and Taylor, 1995) and this would integrate to an extra 0.2 PW of poleward heat transport at 24° N.

ii.) The direct estimate of the transport at 24° N is not representative of the annual average. Lamb and Bunker (1982) suggested that there is a significant seasonal variation in the heat transport in the North Atlantic based on a combined analysis of the surface heat loss fields and internal heat storage calculated from sounding data. Sections across 24° N have been taken on three separate occasions (in 1957, 1981 and 1992) but all were at a similar time of year, two in August and the other in October, so the derived heat transport from hydrography may not reflect the annual average if there are strong seasonal variations.

iii.) The direct estimate of the transport used as a boundary condition at 80° N may be too low. Again, seasonal variations may be important and the estimate at this latitude is based on a tenuous analysis of one-time data which is likely to have an uncertainty of at least 0.1 PW.

iv.) The estimates of the shortwave flux are too high. As noted earlier, Gilman and Garrett (1994) have suggested that aerosols may cause a significant reduction in the incident shortwave but no attempt has been made to correct for this in the current analysis.

v.) The turbulent heat flux transfer coefficients are too low. Significant upward revision of the experimentally determined values has been argued for in past analyses e.g. Oberhuber (1988) on the grounds of reporting error and fair weather bias but this can no longer be justified (Kent & Taylor, 1995).

vi.) The assumption of no net heat storage in the ocean on decadal timescales is not valid.

Further consideration of the above possibilities is required before a meaningful inverse analysis adjustment of the climatological fields using hydrographic estimates of the heat transport as constraints can be carried out.

5. CONCLUSIONS

A base set of climatological heat and momentum flux fields has been calculated for the North Atlantic as part of a pilot study for a global climatology. It should be stressed that the fields are the result of a preliminary analysis and that in the next phase of the study a repeat analysis will be carried out using recent additions to the dataset, a correction scheme for reporting errors on a ship by ship basis and a full objective analysis treatment (Josey, 1995b). The analysis will also be extended to the South Atlantic in order to allow additional recent hydrographic estimates (Saunders and King, 1995) to be employed in the assessment of the implied heat transport.

The base climatological fields are qualitatively reasonable. Comparison with the fields of Isemer and Hasse (1987), which have been adjusted to match oceanographic constraints, indicates that the net heat loss in the base climatology is too low by between 10 - 30 W/m^2 over most of the North Atlantic basin if the constraints are representative of the long-term mean ocean heat transport. The deficit arises mainly as a result of differences between the latent heat flux fields, the shortwave fields are in very good agreement. Our best value for the implied ocean heat transport at 24° N (calculated using the Bignami et al. (1995) formula for the longwave flux) is 0.29 PW less than the lower limit on the hydrographic estimate (Bryden, 1993). Possible reasons for this discrepancy have been discussed and at present it is not clear whether the problem lies in the calculation of the fluxes or inappropriate use of the hydrographic estimates as constraints. If the older formula of Clark et al (1974) is used, clearly unrealistic estimates for the heat transport are found and this highlights the need for an evaluation of the two formulae using cruise data taken over the open ocean.

A diurnal bias in the number of ship reports has been highlighted. The shortwave field calculated using the sampling method is found to be noisy and biased high in poorly sampled areas and it is suggested that this is due to the higher frequency of daytime reports. A correction for the bias (possibly by calculating six-hour means and then averaging) is necessary before a meaningful sampling mean shortwave flux can be determined. The problem may be avoided by using the Reed (1977) formula for the shortwave which makes use of monthly mean estimates of the cloud cover and the mean noon solar elevation. The effect of the diurnal bias in reporting frequency on sampling mean estimates of the other heat flux components may also need to be considered. Finally, note that the wind stress fields have only been briefly considered in the current study; vector averaged means will be calculated in the next phase and the potential use of derived quantities such as the Ekman transport for evaluating the climatology assessed.

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FIGURE CAPTIONS

Fig. 1. Raw $1^{\circ} \times 1^{\circ}$ Annual Mean Meteorological Fields.

a.) Dry bulb temperature ; b.) Sea surface temperature ; c.) Sea surface temperature - dry bulb temperature ; d.) Dewpoint temperature ; e.) Pressure ; f.) Wind speed (WMO 1100 visual wind scale) ; g.) Wind speed (da Silva(1994) visual wind scale) and h.) Cloud cover.

Fig. 2. Frequency Distributions of the Raw $1^{\circ} \times 1^{\circ}$ Annual Mean Meteorological Fields.

Fig. 3. Raw $1^{\circ} \times 1^{\circ}$ Annual Mean Air - Sea Flux Fields

a.) Latent heat flux ; b.) Sensible heat flux ; c.) Longwave flux - Bignami et al (1995) formula ; d.) Longwave flux - Clark et al (1974) formula ; e.) Shortwave flux - Dobson & Smith (1988) formula ; f.) Shortwave flux - Reed (1977) formula ; g.) Total turbulent heat flux (calculated with Bignami et al longwave ; h.) Total turbulent heat flux (calculated with Clark et al longwave and Reed shortwave) and i.) Wind stress.

Fig. 4. Contoured Annual Mean Air - Sea Flux Fields

a.) Latent heat flux ; b.) Sensible heat flux ; c.) Longwave flux - Bignami et al (1995) formula ; d.) Longwave flux - Clark et al (1974) formula ; e.) Shortwave flux - Reed (1977) formula ; f.) Total turbulent heat flux (calculated with Bignami et al longwave ; g.) Total turbulent heat flux (calculated with Clark et al longwave and Reed shortwave) and h.) Wind stress.

Fig. 5. Frequency Distributions of the Raw $1^{\circ} \times 1^{\circ}$ Annual Mean Air - Sea Flux Fields.

Fig. 6. Annual Zonal Mean Air - Sea Heat Fluxes

a.) Latent and sensible heat flux ; b.) Longwave flux ; c.) Shortwave flux - Reed ; d.) Net heat flux.

Fig. 7. Net Heat Flux per 1° Zone.

Fig. 8. Variation in Climatologically Implied Ocean Heat Transport with Latitude.

