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Interannual Variability of Upper Ocean Heat content in the Northern Indian Ocean

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ABSTRACT
The zones of atmospheric convective movements always remain over the warmest surface water of the oceans. In the North Indian Ocean (NIO) (20° S to 25° N and 35° E to 115° E) the warmest surface water (warm pool > 28°C) persists in eastern equatorial region almost throughout the year. The shifting of warm pool from east to west appears to influence the atmospheric conditions in the surrounding regions. The heat content of the water column within the mixed layer depth of the ocean is very important for the synoptic weather disturbances. Hence, not only the high positive sea surface temperature (SST) anomalies in the warm pool region but also the positive heat content anomalies need to be studied. In the present study we have simulated the SST and upper ocean heat content in the NIO, using a simple ocean mixed layer model for the period of 10 years (1992 to 2001). The model results are used to study the interannual variability of SST and upper ocean heat content. It is observed that change in the pattern of warm and cool phase of heat content is similar to that of SST pattern over the equatorial Indian Ocean. The model simulated SSTs are in agreement with the observed Reynolds SSTs.

INTRODUCTION

The SST and the upper ocean heat content are the most important parameters in view of ocean-atmosphere interaction. The thermal energy of the upper ocean is associated with the solar radiation. This energy is generally absorbed within the near surface mixed layer. The heat from this mixed layer is immediately available for exchange with the counterpart, the atmosphere (Ohlmann, Siegel & Gautier 1996). It is mainly due to the ocean's large thermal inertia, that the oceans appear to play a major role in driving the weather and climate variation on time scale of days, months, years, decades and longer scales (Levitus 1984). The heat content of the upper Indian Ocean and its variability depends mainly on the surface wind forcing in monsoon rather than the internal dynamics. It is also associated with the synoptic disturbances which form over the ocean (Wacongne & Pacanowski 1996). The tropical Indian Ocean plays an important role in the variability of Asian (inclusive of Indian subcontinent and Central China) summer monsoon and African rainfall. Saji et al. (1999) have revealed that during 1994 and 1997, the rainfall is observed to have decreased over the oceanic Inter-tropical convergence zone and increased over the western tropical Indian Ocean, which is a reversal to the normal condition. In the equatorial Indian Ocean, normally the trade winds push the water eastward during the southwest monsoon period, causing formation of a large warm pool (5° S to 5° N, 60° E to 100° E). The warm pool water appears to transfer heat to the atmosphere and other parts of the ocean causing convection. The warm pool is observed to have an average SST > 28° C which is the maximum SST required for an active condition for convection to occur over the open ocean (Panchwagh & Seetaramayya 2002).

But on a few occasions normal conditions change and the warm pool gets shifted to west or Central Equatorial Indian Ocean (CEIO) causing a reversal of normal climatological scenario in the sea surface temperature anomaly (SSTA) and hence forth referred to as an Indian Ocean Dipole Mode (Saji et al. 1999). The Indian Ocean positive (negative) dipole evolves as an anomalously negative (positive) SSTA in the East Equatorial Indian Ocean (EEIO) and anomalously positive (negative) SSTA in the Western Equatorial Indian Ocean (WEIO). The connection of Indian Ocean variability with ENSO, through the atmospheric processes, like shifting water circulation and associated change in radiative flux and wind forced evaporation is studied by Venzke, Latif & Villwock 1997. In addition to the ENSO signal, non ENSO surface cooling off Sumatra related to equatorial Indian Ocean winds was also studied by Meyers 1996. In the present study, mixed layer temperature (MLT) and upper ocean heat contents are simulated in the

Northern Indian Ocean. The discussion is mainly concentrated on equatorial Indian Ocean region. The model simulated SSTA agree well with the observed SSTA.

DATA AND METHODOLOGY

The National Centers for Environmental Prediction (NCEP) reanalyzed monthly averaged surface wind components, air temperature and cloud cover (for the period from 1992-2001) were interpolated from a Gaussian grid to 1° × 1° grid in the model region using bi-cubic spline interpolation technique and are used to estimate the surface heat fluxes which are then used to force the ocean model. The monthly mean sea surface height anomaly (SSHA) was calculated using ten day average TOPEX/POSEIDON SSHA produced by the CLS Space Oceanography Division as part of the Environment and Climate EC AGORA(ENV4-CT9560113) and DUACS (ENV4-CT96-0357) projects.

