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An estimation of heat flux and its variability in the Southern Indian Ocean (SIO) using Ocean General Circulation Model

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ABSTRACT
Evaluated annual mean and seasonal means net heat flux at the ocean surface for the period 1975-1998 from an ocean model results for Southern Indian Ocean (SIO) having spatial coverage 0.25°N-74.25°S & 15.75°E-120.75°E. It has been found that model annual mean and seasonal means net heat flux fields agree moderately with Southampton Oceanography Center (SOC) climatological heat fluxes and there are spatial inconsistencies in computation against a good agreement in-between model and SOC data sets in the region of interest. These discrepancies may be due to deficiency with model physics or sampling related bias in SOC data sets. Further, nature of variability of surface heat flux field in SIO was studied using Empirical Orthogonal Functions (EOF) techniques. Interannual variability represented in the first EOF of surface heat flux anomaly shows a strong trend in the Antarctic Circumpolar Current (ACC) region and significance variability around ten years.

INTRODUCTION

Sea surface temperature (SST) assists us in understanding the ocean dynamics and climate studies from which, the ocean heat flux, is derived and is defined as the exchange of energy between the ocean and the atmosphere. The surface heat flux is a component of the ocean heat balance and it has been studied here using Modular Ocean Model (MOM3). Heat flux is neither easily measured in-situ, nor measured by any space-based sensor although efforts are being made to measure it. However, presently surface heat fluxes can be constructed from ship meteorological reports or from satellite retrievals. They are also produced directly from numerical weather prediction models. But, all these sources that produce heat fluxes are plagued by at least one of the four deficiencies: (1) incomplete global coverage, (2) short spanning period, (3) systematic biases, and (4) random errors. (**Yu,** Weller & Sun 2004). However, improving the quality of each data source is essential for the future assessment of the surface heat flux. The sparsity of observation data in time and space over the south of 50°S has forced one to use climatological means or statistical methods to obtain information about the surface heat flux. It has been known that the estimated values of the heat flux are dependent on (1) the bulk formulas used to calculate the heat flux (2) the type of data acquisition (3) the spatial and temporal resolution of the data set (Hsiung 1986).

In this study, we have analyzed ocean surface heat flux datasets of the ocean model output for the period (1975-1998) covering the region south of 0.25°N-74.25°S and 15.75°E-120.75°E. Following these analyses, we have investigated variability of heat flux for the understanding of interannual controls on climatic phenomenon using a statistical analysis known as empirical orthogonal function (EOF) in order to identify the dominant spatio temporal modes of interannual variability using monthly mean anomalies. In the recent years there have been several studies in which EOF analyses were used to highlight potential physical mechanism associated with climate variability (Dommenget & Latif 2002).

The physical interpretation of EOF's is limited by a fundamental constraint. While it is often possible to clearly associate the first EOF with a known physical process, this is much more difficult with the second (and higher–order) EOF because it is constrained to be orthogonal to the first EOF.

However, real–world processes do not need to have orthogonal patterns or uncorrelated indices. In fact, the patterns that most efficiently represent variance do not necessarily have anything to do with the underlying dynamical structure.

The present study is based on analyzing the model results for different cycles such as annual mean cycle, seasonal cycle and monthly mean anomalies using EOF analyses. Mean cycle and seasonal cycles have been compared with SOC climatological fluxes (1° by 1°) (Josey, Kent & Taylor 1997) in order to evaluate the current capability of the model for surface flux evaluation. The seasonal mean in the present study are defined as three months mean for September-November (SON) and March-May (MAM).

MODEL DESCRIPTION AND DATA

The Ocean General Circulation Model (OGCM) used in this study is a version 3 of the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model 3.0 (Pacanowski, Dixon & Rosati 1993; Huang & Schneider 1995; Schneider et al., 1999). Its domain is that of the world oceans between 74.25°S and 65°N. The zonal resolution is 1.5°. The meridional resolution is 0.5 between 10°N and 10°S, gradually increasing to 1.5° at 20°N and 20°S. There are 25 levels in the vertical. The model uses the KPP vertical mixing and diffusion parameterization. Its horizontal viscosity is calculated from the Smagorinsky (1999) nonlinear parameterization while its tracer diffusion is treated in isopycnal coordinate. The model is forced by the monthly averaged surface wind stress from the NCEP-NCAR reanalysis for the period 1958-1998. The original surface reanalysis is on an irregular grid with a zonal resolution of 1.875° and Gaussian latitudes of grid spacing less than 2°, which is linearly, interpolated to the OGCM grids. The model surface salinity is relaxed to Levitus (1982) monthly climatology.

The Heat flux climatology field has been generated from the Modular Ocean Model spanning from the period 1975-1998 and on a variable resolution from 15.75°E- 120.75°E, 74.25°S- 0.25° N.

