

The physics of ENSO-monsoon connection

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The physical mechanism through which El-Nino and Southern Oscillation (ENSO) tends to produce deficient precipitation over Indian continent is investigated using both observations as well as a general circulation model. Both analysis of observations and atmospheric general circulation model (AGCM) study show that the planetary scale response associated with ENSO primarily influences the equatorial Indian Ocean region. Through this interaction it tends to favour the equatorial heat source, enhance precipitation over the equatorial Indian Ocean and indirectly cause a decrease in continental precipitation through induced subsidence. This situation is further complicated by the fact the regional tropospheric quasi biennial oscillation (QBO) has a bimodal structure over this region with large amplitude over the Indian continent. While the ENSO response has a quasi-four year periodicity and tends peak during beginning of the calendar year, the QBO mode tends to peak during northern summer. Thus, the QBO mode exerts a stronger influence on the interannual variability of the monsoon. The strength of the Indian monsoon in a given year depends on the combined effect of the ENSO and the QBO mode. Since the two oscillations have disparate time scales, exact phase information of the two modes during northern summer is important in determining the Indian summer monsoon. The physical mechanism of the interannual variations of the Indian monsoon precipitation associated with ENSO presented here is similar to the physical process that cause intraseasonal 'active', 'break' oscillations of the monsoon.

The relation between ENSO related SST changes in the Pacific and Indian monsoon rainfall has been known since early twenties¹. Studies on the simultaneous relationship between Pacific SST and Indian summer monsoon over the last century reveals that droughts occur in India with and without El Nino in Pacific and there are many years where there were above normal rainfall while there was an El Nino evolving in Pacific. Thus the contemporaneous relationship between Pacific SST and Indian summer monsoon has been rather weak^{2,4}. The simultaneous correlation between ENSO indices and Indian monsoon rainfall is only 0.5, i.e. the ENSO SST has a modulating effect on the monsoon rainfall and is not a dominating one.

Why the ENSO SST does not have a dominating influence on the monsoon rainfall is likely to be related to the physical mechanism through which ENSO SST influence Indian monsoon rainfall. While most variations of precipitation in the equatorial region is related to east-west movement of the precipitating inter tropical convergence zone

(ITCZ), the Indian summer monsoon is associated with a gigantic north south movement of the ITCZ. The special shape of the continent and the position of the Himalayas produce a favourable location for the ITCZ over the land during northern summer. However, the waters to the south-south east are still warm ($>28^{\circ}\text{C}$) with a maximum close to the equator and hence also favours an oceanic ITCZ⁵. As a result, it is a competition between the two ITCZs that determine the precipitation over the continent. This competition results in the intraseasonal oscillations (ISO) of the monsoon and manifest in the northward propagation of the ITCZ⁵⁻⁷. As an outcome of this competition the ITCZ resides over the continent for a longer period, resulting in the precipitation maximum over the land. However, the signature of the oceanic ITCZ can be seen even in the climatological June-August (JJA) mean precipitation with a secondary precipitation maximum over the equatorial Indian Ocean. Because of this special feature, the Indian

monsoon is unique as compared to the other tropical circulations. The interaction between ENSO and monsoon must necessarily take this special feature of monsoon into account. The two favourable positions can be considered as two attractors for the ITCZ. The ITCZ tends to reside in one attractor for some time before a perturbation pushes it out to the other attractor where it tends to reside for some time leading to the intraseasonal oscillations⁸. This process is governed by internal dynamics and may have limited predictability. The interannual variability (IAV) of the seasonal mean monsoon is governed not by detailed evolution of the individual ISO but by the statistics of them (e.g. frequency of occurrence, mean amplitude etc.). The statistics of the ISO may be modulated by the large scale environment created by the slowly varying boundary conditions such as that associated with ENSO. Through such a modulation of the ISO, the ENSO influences the interannual variability of the monsoon. Modelling studies^{9,10} support this perspective where it is shown that the spatial patterns of both the intraseasonal and interannual variability of the simulated monsoon are strikingly similar. The objective of the present study is to bring out clearly the physical mechanism through which ENSO influences the monsoon.

Materials and Methods

Present study examines the three dimensional pattern of the large scale response associated with ENSO related SST. It is studied by conducting a diagnostic study of European Centre for Medium Range Forecasting analysis for 15 years using a multivariate empirical orthogonal function (MEOF) analysis employing the singular value decomposition (SVD) technique. This technique separates the quasi four year planetary scale ENSO response from the regional scale response which appears in the form of a quasi biennial oscillation (QBO).

