

Seasonal cycle of surface fields over the Indian Ocean

S K Dash

Centre for Atmospheric Sciences, Indian Institute of Technology, New Delhi-110016, India
and

P K Mohanty

Marine Sciences Department, Berhampur University, Berhampur-760007, Orissa, India.

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Surface fields such as sea surface temperature (SST), mean sea level pressure, surface wind, wind stress and pseudo-stress, latent heat and sensible heat fluxes are studied over the Indian Ocean and their seasonal characteristics are investigated. Three zones of maxima over Arabian Sea, Bay of Bengal and South China Sea recognised as three branches of the monsoon prominently appear in surface wind, wind stress and pseudo-stress both during summer and winter monsoon period. Sea level pressure and latent heat flux exhibit regionality in their characteristics over the three branching regions. Arabian Sea is dominant in strength and variability in most of the surface fields during summer monsoon season while South China Sea is prominent during winter monsoon season. Except for minor quantitative differences, ECMWF analyses compare well with climatology of observations (NCAR COADS) and FSU observed ship data.

Characteristics of surface fields over the ocean are manifestation of the interplay between ocean and atmosphere, which in turn generate or modify weather/climate system. This is especially true in the tropics where the tropical oceans serve as the main reservoir of heat for the genesis and maintenance of tropical circulation, of which Indian monsoon is a spectacular one. Numerous studies¹⁻⁵ have indicated the important role of the Pacific Ocean in Indian monsoon rainfall variability. Studies also indicate that oceanic regions close to the Indian monsoon area such as the Arabian Sea, the Bay of Bengal, the South China Sea and the southern Indian Ocean within 30°E-120°E and 30°S-30°N are extremely important in supplying necessary heat, moisture and momentum for the monsoon circulation. These regions are of consequence because of their observed large and complex seasonal variability in comparison with other oceanic regions.

Investigators have tried to study the characteristics of surface fields over the Indian Ocean in relation to Indian monsoon activity. Findlater⁶⁻⁸ demonstrated that the low level cross equatorial jet over Kenya was closely associated

with the intertropical convergence zone over the Arabian Sea and western India, and variation in strength of the stress were related to the rainfall over western India during south-west monsoon. Later a study⁹ based on 110 years of surface marine data over the Indian and west Pacific regions revealed that the monsoon current coming from the southern hemisphere has three branches: 1) Arabian Sea; 2) Bay of Bengal and 3) South China Sea. These branches are distinct in their characteristics and influence the rainfall in South Asia.

Surface fields over the Indian Ocean were studied¹⁰ using 30 years (1950-1979) Comprehensive Ocean Atmosphere Data Sets (COADS). This study showed that SST and sea level pressure do not show significant variability over the Indian seas but variability is observed over southern Hemisphere in association with monsoon activity over India. Another study¹¹ made it very clear that it is the annual cycle of SST and its northward propagation in the northern Indian seas which play significant role in monsoon variability. Variability of surface fields over the Indian Ocean was also examined¹² using European Centre for Medium range Weather

Forecasts (ECMWF) analyses for 1985 and 1986. The results of this study indicate that branching is also reflected in the latent heat flux and mean sea level pressure in addition to the wind field as noted earlier².

In the present study, characteristics of surface fields such as SST, mean sea level pressure, zonal and meridional components of wind, wind stress and pseudo-stress, latent and sensible heat fluxes have been examined during summer (June, July, Aug., Sept.) and winter (Dec., Jan., Feb.) monsoon periods from 1985 to 1990. Surface fields which reflect the branching phenomenon have been identified and the changes in the characteristics of the surface fields from summer to winter monsoon and their subsequent effect on the branching phenomenon are investigated.

Materials and Methods

Data for the present study consist of daily uninitialised ECMWF analyses (0 UTC) from 1985 to 1990 at a grid mesh of 2.5° . Monthly mean fields are computed from the daily fields and subsequently seasonal mean fields are obtained. ECMWF analyses are compared with National Centre for Atmospheric Research (NCAR), COADS climatology available at a grid mesh of 2° .