General formulation of surfaces fluxes

The surface heat flux Q is calculated using the formula

$$Q = Q_{sw}\downarrow - Q_{sw}\uparrow + Q_{lw}\downarrow - Q_{lw}\uparrow - Q_{sensible} - Q_{latent} \qquad (1)$$

where $Q_{sw}\downarrow$, $Q_{sw}\uparrow$, $Q_{lw}\downarrow$, $Q_{lw}\uparrow$, $Q_{sensible}$ and Q_{latent} are surface downward and upward short wave radiation, surface downward and upward longwave radiation, sensible heat flux, and latent heat flux respectively. $Q_{sw}\downarrow$, $Q_{sw}\uparrow$ and $Q_{lw}\downarrow$ are derived from NCEP/NCAR reanalysis data. Upward longwave radiation is computed as

$$Q_{lw}\uparrow = \sigma\, T_{sst}^{\ 4} \qquad (2)$$

where σ is Stefan Boltzmann constant and T_{sst} is the model SST. The sensible and latent heat fluxes are estimated by

$$Q_{sensible} = \rho_a\ C_p\, C_h\, |V|\ (T_a - T_{sst}) \qquad (3)$$

$$Q_{latent} = \rho_a\ L\ C_h\ |V|\ (q_a - q_{sst}) \qquad (4)$$

where ρ_a is air density, V is wind speed at 10m, T_a is surface air temperature, q_a is surface air humidity, and q_{sst} is saturation humidity at the model SST, C_p is specific heat of air at constant pressure, L is latent heat of evaporation, C_h is transfer coefficient for sensible and latent heat flux.

RESULTS AND DISCUSSION

Net Heat Flux Annual Climatology and its Comparison with SOC climatology.

Figure 1a shows 24 years (1975-1998) annual mean of net heat flux at the sea surface from the ocean model. The negative heat fluxes contribute to the convergence and heat loss by the ocean and conversely the positive heat fluxes to the divergence and heat gain by the ocean. The net heat flux from the model agrees moderately with the Southampton Oceanography Center (S.O.C.) climatology (Josey, Kent & Taylor 1997) shown in Fig.1b, which was generated from an enhanced version of Comprehensive Ocean Atmosphere data set (COADS 1a, Woodruff et al., 1993) which consists of marine meteorological reports spanning from 1980-1993 and enhanced with additional meta data from the WMO 47 (the WMO Report 47, e.g. WMO 1993) list of ships on a grid resolution of 1° by 1°, however discrepancies in between two values do exist in region of interest in terms of their magnitude and spatial distribution.

The largest heat gains appearing in the study area (Figure 1a) are in Southern Ocean around 50E-70°E, 45°S-50°S and in a very small part near 45°S where maximum value of more than 100 W/m^2 occurs, which seems very unlikely to be real given the surrounding areas of stronger heat loss. Also south of Indian Ocean (Equator to 15°S) and a narrow band

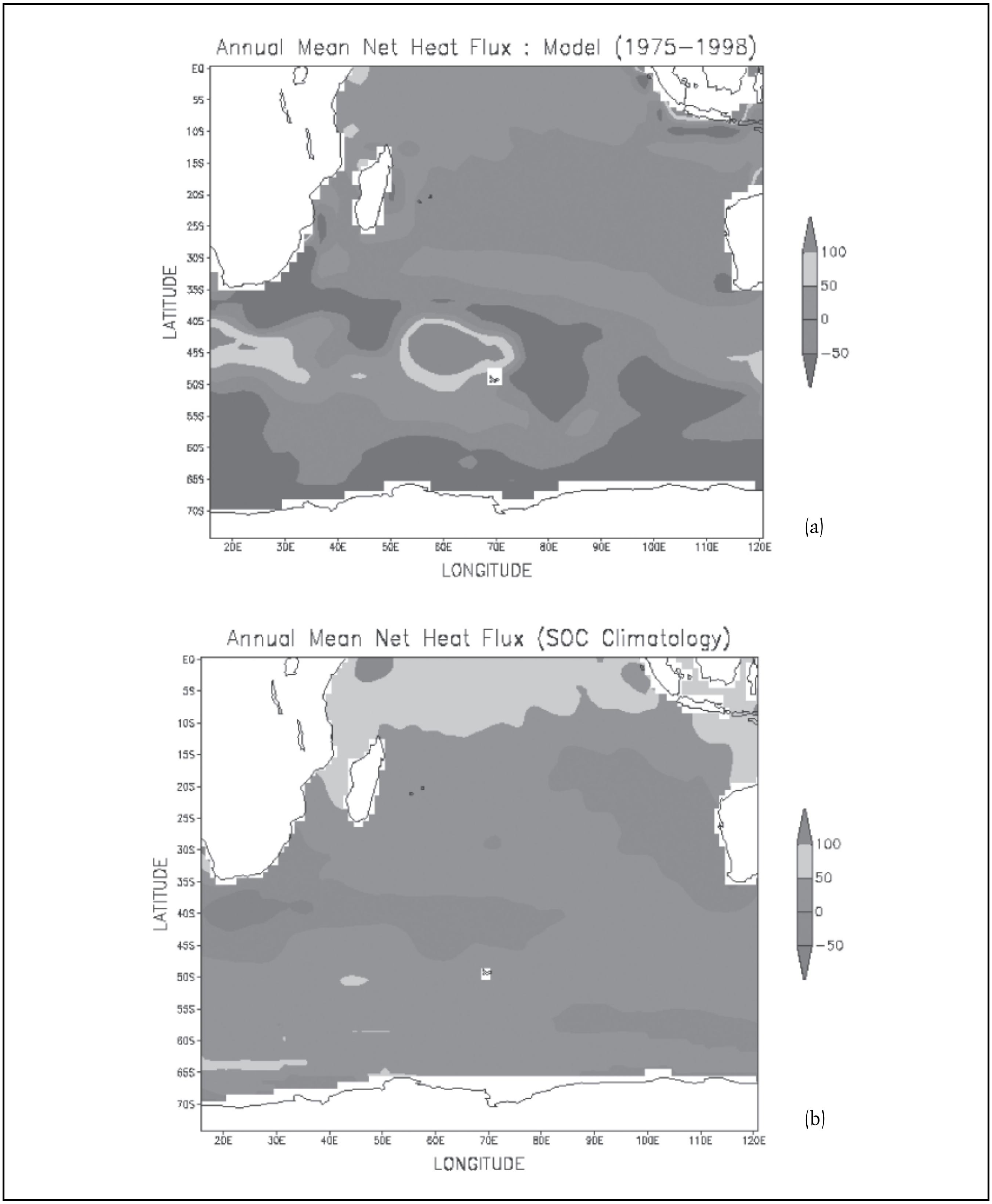

Figure1. (a) Annual Mean Net heat flux climatology at the ocean surface (Model); (b) SOC climatology. Units are in W/m^2. Positive values indicate heat gain by the ocean.