A temperature tendency is obtained as a balance between the net heat flux at the sea surface, the surface short wave radiation penetrated below the ocean mixed layer and the entrainment cooling. The relevant thermodynamic equation for the simple oceanic mixed layer temperature, (as suggested by Alexander et al. 2000), is

$$\frac{\partial T_m}{\partial t} = \frac{Q_{net} + Q_{cor}}{C_p \rho h(x,y,t)} - \frac{Q_{swh}}{C_p \rho h(x,y,t)} - \frac{\omega_e \Delta T}{h(x,y,t)} \quad (1)$$

Where T_m is the MLT (Hereafter the model simulated MLT will be called as model SST), h(x, y, t) is the spatially and temporally varying climatological ocean mixed layer depth (MLD) specified linearly by interpolating the mean monthly MLD values (Levitus & Boyer 1994) and ΔT is the difference between the mixed layer temperature and the temperature of water entrained in the mixed layer, which is taken as 0.5°C. Q_{net} is net surface heat flux into the ocean (positive if ocean gains and negative if ocean looses), ω_e is the entrainment rate, ρ & C_p are the reference density and specific heat of the sea water and Q_{cor} is the surface heat flux correction to account the advective and diffusive processes. The total flux through the surface is reduced by Q_{cor}, which is half as large as net heat flux but have opposite sign. The magnitude and pattern of Q_{cor} resembles the observed annual mean Oceanic heat flux convergence (Alexander et al. 2000), indicating that the correction is primarily accounted for the absence of advection in the Ocean model. Very shallow mixed layer was observed over the Bay of Bengal region and hence the short wave radiation received at the sea surface may penetrate beyond the mixed layer. The penetrative solar radiation Q_{swh} below the ocean mixed layer is computed and used as

$$Q_{swh} = SW(\mathrm{R}e^{-h\nu_1} + (1-R)e^{-h\nu_2}) \quad (2)$$

Where SW is the short wave radiation flux at the sea surface, which is computed from the Earth Radiation Budget Experiment (ERBE) clear sky radiation and the NCEP cloud cover, R is the separation constant, ν_1 and ν_2 are attenuation length scales. And the entrainment velocity

$$\omega_e = (2m_o u_*^3)/\alpha g h \ \Delta T \quad (3)$$

Where u_*^3 = frictional velocity, m_o = 0.5, α = 2.5 x 10^{-4} K^{-1}

The above thermodynamic equation is solved on a finite difference grid of 1° x 1° resolution using central difference scheme with a time step of 1800 seconds (Δt = 1800 sec.). The heat content of the ocean mixed layer of depth h is estimated as;

$$HC = \rho C_p \int_0^h T_m dz \quad (4)$$

The surface heat fluxes were computed using standard bulk aerodynamic relations. In the flux computation, the simulated SSTs are used rather than using observed SSTs. The forcing data at each model time step (of integration) was obtained by linearly interpolating the monthly values. The values of the model SST on day 15th of each month are considered as the representative of the monthly values. For simplicity the model calendar is considered to be of 360 days. The in house developed model has been used to simulate SST for a period of ten years (1992 to 2001) in the entire model region.

RESULTS AND DISCUSSION

The model was initialized with the January 1992 Reynolds SST (representing 15^{th} January 1992) and integrated monotonically from January 1992 to December 2001 with the interannually varying surface heat fluxes over NIO (20° S to 25° N and 35°E to 115° E). Monthly anomalies are departures from the corresponding ten year averaged monthly mean values. However, in the present study, most of the results are shown only along the equator from 45 °E to 95°E.

The Hovmoller diagrams (Longitude-time plots) of Reynolds and model simulated SSTA (from 1992 to 2001) along the equator is shown in Fig. 1(a) & (b) respectively. It is important to note that the model simulated SST reasonably well in most of the time.