The primary data used in the present study are the monthly means of operationally analysed winds from the ECMWF, for the period 1980-1994. The zonal and meridional winds at 1000 mb, 850 mb, 700 mb, 500 mb, 300 mb and 200 mb are used. Also used are the SST (COADS and CAC) for the same period. The domain of analysis covers

the tropical Indian and Pacific oceans. To decipher the recurrent 3-D structure of combined variability, the multivariate EOF analysis is used. This unique technique has brought out some interesting results which have provided new insight into the dynamics of interannual variability of the monsoon.

The results of the diagnostic study is supplemented by a GCM study. In this study the Geophysical Fluid Dynamics Laboratory's climate model simulates the present climate between 1979 and 1993 with the observed monthly SST prescribed as boundary conditions. As in the diagnostic study, monthly mean model simulations are used. The results of the simulation are again subjected to a multivariate EOF analysis. This analysis also allows separation of the response associated with ENSO SST from the regional response. As in the observation, the regional response in the model simulations too manifest in the form of a quasi biennial mode (QBO). The analysis again reveals that ENSO SST response is essentially confined to equatorial Indian Ocean while the QBO has dominant bimodal meridional structure with large response over the continent.

Results and Discussion

The first six recurrent combined spatial and temporal structures obtained from the MEOF analysis represent physical modes. The interesting aspect of these results is the separation of the physical modes corresponding to the quasi-four year oscillation (LF) and the physical modes corresponding to the quasi-biennial oscillation (QBO). It may be recalled that these two oscillations dominate the tropical low frequency variability¹¹.

Based on the examination of the large scale spatial structures, the common coefficient time series (PCs) and the corresponding spectra, the first three modes (MEOFs 1-3) are identified as those associated with ENSO forcing. These modes together explain about 52% of the domain averaged variance. The spectra of all three PCs are dominated by a quasi-four year period. The vertical structure of these planetary scale modes is baroclinic and the phase transition takes place at around 500 mb level. The other three modes (MEOFs 4-6), totally explaining about 15% of the

domain averaged variance are related to regional scale circulations. This is supported by the spatial structures and the spectra of the corresponding PCs. The spectra of all these three PCs (PCs 4-6) are dominated by a quasi-biennial oscillation. However, the vertical structure of these regional scale modes is quite different from that of the planetary scale modes. It is found that the phase transition of the anomalies associated with this mode takes place only around 300 hPa.

The conceptual picture of the monsoon variability is related to the strength and competition of the two heat sources, one over the equatorial Indian Ocean and the other over the Indian continent⁵. From the composites of good minus bad monsoons, we found that the planetary scale modes with a LF quasi-four year variability associated with the ENSO forcing, favour and modulate the oceanic heat source (Fig. 1). Composites of vorticity at 850 mb are shown in Fig. 1. The low level vorticity assumes significance as cyclonic vorticity above the boundary layer makes it possible for the low level moisture to reach the level of lifting condensation and allows it to form deep heat source through boundary layer frictional convergence. The regional scale modes having a QBO variability favour the continental heat source. It is also found that this heat source is responsible for the winds off the Somali coast, Bay of Bengal and into the continent. These two observations support the hypothesis that the net moisture convergence over the oceanic heat source is significantly modulated by the planetary scale circulations while the net moisture convergence over the Indian continent is mainly due to the regional scale circulations. Thus it is clear that the effect of ENSO on monsoon is basically confined to the oceanic ITCZ. The ENSO influences the interannual variability of the monsoon indirectly through interaction between the two ITCZs.

It is not feasible from observations to assess and quantify the various physical processes that are responsible for the moisture convergence into the two heat sources. Nevertheless, the total effect of these processes can be seen in the vorticity fields at 850 mb. Analysis of the relative vorticity fields at 850 mb showed that there are two cyclonic vortices over the monsoon domain, one associated

with the oceanic ITCZ and the other associated with the continental ITCZ. It is seen that during major ENSO events (e.g. 1982) both the LF and QBO are in phase over both the oceanic and the continental ITCZ, thus enhancing the oceanic precipitation and suppressing the continental precipitation. In the period of analysis, it is observed that the contribution of the LF variability dominates the oceanic ITCZ during major ENSO events but its effect over the continent is weak (Fig. 2). In some years, the contribution of the LF and QBO modes are comparable in magnitude over