from 50°E-120°E (Fig.1a) attains the maximum heat gain of 50 W/m^2. It is interesting to note that the regions with the stronger heat loss exceeding to -100 W/m^2 occur near 55°S-70°S (Figure 1a) and in mid of southern ocean while region with lowest heat loss exceeding to -50 W/m^2 occur near east of Madagascar (Fig.1a). On the western side of the ocean basins, where swift western boundary currents carry warm water polewards beneath a cooler atmosphere, there is also a net heat loss by the ocean (Figure 1a) (Bryden & Imawaki 2001).

The pattern of annual mean and spatial distribution of the net heat flux field from the model does not seem follow with SOC data (Fig.1b) and changes considerably in terms of spatial distribution and magnitude. Infact, very similar pattern of net heat flux distribution can be seen in some parts with SOC heat flux (Fig.1b) in terms of location such as stronger heat loss observed in the western boundary near African coast region (Figure 1a) are evidenced by SOC fluxes (Fig.1b), however regions of heat gain and loss are different in model and observation in some parts of the study area. The discrepancies in heat gain and loss may be because of the deficiency with model physics or sampling related bias in SOC data sets, however model and SOC climatology seem to be in agreement in terms of the location at few places but not in terms of magnitude. It may be mentioned that model and SOC fluxes are roughly in some agreement as reflected in two computations.

Heat Flux Seasonal Climatology and its comparison:

The seasonal means of the heat fluxes, which are spatially averaged monthly mean of the flux, are also discussed in the present study for the season MAM and SON.

In the season MAM, model heat flux (Fig.2a) reflect that most of the places in southern ocean are losing heat into the atmosphere i.e. heat flux is negative with stronger heat loss near south west of the Madagascar (-200 to -250 W/m^2) and positive heat flux is observed in small region around 50°E-60°E i.e. ocean is gaining heat in small region while in the SOC climatology (Fig. 2b), ocean is losing heat into the atmosphere in most part of the domain and gaining heat from the atmosphere only from equator to 25°S. Stronger heat gain is reflected in the SOC climatology (Fig.2b) in the equatorial region and in the region extending from 40°E to 60°E. Stronger heat loss is observed near south west of Madagascar in the SOC climatology (Fig.2b).

In the season SON, ocean is losing heat into the atmosphere below 35°S except (Fig.3a) region around 50°E - 60°E where ocean is gaining heat from the atmosphere and the same is evidenced by the SOC climatological fluxes below 35°S (Fig.3b) and above 35°S in most part of the model domain (Fig.3a) ocean is gaining heat from the atmosphere excluding some region in the eastern side where negative heat flux is observed and these are also evidenced by the SOC climatological heat fluxes (Fig.3b).

In general, there are spatial inconsistencies in computation against a good agreement in between model and SOC fluxes and this may be due to deficiency with model physics or sampling related bias in SOC data sets; however ocean heats gain and loss are in agreement in terms of the location, but not in terms of the magnitude.

Infact, a qualitative comparison between the model and SOC climatology have been shown here on different time scales. It would be reasonable to mention that inspite of several development in ocean model simulation, model solutions are still not reliable due to its various limitations such as model physics, insufficient parameterization of mixing processes and data sets (Mellor & Ezer 1991), whereas SOC climatology suffers its own drawbacks as stated in their literatures (Josey, Kent & Taylor 1996; Josey, Kent & Taylor 1999) and therefore, the coarser and finer distribution of heat flux data between model and SOC climatology [figs. 1(a) and 1(b), 2(a) and 2(b)] may be due to inherent limitations of the model and shortcoming associated with SOC climatology. Moreover, different bulk schemes and data sets have also been used in the computation of heat fluxes, so they are significantly different. In brief, this erroneous feature of the comparison may be assumed to associate with the spuriously regional biases, deficiencies in the model physics and sampling related problems in SOC data.

Empirical Orthogonal Function [EOF] and Principal Component (PC) Analysis of Monthly Mean Heat Flux Anomaly

The EOF/PCA method is the method of choice for analyzing the variability of a single field i.e. a field of only one scalar variable (say SST, heat flux). However this approach finds the spatial patterns of variability, their time variation and gives a measure of "importance" of each pattern. We must clarify that this approach breaks the data into 'modes of variability'; these modes are primarily data modes and not necessarily physical modes. Whether they are physical will be a matter of subjective interpretation (Bjornsson & Venegas 1997).