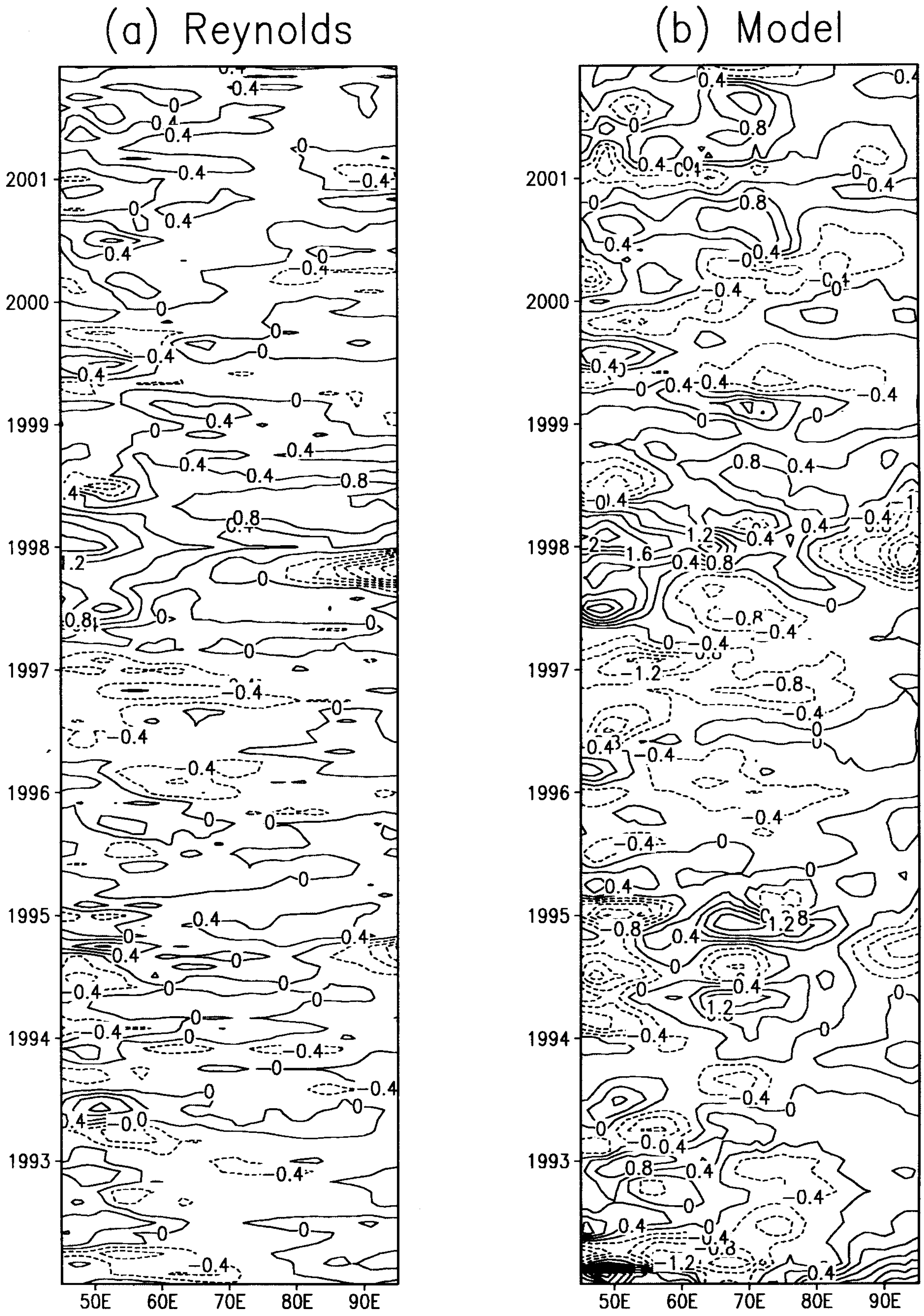

Figure 1. Longitude-time plots of the SST anomalies at equator

However there are some epochs where the model SST slightly deviated from observed ones, which are mainly due to the absence of advection term in the model. The model has captured the unusual cooling in the EEIO and warming in the WEIO during the years 1994, 1997-98 as seen in the observations. However, the model (simulated) western warming in 1994 extended up to 55° E only whereas the observation showed warming up to 45° E. This clearly indicates that the eastern cooling is mainly controlled by the surface heat flux but western warming is highly influenced by the advective processes in the region, which is not resolved in the model. It is important to note that strong warm anomaly bands along the equator during these years seem to be consistent with the El Nino like events in conjunction with the Pacific Ocean. Both the model and observation showed 1998 as warmest year of the decade (IPCC report also declared that 1998 was the warmest year of the decade). The reason for this unusual warming is reported to be due to the shift in southeast trades towards the equator, and the reduced latent heat flux in the region during 1997-98 (Yu, & Reienecker 2000).