Pseudo-stress is defined as the magnitude of the wind vector multiplied by the wind speed. Following this definition, ECMWF pseudo-stress were computed from the ECMWF analysed wind fields. Further, ECMWF pseudo-stress were compared with Florida State University (FSU) pseudo-stress based on observed ship data at a grid mesh of 1° . All these data were retrieved from ECMWF, World Climate Research Programme (WCRP), Tropical Ocean Global Atmosphere (TOGA) archive.

Results and Discussion

Results are presented under the categories, (a) sea surface temperature, (b) mean sea level pressure, (c) wind, wind stress and pseudo-stress, (d) latent heat flux and (e) sensible heat flux. The seasonal mean characteristics of these surface fields and their variabilities are discussed in detail.

Sea surface temperature

The seasonal mean SST during summer (JJAS)

and winter (DJF) monsoon periods are presented in Fig. 1. ECMWF analyses (Fig. 1b) for summer season (June, July, Aug, Sept) compare reasonably well with the respective seasonal mean of NCAR COADS climatology (Fig. 1a). Figure 1c presents the ECMWF model analysed seasonal mean SST during winter (Dec, Jan, Feb). The SST in the northern Indian seas decreases by $3-4^\circ\text{C}$ from summer to winter while an increase (2°C) was observed in the southern Indian Ocean. The distributional trend in SST and its seasonal change clearly indicate the influence of solar forcing and its seasonal reversal in the region. Strongest upwelling occurs near Somalia associated with the strong Somali jet and thus the region of coldest sea

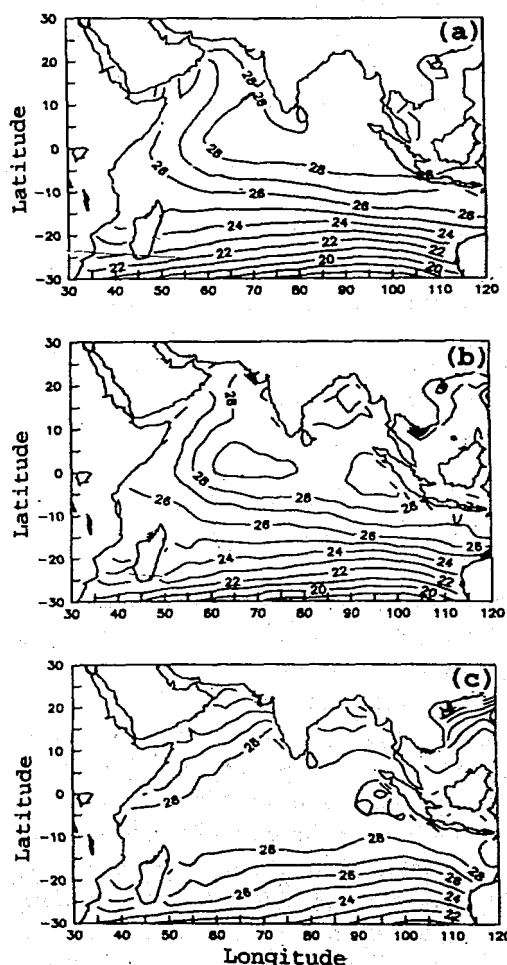


Fig. 1—Seasonal mean SST($^\circ\text{C}$) (a) NCAR COADS climatology for JJAS (b) ECMWF analysis for JJAS (c) ECMWF analysis for DJF.

surface in the northern summer (Fig. 1b). SST variations in Bay of Bengal is also significant because of fresh water input. This might be one of the factors for the colder SST in the northern Bay (Fig. 1b) as compared to that over Arabian Sea. An approximate seasonal difference of 5°C is observed in the northern South China Sea. Further, the most striking feature is the strong winter SST gradient ($\sim 5^{\circ}\text{C}$) along the north south direction unlike that in the Arabian Sea and Bay of Bengal. These large SST gradients in the north-south direction¹³ in South China Sea are attributed to the differential heating between Asia and Australia.

