Unusual ocean-atmosphere conditions in the tropical Indian Ocean during 1994

S.K. Behera[1], R. Krishnan[1] and T. Yamagata[2]

IGCR, Frontier Research System for Global Change, Tokyo, Japan

Abstract. The southeastern tropical Indian Ocean (SETIO) was characterized by unusually cold sea surface temperature (SST) and strong northwestward alongshore surface winds during 1994. Using multi-source data sets including ocean model simulation, two key processes are identified for the SETIO cooling. Entrainment cooling produced most of the negative SST anomaly near the coast whereas evaporative cooling dominated the process away from the coast. Convection was anomalously suppressed over SETIO and the divergence of moist air from the region helped the local evaporative process. This also led to anomalous moisture transports that explain the enhanced convection over the central equatorial Indian Ocean, India and East Asia. The positive feedback between the enhanced and suppressed convection regions in turn helped maintain the surface wind anomalies. These evidences clearly indicate the existence of an ocean-atmosphere coupled phenomenon in the Indian Ocean during 1994.

1. Introduction

A conspicuous feature in the southeastern tropical Indian Ocean (SETIO) during 1994 was the occurrence of an unusually cold sea surface temperature (SST) anomaly. The cold anomaly started developing around the beginning of 1994 (Fig.1a), attained very large amplitude (< -2°C) during the northern summer monsoon months and continued into fall. Examination of SST data from 1982 did not reveal any colder anomaly in the previous years reaching such large amplitude in SETIO region. West of the cold anomaly, a warm SST anomaly (0.5°C) prevailed in the central Indian Ocean (CIO). Moreover, there was a drop (rise) in the sea level over the SETIO (CIO) as revealed from the sea surface height anomaly (Fig.1b). Like SST, winds were also unusual in the tropical Indian Ocean during 1994. From the cross sections of wind stress anomalies (Figs.1c & 1d), it can be seen that the easterly anomaly of magnitude greater than 0.1 dyn cm^{-2} covers most of the tropical ocean east of 60°E. The corresponding southerly anomaly is confined to the east of 80°E.

It is well known that the annual cycle of the monsoon influences the seasonal changes in the Indian Ocean through local and remote responses [*McCreary et al.* 1993; *Yamagata et al.* 1996; *Masumoto and Meyers* 1998]. The variability associated with the passage of the equatorial Yoshida-Wyrtki jet [*Wyrtki* 1973] affects the thermocline depth along the Indonesian coast [*Vinayachandran et al.* 1999]. However, the process peaks only during the transition months of spring and fall. Therefore, it is interesting to understand the key dynamics and thermodynamics that are responsible for the 1994 boreal summer SST anomalies in SETIO considering the anomalous conditions as described above. To address the problem, we have made diagnostic analysis of NCEP reanalysis data [*Kalnay et al.* 1996], SST data [*Reynolds and Smith* 1994], TOPEX/POSEIDON sea surface height anomaly data, precipitation data [*Xie and Arkin* 1996] and experiments with an intermediate ocean model [*McCreary et al.* 1993].

[1]Also at Indian Institute of Tropical Meteorology, Pune 411 008, India

[2]Also at Department of Earth and Planetary Physics, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan

