

Comparison of Met Office air-sea heat fluxes with the SOC flux climatology.

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SUMMARY

We tested air-sea heat flux climatologies derived using fluxes from the Met Office's global Numerical Weather Prediction (NWP) model (named MO1 and MO2) and ones derived by Josey et al. (1998) and Grist & Josey (2003) (SOC98 and SOC03) by calculating global and Mediterranean heat budgets, and derived ocean heat transports.

The heat transports derived from MO2 and SOC03 were much closer to the observed values from oceanic sections. However, both MO1 and MO2 underestimated the northward *Atlantic* transport at 24°N by 0.6 PW, which suggested that the ocean heat losses were underestimated north of this latitude by 36 Wm⁻². This error could cause a cooling of the NWP model's troposphere by about 1.7K over a five-day forecast.

The northward *global* heat transports derived from MO1 (the fluxes used by the Met Office's Forecasting Ocean Assimilation Model) and SOC03 increased southward from 60°S to the coast of Antarctica, implying that MO1 and SOC03 overestimate ocean heat loss in this latitude band. In contrast, the transports derived from MO2 remained small near this coast. This implies that MO2 is more realistic in this area.

MO2 showed over 20 Wm⁻² more ocean latent heat loss, relative to SOC03, wherever, and whenever, tropical cyclones occurred. This suggests that there is a tropical fair-weather bias in SOC03.

1. INTRODUCTION

The exchange of heat between the ocean and the atmosphere (Q_H) can be written as:

$$Q_H = Q_{SW} + Q_{LW} + Q_{LA} + Q_{SE}$$

where Q_{SW} represents the downwards short-wave heat radiation from the sun, Q_{LW} is the air-sea heat exchange by long-wave radiation, and Q_{LA} and Q_{SE} are the latent and sensible heat fluxes. The latter two fluxes can be calculated from observed meteorological variables (for example: air and sea temperature, wind speed and humidity gradients) using the semi-empirical bulk-formulae (see Isemer et al., 1989), but the parameters in the formulae are uncertain.

The errors due to these uncertainties were estimated by Isemer et al. (1989) who calculated the northward Atlantic heat transport at each latitude implied by the annually-averaged ocean heat loss north of that latitude (using the fluxes of Bunker, 1976) and compared the transports with observed values derived from ship transect data at 0°N and 24°N and 32°N. They found that the transports implied by Bunker's fluxes were much lower than those observed, suggesting that Bunker's ocean heat losses in the north Atlantic were 30 Wm⁻² too low. They then produced new fluxes, using an inverse technique to adjust the uncertain parameters in the flux formulae so that the derived transports did agree, within error bars, with those observed.

Josey *et al.* (1998) and Grist and Josey (2003) showed that new climatologies are little better, unless, as in the latter, they are adjusted, using inverse techniques, to agree with transport observations. To put the problem in context, an error of 30 Wm⁻² implies that when the fluxes are used to drive an ocean or atmosphere model, after a five day period (eg: the Met Office weather forecast period) the temperature error for an ocean mixed layer 50m deep would be 0.06K, and for a troposphere 10km high with 50% relative humidity it would be 1.4K.

The Forecasting Ocean Assimilation Model (FOAM) and the ocean shelf model, which run daily at the Met Office, are driven by heat fluxes derived from the NWP (Numerical Weather Prediction) atmosphere model, and, when these are missing, by climatologies derived from these fluxes (eg: the MO1 and MO2 tested here). Since the flux uncertainties are so large, and can cause significant temperature errors, the original aim of this work, was to assess the climatologies we use to drive FOAM.

2. METHOD: The Climatologies.

MO1 (Met Office, 1997). This climatology was derived by monthly averaging six-hourly fluxes from the Met Office's global numerical weather prediction (NWP) model between June 1995 and June 1996. It has the disadvantage that it covered only one annual cycle. MO1 is used by FOAM when NWP fluxes are unavailable.

MO2 (Met Office, 2001). The new FOAM flux climatology was derived in the same way as MO1, using Met Office fluxes archived from the daily operational runs between May 1997 and June 2001 (the fluxes between the 28th March and 20th April 1999 were excluded because they contained large errors caused by the introduction of the 3D-VAR assimilation scheme into the NWP model). This climatology has two

advantages over MO1. First: it is a four year average, instead of a one year average, and second: in November 1996 the NWP model began to assimilate GLOSS (Global Sounding System) humidities in clear air. These humidities are derived from satellite radiance data, and, as we show later, the GLOSS data may have had a small positive effect on the fluxes, similar to the effect found by ECMWF (European Centre for Medium Range Forecasting) when they began to assimilate GLOSS humidities (see McNally & Vesperinni, 1996).

SOC98 (SOC, 1998) This climatology was derived at SOC (see Josey et al., 1998) from COADS-1a data, which included oceanographic & meteorological data from 1980 to 1993. The data (eg; humidity or sea surface temperature) were corrected for biases using information about measuring procedures from the WMO047 list of ships.

SOC03 (SOC, 2003) This climatology was derived from SOC98 using an inverse technique to adjust the sizes of the four heat flux components so that the implied ocean heat transports agreed, within reasonable error margins, with ten observed heat transport estimates (see Grist & Josey, 2003). The changes to the flux components of SOC98 were as follows: shortwave -6% , longwave $+9\%$, latent $+19\%$ and sensible $+7\%$ (a $-ve$ sign indicates a reduction). These changes were applied globally.

3. RESULTS: Comparison of NWP and SOC fluxes.

Global maps.

