Trends in SST and reanalysis 850 & 200 hPa wind data of Asian summer monsoon season during the recent six decades

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In the global warming scenario the Sea Surface Temperature (SST) of equatorial Indian ocean has warmed much more than the other tropical oceans during the period 1950 to the present. In this paper we study using reanalyzed data the effects of this rapid warming in SST on the atmospheric circulation, particularly on the jetstreams through the changes induced in the Hadley cell which are opposite during the summer and winter seasons.

SST for the period 1950-2003 given along with the NCEP/NCAR reanalysis data (Kalnay *et al.,* 1996) has been used. In this data set GISST v2.2 from the UK met office was used prior to 1982 and Reynolds SST for later years. There is a shipping lane from Suez canal to Singapore which has high density SST observations during 1950 to the present and so equatorial Indian ocean has good SST data coverage. Since 1982 this high density ship data is combined with satellite measurements of SST.

Figure 1a gives the difference of the June-September (JJAS) SST of 1999-2003 minus that of 1950-54. Central equatorial Indian ocean has warmed through 1 to 1.2°C during the decades after 1950. The JJAS mean SST of the box (7°S-3°N, 60-90°E) of each year is shown in Figure 1b. The linear trend line shows the rapid increase in SST of this box. The trend of the period 1950 to 1981 is almost the same as the trend during the later period of ship cum satellite observation (Reynolds SST). That SST of equatorial Indian ocean has rapidly warmed since 1950 has been shown in several recent studies (Charles *et al.,* 1997 and Knutson *et al.,* 2006)

The monsoon flow through peninsular India in the lower troposphere is dominated by the Low Level Jetstream –LLJ (Joseph and Sijikumar 2004). Joseph and Simon (2005) showed that the mean JJAS monsoon flow through India from surface to 1.5 Km altitude between latitudes 10-20°N had significant decreasing trend and that between 2.5-7.5°N a significant increasing trend during the period 1950 to 2003. As a consequence, the duration of break monsoon spells in a monsoon as defined by an index of wind flow through peninsular India has increased by about 30% during this period. These changes are seen both in NCEP and ERA (http://data.ecmwf.int/data/d/era40_mnth/) reanalysis data. The 30 year difference (1990-99 minus 1960-69) in 850 hPa wind flow through south Asia in NCEP and ERA reanalysis data are given in Figure 2 which shows that during the later part of the period the flow has become more prone to break monsoon conditions. Sperber *et al.,* (2000) had reported a weakening of monsoon circulation during the recent 50 years and related it to the Indian ocean warming and the consequent reduction in land-sea contrast in temperature. Krishnan *et al.,* (2003) has shown in a modeling study that higher SST over equatorial Indian ocean leads to more number of break monsoon days. High resolution 1 deg lat X 1 deg lon gridded rainfall data of India 1951 to 2003 (Rajeevan *et al.,* 2006) has shown that the mean July and August rainfall of decade 1991-2000 when compared to that of 1951-1960 indicates increased break monsoon conditions during the later decade (increased rainfall over northeast India and decreased rainfall over central and northwest India).

