Weakening trend of the southwest monsoon current through peninsular India from 1950 to the present

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The southwest monsoon current in the form of a cross-equatorial low level jetstream (LLJ) with its core at an altitude of about 1.5 km and core wind speeds of 80–100 km/h is a conduit carrying moisture generated over south Indian Ocean and the Arabian Sea that supports the June to September monsoon rainfall in India. During spells of active (strong) monsoon, the core of the LLJ passes through peninsular India between latitudes 12.5 and 17.5 N. In break (weak) monsoon spells, LLJ bypasses India and flows to its south through the latitude belt 2.5 to 7.5 N. The mean June to September monsoon flow through India from surface to 1.5 km altitude between latitudes 12.5 and 17.5 N, had a significant decreasing trend and that between 2.5 and 7.5 N a significant increasing trend during the recent half century, i.e. 1950 to the present. The duration of break (weak) monsoon spells in a monsoon season has increased by about 30% during this period. These changes have resulted in the number of days during the monsoon season 1 June to 30 September with daily average rainfall less than 8 mm/day increasing and days with rainfall more than 12 mm/day decreasing through 45.4% and 78.1% respectively, during the last 53 years. These are alarming findings for a country whose food production and economy depend heavily on monsoon rainfall.

Keywords: Active (strong) monsoon, break (weak) monsoon, low level jetstream, monsoon depression, typhoons.

A strong cross-equatorial low level jetstream (LLJ) with its core at an altitude of about 1.5 km exists over the Indian Ocean and South Asia during the southwest monsoon season of June–September[1,2]. It has core wind speeds of 80–100 km/h. LLJ has two main functions. It is a conduit carrying moisture generated by the trade winds over the vast expanses of the south Indian Ocean and also the moisture evaporated over the Arabian Sea, to areas of monsoon rainfall production over South Asia. The cyclonic rotation of air (vorticity) north of the LLJ axis in the atmospheric boundary layer over South Asia is a dynamic forcing for the generation of vertical upward air motion and rainfall and for the genesis of monsoon depressions[3]. It is well known that monsoon depressions take monsoon rains to northwest India and Pakistan.

During the last decade a number of studies[4–8] have been reported on the interannual and intraseasonal variability of the lower tropospheric monsoon flow, particularly about the well-known active–break cycle of the monsoon[9–11]. Active monsoon spells last three to five weeks when most parts of India get copious rainfall. During break monsoon spells that last one to three weeks, most parts of the country have highly deficient rainfall; however, it is abundant over Northeast India and the Himalayan slopes. A recent study by Joseph and Sijikumar[12] has shown that during active monsoon, the core of the LLJ from central Arabian Sea passes eastwards through peninsular India between latitudes 12.5 and 17.5 N. In break monsoon, LLJ from central Arabian Sea moves southeastward and bypassing India, passes eastwards south of India between latitudes 2.5 and 7.5 N. Thus in break monsoon spells, the large amount of moisture carried by the LLJ does not reach India, but goes to the west Pacific Ocean to feed the increased frequency of typhoons forming there[13,14]. Figure 1 shows the wind at 850 hPa and LLJ axis during active and break monsoon conditions as composites of a large number of days. The associated rainfall is shown by the satellite measured outgoing longwave radiation (OLR). Lower the OLR, larger is the rainfall.

Figure 2 gives the mean June–September zonal (u) component of wind for each year during the period 1950–2002, averaged over the areas bounded by latitudes/longitudes 12.5 N, 17.5 N/70 E, 85 E (Figure 2 *a*) and 2.5 N, 7.5 N/70 E, 85 E (Figure 2 *b*) for three levels, i.e. 1000 hPa (close to the mean sea level), 925 hPa (altitude about 0.7 km) and 850 hPa (altitude about 1.5 km). The wind data are from the global datasets generated on a twice-daily timescale in the NCEP–NCAR reanalysis project[15]. The data have little influence on the model used and are close to the original station data fed into the model to derive the grid point data[15]. At all these levels, the zonal wind has a decreasing linear trend in the peninsular India box and an increasing linear trend in the box south of India. Figure 2 *c* gives the difference in zonal winds of the peninsular box minus the box south of India. These changes are large, close to 20% of the long-term mean in 50 years and are statistically significant at a level better than 99% by the Mann–Kendall rank test. The 11-year moving averages are also shown in Figure 2, which shows decadal variations superposed on the long-term trend.