Mean sea level pressure

Mean sea level pressure during summer and winter are depicted in Fig. 2. Three distinct troughs (Fig. 2a) are observed at the southern edge of the monsoon low. The first one over the Arabian Sea is located adjoining the west coast of India. The second one over the Bay of Bengal is most prominent with the trough extending from the head of the Bay to the central Bay of Bengal and the third one over the South China Sea is along the east coast of South China. These results support the findings¹² reported earlier and emphasise the influence of land-sea heating contrast. Three high pressure centres are also observed over the land mass in the extreme northern end of Arabian Sea, Bay of Bengal and South China Sea during winter monsoon period (Fig. 2b). Thus, both summer and winter pressure fields reflect the regionality. With the transition of the season from summer to winter, the low pressure centres during summer are replaced with highs during winter and the orientations of the pressure patterns are reversed. However, the orientation in the pressure pattern over the southern Indian Ocean remains unchanged from summer to winter. While seasonal variability (summer to winter) over the northern Indian seas is significant (~ 16 hPa) it is minimum in the southern Indian Ocean (~ 4 hPa) and almost negligible in the equatorial Indian Ocean.

Surface pressure during winter monsoon (Fig. 2b) clearly depicts Hadley type cell with lowest pressure at the equatorial belt and the pressure increasing towards the subtropics in both the hemispheres. This suggests that the interhemispheric pressure gradient (20 hPa) as well as zonal pressure gradient along the equator (8 hPa) during summer act jointly as the

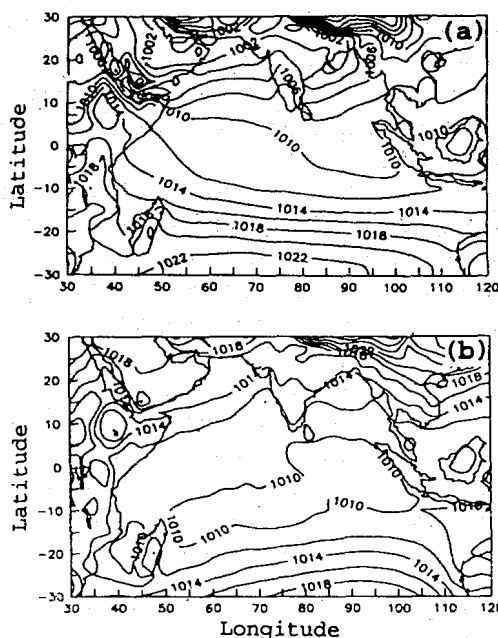


Fig. 2—Seasonal mean sea level pressure(hPa) (a) ECMWF analysis for JJAS (b) ECMWF analysis for DJF.

driving force for the summer monsoon. Further, comparison amongst the three regions shows that the meridional pressure gradient during summer is the highest over the Arabian Sea followed by Bay of Bengal and South China Sea. Interestingly, during winter monsoon period, maximum meridional gradient in pressure (10 hPa) is observed over South China Sea. This is consistent with the large SST gradient observed over South China Sea during winter monsoon period. The trough over the Bay of Bengal is very much distinct compared to other two regions. The positions of the troughs/ridges and their seasonal movement clearly establish the land-sea heating contrast as one of the important factors responsible for the three zones of significance.

Wind, wind stress and pseudo-stress

Seasonal mean fields for zonal and meridional components and wind vector are presented in Figs.3-5. NCAR COADS climatology during summer (Fig 3a) clearly depicts the three branches of maximum wind concentrated over the Arabian Sea, Bay of Bengal and South China Sea. Also, the southeast trade wind in the southern hemisphere is well depicted. Features of the seasonal mean zonal wind fields during summer (Fig. 3b) are consistent

with the NCAR COADS climatology and a good agreement exists between the two. The easterlies over the southern trade wind region are stronger than that in the climatology. The strength of wind is maximum (8 msec^{-1}) over the Arabian Sea. Findlater⁸ showed that the jet is very much intense at 1 km height from the mean sea level during the summer monsoon period and the axis of the jet down stream from the Somali coast splits into two branches. Consequent upon and associated with land-sea heating contrast, three regions of wind maxima are observed and are referred to as the three branches.