Figure 1a and 1b show the annual average shortwave heat fluxes from MO1 and MO2 minus those from SOC03. In the MO1 fluxes there was a 75 W m^{-2} over-estimate (relative to SOC03) of the short-wave flux west of Angola and Peru. These are both areas with much low level cloud which was poorly forecast by the atmosphere model before the use of GLOSS data (pers.comm, S.English) because low cloud is hard to distinguish, by temperature, from the surface. These large differences are lower in MO2 (after use of GLOSS). See the comparison between MO2 and SOC03 (Fig. 1b).

Although small scale differences from climatology are reduced (see above) in MO2, large scale differences have increased. In MO2 the short-wave heating at midlatitudes has increased by about 25 W m^{-2} , because the assimilation of GLOSS humidities has dried out these areas in the model. A similar result was found by McNally & Vesperinni (1996) who assimilated GLOSS data in the ECMWF atmosphere model.

Figure 2 is similar to Fig. 1, but shows the longwave heat flux. MO2 shows 20 W m^{-2} more ocean heat loss than MO1 especially in the mid-latitudes. This is again, due to the assimilation of GLOSS humidities. The mid-latitudes have become drier, therefore longwave back radiation has decreased, and the resulting ocean heat loss is greater. Again, the large local differences near Peru and Angola are absent with MO2.

The differences between the MO1 and MO2 latent and sensible fluxes were small.

Heat budgets.

Over an annual cycle the ocean heat budget should close, as interannual variability is small relative to seasonal changes. Therefore the annual average of the air-sea heat

fluxes over the whole ocean, should be close to zero. Also, it is known that the equivalent of 5 Wm^{-2} (McDonald et al., 1994) of heat enters the Mediterranean through the Straits of Gibraltar, and that this basin is otherwise closed, so the Mediterranean must lose 5 Wm^{-2} of heat through its surface annually. The annual average heat flux for the four climatologies, globally and for the Mediterranean, are shown in Table 1:

Heat budget area:	Observed	SOC98	SOC03	MO1	MO2
Global ocean	0+/-2	30	-3	-10	+1
Mediterranean Sea	-5	41	+7	+2	-3

For the global ocean heat budget SOC98 and MO1 were further from closure than SOC03 and MO2. The improvement from MO1 to MO2 may be due to GLOSS data, but could also be due to the larger number of annual cycles in MO2, or the possibility that 1996-1997 was a period of cooling, whereas 1997-2001 was a period of stasis.

For the Mediterranean heat budget the MO1 & MO2 fluxes out-performed the SOC ones, although it should be stressed that a separate Mediterranean climatology, which has not been assessed here, is available from SOC.

The most certain conclusion from Table 1 is that the new SOC03 fluxes are 34 Wm^{-2} better than the SOC98 fluxes in the Mediterranean. This is a objective test of SOC03 because the Mediterranean heat budget was not used as a constraint in deriving them.

Atlantic heat transports.

Figure 3a shows the north Atlantic northward heat transport (in PW) versus latitude as inferred from the climatologies. The long dashed line shows the transport from Isemer et al. (1989) (IWH). The dotted lines are SOC98 (light) & SOC03 (heavy). The grey line is MO1 (light) and the solid black line is MO2. The observed heat transports at 0°N , 10°N , 24°N and 32°N are shown by the squares with error bars.

None of the climatologies produced enough northward heat transport. The IWH fluxes were closest to the observed transports, but they were adjusted to agree with them, so this was not surprising. The SOC03 fluxes were also close, but they were also adjusted to agree with the transport estimates (in this case worldwide).

The transports derived from MO1 and MO2 were further from the observed transports than IWH and SOC03, but they had not had the advantage of being adjusted to agree with the observations. The MO2 fluxes underestimated the transport at 24°N by 0.6 PW, implying that ocean heat losses north of 24°N were underestimated by 36 Wm^{-2} . This error would cause a warming of the ocean by 0.07K over a five day forecast period (assuming a mixed layer 50m depth) or a cooling of the troposphere by 1.7K over five days (assuming it is 10km high and has 50% relative humidity). The difference between the MO1 and MO2 transports are not significant, given the errors.

The SOC98 fluxes under-estimated the heat transport at the equator by 1 PW, and at 32°N by 0.6 PW which implies that they under-estimate the ocean's heat loss by 69 Wm^{-2} over the central north Atlantic (this was noted by Grist and Josey, 2003). One

explanation for this discrepancy was that of a *mid-latitude* fair-weather bias in the SOC98 fluxes (since ships tend to avoid storms). Figure 3a does not support this conclusion, because the MO1 and MO2 fluxes, which should represent, if not resolve, these storms are further from the observed transports than SOC98 in mid-latitudes.

Global heat transports

Figure 3b shows the *global* northwards heat transport from each climatology. The observed transports are shown by the squares. At 32°S there is a transport observation that was not used to constrain the SOC03 fluxes, and therefore can be used to test the fluxes objectively. MO1, MO2 and SOC03 all agreed, within error bars, with this observation, whereas SOC98 did not.

The transports derived from SOC03 and MO1 increased southward to Antarctica at 70°S, whereas the transport from MO2 became small approaching this coast. This implies that MO2 is more realistic because its global ocean heat budget closed (see, eg: Foreman *et al.*, 1994) and because the normal transport should decrease as we approach the boundary layer near a coast. This ‘coastal’ test could be used as an additional constraint in the inverse techniques used to adjust the SOC03 fluxes.

This ‘coastal’ test could be used to test fluxes more locally. The air-sea fluxes could be integrated, starting from a transport value from an oceanic section parallel to a coast (eg: the global section at 32°S) and the derived northward transport could then be expected (and could be constrained) to approach zero at that coast (eg: Antarctica).