Empirical Orthogonal Function (EOF) analysis

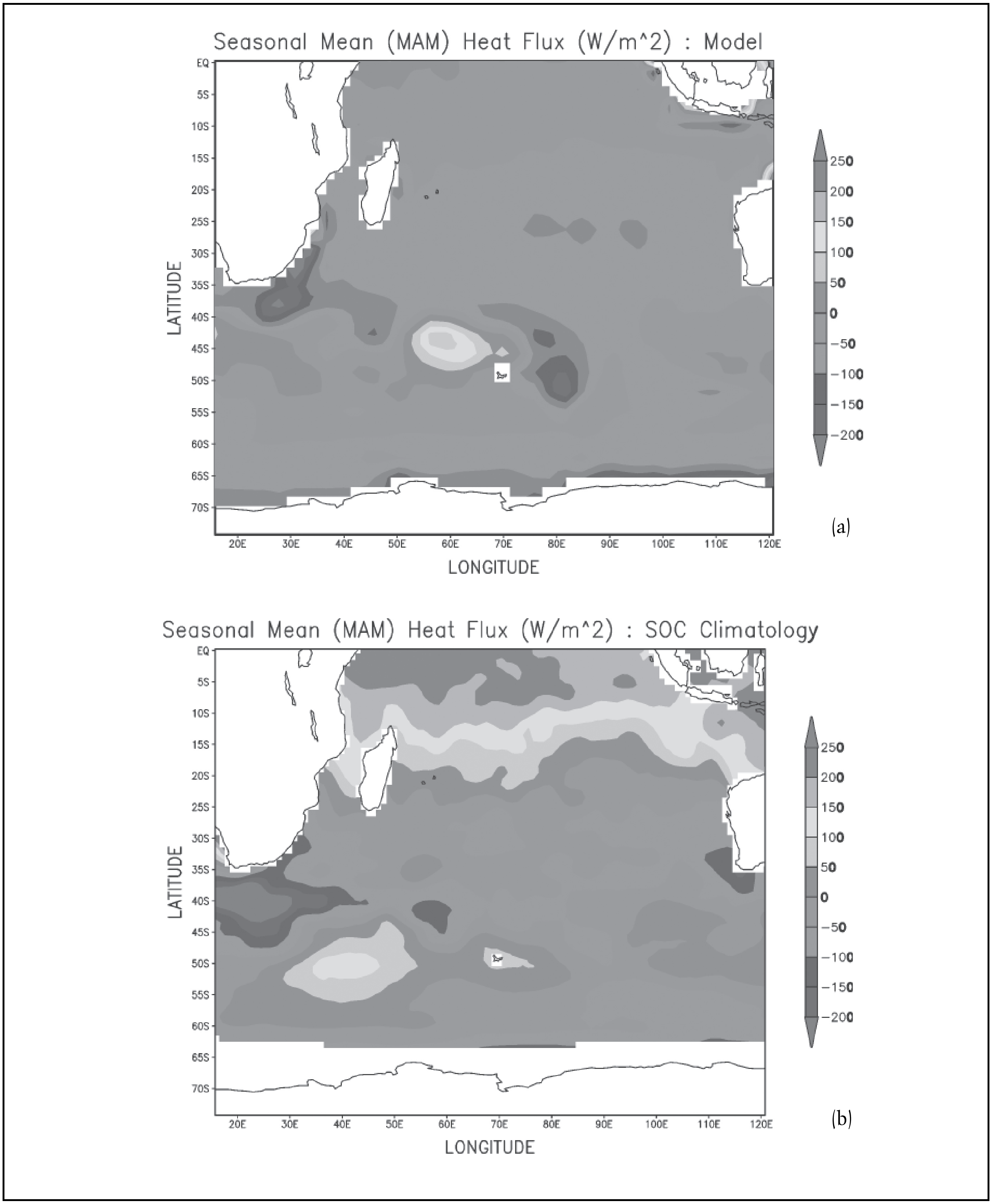

Figure 2. (a) Heat flux at the ocean surface for the season (MAM) (Model) and (b) SOC climatology for MAM. Units are in W/m^2. Positive values indicate heat gain by the ocean