Branching is also reflected in the zonal components of the winter monsoon (Fig. 3c) but with rela-

tively weak wind as compared to summer monsoon season. Comparing the seasonal mean fields of zonal wind during summer monsoon and winter monsoon period, the shifting in the northern boundary of the zone of easterlies of the southern hemisphere is evident with its position at around 2.5°S during summer monsoon to 15°S during winter monsoon period. Considering the simple definition of ITCZ as the region of confluence of surface winds from both the hemispheres, the present results point to the fact that the ITCZ over the Indian Ocean changes its position from summer to winter in the same way as it does based on maximum cloudiness zone¹⁴.

Three branches are well depicted in the

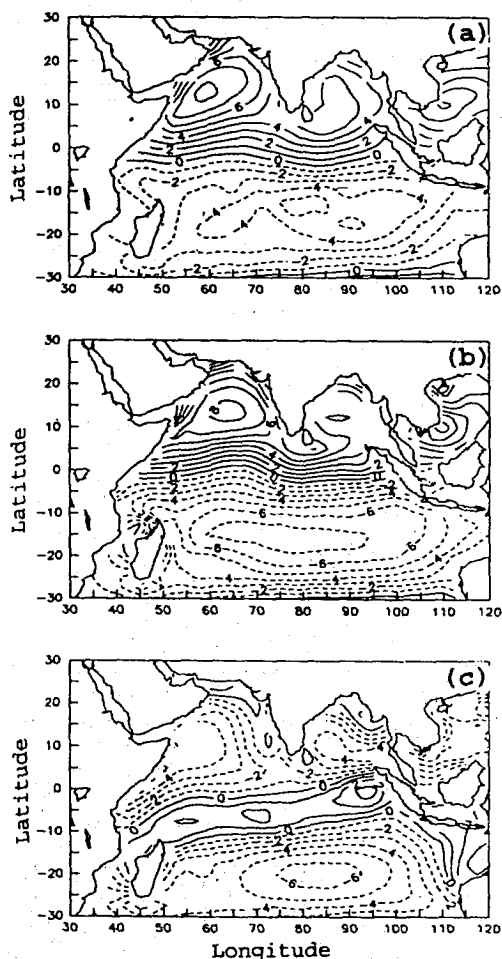


Fig. 3—Seasonal mean zonal wind (msec^{-1}) (a) NCAR COADS climatology for JJAS (b) ECMWF analysis for JJAS (c) ECMWF analysis for DJF.

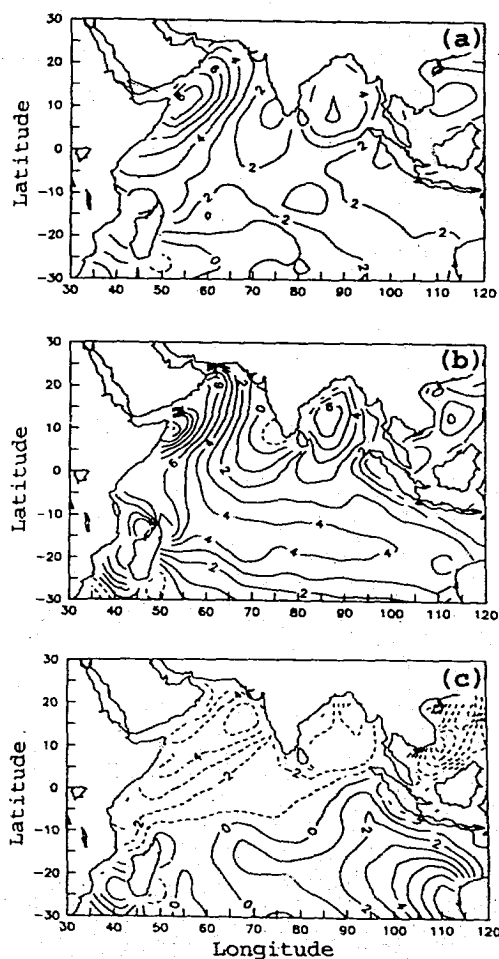


Fig. 4—Seasonal mean meridional wind (msec^{-1}) (a) NCAR COADS climatology for JJAS (b) ECMWF analysis for JJAS (c) ECMWF analysis for DJF.