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2. Oceanic processes

The spatial pattern of the summertime SST anomaly from the data clearly shows a dipole structure in the southern tropical Indian Ocean (Fig.2a) having a cold eastern pole east of 85°E in the SETIO and a warm western pole in the CIO. Strong southeasterly wind stress anomalies prevail over the cold pole; while easterly anomalies dominate over the warm pole (Fig.2a). In order to simulate the oceanic processes, we adopt the 2.5 layers ocean model known to produce a fairly realistic simulation of the climatology [*McCreary et al.* 1993] as well as the interannual variability of SST in the Indian Ocean [*Behera et al.* 1998]. In short, the model has two active layers, which interact with each other through entrainment and detrainment while conserving mass and heat of the total system. The top layer is composed of a well-mixed upper turbulent sub-layer and a non-turbulent fossil sub-layer. The upper sub-layer entrains or detrains water due to turbulent mixing generated by both wind stirring and surface cooling. The temperature of the upper sub-layer is considered as the model SST. For further details of the model, readers are referred to *McCreary et al.* [1993]. The model is forced using the surface fluxes derived from the daily NCEP reanalysis data. Computations of the latent and sensible heat fluxes make use of the model simulated SST. The model is first spun up for 10 years from an initial condition of rest using the daily mean surface fluxes obtained from a 7-year (1992-1998) climatology. Following the spin-up period, two 7-year experiments (EXP-1 and EXP-2) are carried out. EXP-1 makes use of the climatological forcings whereas interannually varying daily fluxes are used in EXP-2. A difference of EXP-1 and EXP-2 is thus intended to bring out the changes in the ocean response induced by the surface flux anomalies.

The dipole in the simulated SST anomalies (Fig.2b) agrees quite well with that of the observed anomalies (Fig.

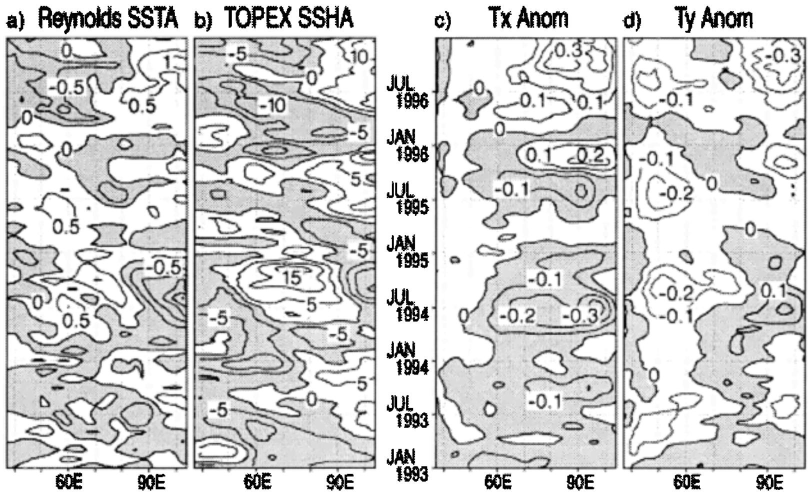

Figure 1. Longitude-time cross section of a) Reynolds SST anomaly b) TOPEX/POSEIDON sea surface height anomaly c) NCEP zonal and d) meridional surface wind stress anomalies along 7°S. SST anomaly contour interval is 0.5°C and negative values are shaded. Sea surface height anomaly contour interval is 5 cm and negative values are shaded. Stress anomaly contour interval is 0.1 dyn cm^{-2} and negative (positive) values for zonal (meridional) component are shaded. A three month running mean is applied to smooth the time series.

2a). The model current anomalies (Fig.2b) are diverging westward from the Sumatran coast in response to the anomalous southeasterly winds. The mass divergence causes the upper layer to shallow by as much as 35 meters near the coast (figure not shown). At the same time, anomalous convergence causes deepening of upper layer in the central region. Near the Sumatra coast, the model cold SST anomalies match with the anomalous shallowing of the upper layer. Farther away from the coast, however, the upper layer is not shallow enough to explain the cooling. The anomalies of SST and the sea surface height from the data also show this miss-match (Figs.1a and 1b), which suggests the role of multiple processes for the SETIO cooling as discussed in the next paragraph. The seasonal mean upper layer depths in the eastern tropical Indian Ocean, north of the equator, are deeper compared to that of the south explaining the asymmetry in the SST anomalies on both sides of the equator.