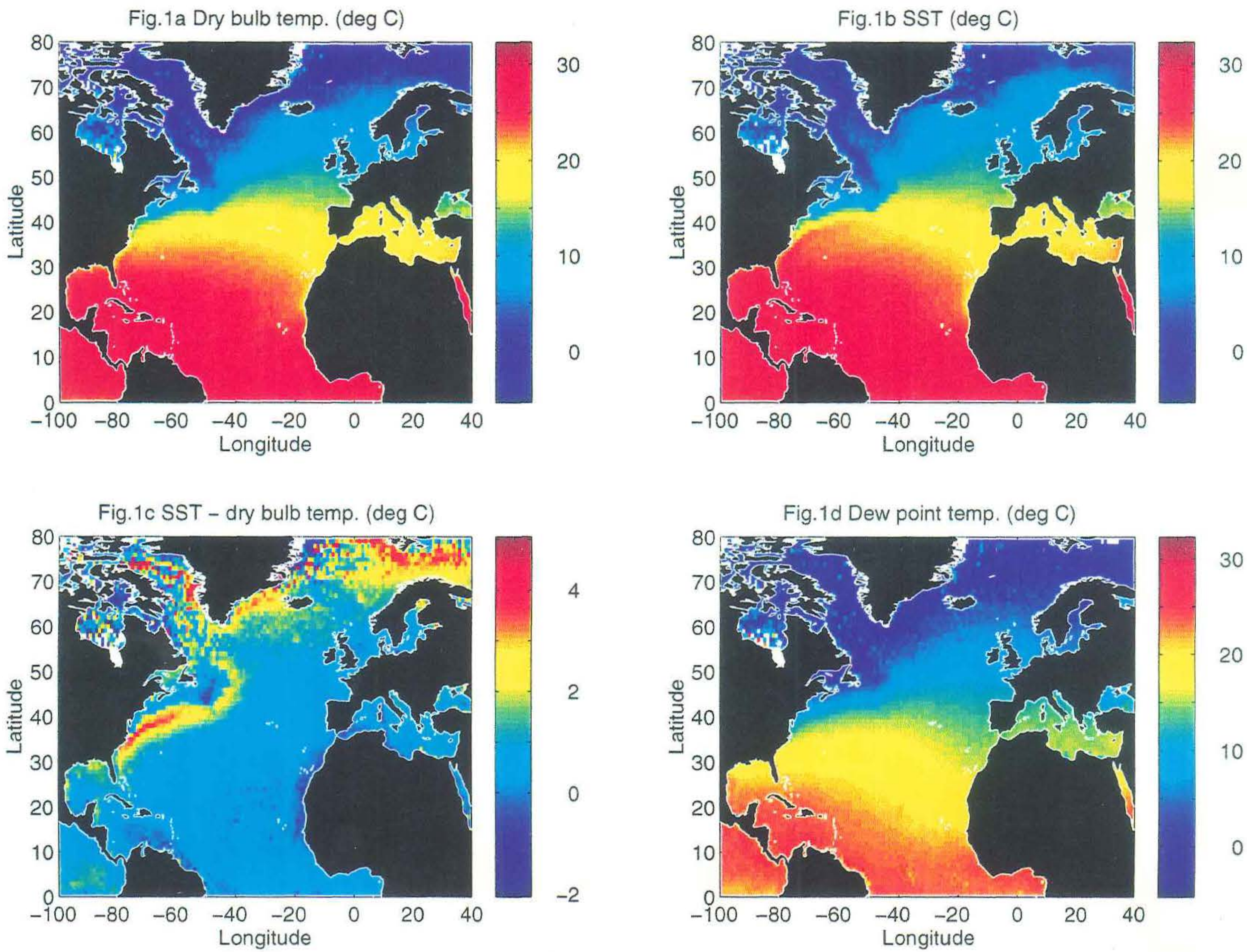


Fig.1a Dry bulb temp. (deg C)
Fig.1b SST (deg C)
Fig.1c SST – dry bulb temp. (deg C)
Fig.1d Dew point temp. (deg C)
Latitude
Longitude
80
70
60
50
40
30
20
10
0
-100 -80 -60 -40 -20 0 20 40
30
20
10
0
4
2
0
-2

Fig.1e Pressure(mb)

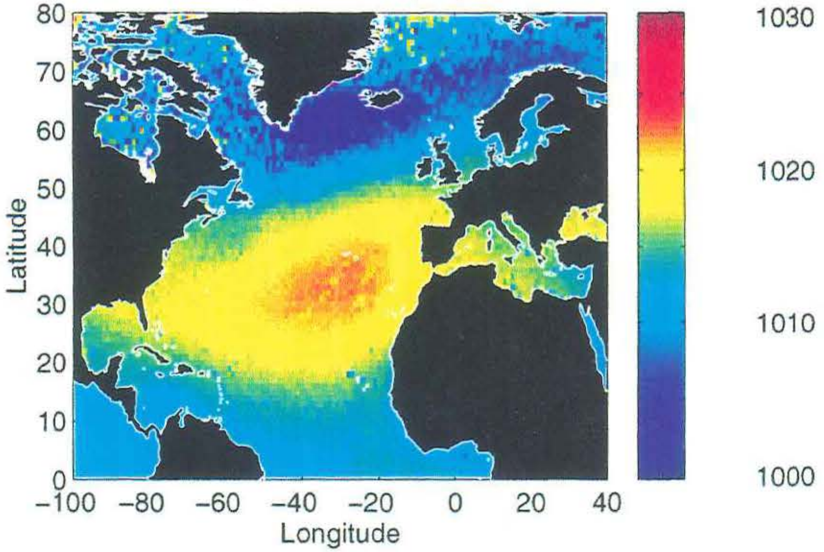


Fig.1f Wind speed WMO1100 (m/s)

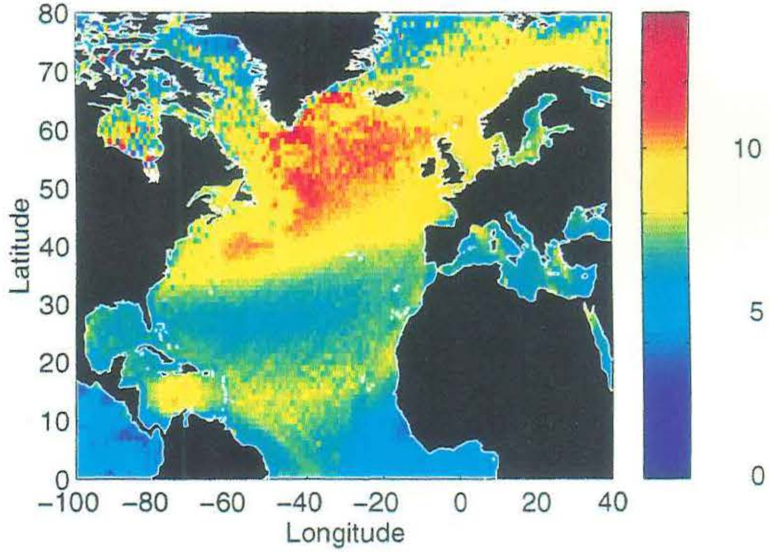


Fig.1g Wind speed UWM (m/s)

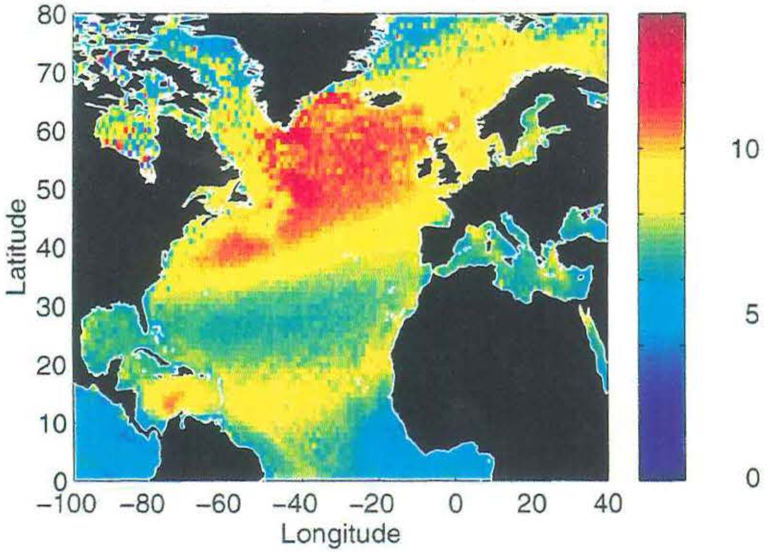
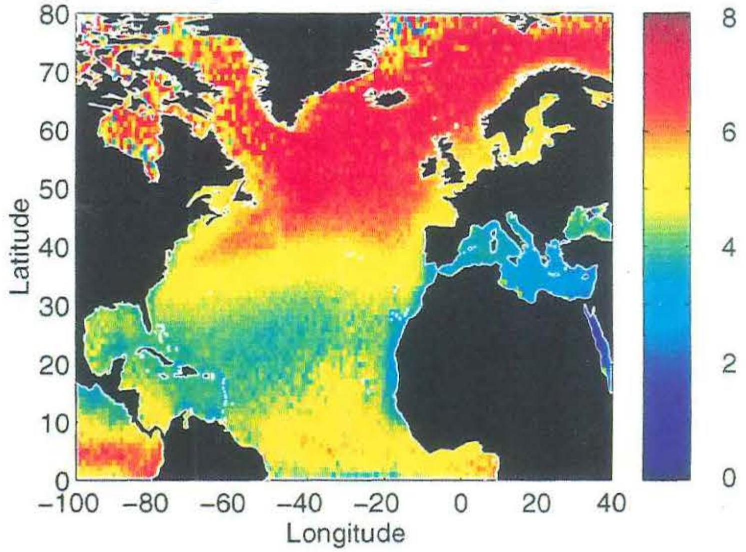