ECMWF seasonal mean meridional wind fields during summer (Fig. 4b) and winter (Fig. 4c). As in the case of zonal wind, the strength of the meridional wind during summer is also maximum (12 ms^{-1}) over the Arabian Sea and then reduces over Bay of Bengal and South China Sea. But during winter, South China Sea is dominant over the other two branches. NCAR COADS climatology during summer (Fig. 4a) shows magnitude of meridional wind field less over all the three branches compared to that in ECMWF analyses.

Wind maxima over the three branching regions and over the southern hemisphere trade wind region are well depicted in the seasonal mean wind vectors during summer (Fig. 5a) and winter (Fig. 5b) monsoons. The vector wind field during summer monsoon also clearly shows the S-shaped pattern very similar to the climatological wind pattern¹⁵. Seasonal mean wind stress field (Fig. 6) during summer and winter monsoon have been examined which show very close qualitative resemblance with the respective seasonal mean wind fields (Fig. 5). Although comparison between ECMWF wind field and climatology shows close agreement, further verification of ECMWF wind field is made by

comparing it with the FSU observed pseudo-stress data based on ship reports. ECMWF and FSU seasonal mean (JJAS) zonal pseudo-stress are respectively depicted in Fig. 7 a and c while the respective meridional pseudo-stress are depicted in Fig. 7 b and d. It is found that the strengths of the westerlies and easterlies in case of ECMWF are underestimated by about 15% compared to FSU zonal pseudo-stress. However, an agreement exists between meridional components of ECMWF and FSU pseudo-stress except for stronger cross equatorial flow off Madagascar in the FSU pseudo-stress.

Latent heat flux

The seasonal mean (JJAS) climatology (NCAR COADS) is presented in Fig. 8a and Fig. 8b and c present summer mean (JJAS) and winter mean (DJF) latent heat fluxes respectively based on ECMWF analysis. Except over the western Arabian Sea, off Somalia, good agreement exists between the climatology and seasonal mean model analysed fields during summer. Compared to climatology, relatively high latent heat flux off the Somali region figures prominently in the ECMWF seasonal mean

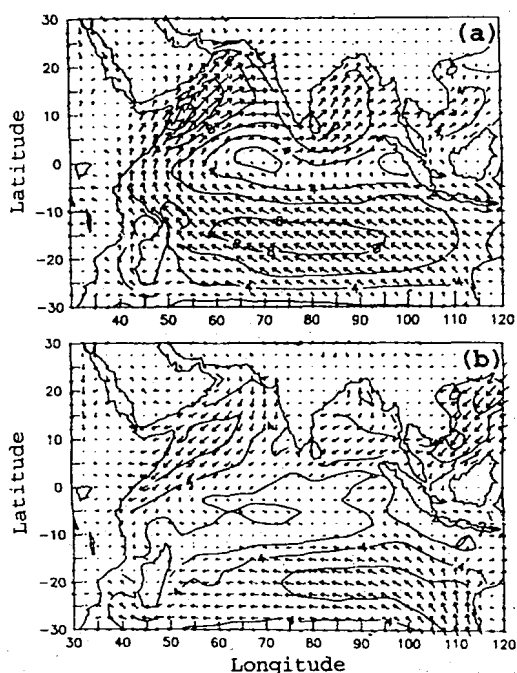


Fig. 5—Seasonal mean wind vector (msec^{-1}) (a) ECMWF analysis for JJAS (b) ECMWF analysis for DJF.