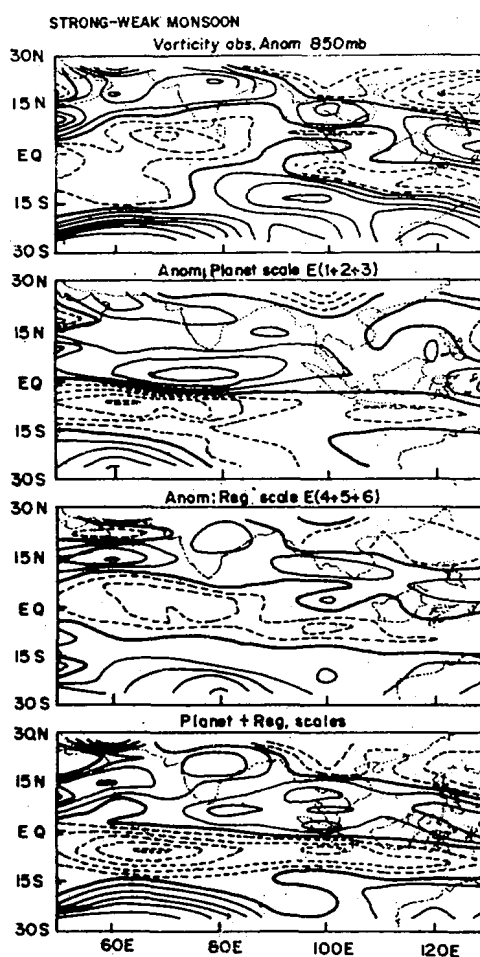


Fig. 1 — Difference of anomalous vorticity at 850 mb between strong monsoon years (1983, 1988 and 1994) and weak monsoon years (1982, 1987, 1985). Top panel shows the total field. Anomalies associated with EOFs 1-3 and EOFs 4-6 are shown. The positive contours are thin solid lines while the negative contours are dashed lines. The zero line is thick solid line, contour interval is $0.5 \times 10^{-6} \text{ s}^{-1}$.

the oceanic region, but the QBO modes always dominate the vorticity field over the Indian continent (Fig. 3). The circulations over the ocean and continent associated with the ENSO forcings, have opposite structures throughout the vertical plane. This is further supported by the regional scale modes. These results confirm that the circulation over the equatorial Indian Ocean, during monsoon season, tends to oppose the circulation over the Indian continent. However, recall that the planetary scale part of the circulation modulating mainly the oceanic heat source oscillates with a quasi-four year period and peaks in the beginning of the calendar year while the regional part modulating the continental heat source oscillates with a QBO, and peaks during summer monsoon season. Thus, in a particular year, whether the monsoon will be 'good' or 'bad'

depends crucially on the phases of these two oscillations. This explains why in some year the Indian monsoon may be 'good' while there may be an El-Nino in Pacific, as was the case in 1997.

The following important point may be noted from Figs 1-3. Although EOFs 1-3 together explain 52% of domain averaged variance and EOFs 4-6 explain only 15% of domain averaged variance, over the continent, the anomalies associated with EOFs 4-6 are in fact larger than those associated with EOFs 1-3 (Figs 2, 3). Thus, regional quasi biennial oscillation imparts a significant control in determining the interannual variations of the Indian monsoon.

The conceptual picture stressed in the introduction is clearly brought out in the present study from observational data set. To conclude, in order to explain the relationship between monsoon and ENSO, the contribution and competition