Fig.1h Cloud cover (octas)



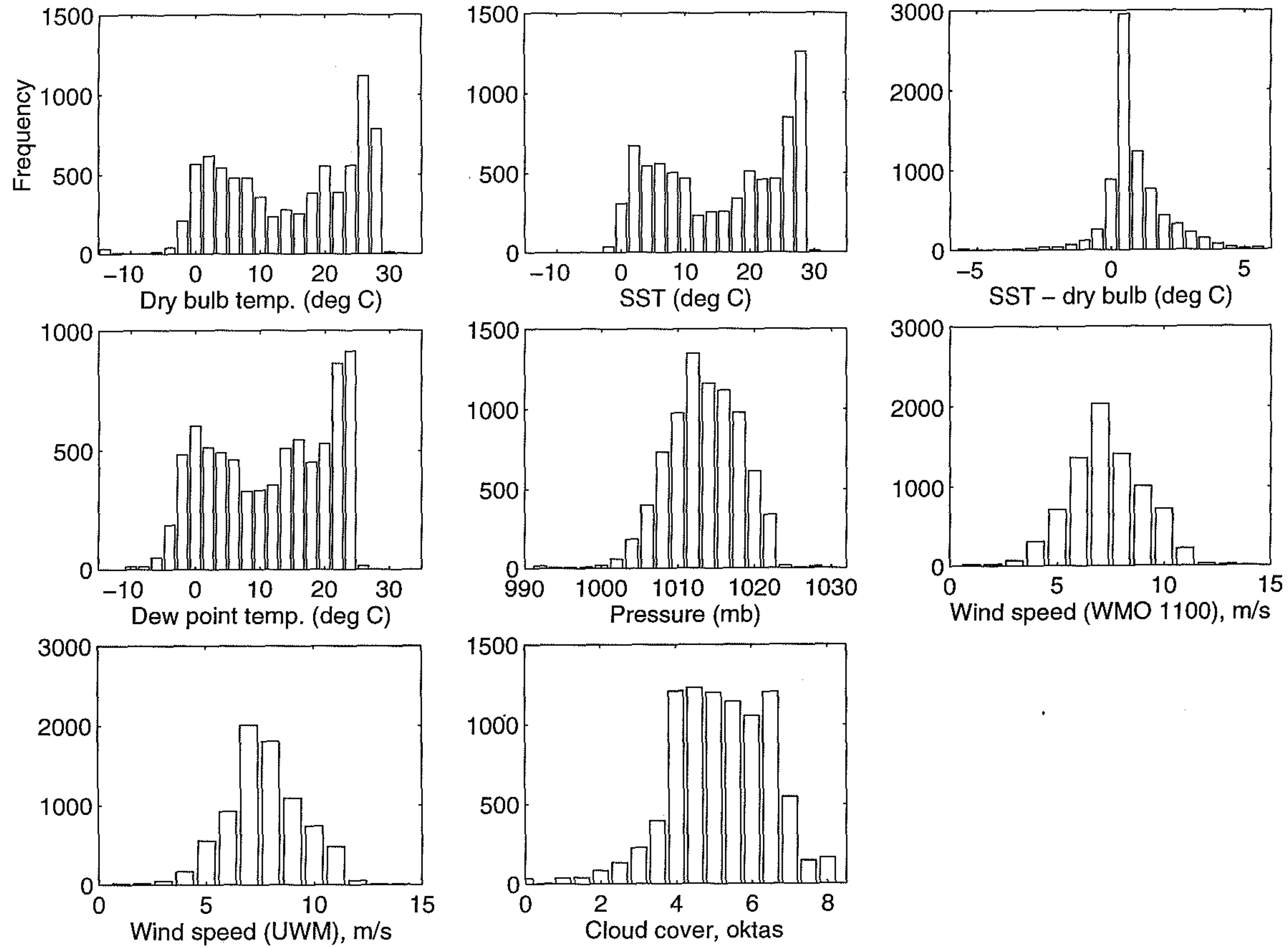


Fig.2 Frequency Distributions of the Raw 1 x 1 Degree Annual Mean Meteorological Fields

Fig.3a Latent heat flux (W/m**2)

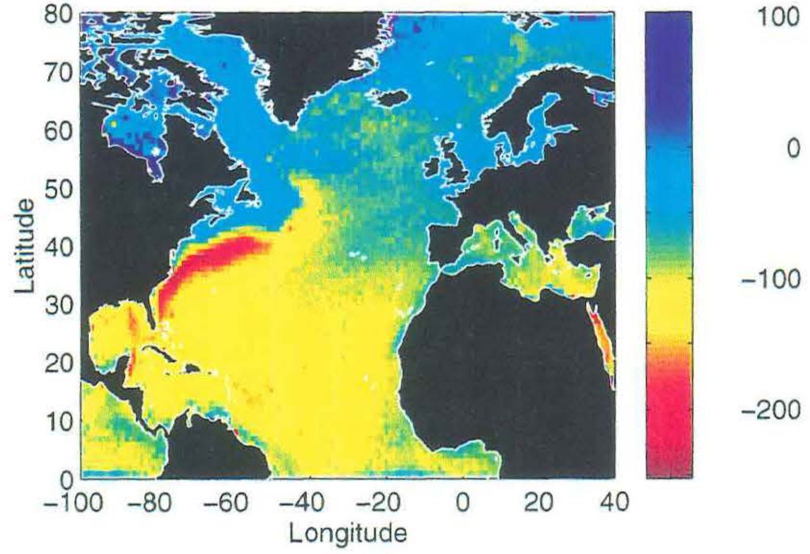


Fig.3b Sensible heat flux (W/m**2)

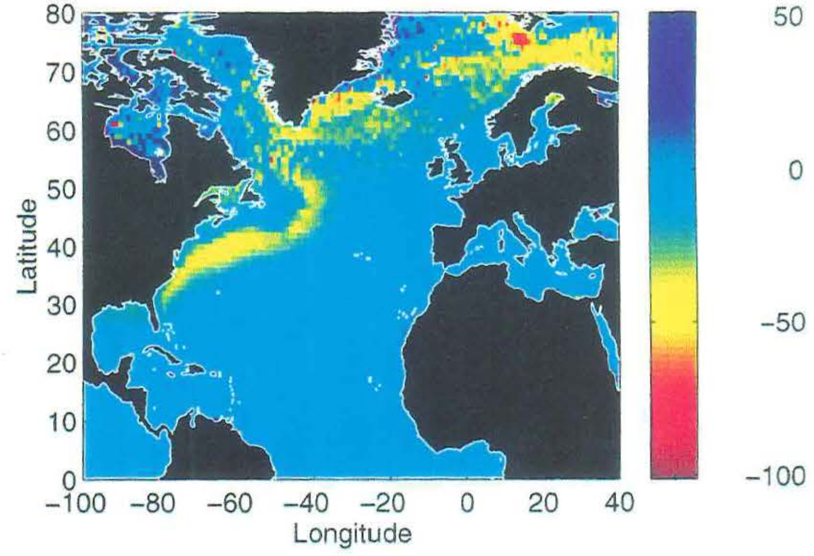


Fig.3c Longwave flux - Clark et al (W/m**2)