We estimated the linear trend in zonal wind at each grid point for the period 1950–2002 for the 850 hPa level and calculated the change according to the trend line from 1950 to 2002. This is given in m/s in Figure 3 *a* for the NCEP–NCAR dataset[15]. Figure 3 *b* gives a similar computation done using the ERA-40 dataset available for the period 1958–2002 from the website http://data.ecmwf.int. (The data is based on the ECMWF reanalysis). Both datasets show decreasing u-field through peninsular India at 850 hPa. South of India, 850 hPa zonal wind increases with time; however, in Figure 3 *a* the maximum increase is at about latitude 5°N, whereas in Figure 3 *b* the maximum increase is further south around the equator.

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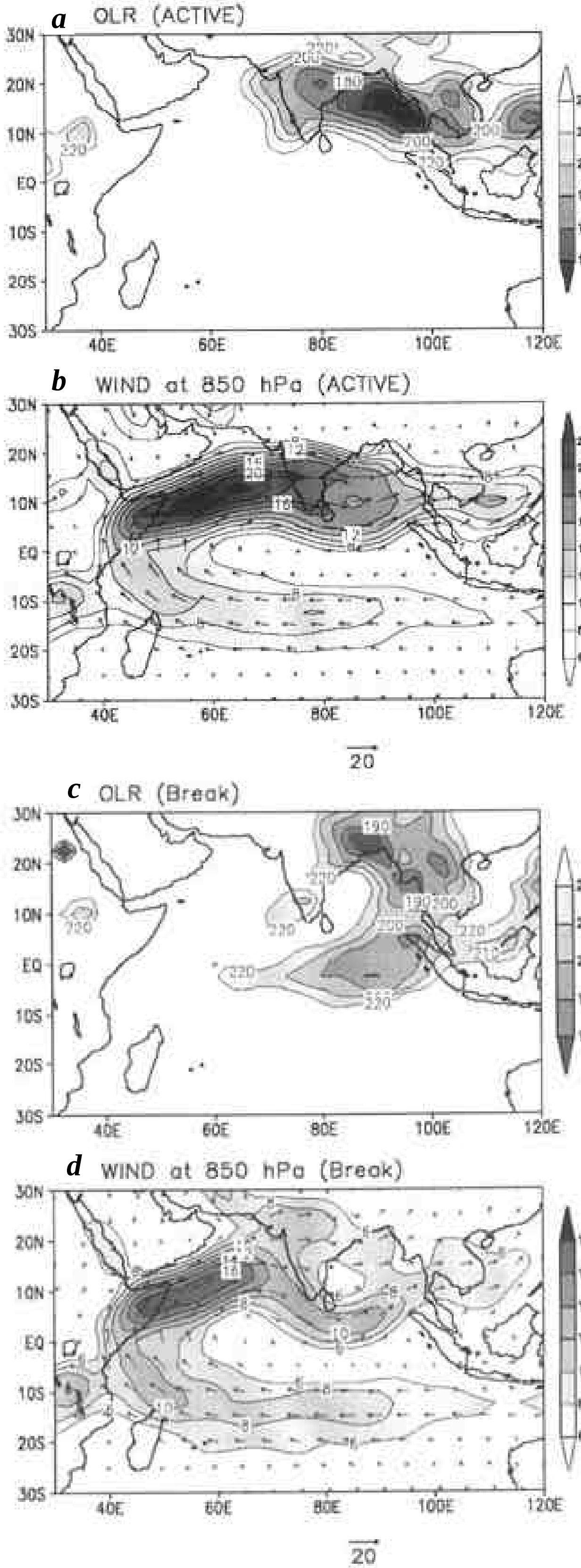

Figure 1. Composites for active monsoon days (***a***, ***b***) and break monsoon days (***c***, ***d***) during June–August 1979–90 (from Joseph and Sijikumar[12]). ***a***, OLR in W/m^2; ***b***, Wind flow at 850 hPa in m/s; ***c***, OLR in W/m^2 and ***d***, Wind flow at 850 hPa in m/s (1 m/s = 3.6 km/h).