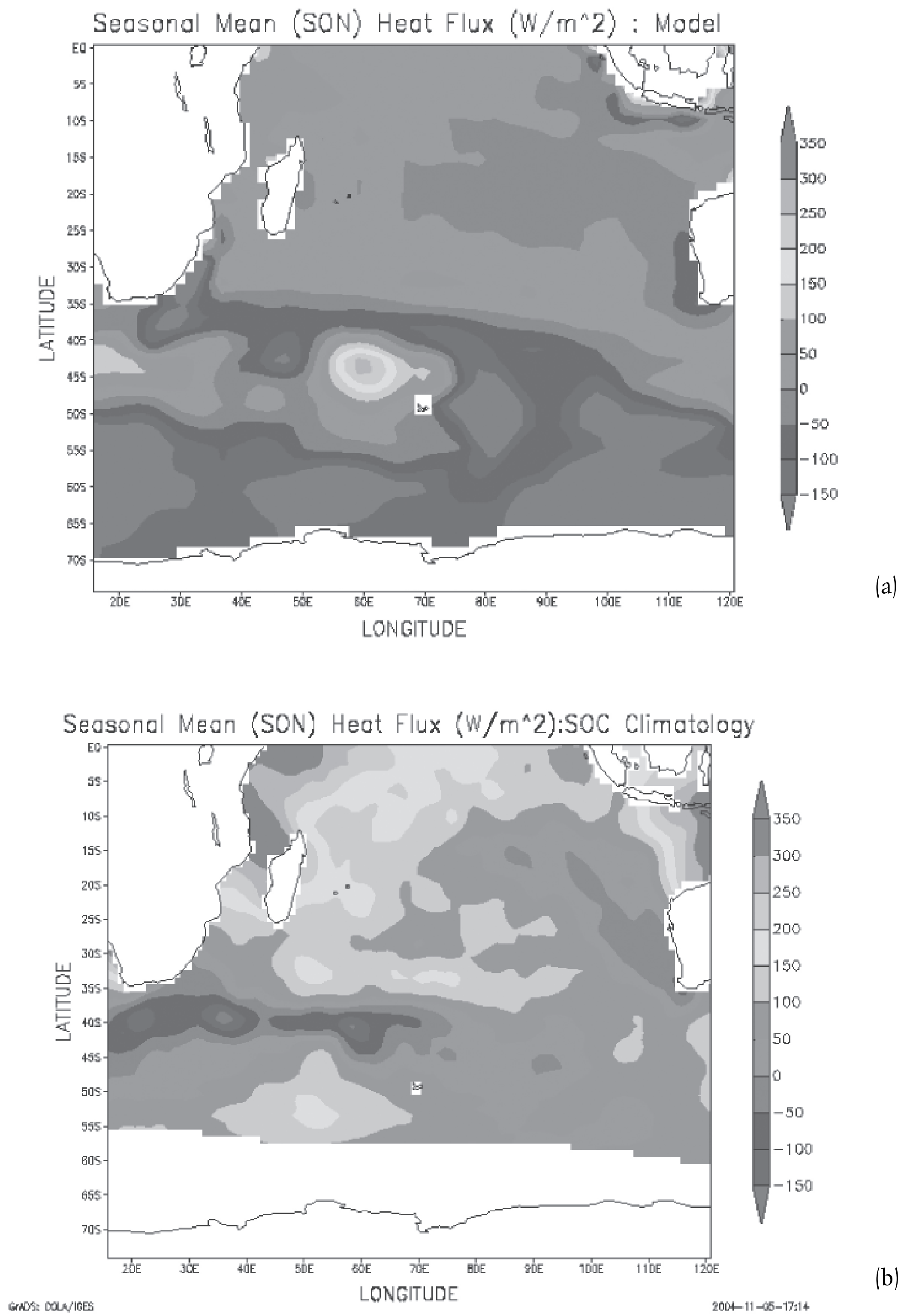

Figure 3. (a) Heat flux at the ocean surface for the season (SON) (Model) and (b) SOC climatology for SON. Units are in W/m^2. Positive values indicate heat gain by the ocean.

(Lorenz 1956) widely used in oceanographic and meteorological research (e.g., Weare, Navato & Newell 1976 and see review by Richman 1986) is the same as Principal Component (PC) Analysis (Hotelling, 1933) in the statistics community. PCs are the amplitudes, which are functions of time, of their corresponding EOFs. These EOFs can be found by calculating the unitary eigenvectors of the covariance matrix associated with the sample data field.

The EOF method is a "map-series" method of analysis that takes all the variability in the time evolving field and breaks it into (hopefully) a few standing oscillations and a time series to go with each oscillation. Each of these oscillations (each EOF) is often referred to as a "*mode of variability*" and the expansion coefficents of the mode (the PC) show how this mode oscillates in time. We wanted to use a method that can reduce the data to a few different mode of variability.

Interannual anomalies of the present ocean surface heat flux data, thus, can be quantitatively investigated with the method of EOF analysis and a number of generalized forms. In order to delineate the major modes of variability in the analysis of twenty four years (1975-1998) model output, we have performed an EOF analysis and obtained the first three leading EOF's, which are able to account for total variance of 53%. Since these patterns of first three EOF's are enough to explain the spatial anomalies of whole data. Hence it suffices to focus on the first three EOF's. The first three EOF's patterns of the Southern Indian Ocean heat flux variabilities are shown in the figs. 4, 5 and 6 respectively.