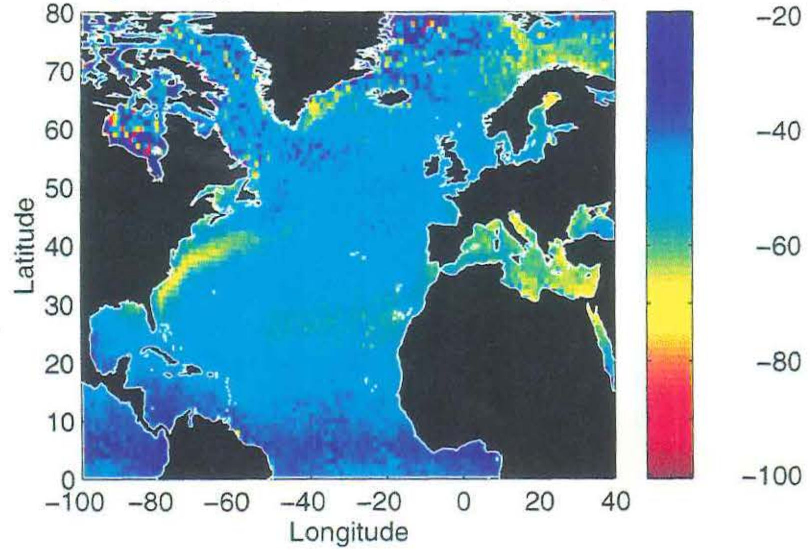


Fig.3d Longwave flux - Bignami et al (W/m**2)

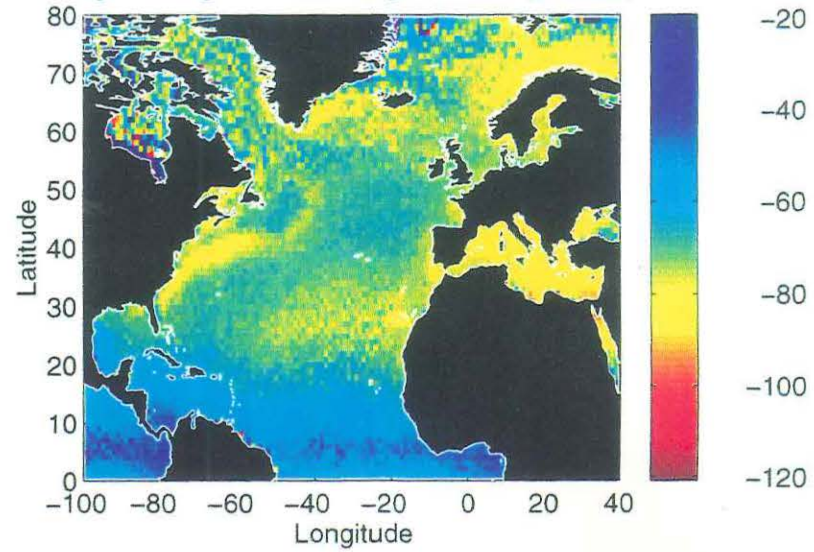


Fig.3e Shortwave flux -Dobson & Smith (W/m**2)

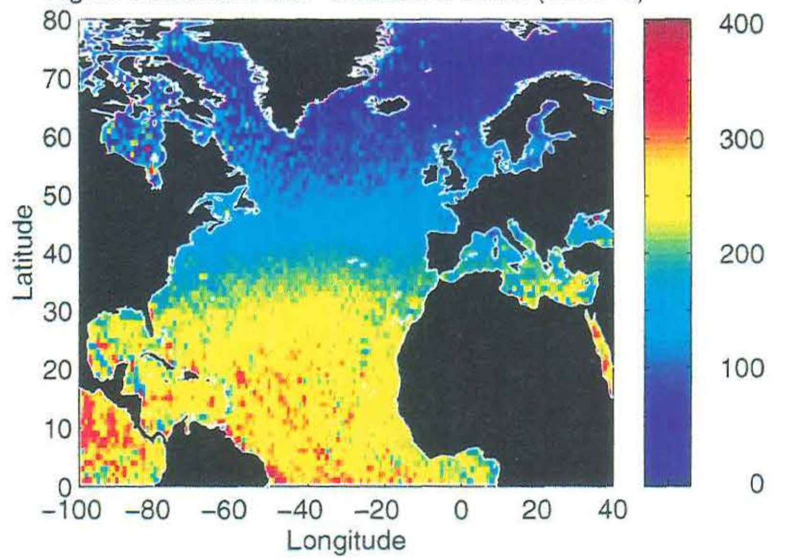


Fig.3f Shortwave flux - Reed (W/m**2)

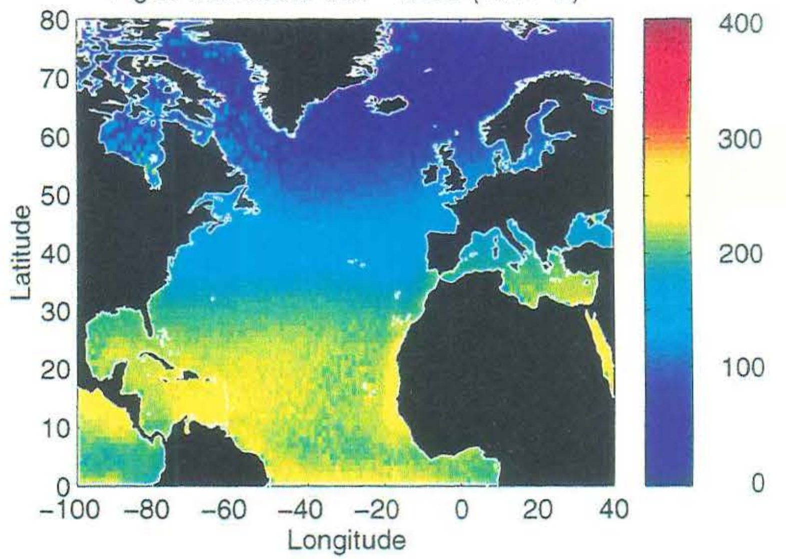


Fig.3g Net heat flux with Clark LW (W/m**2)