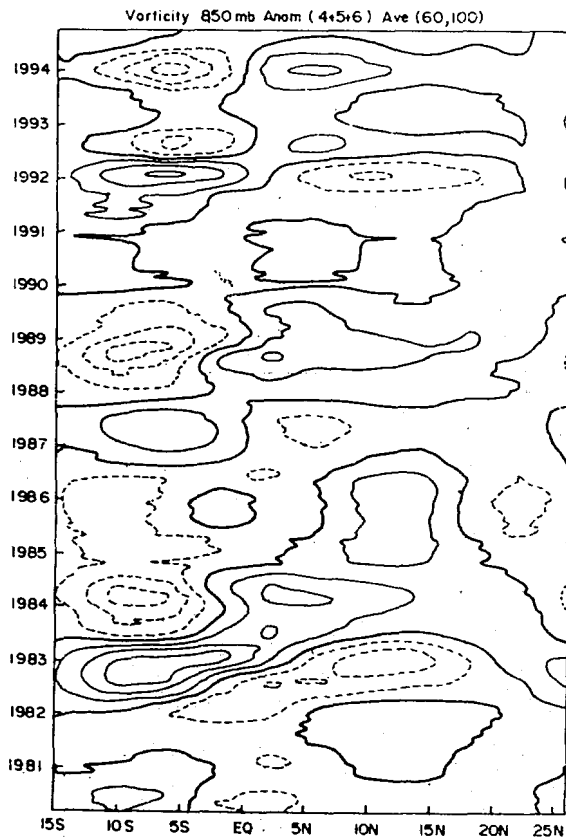


Fig. 2—Time-latitude section of 850 mb vorticity anomalies associated with EOF1-EOF3 averaged between 60° E-100° E. Contour interval same as in Fig. 1. Contour interval $0.5 \times 10^{-6} \text{ s}^{-1}$.

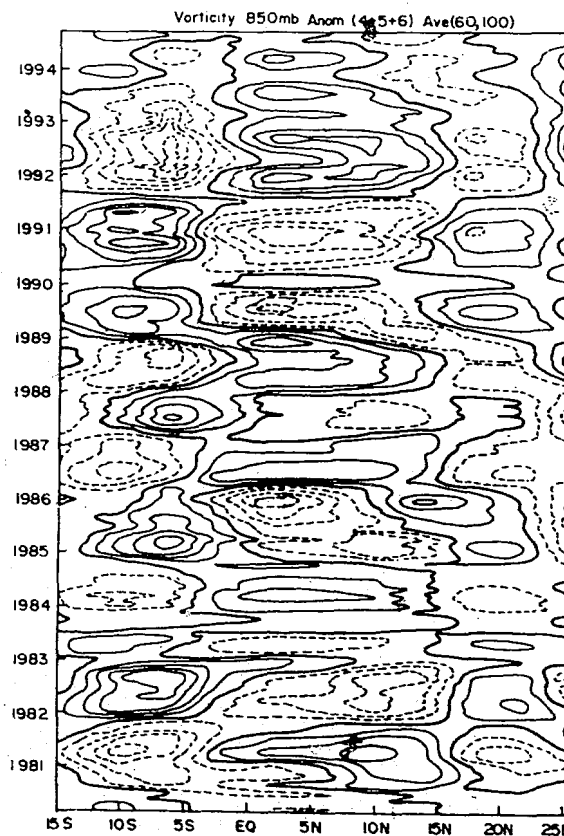


Fig. 3—Same as Fig. 2 but associated with EOF4-EOF6. Contour interval same as in Fig. 1. Contour interval $0.2 \times 10^{-6} \text{ s}^{-1}$.

between the planetary scale circulation (ENSO forcing) and the regional scale circulation (QBO may be due to internal dynamics) should be taken into account.

The connection between ENSO related planetary scale response on the Indian monsoon within the context of an atmospheric general circulation model is also studied. For this purpose, the simulation of the present climate from January 1979 to December 1993 by the GFDL climate model is examined. This version has R30 horizontal resolution and 14 levels in the vertical. Monthly mean observed sea surface temperatures

(SST) for the period are prescribed as boundary condition. Further details about the physical parameterization used in the model and the experiment are described in Goswami¹². The simulation of the mean monsoon climatology by the model is quite realistic. Figure 4 shows mean January, August and June-September precipitation based on 15 years simulation of the model. Comparison with corresponding observation shown in the left panel. One systematic weakness of the model is to simulate a weaker secondary precipitation maximum over the equatorial Indian Ocean during the summer season. The reasonably