The Met Office’s FOAM (Forecasting Ocean Assimilation Model) still uses the MO1 fluxes. Fig. 3b shows that south of 60°S the ocean heat losses from MO1 are too large and the model’s ocean could therefore be expected to be too cold.

4. DISCUSSION

Comparison of annual average latent heat fluxes.

Figures 4 and 5 show the differences between the annual average latent heat flux of MO2 & SOC98 (Fig. 4) and MO2 & SOC03 (Fig. 5). Figure 5 shows that SOC03 is closer to MO2 than SOC98. In both cases MO2 shows up to 50 Wm⁻² extra heat loss than SOC in areas with tropical cyclones: the shaded areas with arrows in Figure 7 (from: Ocean Circulation by the Open University, 1989). The only exception is the large ocean heat loss in MO2 in the south Atlantic, an area with few cyclones (for completeness, Figure 6 shows the differences for the total heat flux).

If the differences are due to tropical cyclones, they should peak in late summer, when cyclones occur most frequently. Figure 8 shows the seasonal cycle of the latent heat fluxes from SOC03 (long dashed line) and MO2 (short dashed line) averaged within 5-degrees of the position of the FASINEX buoy array at 70°W, 27°N, which is an area prone to cyclones. Their difference is shown by the solid line. The MO2 fluxes show an extra heat loss that increases through the summer and peaks at an extra 50 Wm⁻² in October. Since tropical cyclone activity also increases through the summer and peaks in October, this suggests that tropical cyclones in MO2 are responsible for most of its extra ocean heat loss relative to SOC03. This difference could be caused by 1) a fair-

weather bias in SOC03, which is based on hurricane-avoiding-ships' data, or 2) the period of MO2 (97-01) being more hurricane-prone than the period of SOC03.

Hypothesis 1: Tropical fair-weather bias in SOC03?

The fair-weather bias was first suggested to account for underestimates of latent heat loss in the Mediterranean by Bunker *et al.* (1982). The idea, in our case, is that MO2 includes the large ocean latent heat losses caused by tropical cyclones which do appear in the Met Office's NWP model, but the SOC climatology does not, since it is based on ship data, and modern ships are routinely re-routed to avoid hurricanes.

Table 2 lists the hurricanes or tropical storms that passed the FASINEX site during the four years covered by MO2 (May 1997 to June 2001) (Unisys web site, 2003).

Hurricane	Date	Wind speed (mph)
Alex	July 1998	45
Floyd	September 1999	135
Subtropical storm	October 2000	55

If there is a fair weather bias in SOC03, then these storms made the difference between MO2 (which included them) and SOC03 which may not have. The fair-weather bias was criticised by Quayle (1980) who suggested that the increased number of data points from the reduced speed of ships in bad weather would compensate for the fair-weather bias. Also observations of the wind speed at weather ship Lima (at 57°N, 20°W) in the northern northeast Atlantic have been shown to have no such bias (Kent & Taylor, 1995). Our heat transport results (above) also indicate no bias in the northern north Atlantic, since MO2 under-estimates the northward heat transport just as much as SOC03. However, a tropical fair-weather bias is possible.

Hypothesis 2: Difference in sampling periods.

Another reason that MO2 shows more ocean heat loss in cyclone-prone areas could be that between 1980 and 1993 (the period covered by the data used in SOC03) the annual average number of tropical storms and hurricanes in the North Atlantic was 9.3 (Landsea, 1999), whereas between 1997 and 2001 (the period of MO2) this average was 26% higher, at 11.75 (Met Office data, 2003). In SOC03 the October ocean latent heat loss was 160 Wm^{-2} . An increase of 26% would produce 201 Wm^{-2} , an increase of 41 Wm^{-2} , which is similar to the observed difference of 50 Wm^{-2} (Fig. 8).

However, in other regions of the world, the period from 1997 to 2001 had fewer than average tropical cycones (concluded using Met Office data (2003) on various regions' cyclone frequency from 1988 to 2003). These regions were the southwest Indian, and the northwest and northeast Pacific. In these areas the MO2 ocean latent heat losses are still greater than those of SOC03. Hence we favour the tropical fair-weather bias.

5. CONCLUSIONS.

We tested two Met Office (MO1 and MO2) and two SOC (SOC98 and SOC03) flux climatologies. The implied global heat transport from the newer climatologies (MO2 and SOC03) agreed more closely with the observed transport at 30°S. The global and Mediterranean heat budgets of the newer climatologies also closed more successfully.

The northward global zonally averaged transports from MO1 and SOC03 increased from 60°S to the coast of Antarctica (70°S), whereas the transport from MO2 was small. This implied that, in this latitude zone, the ocean heat losses in MO1 (the fluxes used to drive FOAM), and SOC03 are too large, whereas MO2 is more realistic.

Both MO1 and MO2 underestimated the northward *Atlantic* heat transport at 24°N by 0.6 PW, suggesting that the Met Office fluxes underestimate ocean heat loss north of 24°N by 36 Wm⁻². This error could cause a warming of the modelled ocean by 0.07K over the 5 day forecast (assuming a mixed layer 50m depth) or a cooling of the troposphere by 1.7K over 5 days (assuming 10km height, and 50% relative humidity).