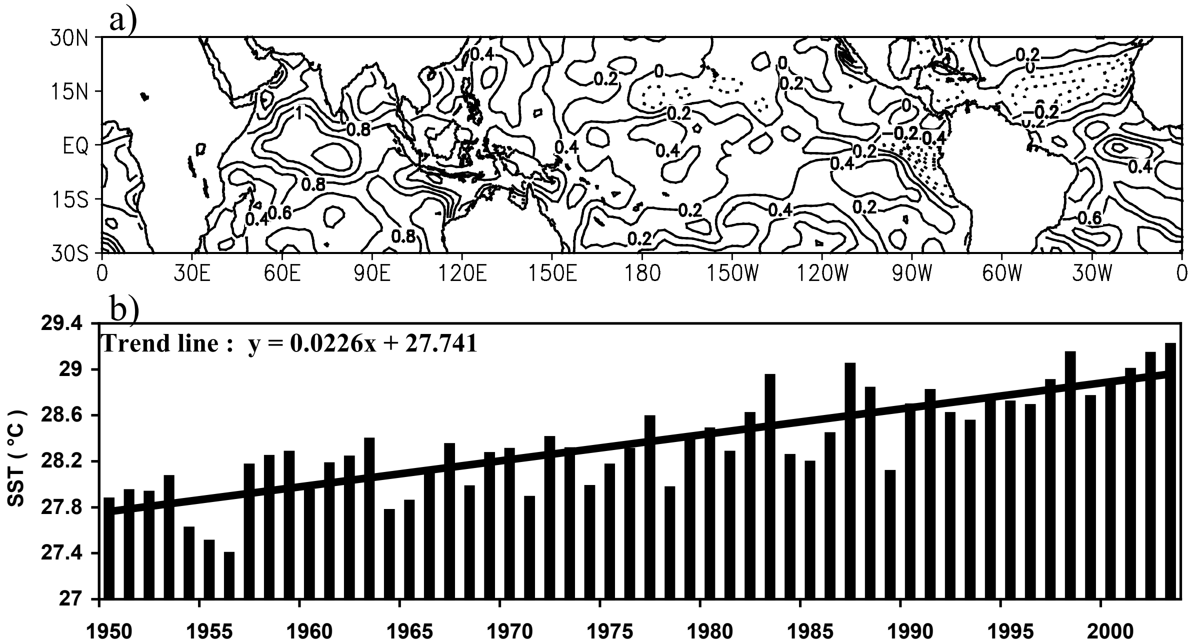

Figure 1 a) Difference of June-Sept SST (1999-2003) minus (1950-1954) b) Jun-Sept. SST averaged over 60-90°E, 7°S-3°N and linear trend line 1950 to 2003

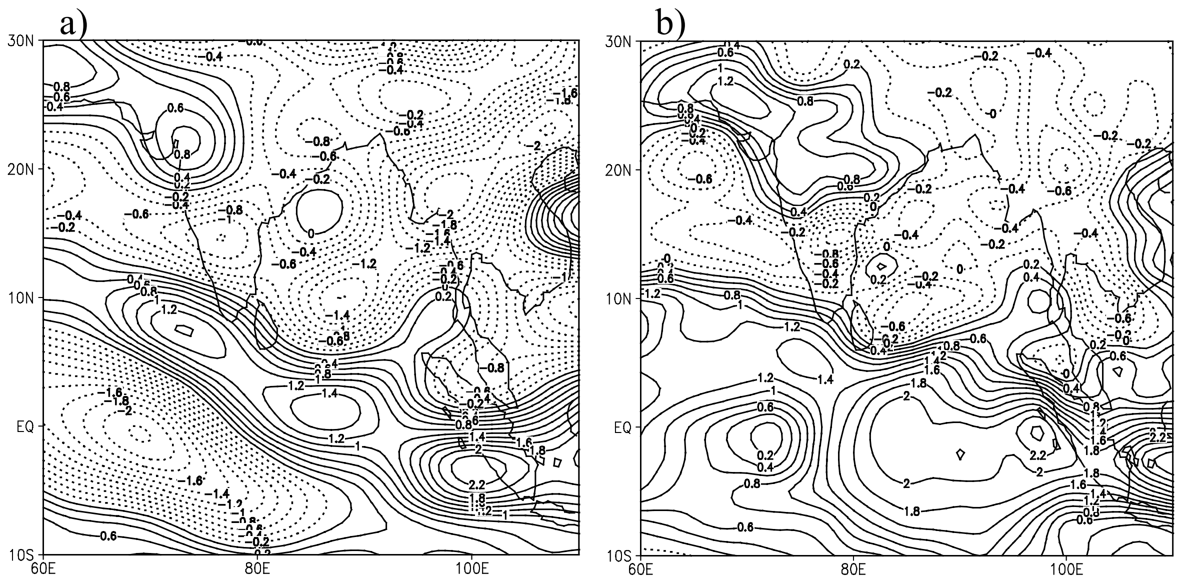

Figure2: Change in July and August mean U-wind at 850 hPa (m/s) 1990-99 minus 1960-69 (a) NCEP and (b) ERA data

Studies (Sathiyamoorthy 2005 and Rao *et al.,* 2004) using reanalysis data have shown a decreasing trend of the strength of the Tropical Easterly Jetstream (TEJ) during the recent 5 decades. We have confirmed these findings Figure 3 shows the 3 decade difference in the zonal wind (1990-99 minus 1960-69) at 150 hPa. During the decade 1990-99 TEJ is weaker compared to the decade 1960-69, particularly over equatorial Africa. It is also seen that the amplitude of weakening is slightly less in the ERA reanalysis compared to NCEP.