Figure 4 (a, b) represents spatial pattern of the 1st

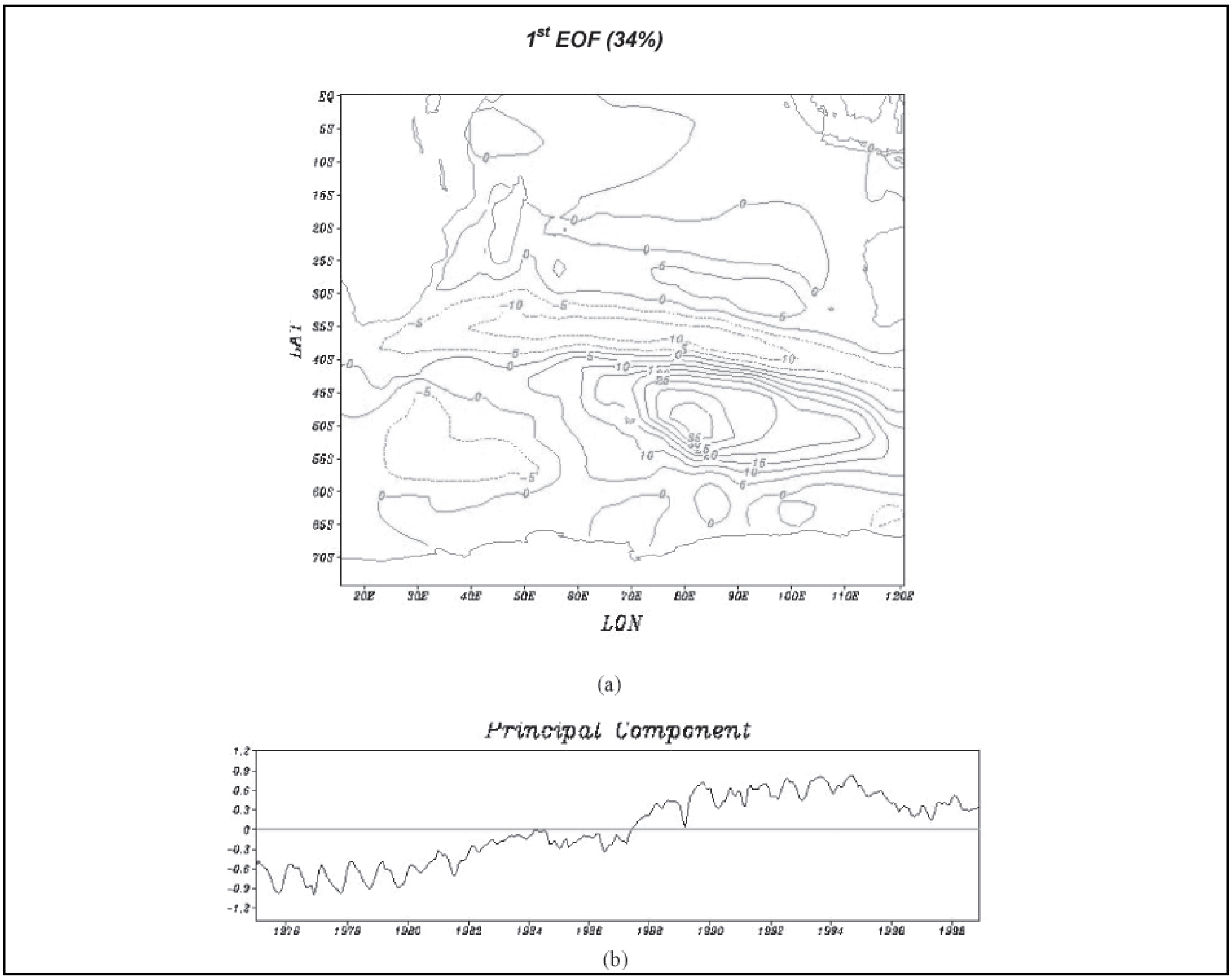

Figure. 4. (a) The spatial structure of 1st independent EOF mode for monthly mean anomaly of heat flux from 24 year (1975-1998) model integration. The contour interval is 5.0 W/m^2 and (b) shows principal component (nondimensional).

mode of EOF of monthly mean anomaly of heat flux for the period (1975-1998) and its accompanying time series (Principal Component). In the standard EOF analysis it is assumed that modes are orthogonal in space and time and that the first mode EOF is the mode that maximizes the explained variance over the entire period, the first EOF mode (Fig.4a) explains 34% of the total variance and its principal component (Fig.4b) is normalized by its maximum. Heat Flux Anomaly (HFA) is mostly distributed in between 25°S-65°S. Positive HFA is elongated between 60°E-120°E, 40°S-60°S. Negative HFA is seen in very small region 32°S-38°S, 30°E-120°E and in the region south of 50°S-60°S and 25°E-55°E (western part of the Southern Ocean).

In the Fig.4a it is obvious that large areas of positive loadings (Shabbar, Higuchi & Yuen 2003) in the eastern Southern Ocean (40°S-60°S, 55°E-120°E) signify a decrease in the energy transfer from atmosphere to the ocean. Fig.4a also identifies negative loadings pattern in the south of 30°S to 40°S elongated in zonal direction (longitudinally covering whole domain) and near 50°S-60°S, 25°E-55°E which shows a net increase in the net transfer of energy from atmosphere to the ocean. The internal circulation in the Southern Ocean and related ocean may be responsible for such a role in this region.

The first Principal Component (PC) for 1975-1998 shown in Fig.4b represents the temporal variation of associated spatial pattern described by EOF1. Further