The distribution of the differences between MO2 and SOC03 in the latent flux, in space (compare Figs. 5 and 7) and time (Figure 8a), suggests that most of the difference is due to the greater ocean heat loss during tropical cyclones in the MO2 climatology. We suggest this is due to a tropical cyclone fair-weather bias in SOC03. This suggests that instead of adjusting the SOC latent fluxes globally, as Grist and Josey (2003), they could be increased only where, and when, tropical cyclones occur.

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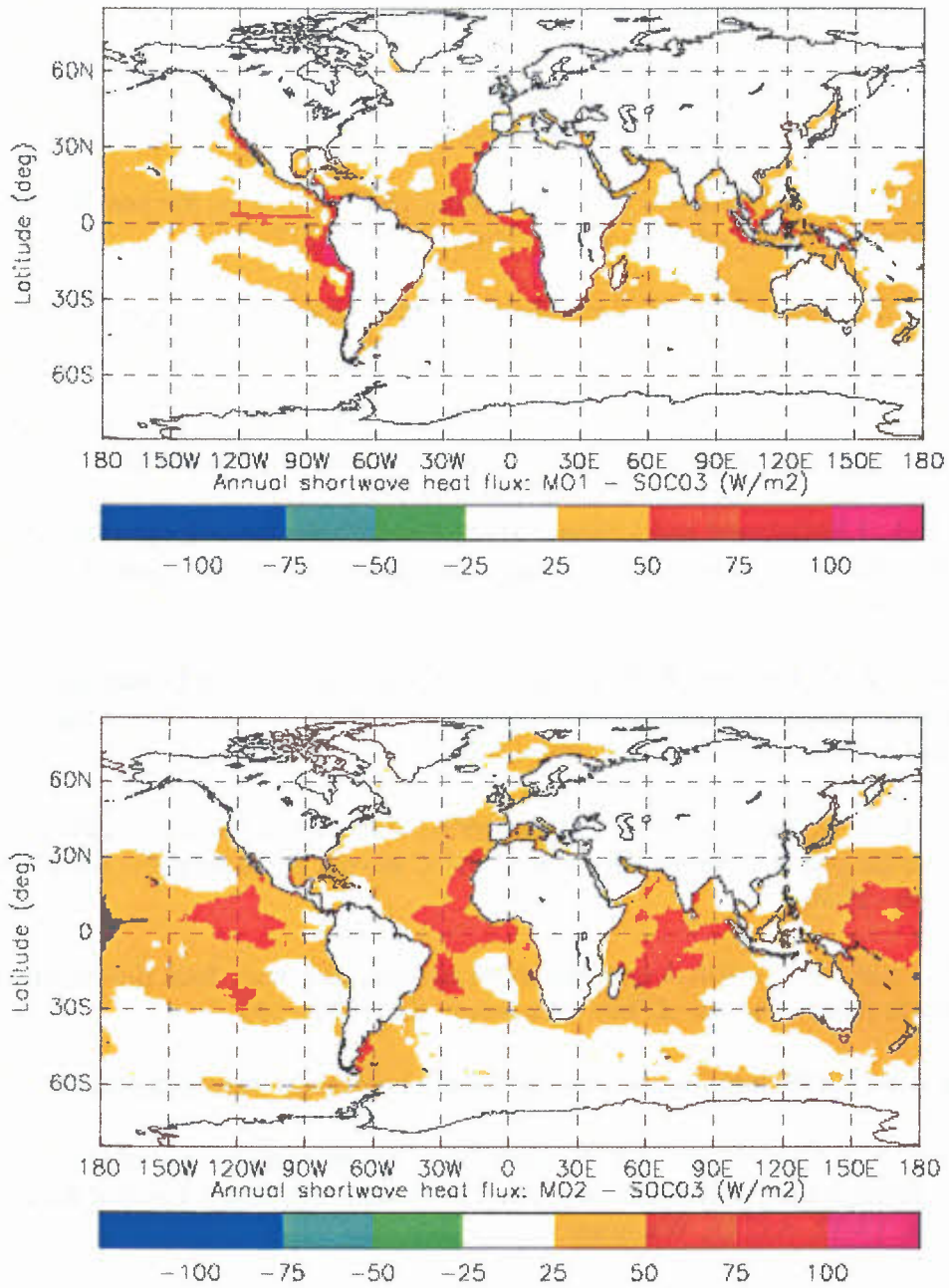


Figure 1. Annual average shortwave heat flux difference (Wm^{-2}) between a) MO1 and SOC03 and b) MO2 and SOC03. Note the large differences west of Peru and Namibia in 1a, and the greater MO2 shortwave down fluxes in 1b.