One possibility is that over the years, the total length of active (strong) spells in the monsoon season has decreased or the length of the break (weak) spells has increased. To identify strong and weak monsoon spells, we used the twice-daily NCEP–NCAR zonal wind data of the 850 hPa level, as done by Joseph and Sijikumar[12]. Daily data of zonal wind (u) at 850 hPa level were averaged over the area bounded by latitudes 10 and 20 N, and longitudes 70 and 80 E, and a five-day running mean was applied to remove synoptic system influences. Figure 4 *a* gives the variation of 850 hPa zonal wind thus averaged during the monsoon season of 1979. The long break monsoon spells of 1979 (17–23 July and 15 August–3 September), as derived by De *et al.*[16], occurred when the mean u-wind of the box was less than 9 m/s. Joseph and Sijikumar[12] defined active monsoon spells as those with u-wind averaged in the same manner of 15 m/s or more. There were two such active spells in 1979, one in June–July and the other in August,

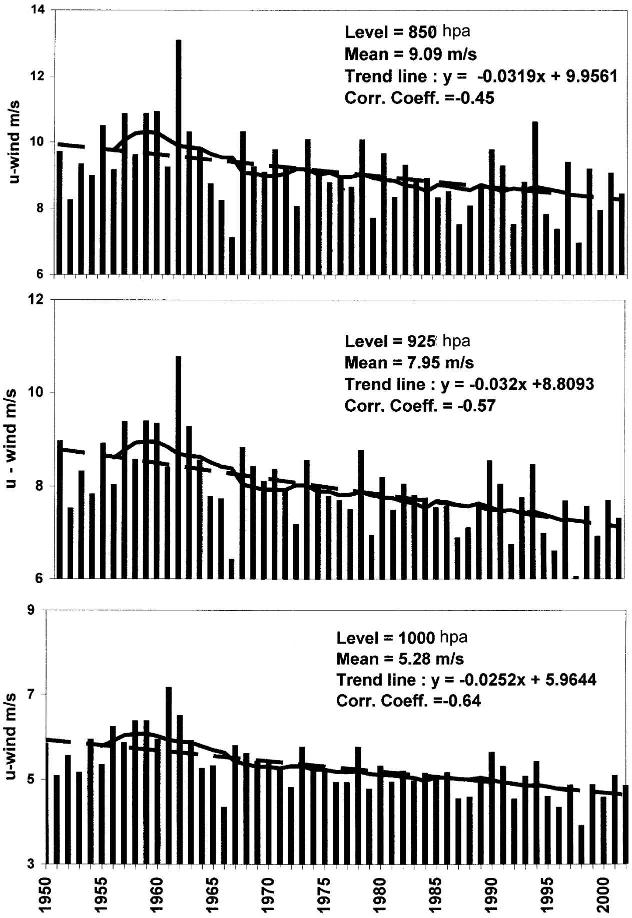

Figure 2 *a*. Mean zonal component of wind (June–September) at 1000, 925 and 850 hPa levels through Box 1 bounded by latitudes 12.5 and 17.5 N, and longitudes 70.0 and 85.0 E in m/s during 1950–2002. The linear trend line marked by broken line shows decrease by 25.5% at 1000 hPa, 21.3% at 925 hPa and 18.6% at 850 hPa of the long-term mean during 1950–2002 at these levels. Eleven-year moving averages are shown. Correlation coefficient between the wind (y-axis) and year (x-axis) is shown.

as may be seen from Figure 4. In 2002, there was a long break (weak) monsoon spell covering the whole of July, as seen from Figure 4 *b*.

We studied the twice daily zonal wind data as derived in the NCEP–NCAR reanalysis for the period 1950–2002. Linear trend analysis has shown that the duration of weak monsoon spells in a monsoon season had increased through 20–30% of its long-term mean (Figure 5) during 1950–2002. Weak monsoon is defined as one with mean wind (*u*) at 850 hPa in the 10–20 N, 70–80 E box equal to or less than 9 or 11 m/s. With such a strong decreasing trend, it is not surprising that the whole of July 2002 had highly deficient rainfall in India, causing a severe drought that year[17,18]. The duration of active spells in the monsoon seasons with zonal winds in the same box at 850 hPa, equal to or greater than 13 or 15 m/s, have shown prominent decreasing trends (Figure 6) during 1950–2002. The linear trends in both Figures 5 and 6 are significant at 95% level by the Mann–Kendall rank test.