The contribution of each term in the model SST equation [*McCreary et al.* 1993] in generating the cold anomaly is diagnosed. The spatial pattern of model SST anomaly tendency (Fig.3b) is in fairly good agreement with that of the data (Fig.3a). The plots show cooling (warming) tendency to the north (south) of 10°S in SETIO. This has happened due to the northward shift of the maximum amplitude of the cold anomalies along the coast as the stronger southeasterly winds move northward with the progress of the season. The entrainment (Fig.3c) and the latent heat (Fig.3d) terms are found to be the two dominant contributors for the cooling tendency. Negative anomalies of the entrainment term are seen east of 88°E centered close to the Sumatran coast with values less than -35 Wm^{-2}. On the other hand, the negative anomalies due to latent heat are extended up to 70°E and the center is offset by several hundred kilometers from the coast with central anomaly of -35 Wm^{-2}. We also noted a minor contribution from the zonal advection term with central value of -5 Wm^{-2} near the coast. This suggests that the entrainment term is responsible for most of the strong cooling near the coast whereas the latent heat term largely contributes to the cooling farther away from the coast. *Meyers* [1996] has discussed the role of upwelling for the cold anomalies off Java found in the second empirical orthogonal function i.e. not related to El Niño - Southern Oscillation response. It can be noted that the reduction of the seasonal upwelling due to the positive anomaly in the entrainment term is responsible for the warming in CIO.

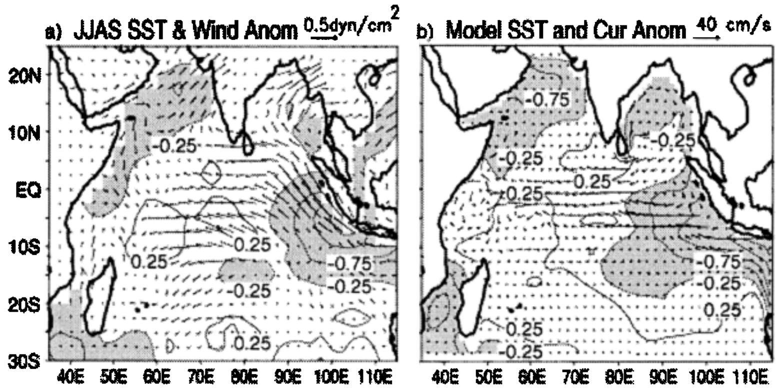

Figure 2. The mean 1994 JJAS (June, July, August and September) anomalies for a) Reynolds SST and NCEP wind stress b) model SST and upper layer current. Contour interval is 0.5°C and negative values are shaded.