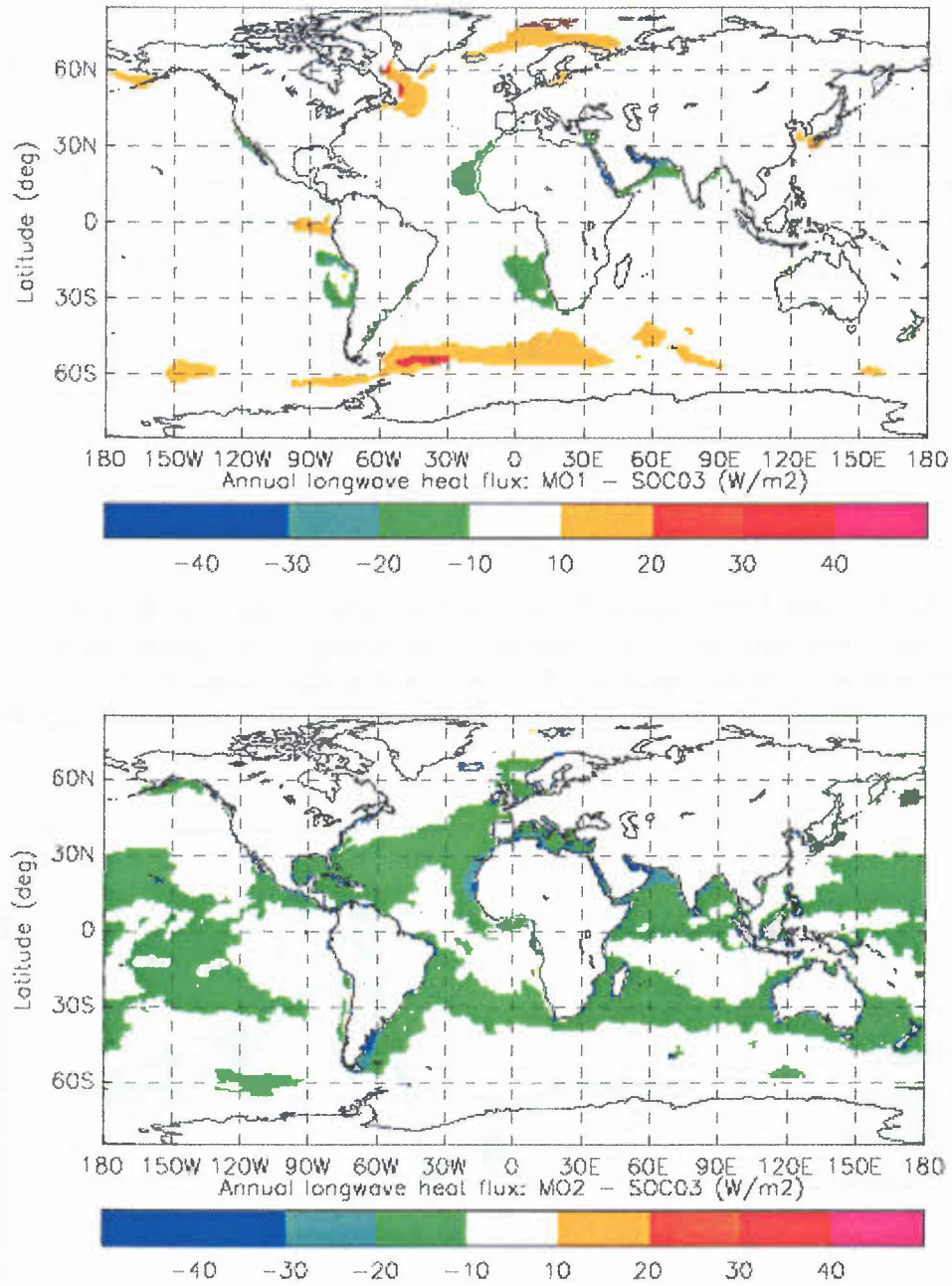


Figure 2. Annual average longwave heat flux difference (Wm^{-2}): a) MO1 minus SOC03 and b) MO2 minus SOC03. Note the differences between MO1 & SOC03 west of Peru & Namibia, and the large differences between MO2 and SOC03 in mid-latitudes (3b).

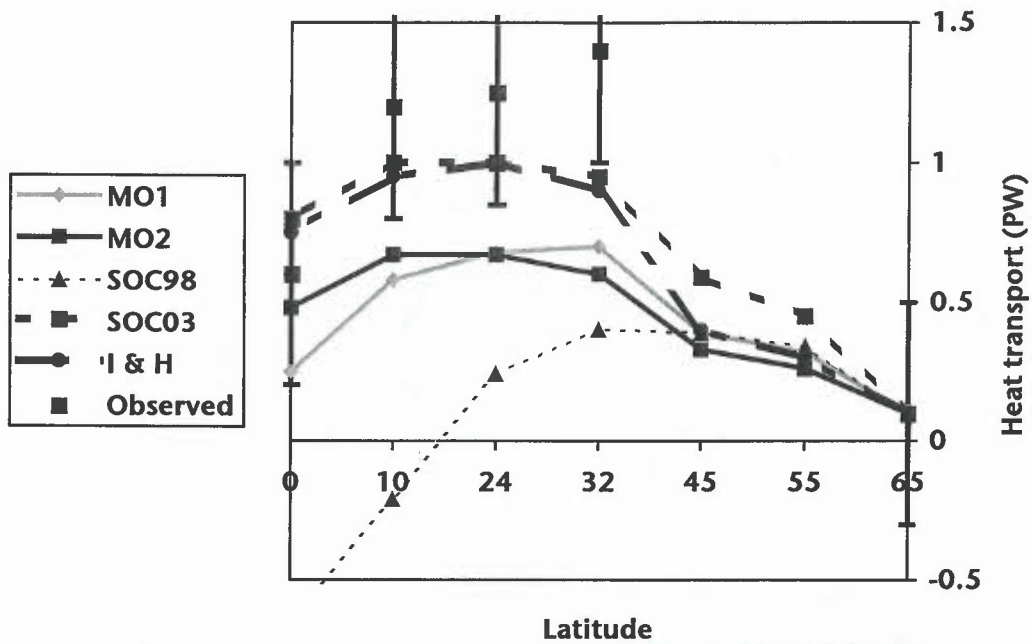


Figure 3a. The northward *north Atlantic* heat transport calculated by integrating the annually-averaged heat flux from each climatology (see legend) southward from the known heat transport at 65°N (Aargard & Greisman, 1975). The observed transports are shown as squares and have errors of typically 0.5 PW.