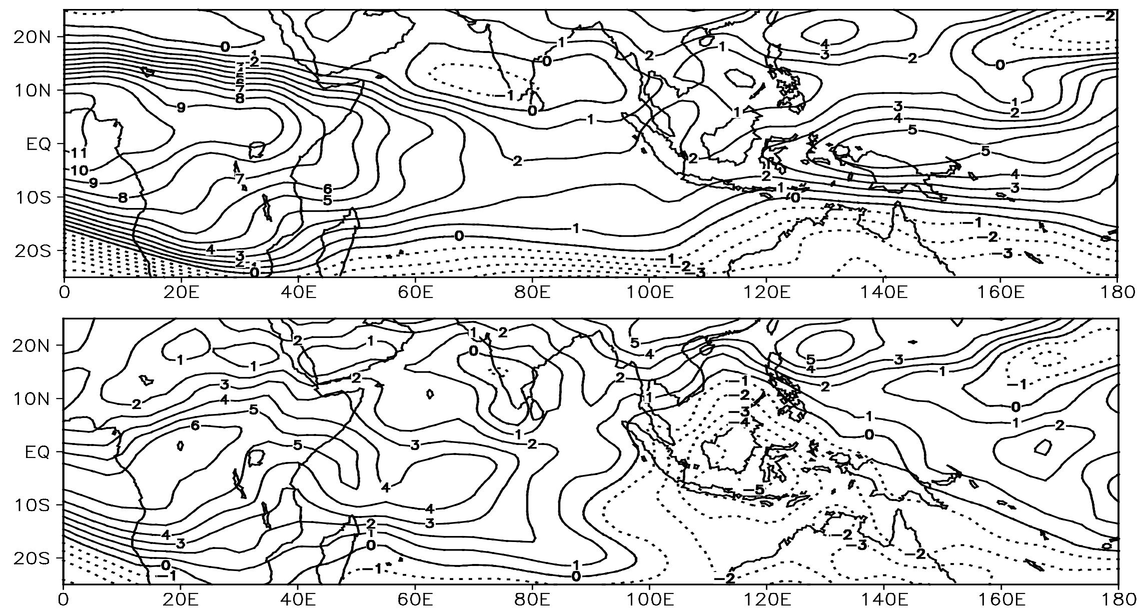

Figure3: Difference (30 years) of 150 hPa U wind July & August in m/s (1990-1999) minus (1960–1969): NCEP at top and ERA at bottom

It is well known that during the Asian summer monsoon in the eastern hemisphere 0-180°E there is a reverse Hadley cell with its upward limb at latitude about 20°N and downward limb at about 30°S. The normal Hadley cell with upward limb close to the equator exists in the rest of the globe. Weakening of the LLJ and the TEJ indicate weakening of the reverse Hadley cell during the Asian summer monsoon. We have found that this is occurring both in NCEP and ERA reanalysis data. Since the reverse Hadley cell associated with LLJ and TEJ is also associated with the southern hemisphere Sub Tropical Jetstream (STJ) of the Asian summer monsoon season, this STJ should also show weakening during the recent 50 years. Both NCEP and ERA reanalysis data show the weakening of the STJ particularly around Australia (see fig 4).

We looked into the cause for the weakening of the LLJ, TEJ and STJ of the Asian summer monsoon season. OLR data of the period 1979 to the present showed increasing trend in the deep convective heating of the equatorial atmosphere over the Indian ocean in association with the increasing trend in SST. With an increasing heat source near equator the tropospheric temperature gradient over Asia from equator to about 20 degrees north latitude should decrease weakening the reverse Hadley circulation. Reanalysis data confirmed that the meridional wind averaged over longitudes 0-180°E has weakened showing a weakening of the reverse Hadley cell there.