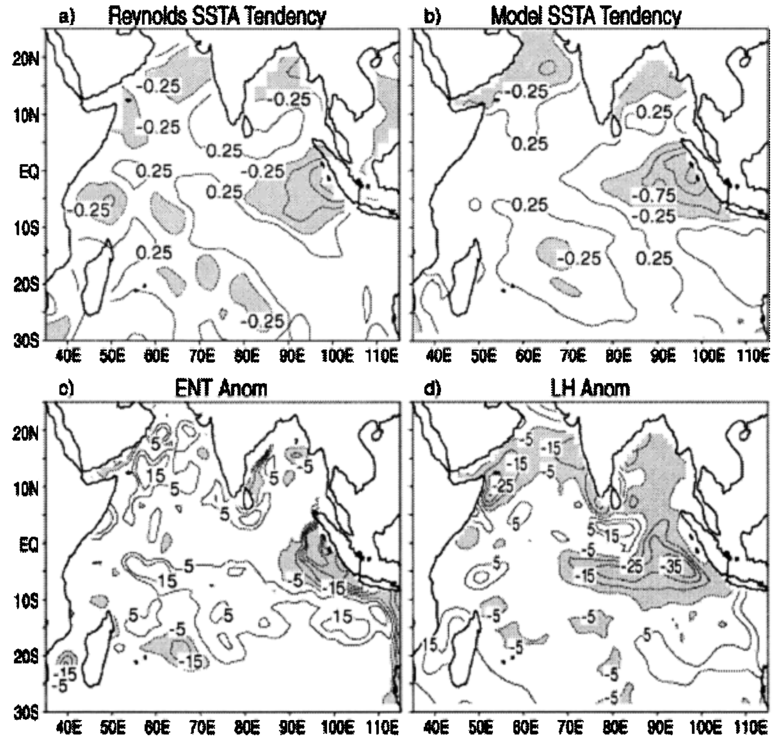

Figure 3. The 1994 summertime anomaly tendency (difference between the last week of September and the first week of June) of a) Reynolds SST and b) model SST. Contour interval is 0.5°C and negative values are shaded. The mean JJAS anomalies (EXP1-EXP2) of the c) entrainment term and d) latent heat term. Contour interval is 10 Wm^{-2} and negative values are shaded.

3. Anomalous atmospheric conditions

The cold anomaly in SETIO during 1994 coincided with suppressed convection as revealed from the precipitation anomalies [*Xie and Arkin* 1996] shown in Fig.4a. At the same time, enhanced convection prevailed over the equatorial CIO, India and East Asia. Considering a negative phase of the Southern Oscillation during the 1994 summer, one would have expected a deficit monsoon rainfall over India for that season [*Rasmusson and Carpenter* 1983]. But, it so turned out that the Indian subcontinent surprisingly experienced one of the heaviest monsoon rains in that season [*Parthasarathy et al.* 1995]. Further, the convective anomalies are consistently supported by the observed circulation anomalies, from NCEP reanalysis, which reveal ascending motions over India, East Asia and the CIO region and strong descending motions over the SETIO region (figure not shown). Thus, the lower tropospheric divergence i.e. associated with the suppressed convection over SETIO is responsible for the surface wind anomalies. The wind anomalies are further enhanced by the surface convergence due to enhanced convection over warmer waters in equatorial CIO. The anomalous convergence and divergence are even traced in the wind stress anomalies (Fig.2a). So, the anomalous atmospheric vertical cells produced by these two anomalous convective regions and that over India and East Asia sustained the process. The feedback mechanism in SETIO evolved from the beginning of boreal spring and peaked in the boreal summer and then died down as the monsoon