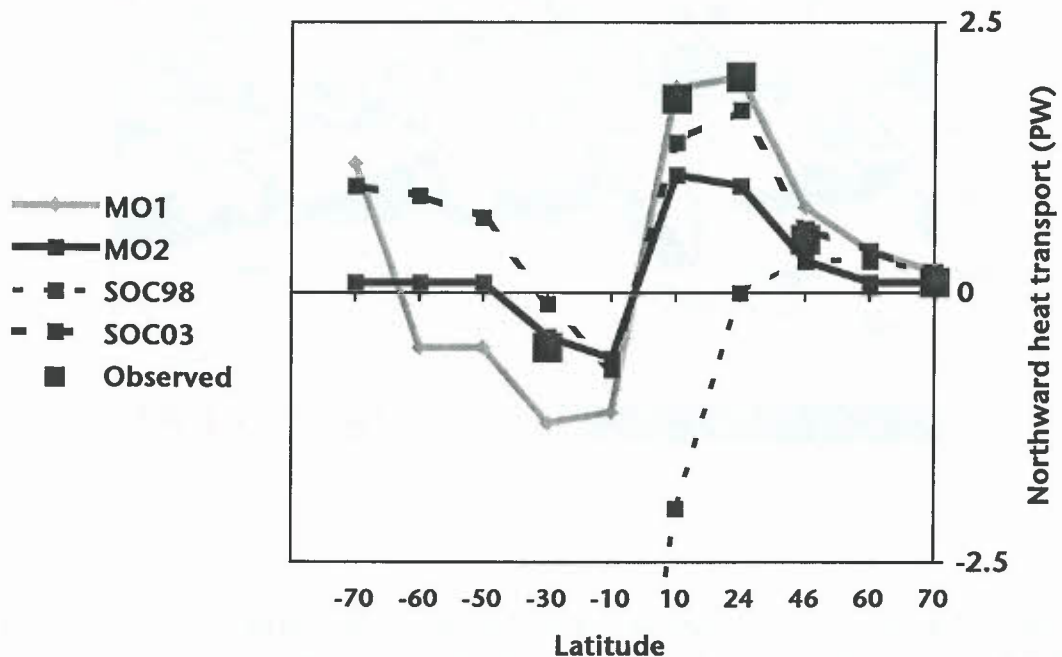


Figure 3b. The northward *global* heat transport (in PW). The observations are shown by squares. MO2 and SOC03 are closer to the independent observation at 30°S than MO1 and SOC98 (which is off the graph). The northward transports from SOC03 & MO1 increase towards Antarctica (70°S) whereas that from MO2 remains small as it approaches the coast.