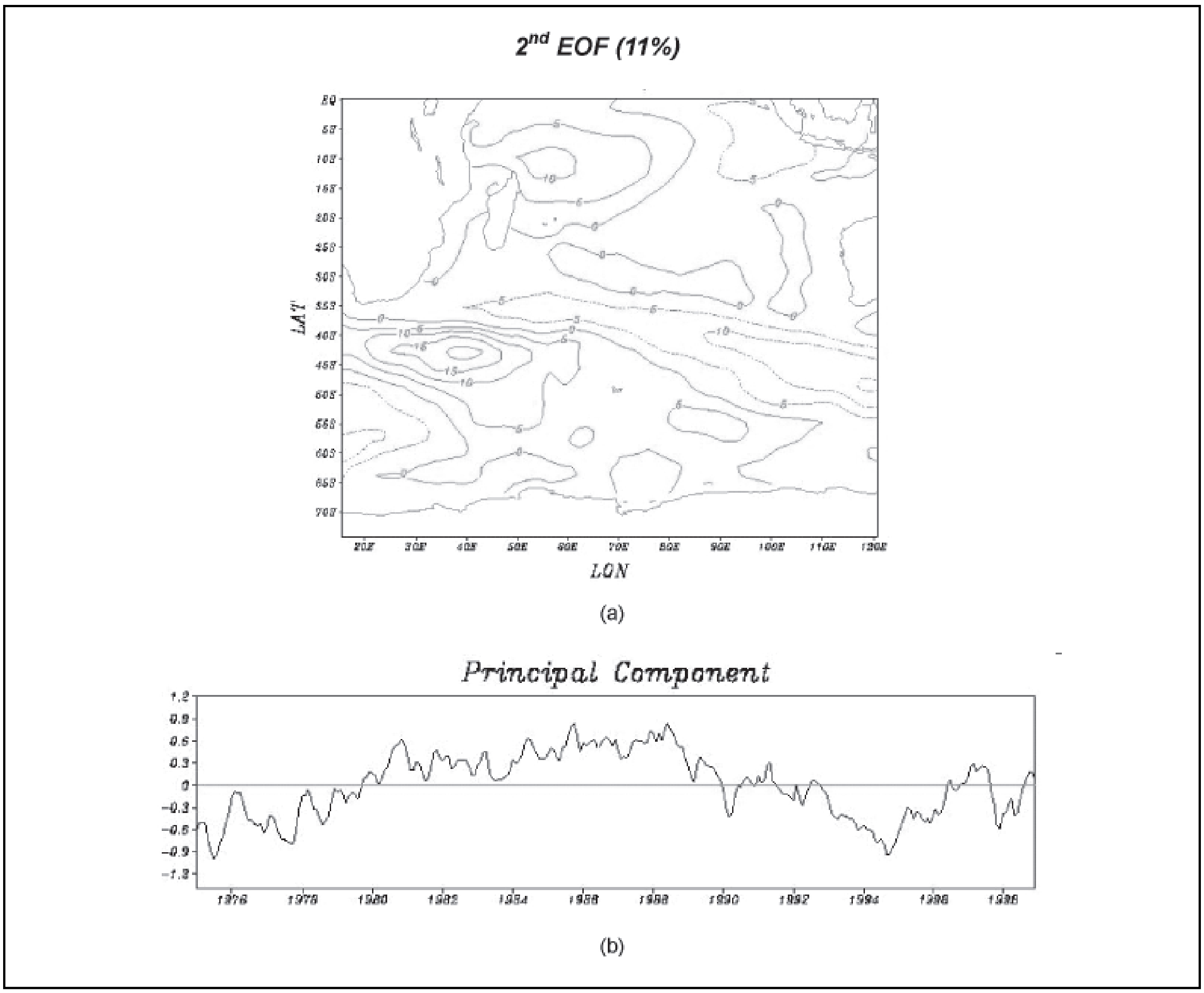

Figure 5. (a) The spatial structure of 2nd independent EOF mode for monthly mean anomaly of heat flux from 24 year (1975-1998) model integration. The contour interval is 5.0 W/m^2 and (b) shows principal component (nondimensional).

if the EOF1 mode is showing negative for certain years then PC < 0 corresponds to negative heat flux anomaly (HFA) and PC > 0 corresponds positive heat flux anomaly (HFA). Therefore as evidenced from time series from 1975-1987 (early January to late December), PC is always negative and reaching a minimum value of -1.0 which implies the negative HFA over this period with a net heat flux loss component in between 30°S-40°S, 30°E-120°E and the positive heat flux anomaly (HFA) with a heat flux gain component to South of 40°S i.e. 40°S-60°S; 60°E-120°E confined in the eastern part of the Southern Ocean.

Hence above facts indicate the appearance of two regions either having the components, net heat flux gain or net heat flux loss in the domain. Of particular importance is that spontaneous decadal variability (~11 yrs) has been found to exist in the present case with positive heat flux gain component in one oscillation and negative heat flux loss component in other oscillation. We thus identify that fluctuation of this pattern (EOF1) show decadal time scale variability.

Figure 5(a, b) represent 2nd EOF, which explains 11% of total variance and its Principal Component (PC). Second eigen vector (EOF2) indicates few contour lines close to the equator and also away from the south of 35°S which may be described as negative HFA residing in the eastern Indian Ocean in-between 35°S-50°S and getting elongated from 40°E-120°E and positive HFA is seen at two different places in the larger domain. First positive HFA is seen near western part of the southern Indian Ocean, equator to 20°S and second positive HFA is near 40°S-60°S (western