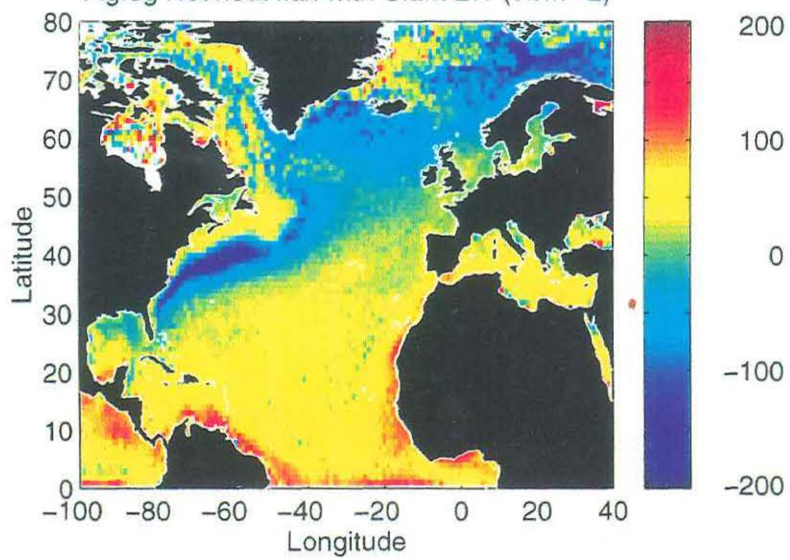


Fig.3h Net heat flux with Bignami LW (W/m**2)

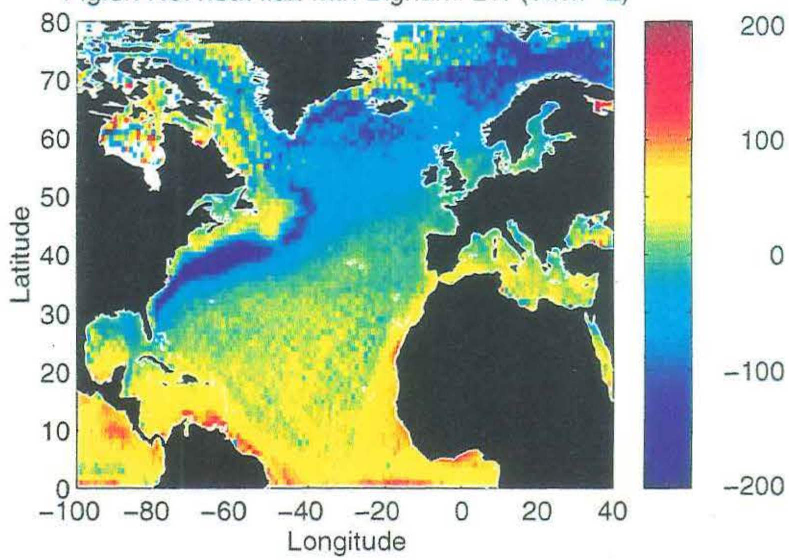


Fig.3i Wind Stress (N/m**2)

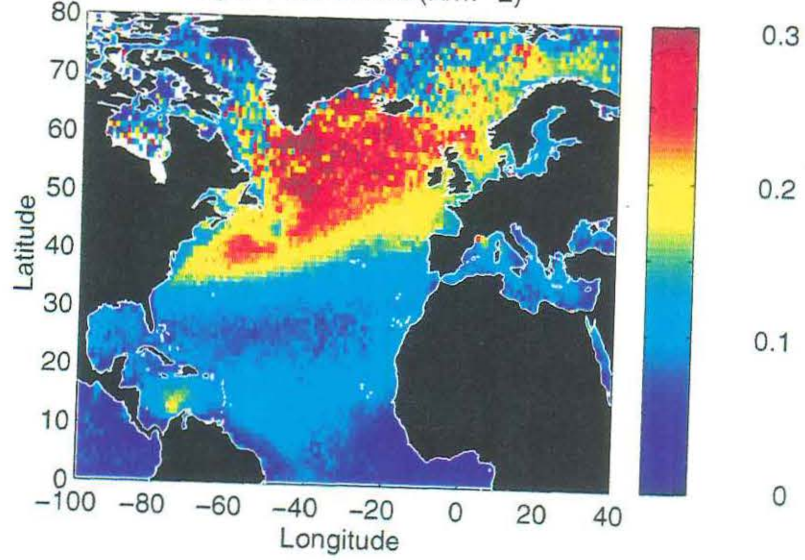


Fig.4a Latent heat flux (W/m**2)

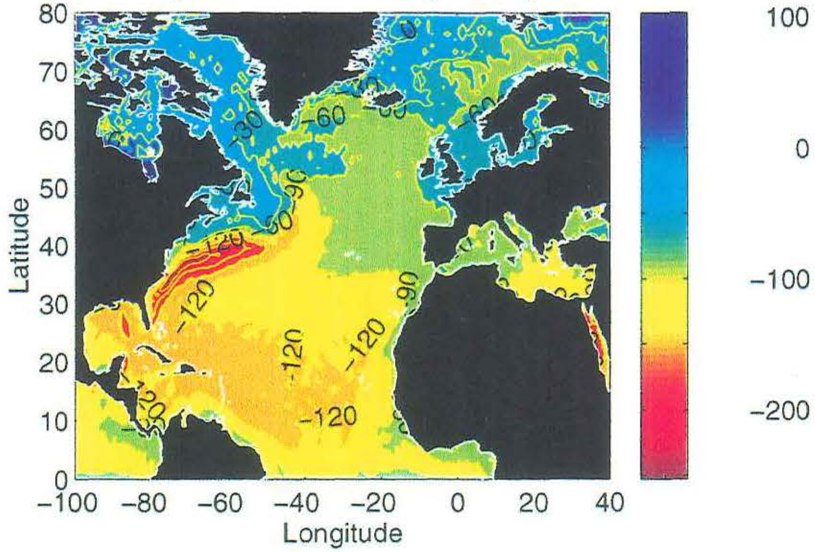


Fig.4b Sensible heat flux (W/m**2)

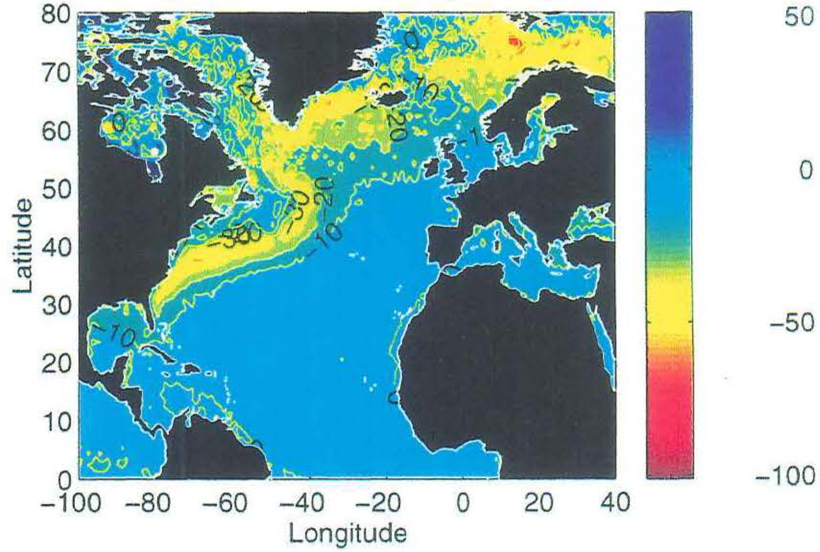


Fig.4c Longwave flux – Clark et al (W/m**2)