It has been shown that production of convective rainfall in the Bay of Bengal and the consequent heating of the atmosphere in a deep layer are needed to pull the LLJ through peninsular India and accelerate the flow (monsoon current). Joseph and Sijikumar[12] have also shown that the strength of the LLJ through peninsular India is positively correlated to the convective heating of the atmosphere over the Bay of Bengal. Maximum correlation has a lag of about three days, convective heating leading. Once the LLJ through peninsular India becomes strong, we get active monsoon conditions over India and genesis of monsoon depressions in the head Bay of Bengal[3]. A feeble area of convection in the Bay of Bengal can grow in a positive feedback process between the convective heating and the LLJ to make an active monsoon spell[12]. When the convective cloud population (and therefore the associated deep heat source) decreases in the Bay of Bengal, the LLJ turns clockwise in the Arabian Sea under conservation of potential vorticity, and bypassing India it flows south, as shown in

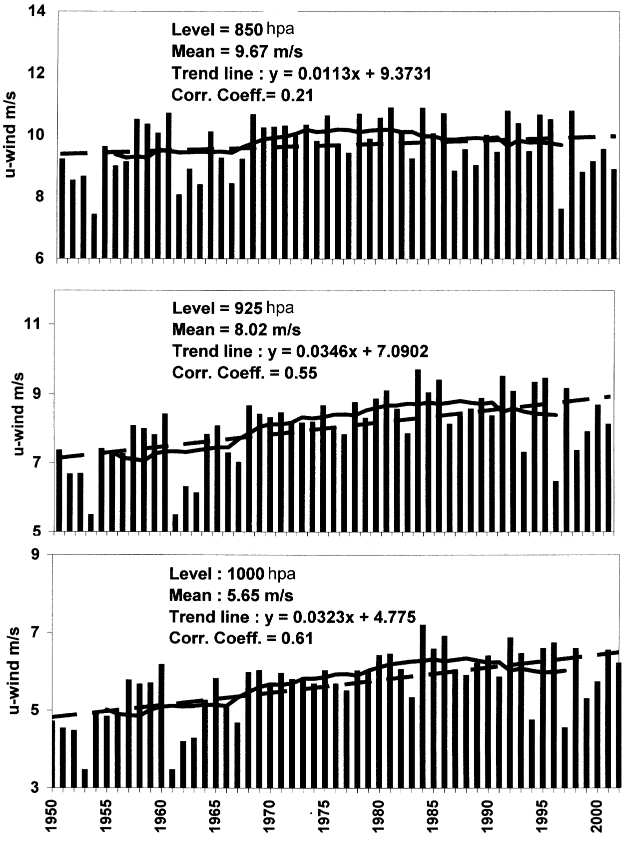

Figure 2 *b*. Mean zonal component of wind (June–September) at 1000, 925 and 850 hPa levels through Box 2 bounded by latitudes 2.5 and 7.5 N, and longitudes 70.0 and 85.0 E in m/s during 1950–2002. The linear trend line marked by broken line shows increase by 30.3% at 1000 hPa, 22.9% at 925 hPa and 6.2% at 850 hPa of the long-term mean during 1950–2002 at these levels. Eleven-year moving averages are shown. Correlation coefficient between the wind (*y*-axis) and year (*x*-axis) is shown.