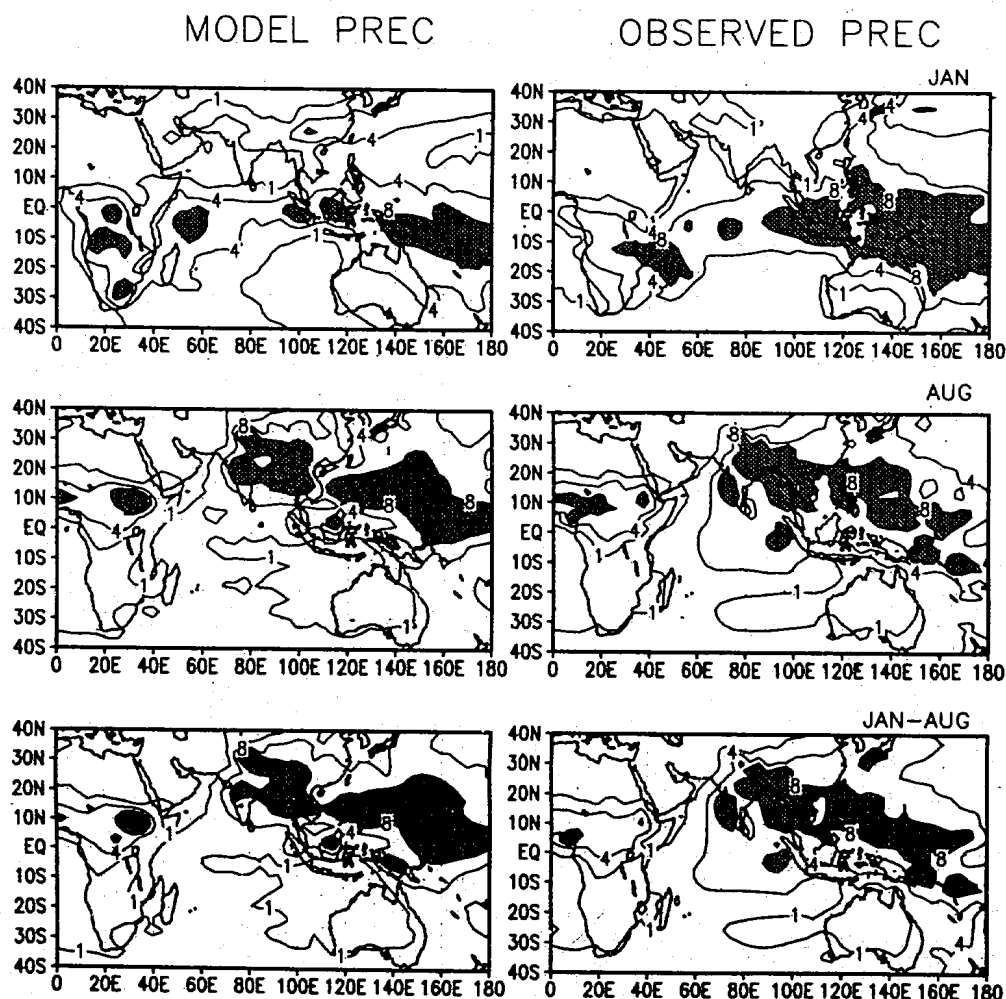


Fig. 4—Climatological mean January (JAN), August (AUG) and June-September (JJAS) precipitation. The simulated mean derived from the 15 years simulation (right panels) is compared with observations (Legates and Willmot, 1990, Left panels). Contours are 1, 4, 8, 16, 32 mm/day. Precipitation greater than 8 mm/day is shaded.

good monsoon climatology of the model makes it suitable for studying interannual variability.

The multivariate EOF analysis used in the observations is also employed to study the model results. To bring out the three dimensional structure of the combined variability, SST and

simulated surface pressure, precipitation, winds at 860 mb and 170 mb are used in the MEOF analysis. The first six EOFs are again found to be above noise. The first two EOFs that explain 32% of the domain averaged variance represent the ENSO response while the next four EOFs, in this