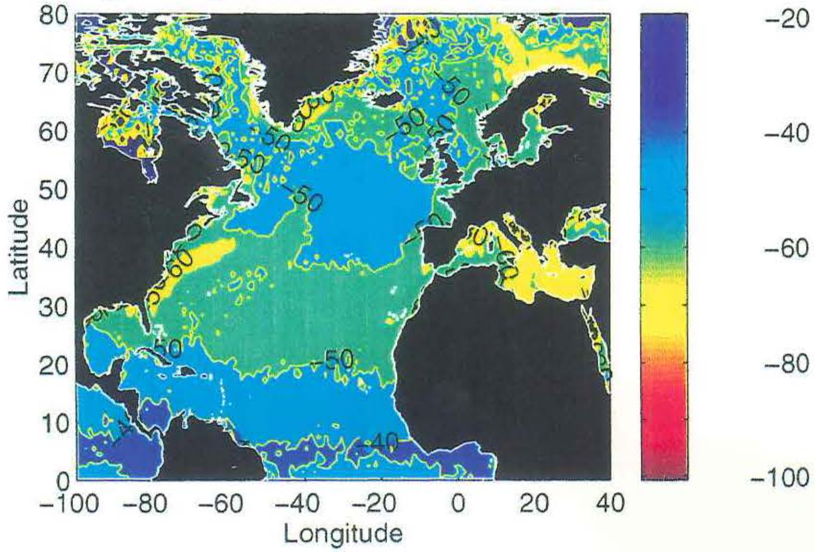
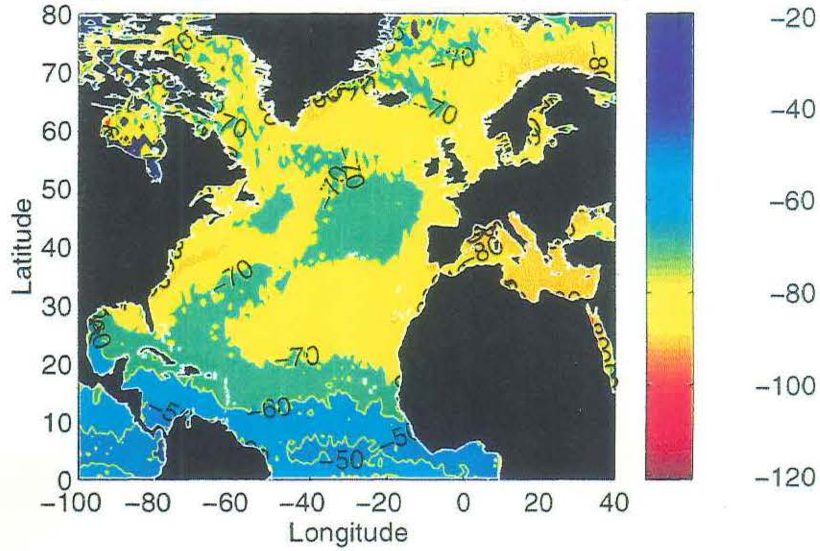


Fig.4d Longwave flux – Bignami et al (W/m**2)



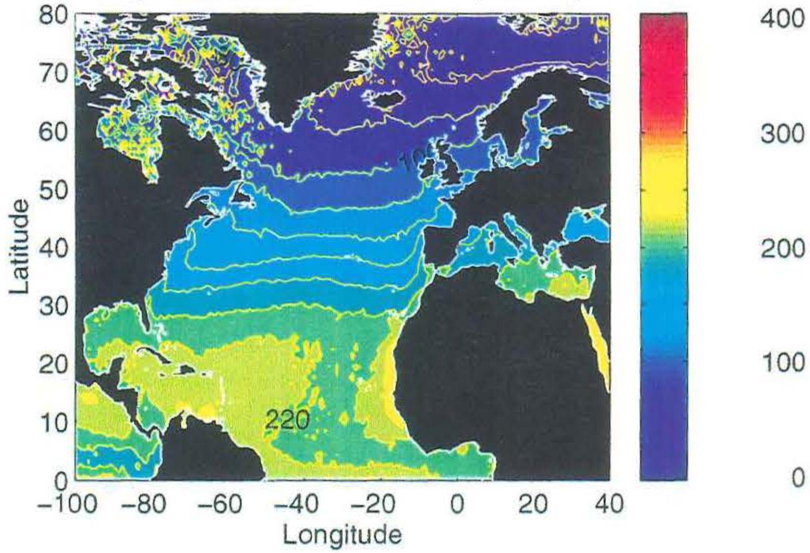


Fig.4e Shortwave flux – Reed (W/m**2)

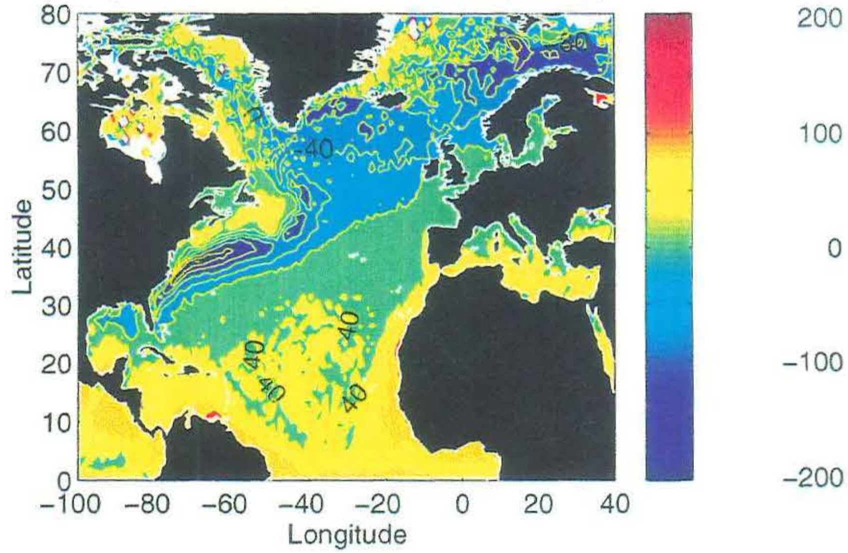


Fig.4f Net heat flux with Clark LW (W/m**2)

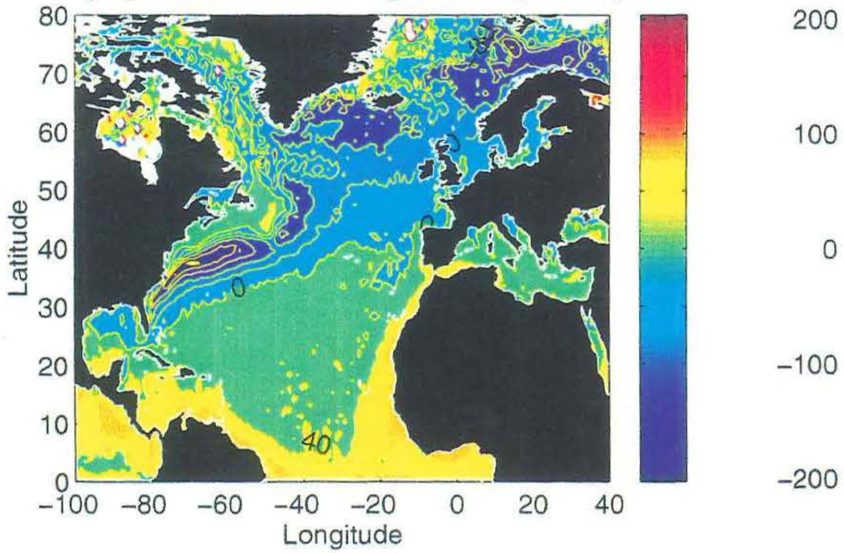


Fig.4g Net heat flux with Bignami LW (W/m**2)