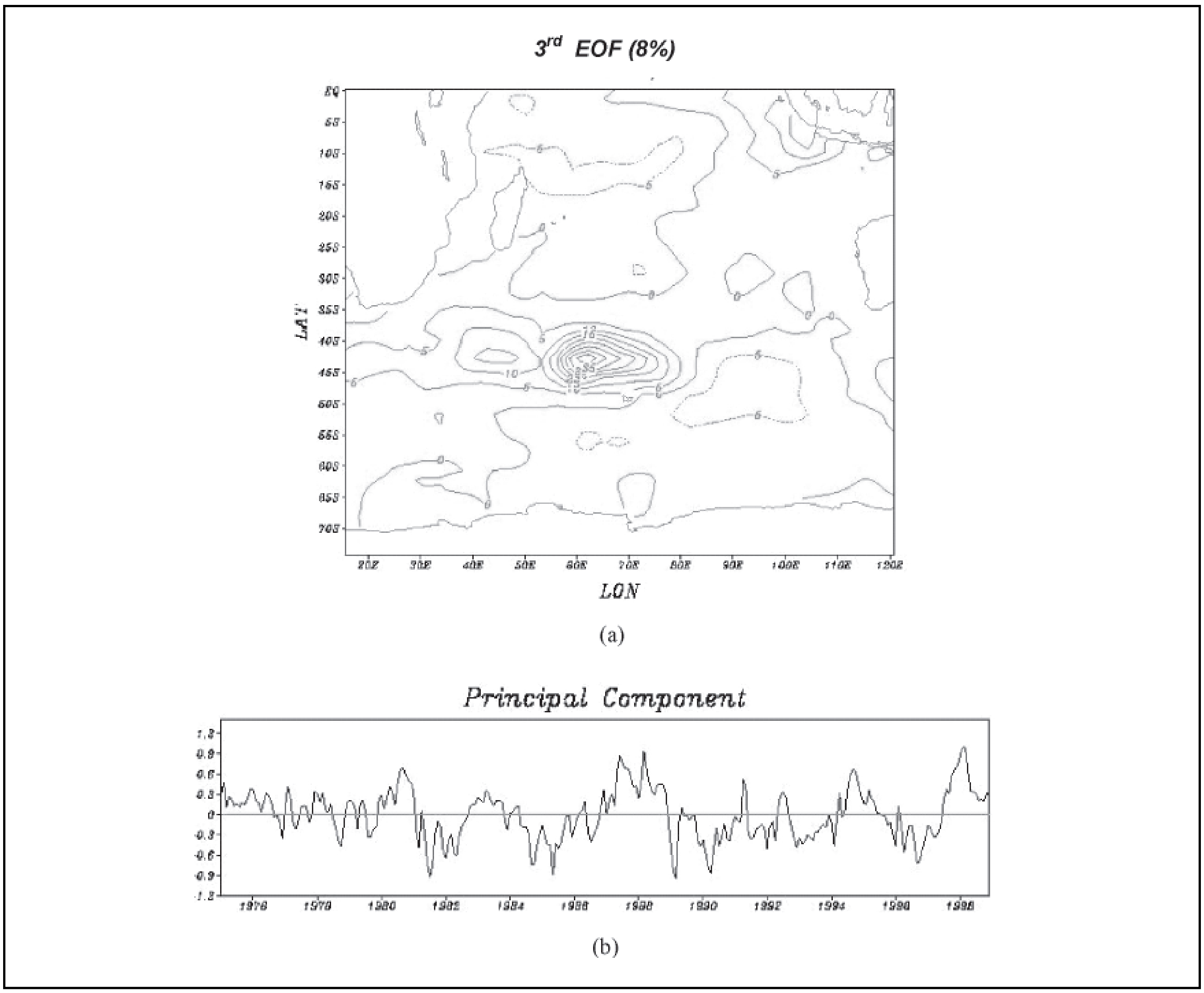

Figure 6. (a) The spatial structure of 3rd independent EOF mode for monthly mean anomaly of heat flux from 24 year (1975-1998) model integration. The contour interval is 5.0 W/m^2 and (b) shows principal component (nondimensional).

southern ocean) and corresponding PC seems to be quasi periodic with a period of few years. Thus we identify EOF 2 is associated with quasi-periodic oscillation pattern.

Figure 6 (a, b) represents 3rd EOF mode, which explains 8% of total variance and its PC. Third eigen vector (EOF3) indicates few contours spread in Southern Ocean (40°S and 50°S) that are positive and negative but the corresponding PC do not show any periodicity. So we recognize that no other eigen vector contribute much (all except first two are small) therefore we assume that everything else found in the data is just noise.

The EOF method thus allows us to view all the complicated variability of surface heat flux data and explain it only by first two processes.

The EOF analysis indicate that decadal variability has a positive feedback mechanism that operates mostly in the midlatitudes ocean / Southern Ocean and negative feedback mechanism that operates in tropics and partly in midlatitudes, so the largest heat flux anomalies are in the mid-latitude of the southern ocean. Previous studies have cited the contribution of the heat flux anomalies as the primary cause of decadal surface temperature anomalies. These model studies indicate that meridional advection of heat is at least an important. The timing of interannual and decadal changes in the atmosphere and in the ocean suggests that the atmosphere plays an important role connecting these phenomenons. One interpretation of the results is that interannual and decadal variability are manifestation of the same climate phenomenon but have crucially different feedback mechanisms

SUMMARY AND CONCLUSIONS

Comparisons of the annual mean and seasonal means net heat flux field from the model with the SOC climatological heat flux at the ocean surface along with its interannual variability have been presented qualitatively in this study. It is found that model and SOC net heat flux field seems to be in agreement in terms of the location at some places but not in terms of magnitude. However, the net heat flux field from the model agrees with SOC climatological heat fluxes moderately having spatial discrepancies involved in the two values at various locations. The SOC climatological heat flux is found to be overestimate the model heat flux values and vice–versa at various locations in the present domain. The mechanism responsible for these differences may be attributed to the deficiency with model physics or sampling related bias in SOC data sets and also different bulk formulas used in computing the heat fluxes in model and SOC climatology. Further, the seasonal climatology from the model is also in agreement with the SOC seasonal means in terms of location, but not in terms of magnitude. However, it is reasonable to mention that quality of the field has a strong spatial dependence and decreases in Southern Hemisphere, in particular south of 30°S where the number of observations decreases considerably and uncertainties on the flux estimate increases (Glecker & Weare 1997) the errors tend to be large and therefore model results and cliamtologies have differences in the region.

The impression of the EOF's is that the spread in percent variance explained looks reasonable and they appear to be well separated. As far as trends in the model are concerned, then the first EOF represent strong trend in surface heat flux field in the region of the Antarctic Circumpolar Current (ACC) and in the Southern Polar Ocean and dominant pattern represents a decadal trend in high-latitude heat fluxes over the period of the integration.

Once again, it could be stated that our results are consistent with the notion that regional biases in the simulation of Southern Indian Ocean may not be attributed to deficiencies in the representation of a single physical processes, but are rather due to discrepancies amplified individually by OGCM's and SOC data.

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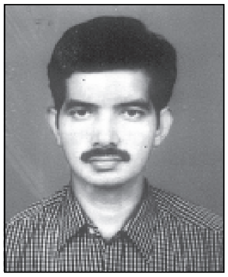

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