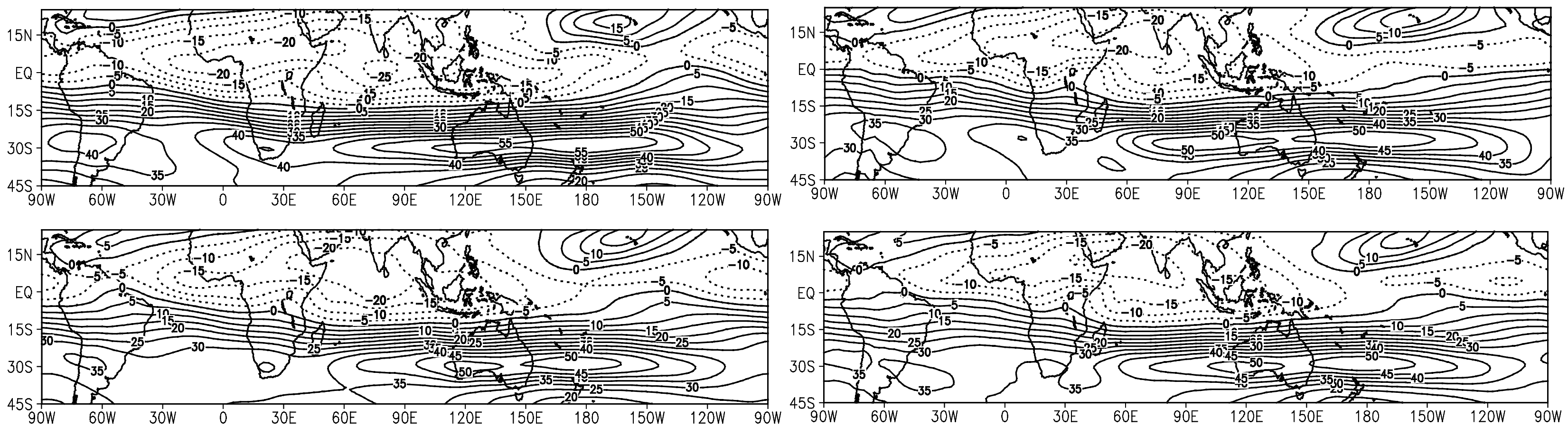

Figure 4: Mean 200 hPa U-wind in m/s of July and August (1950 -1959) at top left and (1990-1999) at bottom left (NCEP data). (1960 -1969) at top right and (1990-1999) at bottom right (ERA data). Weakening of TEJ and southern hemisphere STJ seen.

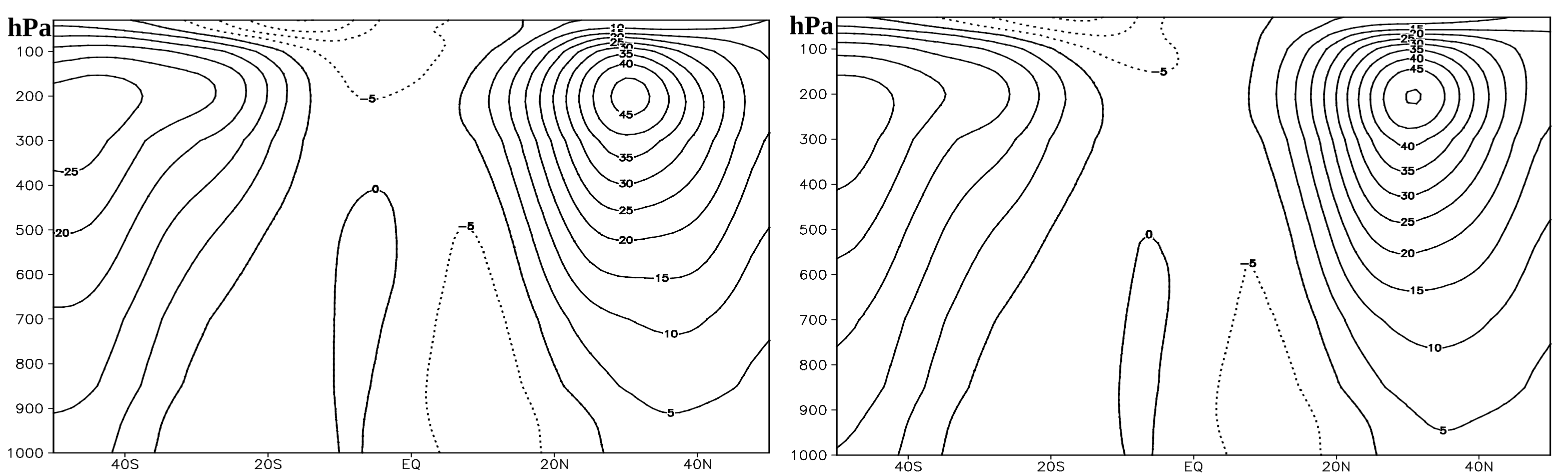

Figure 5: Vertical section Jan & Feb U-wind (NCEP) averaged 60°E-120°W longitude showing STJ for period 1950-1959 (left) and 1990-1999 (right). Strengthening of STJ during the 4 decades is seen.

The increasing trend of SST over the equatorial Indian ocean has occurred throughout the year (in all seasons). We examined the change in circulation during the winter months of January and February. During these months we have the normal Hadley cell over Asia with ascending limb near the equator and descending limb near latitude 30°N (the Hadley cell into the winter hemisphere is known to be the predominant one). Since the SST near the equator during the winter months had a large increasing trend over the Indian ocean, we expect increased convective heating of the equatorial troposphere and increasing strength of the Hadley cell into the winter hemisphere. Examination of the meridional winds averaged over the longitudes 60°E-120°W and the OLR data confirmed the increasing trend in the strength of the winter Hadley cell and of the equatorial convective heating of the atmosphere. We also found that the STJ over Asia and west Pacific ocean had increased in strength during the recent 50 years, as shown by the vertical section of January and February mean zonal wind of the longitude belt 60°E-120°W (see fig5). The increase in the strength of the STJ has been particularly large in the STJ velocity maximum over east Asia.