Fig.2 shows the longitude time variation of the model simulated heat content anomaly along the equator, the heat content anomaly greater than 1.0 x 10^8 J/m^2 are darkly shaded and less than -1.0 x 10^8 J/m^2 are lightly shaded. As we have discussed earlier, the warm pool area of equatorial Indian Ocean east of 60^{o}E has shown positive heat content anomaly and an east to west thermal gradient, except during 1994, 1997-98 and 2000-01. In 1994 and 1997-98 a strong negative heat content anomaly appeared in the eastern Indian Ocean and the warm anomaly is observed to have shifted towards the west resulting a west to east thermal gradient.

Fig.3 shows the time-longitude diagrams of the sea surface height anomaly (SSHA, Fig. 3(a)) and zonal wind anomaly (ZWA, Fig. 3 (b)). The SSHA data are computed from the TOPEX dynamic height data sets for the period from January 1993 to August 2001. In Fig.3 (a & b) the positive anomalies are shown in continuous lines whereas the negative anomalies are shown in dashed line. Similarly the positive ZWA shows the westerly wind component (i.e. winds from west to east) and the negative ZWA shows the easterly component (east to west) along the equator. It is interesting to note that positive (negative) SSHA appear to have coincided with the positive (negative) ZWA during most of the time period of study. The upper ocean heat content anomaly is observed to be linearly related to TOPEX dynamic height anomalies on interannual time scale. Normally in the EEIO westerly present and causing for increase in SSH, leading to warm SST's and high heat content values over the region. Due to these high values the warm pool persisted in the EEIO most of the time. But in the year 1997-98 over the EEIO, negative ZWA (easterlies) negative SSHA, indicating that the strong easterlies causing for decreasing SSH in the EEIO region and increasing in the SSH in the WEIO. This shifting of warm pool from EEIO to west caused reduction in rainfall in Indonesia (causing drought during 1997-98) and normal rainfall in the Indian subcontinent.

Fig. 4(a-f) shows the spatial distribution of the model monthly mean heat content (in 10^{11} J/m^2) over the model region (mean of 1992 to 2001). Fig. 4(a) shows relatively high values of heat content (of 0.7 x 10^{11} J/m^2) in the northwest Arabian Sea near Oman coast and in the south east Indian ocean between 90^{o}E and 100^{o}E and south of 15^{o}S (of 0.5 x 10^{11} J/m^2) in February. The high values of the heat content observed in the North West Arabian Sea region is mainly because of the deeper mixed layer depths. In Fig. 4(b) high values are seen around 15^{o}S between 70^{o}E to 100^{o}E (0.75 x 10^{11} J/m^2). During the height of the south west monsoon months high values of heat content (1.1 x 10^{11} J/m^2) is observed in the Arabian Sea centered at 62^{o}E, 10^{o}N. The centers of high values appear to have shifted equator ward in October (Figure 3 (e)), which clearly indicates the southward heat transport during the southwest monsoon period. The heat content contours of November shows that the high values of the heat content are seen in the south Indian ocean near 15° S and between 90° E and 100° E. The heat content pattern clearly shows the existence of a dominant mode of North West heat transport in the model region.