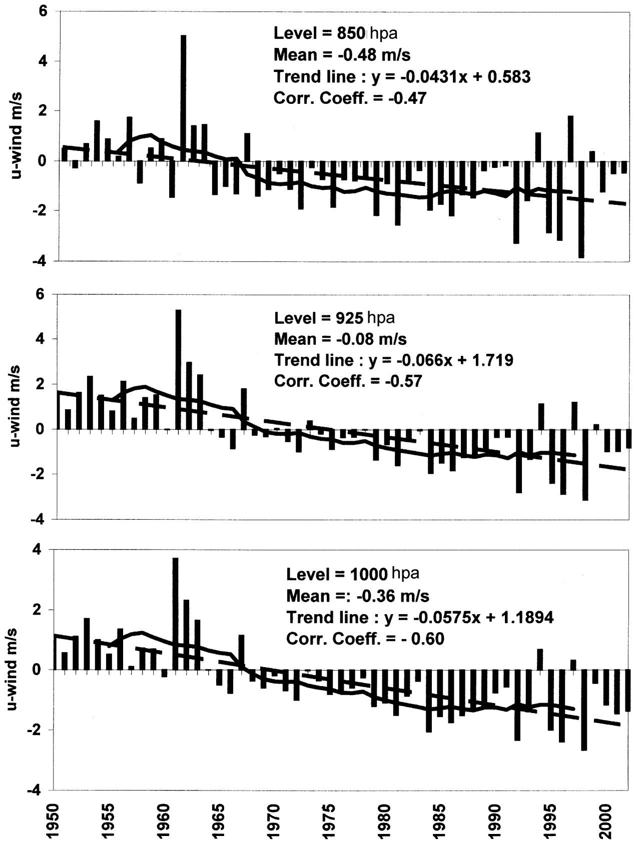

Figure 2 *c*. Difference in monsoon season zonal flow through Box 1 (bounded by latitudes 12.5 and 17.5 N) minus flow through Box 2 (bounded by latitudes 2.5 and 7.5 N) and longitudes 70.0 and 85.0 E at 1000, 925 and 850 hPa levels in m/s during 1950–2002. The difference has decreased by 3.05, 3.51 and 2.28 m/s at 1000, 925 and 850 hPa levels. This shows that break (weak) monsoon type flow is becoming more prominent with time than active (strong) monsoon type flow. Linear trend and 11-year moving average are shown. Correlation coefficient between the wind (*y*-axis) and year (*x*-axis) is also shown.

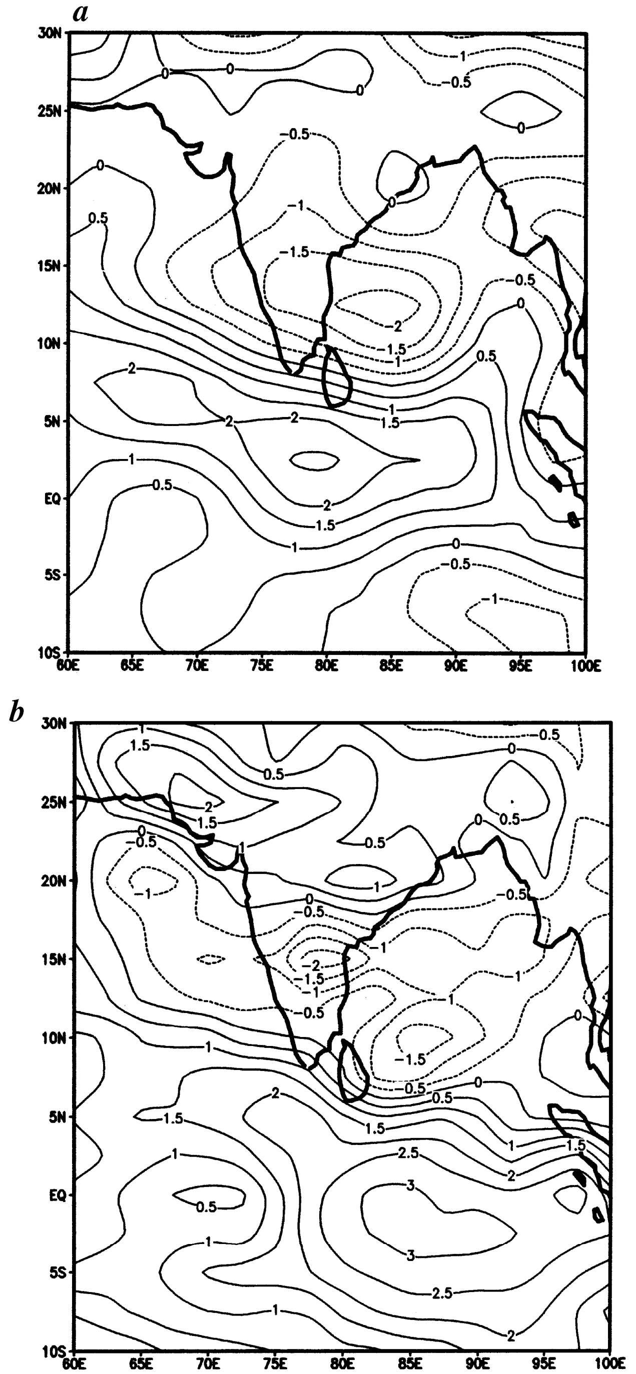

Figure 3. Change in mean zonal wind at 850 hPa during the monsoon season in m/s at each grid point obtained by fitting a linear trend line for the period (***a***) 1950–2002 using NCEP/NCAR reanalysis data and (***b***) 1958–2002 using ERA-40 data.