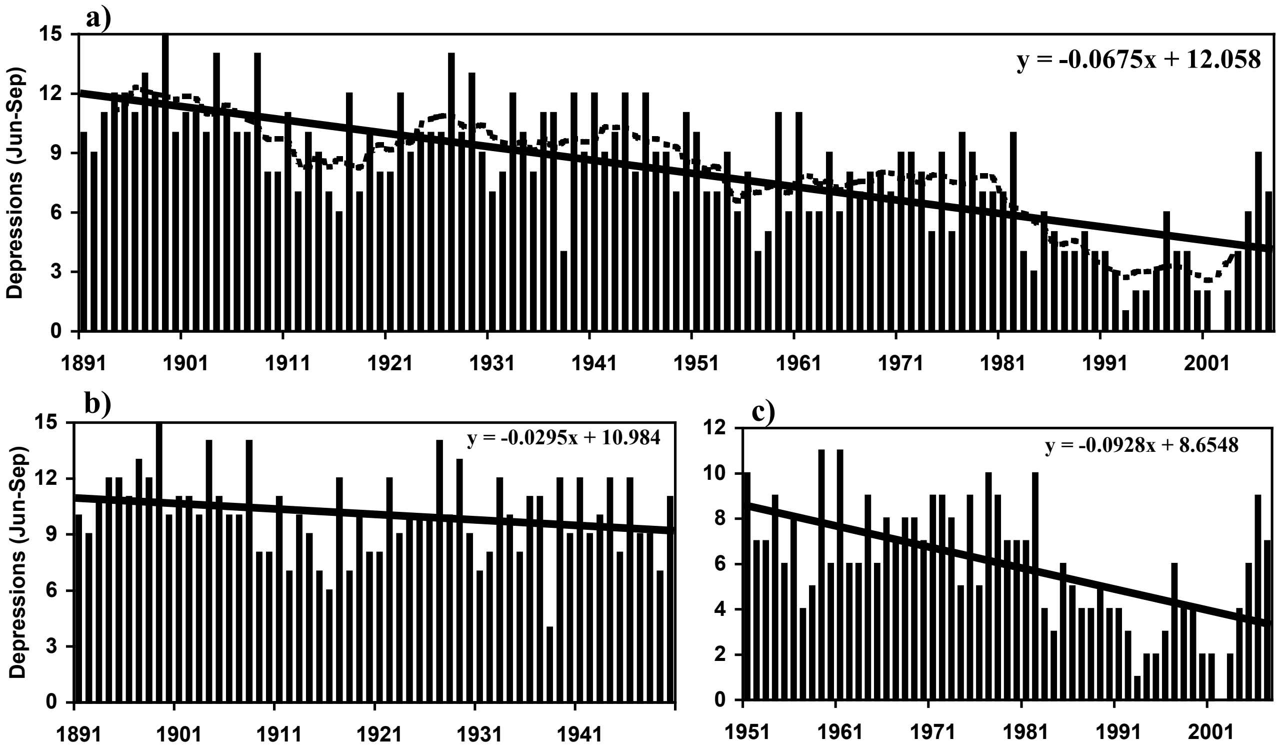

Figure5: Number of Monsoon Depressions in a Monsoon Season during a) 1891 to 2007, b) 1891 to 1950 and c) 1951 to 2007. The rapid decrees after 1950 is clearly seen from the trend lines.

Using HadISST data (http://badc.nerc.ac.uk/data/hadisst/) we compared the warming trend over the Indian ocean separately for the periods 1891 to 1950 and 1951 to 2003. It was found that the warming during the earlier period was much less than that during the later period. With the decreasing trend of the lower tropospheric wind flow through peninsular India during 1951 to the present the number of monsoon depressions forming over north Bay of Bengal during the JJAS season had also shown a strong decreasing trend. Sikka (1977) had shown that monsoon depression form over north Bay of Bengal when the LLJ through peninsular India is strong. We have good depression data from 1891 onwards. Although depression frequency during the monsoon season decreased during the period 1891 to 1950, the decreasing trend during this period is considerably smaller than that during the later years as may be seen from figure 6 (a, b and c) (It may be noted that monsoon depression frequency has superposed on the long term trend a 36 year oscillation-Joseph and Prince 1999).

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