CONCLUSIONS

The in-house developed simple model could successfully simulate the interannual variability in the SST and the heat content of the upper equatorial Indian Ocean. It is found that during the positive dipole mode years (1994 and 1997-1998 during the period of study) a strong west to east thermal gradient exists consistently for a period of four to six months in the equatorial Indian Ocean. It is observed that the eastern cooling during the positive dipole years are mainly contributed by the surface heat fluxes in the form of latent heat flux and entrainment cooling. However, apart from the surface heat flux, the horizontal advection plays an important role in the western warming. The upper ocean heat content variability is found to be linearly related to the TOPEX dynamic height variability in interannual time scale. The spatial pattern of heat content during different

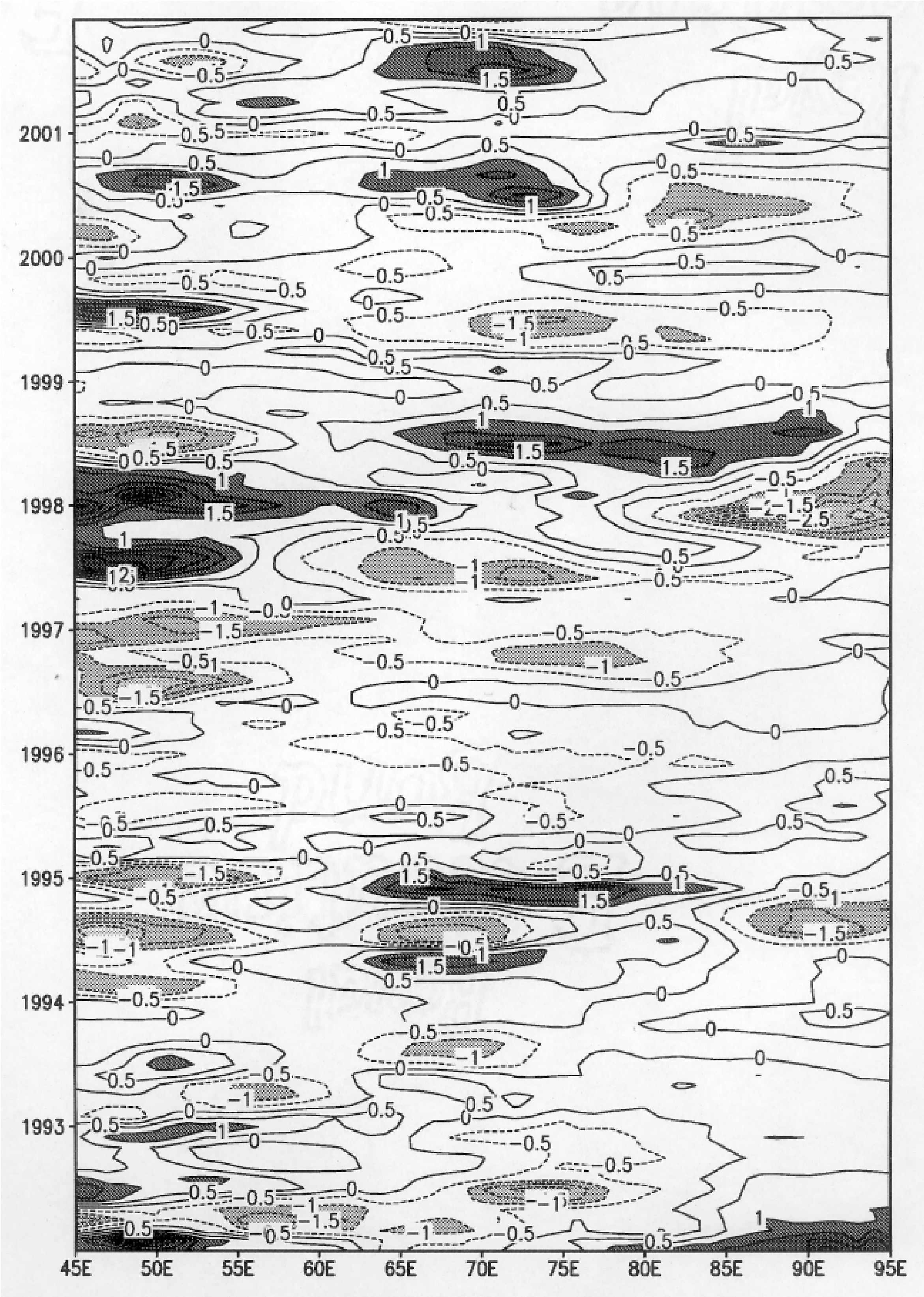

Figure 2. Longitude-time plot of the model Heat content anomaly (x10 ^ 8) in J/m ^ 2 at equator (contours > 1.0 are darkly shaded while < -1.0 are lightly shaded)