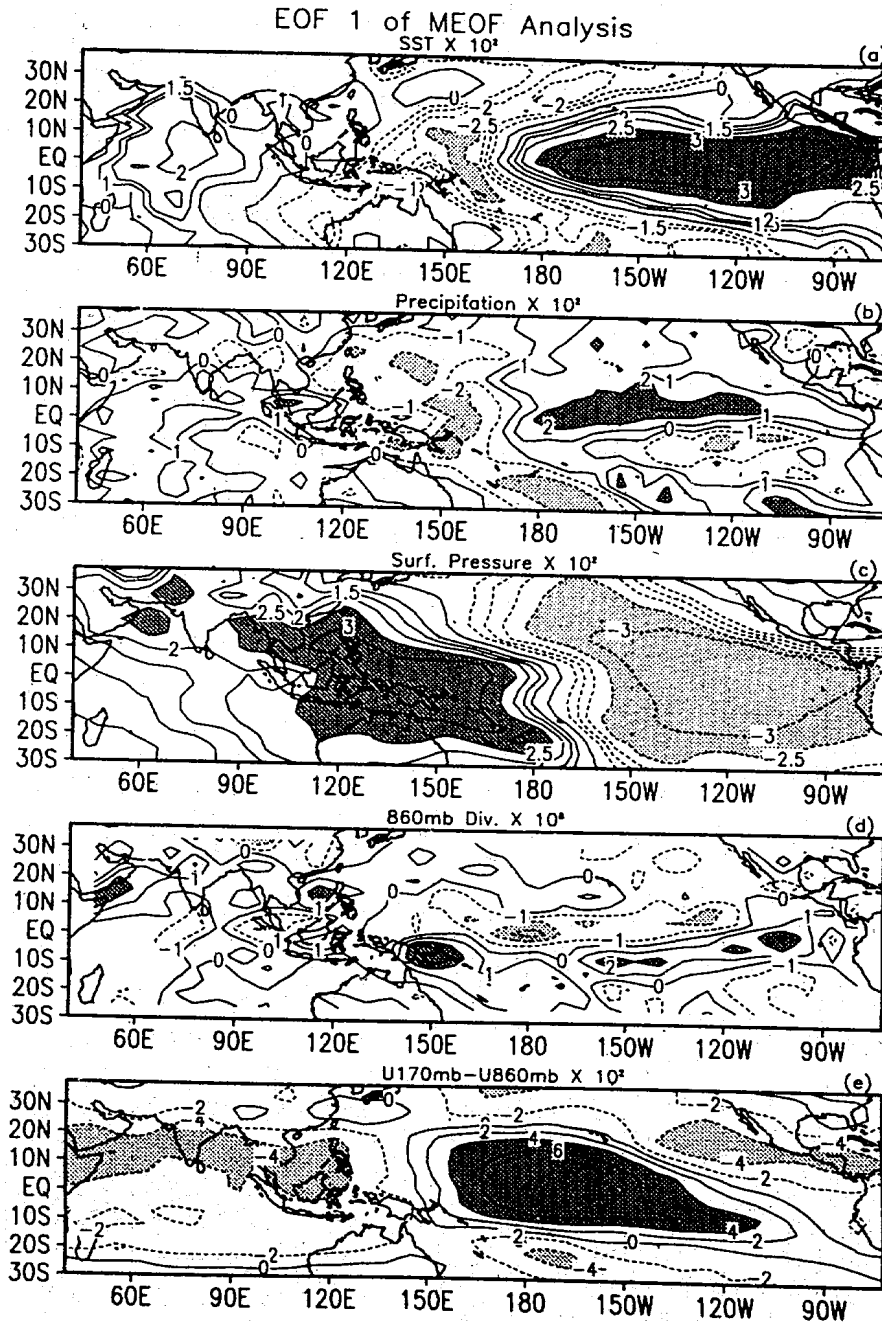


Fig. 5—EOF1 of AGCM simulated variability (a) SST, (b) precipitation, (c) surface pressure, (d) 850 mb divergence (e) U170 mb-U860 mb. Units of the EOF loadings are arbitrary.

case, represent regional response and together explain 20% of total domain averaged variance. The reason for the two dominant EOFs explaining lesser amount of total variance as compared to the respective EOFs of the observation is that it included precipitation as a variable in the MEOF

analysis. Precipitation contains much more small scale high frequency variability. This results in the low frequency modes (the dominant MEOFs) explaining relatively lesser amount of variance. Again the ENSO response is dominated by a quasi-four year period while the regional component is