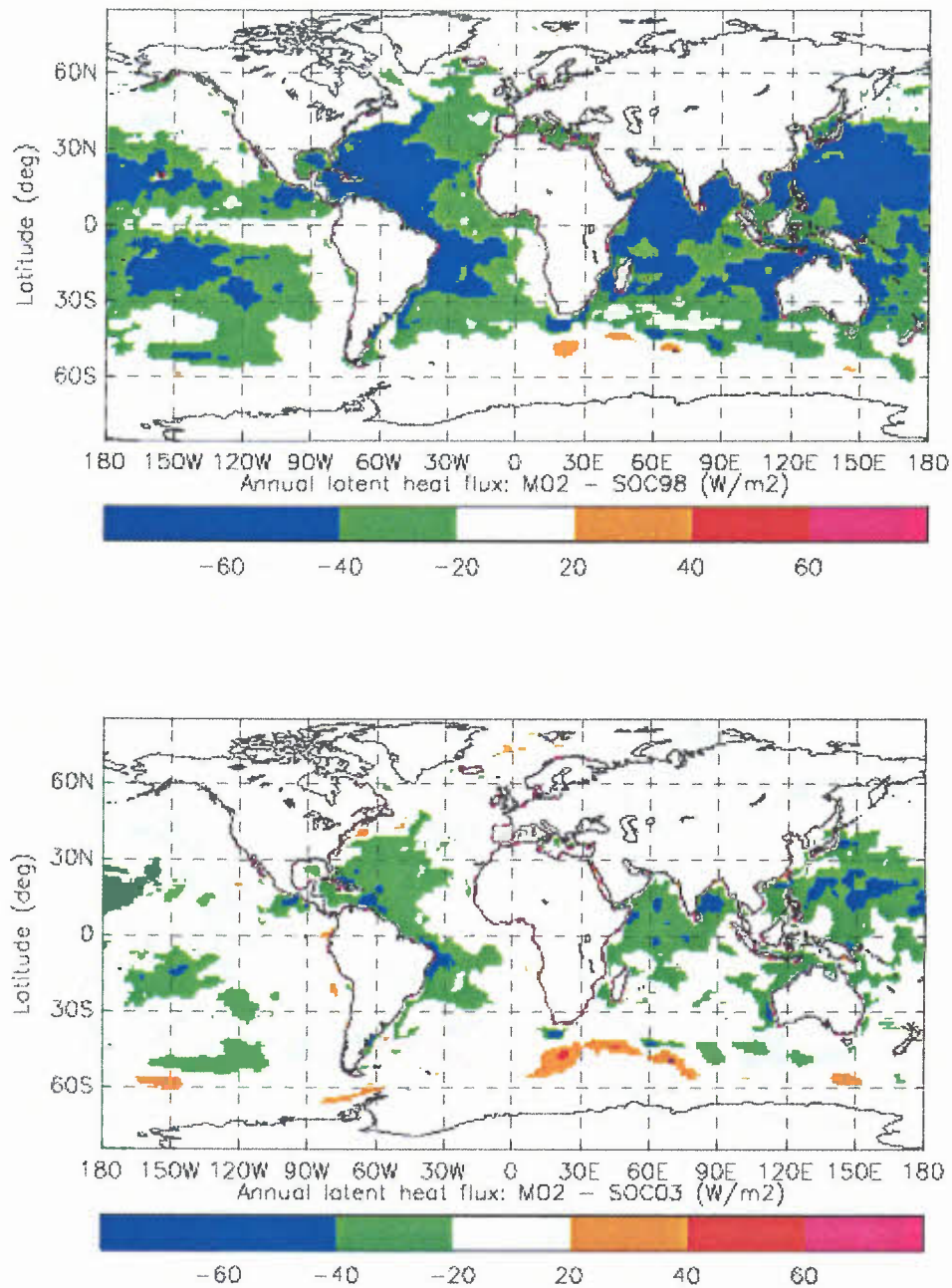


Figure 4. Annual latent heat flux (Wm^{-2}) difference: MO2 – SOC98.

Figure 5. Annual latent heat flux (Wm^{-2}) difference: MO2 – SOC03. MO2 has more than 20 Wm^{-2} more ocean latent heat loss than SOC03 in the west Atlantic, west Pacific, Indian and southwest Pacific, areas which are effected by tropical cyclones, see Fig. 7. Is there a tropical cyclone fair-weather bias in SOC03?

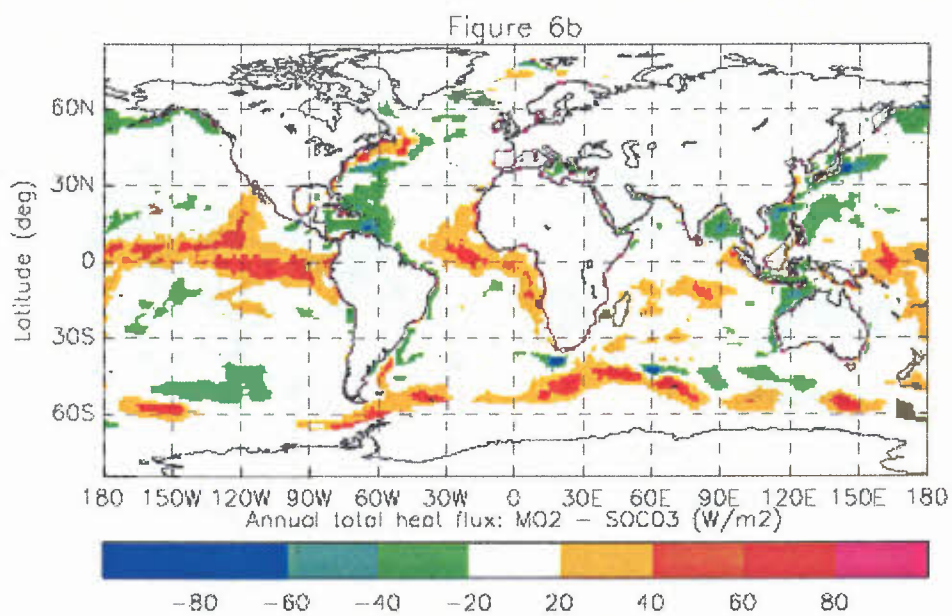
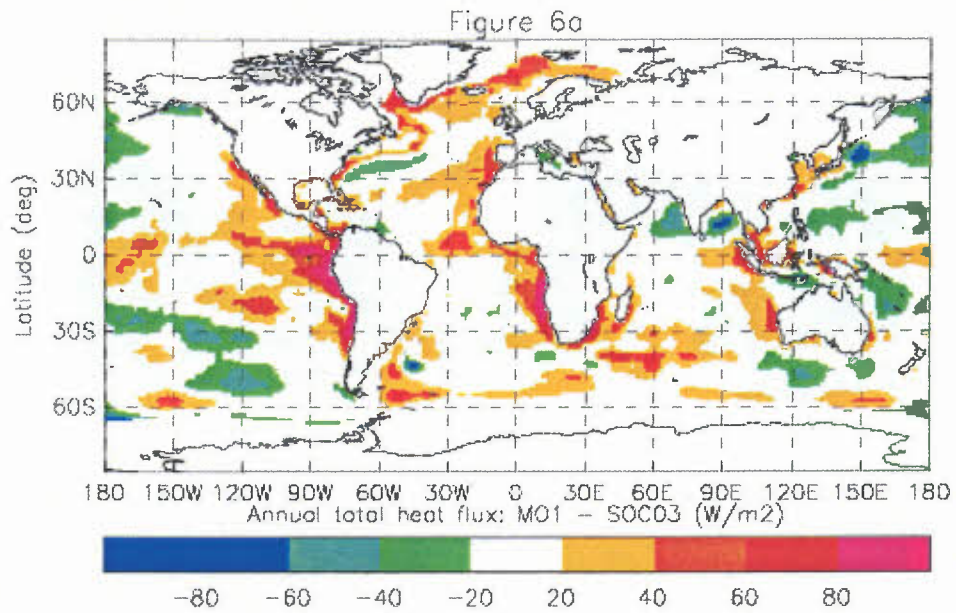


Figure 6a,b. Annual average TOTAL heat flux (Wm^{-2}) difference: MO2 - SOC03. Note: MO2 has more (SW) warming at the equator, and more (latent) heat loss in the west Atlantic and west Pacific.