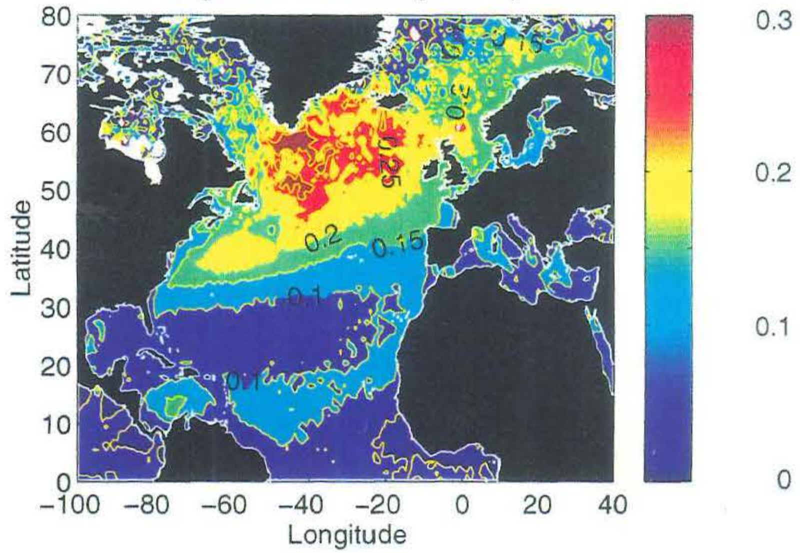


Fig.4h Wind Stress (N/m**2)