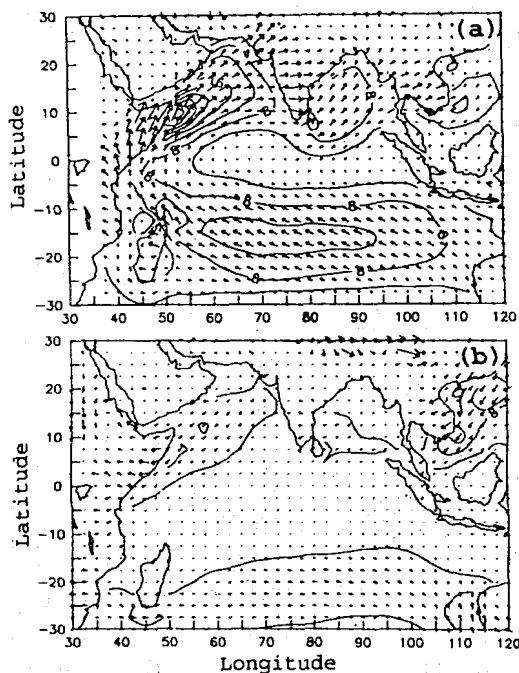


Fig. 6—Seasonal mean wind stress vector (10^{-2} Nm^{-2}) (a) ECMWF analysis for JJAS (b) ECMWF analysis for DJF.

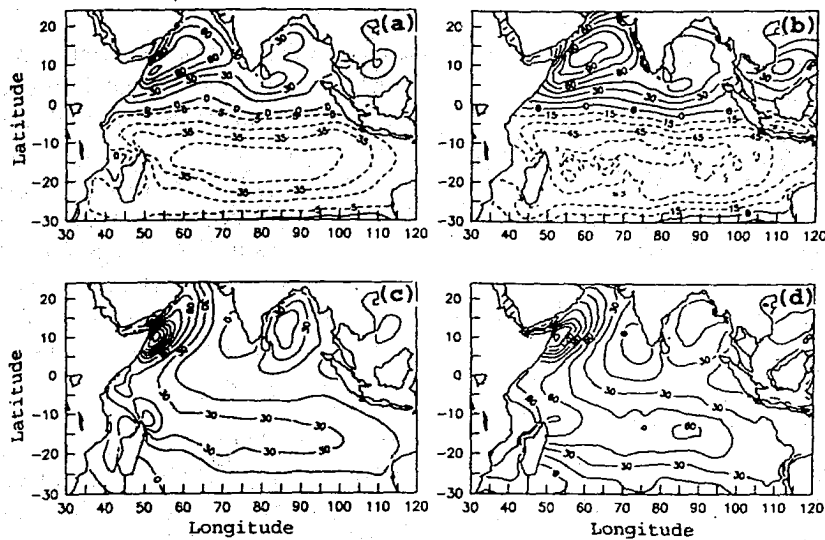


Fig. 7—ECMWF and FSU seasonal mean(JJAS) pseudo-stress(m^2s^{-2}) (a) ECMWF zonal pseudo-stress (b) FSU zonal pseudo-stress (c) ECMWF meridional pseudo-stress (d) FSU meridional pseudo-stress.

field (JJAS) (Fig. 8b) and is attributed to the maximum uncertainty (20% of the data) of the mean westerly wind component over this region¹⁶. Both the climatology and the seasonal mean fields depict the zones of latent heat flux maxima over Arabian Sea, Bay of Bengal, South China Sea. In addition to these three regions, zone of latent heat maximum is also observed over the southern hemisphere trade wind region. It is noticed that the regions of latent heat maxima are the regions of wind maxima. The latent heat flux along the coastal belt from Arabia to Bangladesh is low, which may be explained based on the onset of strong south-westerlies and the resulting strong coastal up-welling and reduction in SSTs along the coast. With the transition of the season, the reduction in latent heat flux during winter monsoon (Fig. 8c) is observed over the southern Indian Ocean and most of the seas to the north associated with the slackening of the wind. However, northern parts of Arabian Sea, Bay of Bengal and South China Sea experience relatively more latent heat flux compared to the other oceanic regions. Regions of latent heat maxima are not significant during winter monsoon.