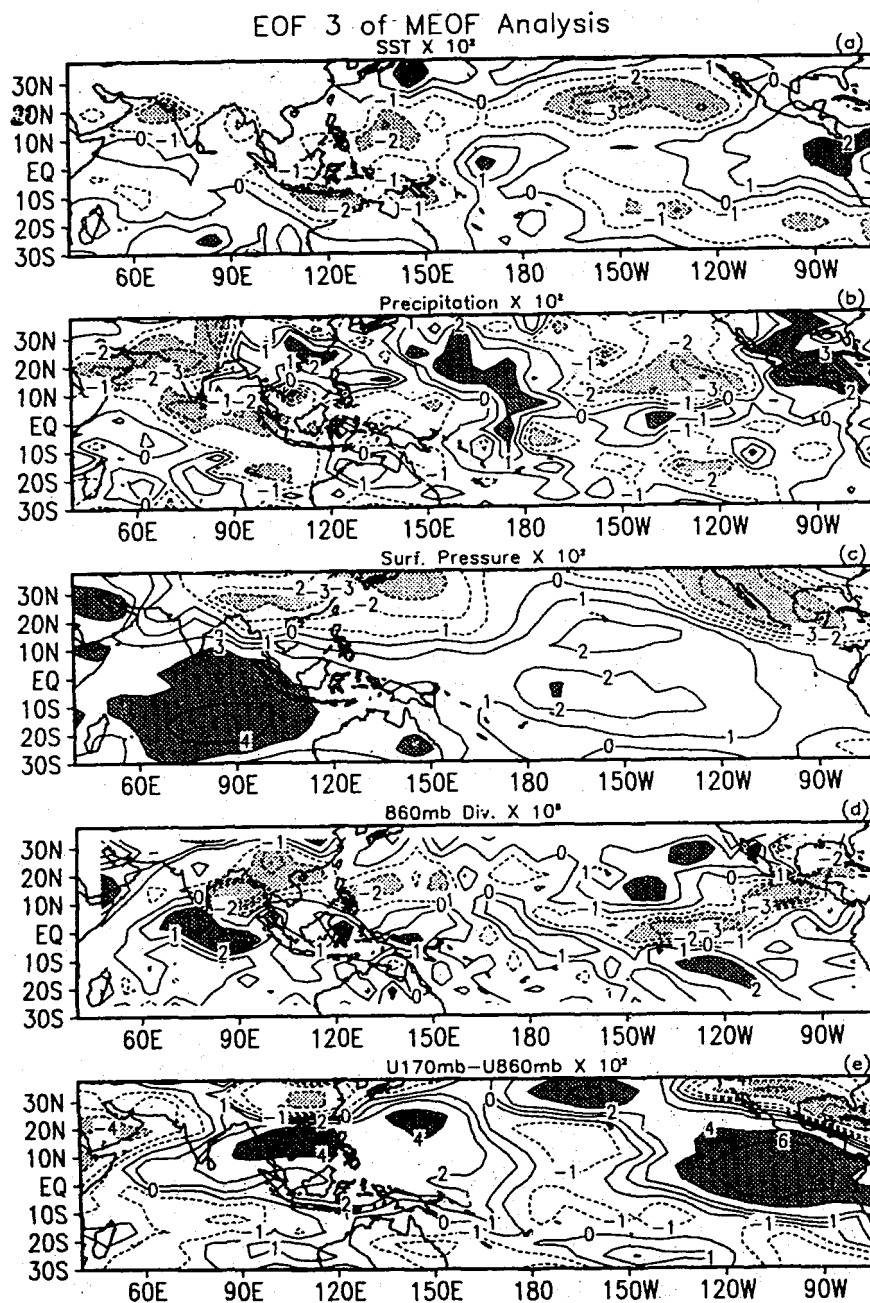


Fig. 6—EOF3 of AGCM simulated variability (a) SST, (b) precipitation, (c) surface pressure, (d) 850 mb divergence (e) U170 mb-U860 mb. Units of the EOF loadings are arbitrary.

dominated by quasi biennial mode. As a representative of the ENSO response, EOF1 is shown (Fig. 5) while EOF 3 is shown as representative of the regional response (Fig. 6). If the precipitation field is not included in the MEOF analysis, the variance explained by the dominant EOF of the model simulations is indeed close to that explained by the dominant mode of the observed fields (not shown).

It is clear from EOF 1 that the ENSO response over the Indian region is mainly confined to the equatorial region and has weak amplitude over the Indian continent. There is an increase in equatorial precipitation in the equatorial Indian Ocean as a result of shift of the Indonesian precipitation band over to central Pacific during a mature warm event. This is due to increase in the low level convergence of moisture in the equatorial Indian Ocean (as seen in divergence of 860 hPa levels). This is essentially the mechanism through which ENSO influences monsoon. The shift of the ascending branch of the Walker circulation to the central Pacific results in decrease in subsidence (i.e. enhanced low level convergence) over equatorial Indian Ocean. This favours the equatorial ITCZ. Stronger equatorial ITCZ induces subsidence over the continent and results in decreased monsoon precipitation. On the other hand the regional modes (e.g. EOF 3), has large amplitude over the continent too. The contributions from the ENSO response and that from the regional modes can be compared by

plotting the anomalies of precipitation associated with modes 1 and 2 against those associated with modes 3 through 6. It is found (not shown) that ENSO response is primarily over the equatorial Indian Ocean, while the regional QBO response is even larger than the ENSO response over the continent.

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