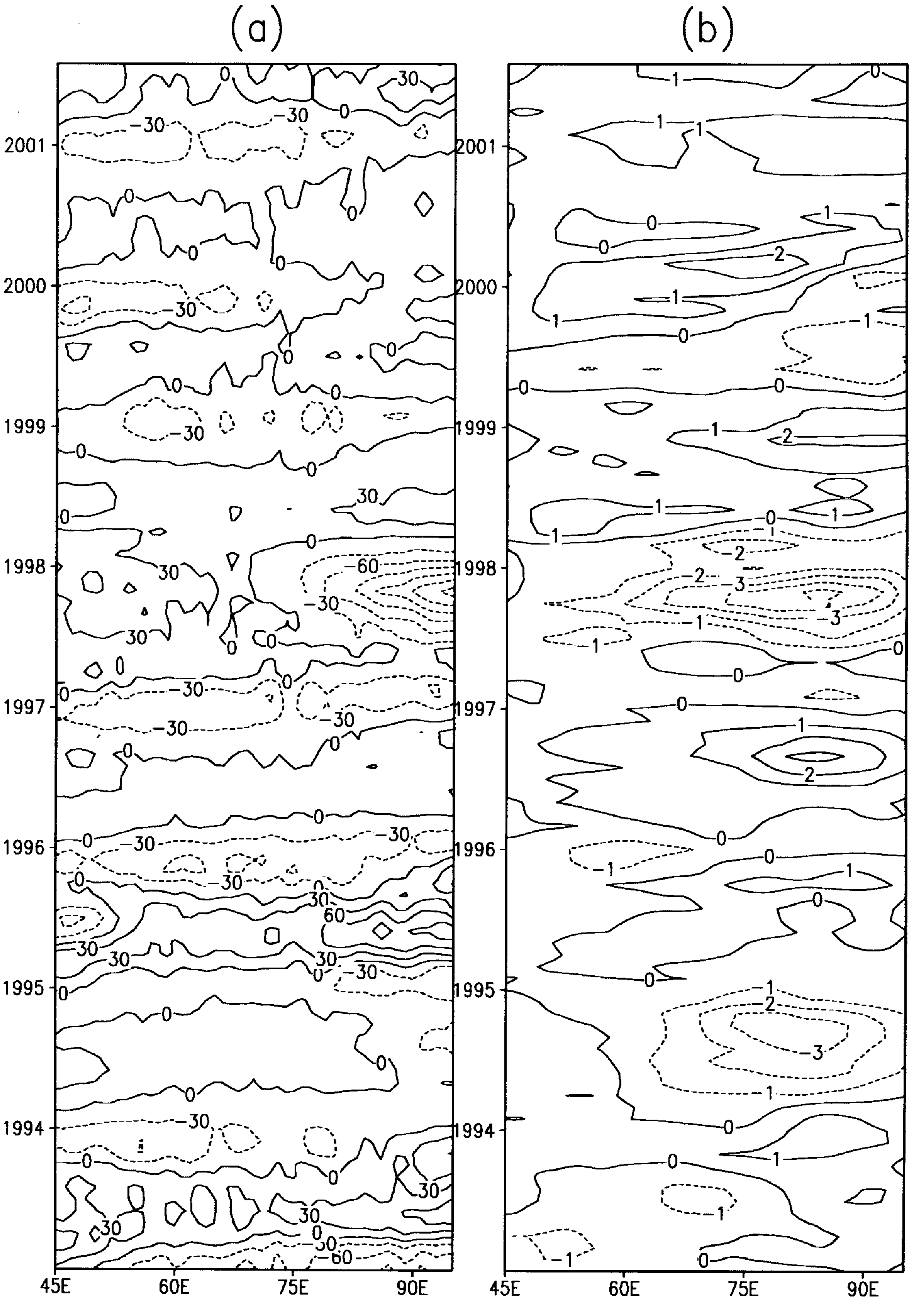

Figure 3. Time-longitude plots of the (a) SSHA (cm), (b) Zonal wind anomaly (m/s) at equator A 3-months running mean is applied for smooth anomalies.