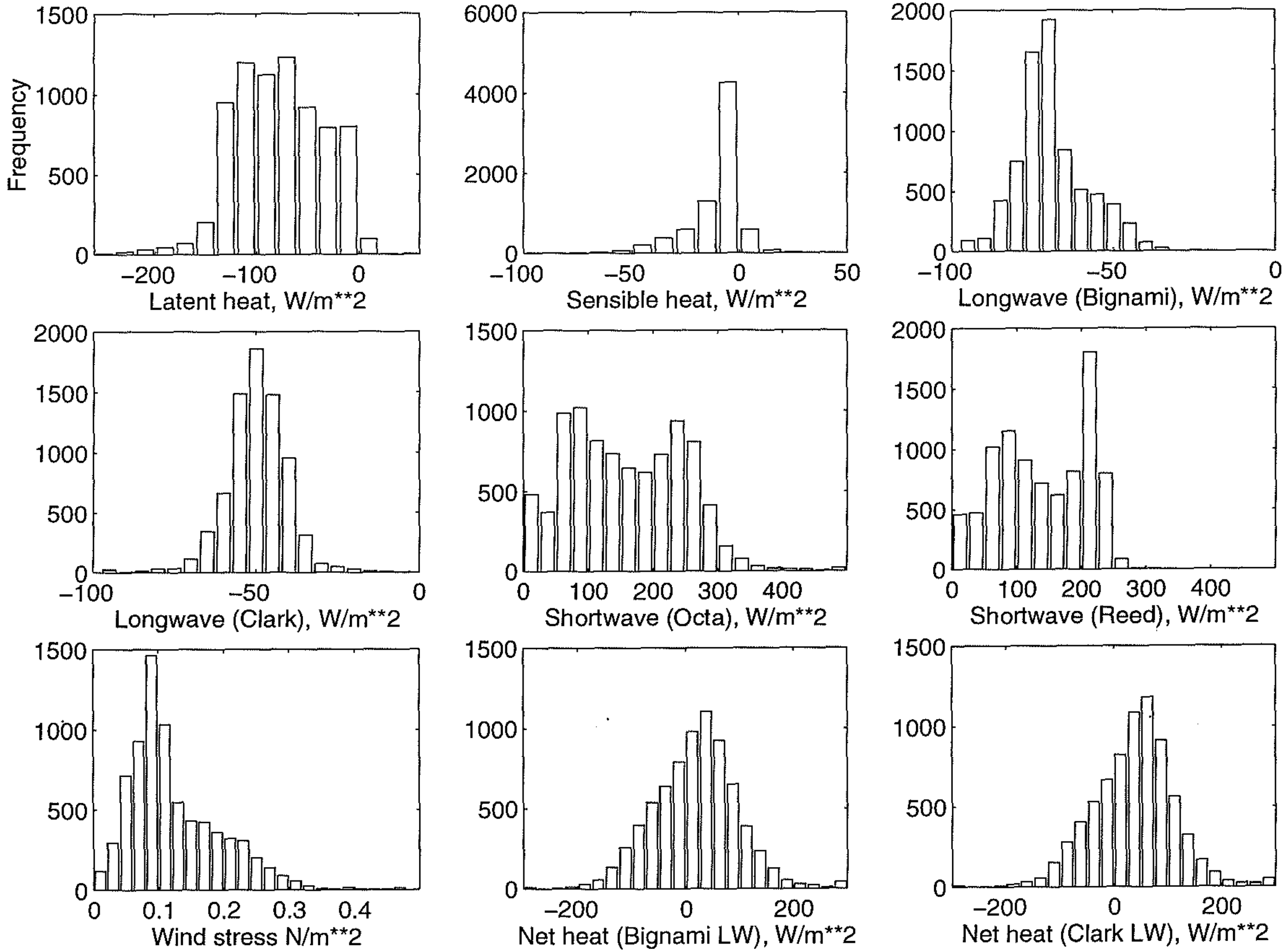


Fig.5 Frequency Distributions of the Raw 1 x 1 Degree Annual Mean Flux Fields

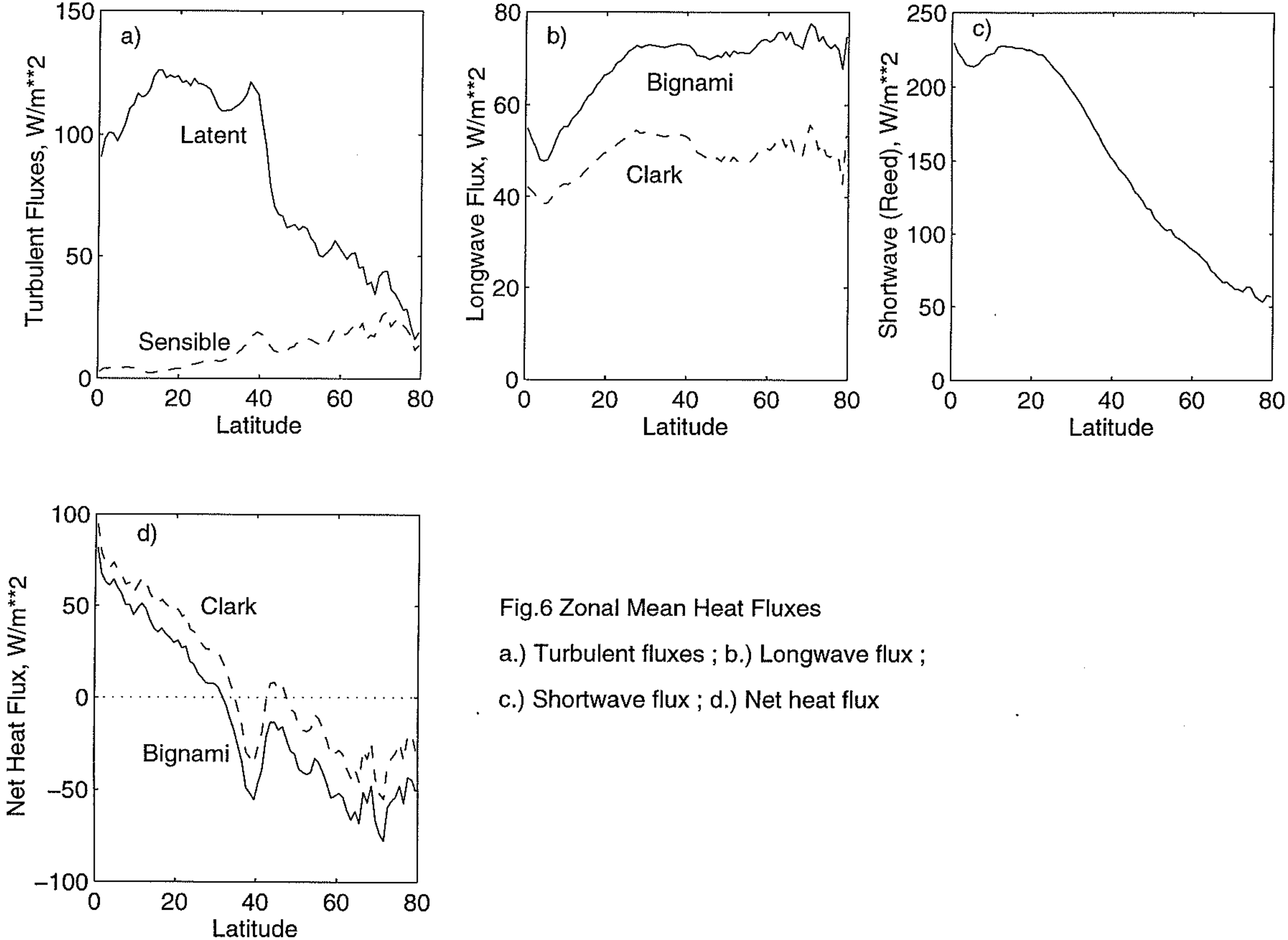


Fig.6 Zonal Mean Heat Fluxes

a.) Turbulent fluxes ; b.) Longwave flux ;

c.) Shortwave flux ; d.) Net heat flux

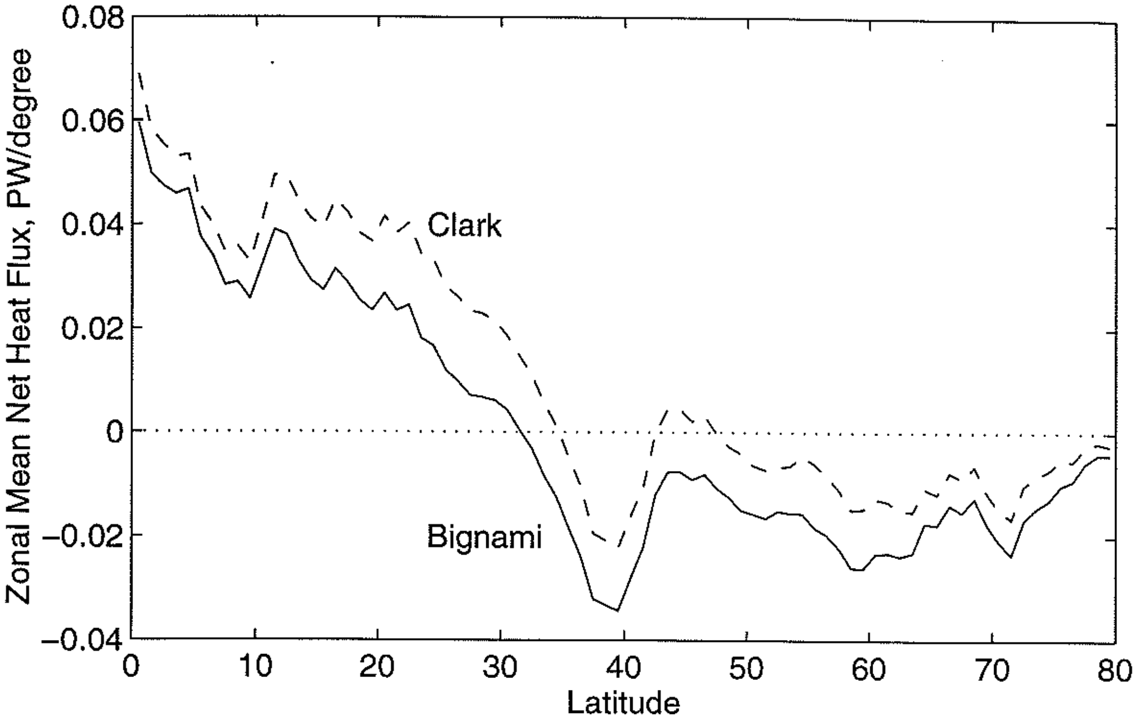


Fig.7 Zonal Mean Net Heat Flux (PW per one degree strip)

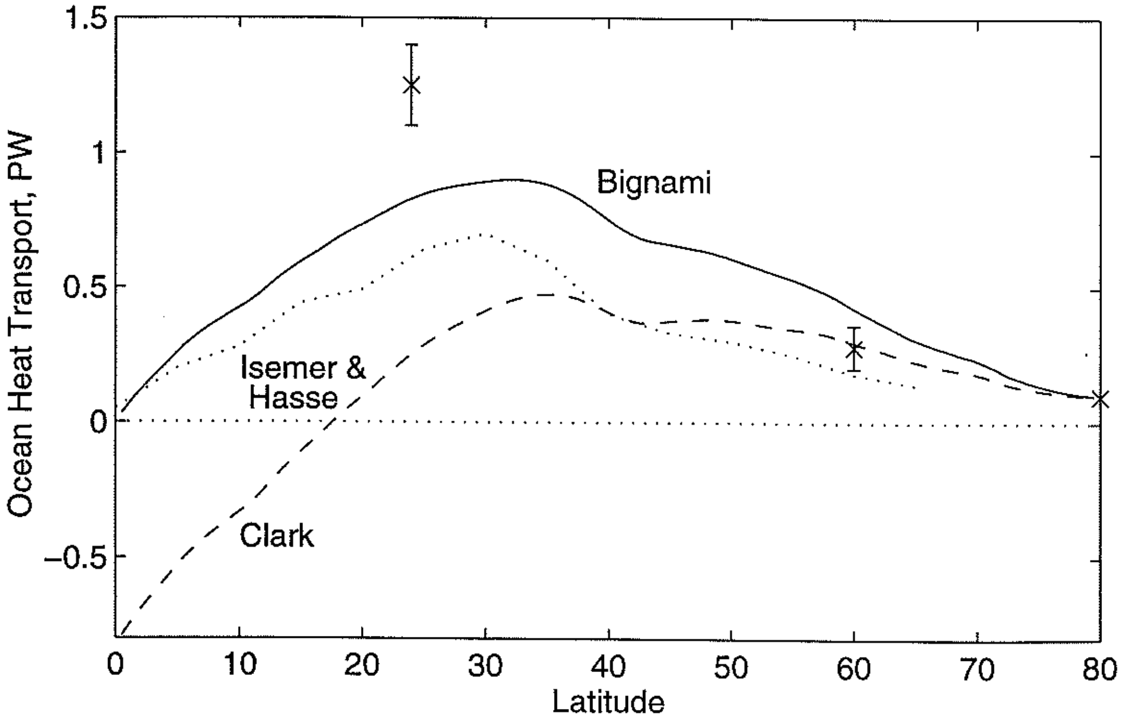


Fig.8 Implied Ocean Heat Transport (PW). Crosses represent hydrographic estimates as detailed in text.

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