Sensible heat flux

The minimum sensible heat flux over the western Arabian Sea and its increase in the southeast direction to reach the maximum value near the northwestern Australia are observed in the seasonal,

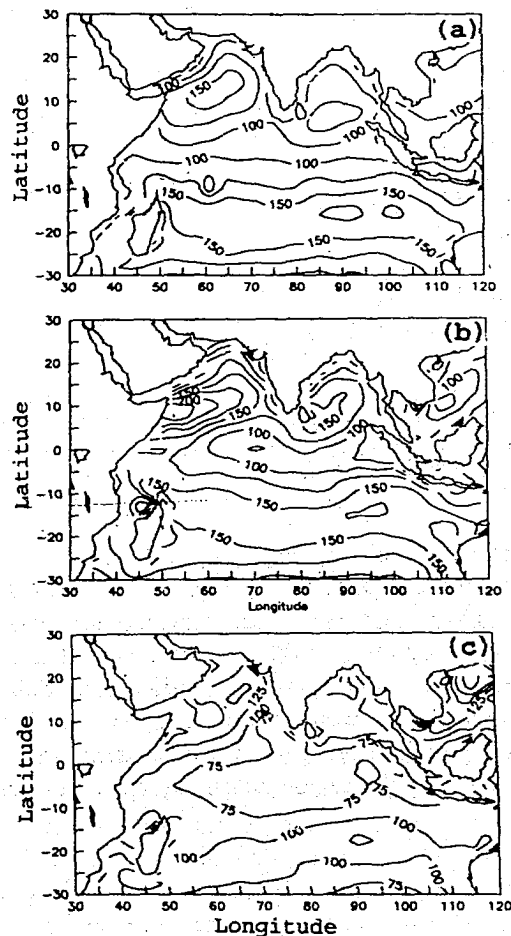


Fig. 8 Seasonal mean latent heat flux (Wm^{-2}) (a) NCAR COADS climatology for JJAS (b) ECMWF analysis for JJAS (c) ECMWF analysis for DJF.

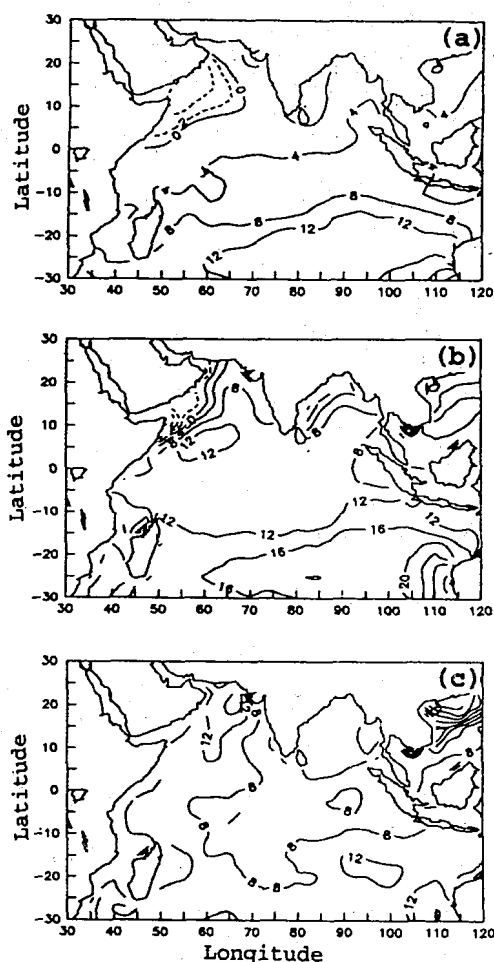


Fig. 9—Seasonal mean sensible heat flux (Wm^{-2}) (a) NCAR COADS climatology for JJAS (b) ECMWF analysis for JJAS (c) ECMWF analysis for DJF.

mean (JJAS) climatology (Fig. 9a) and ECMWF seasonal mean (JJAS) field (Fig. 9b). Compared to climatology, ECMWF seasonal mean fields are over estimated by about 50%. Sensible heat flux is a function of sea-air temperature difference. This is qualitatively as well as quantitatively consistent with the sensible heat gain over the extreme western Arabian Sea, the region of strong up-welling and

colder SSTs. During winter monsoon period (Fig. 9c), the sensible heat flux over the northern parts of the Arabian Sea, Bay of Bengal and South China Sea is more compared to the summer monsoon (Fig. 9b). Over South China Sea, the large horizontal gradient in sensible heat flux during winter monsoon (Fig. 9c) is consistent with SST gradient in that region (Fig. 1c). Sensible heat flux does not reflect the regional characteristics of branching during summer monsoon as well as winter monsoon.

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