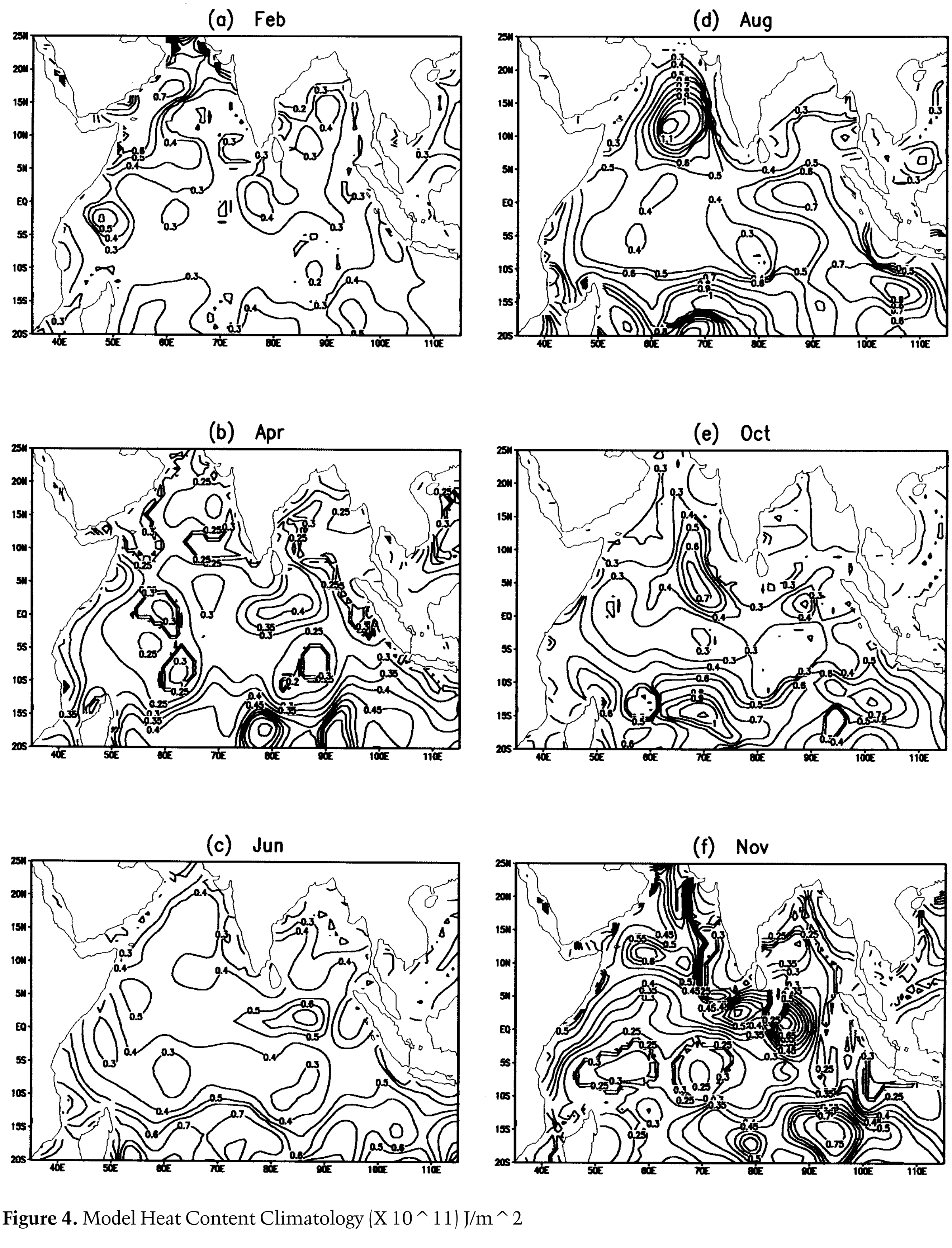

Figure 4. Model Heat Content Climatology (X 10 ^ 11) J/m ^ 2

months clearly shows the existence of a dominant mode of meridional heat transport.

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