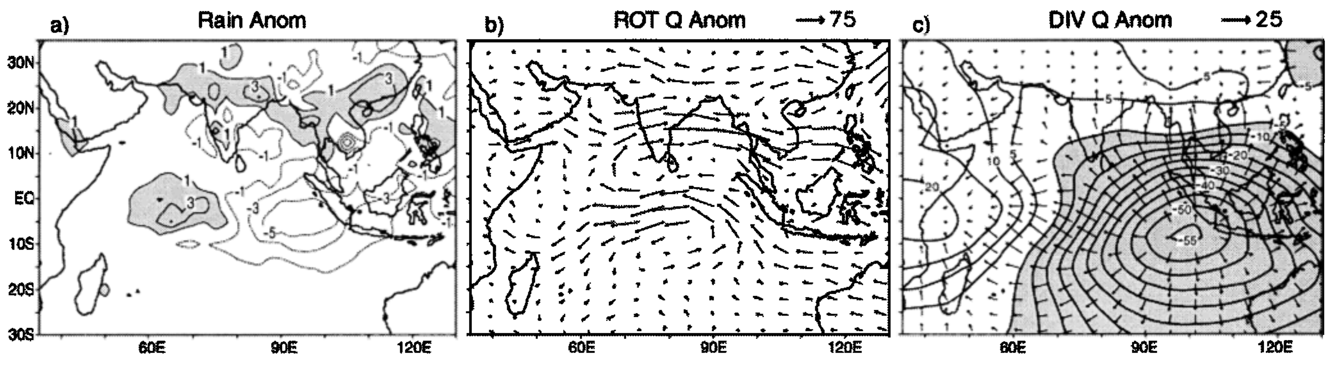

Figure 4. Same as Fig.2 but for a) precipitation anomalies, contour interval is 2 mm day^{-1} and values greater than 1 mm day^{-1} are shaded. b) The anomalies of rotational component ($\vec{Q_\psi} = \hat{k} \times \nabla\psi_Q$) of $\vec{Q}$ in units of kg m^{-1} s^{-1}. The scalar ψ_Q is the streamfunction and the unit vector $\hat{k}$ is in the vertical direction. c) The divergent ($\vec{Q_\chi} = \nabla\chi_Q$) component of $\vec{Q}$ expressed as kg m^{-1} s^{-1}. The values of scalar χ_Q i.e. the velocity potential are contoured. The negative anomalies are shaded and contour interval is 5×10^6 kg s^{-1}.

reversed. This can be clearly seen east of 90°E in the SST and wind stress anomalies shown in Fig.1.

To gain further dynamical insight about the 1994 phenomenon, we have examined the anomalous moisture transport using the NCEP reanalysis data. Past studies suggest that the cross-equatorial transports of moisture from the Indian Ocean [*Saha and Bavadekar* 1973] and the Arabian Sea are the major contributors to the summer monsoon precipitation over India. Following *Chen* [1985] and *Krishnan* [1998], the vertically integrated water vapour transport vector is defined as $\vec{Q} = \frac{1}{g}\int_{P_u}^{P_l} q\vec{V}\, dP$, where g is the acceleration due to gravity and q is the specific humidity, $\vec{V}$ is the horizontal wind field, P_u is the pressure at the top of the atmosphere and P_l is the surface pressure. The use of Helmholtz theorem allows us to separately describe the moisture transport (rotational) and flux divergence (irrotational) terms. The anomalous moisture transports in Fig.4b show easterly anomalies near 5°S taking moisture away from the SETIO region towards the CIO region. Significant amount of moisture is also anomalously transported to the northern hemisphere as evident from the cross-equatorial deflection of the flow around 65°E. Here it is also important to note the strong latitudinal variation of anomalous $\vec{Q_\psi}$ from 60-100°E (Fig.4b). The anomalous westerly flow in the northern hemisphere forms a cyclonic circulation that represents an intensification of the lower tropospheric trough over India better known as the monsoon trough [*Krishnamurti and Surgi* 1987]. It can be seen that the intensified monsoon trough is co-located with the belt of enhanced precipitation over the Indian and Asian landmass. The significance of the SETIO region as an important source of moisture during 1994 is further illustrated by the anomalies of moisture divergence ($\vec{Q_\chi}$) in Fig.4c. One can clearly see the large anomalous divergent outflow of moisture from the SETIO region and convergence over the CIO and the monsoon regions of India and East Asia. Such a strong removal of moisture and the associated loss of latent heat from the ocean explain the large evaporative cooling of the SETIO.

4. Summary

Enhanced atmospheric convection (ascending motions) over the monsoon regions of India and East Asia, the warm CIO region and strong vertical subsidence over the cold SETIO region maintained the anomalous surface wind forcing that was responsible for the SETIO cooling during 1994. The SETIO region in turn acted as an important source of moisture so as to sustain the anomalous convection. These findings clearly demonstrate the existence of a feedback mechanism between atmospheric convection and SST in the tropical Indian Ocean. The question still remained is what caused the selective evolution of such a phenomenon in 1994. Investigation for the existence of such events in the past is greatly hindered by the poor data coverage. Strengthening of the data coverage will enhance the understanding of the complex ocean-atmosphere-land coupled phenomenon and its influence on the regional and global climate.

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S.K. Behera, R. Krishnan and T. Yamagata, Institute for Global Change Research, FRSGC, SEAVANS N 7F, 1-2-1 Shibaura, Minato-ku, Tokyo 105-6791, Japan (e-mail: skb@frontier.esto.or.jp; krish@frontier.esto.or.jp; yamagata@geoph.s.u-tokyo.ac.jp)

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