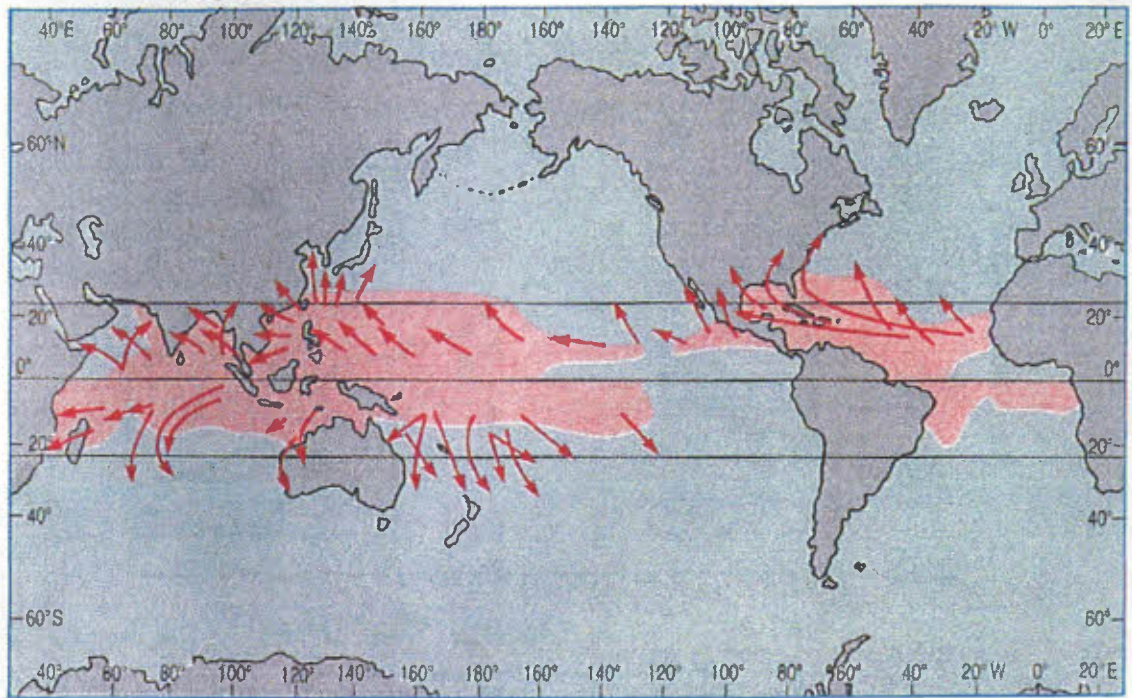


Figure 7. The red arrows show the typical tracks followed by tropical cyclones. The red shaded areas show the areas where cyclones form (taken from 'Ocean Circulation' by the Open University, 1989). Compare with Fig. 5.

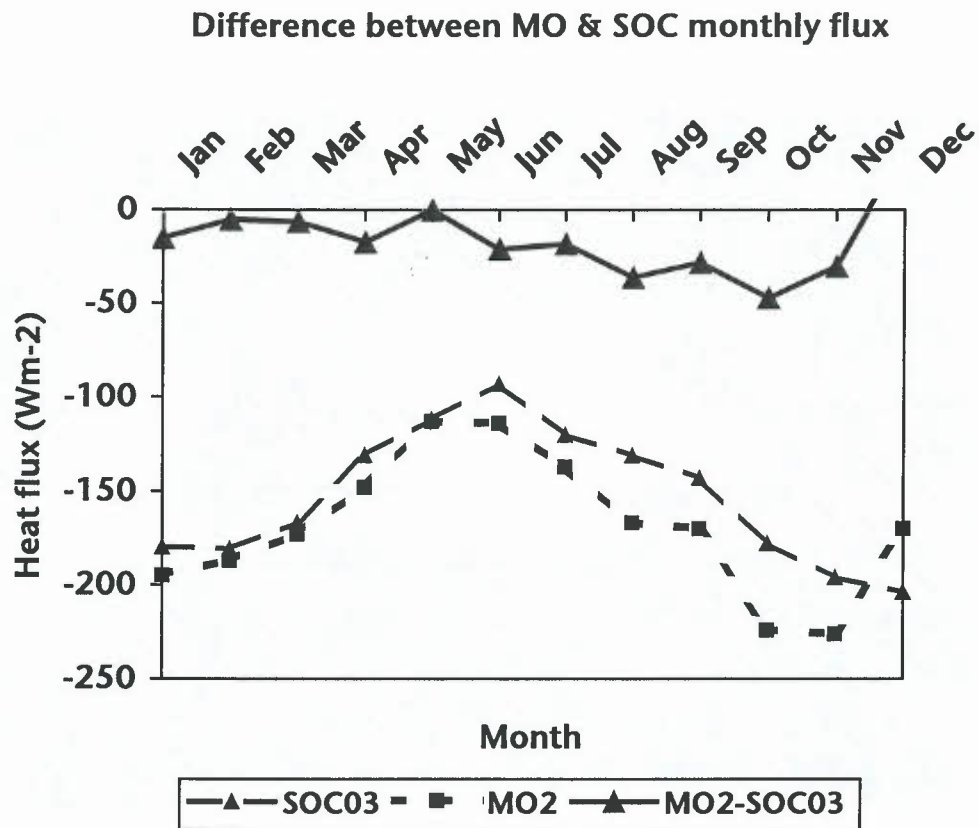


Figure 8. Seasonal cycle of air-sea latent heat flux at the FASINEX buoy array at 70°W, 27°N (Fig. 8a) according to SOC03 (dashed line) and the Met Office weather model (dotted line). The difference is shown by the solid line, and is greatest in October, when tropical cyclones are most common.