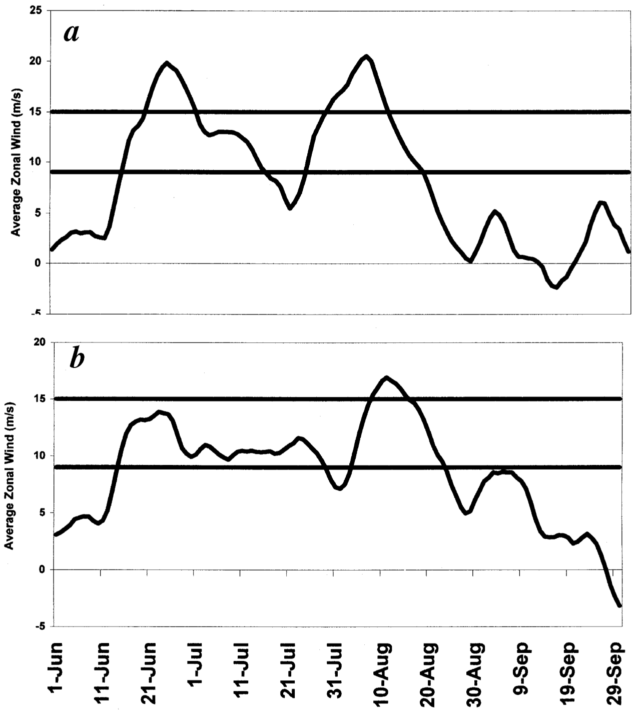

Figure 4. Five-day moving average of the daily zonal flow in m/s at 850 hPa through the box bounded by latitudes 10 and 20 N and longitudes 70 and 80 E for the monsoon season of (***a***) 1979 and (***b***) 2002. Limits for break (9 m/s) and active (15 m/s) monsoon are marked by straight lines.

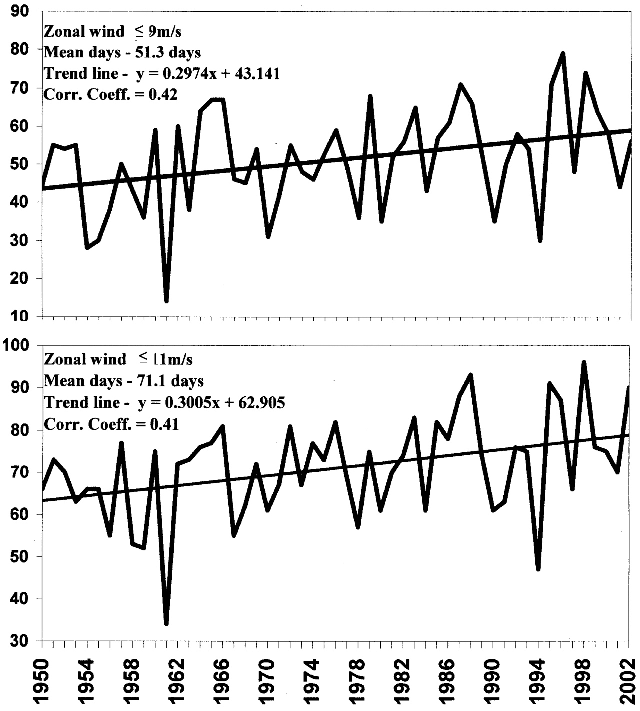

Figure 5. Number of days during monsoon season from 1 June to 30 September with mean zonal flow at 850 hPa level through box bounded by latitudes 10 and 20 N, and longitudes 70 and 80 E less than or equal to 9 m/s (top) and 11 m/s (bottom), shown by wavy line. Linear trend line is also shown. Number of break or weak monsoon days has increased by 30.7 and 22.4% for wind speeds 9 m/s and 11 m/s respectively.

the modelling studies of Rodwell and Hoskins[19]. It is an alarming signal that the active monsoon spells are becoming shorter and the weak monsoon spells longer in recent years. It will be interesting to examine how the 850 hPa zonal wind in the peninsular India box and the average daily monsoon rainfall of India are related.

The Indian Institute of Tropical Meteorology (IITM), Pune has derived time series of the daily averaged 1 June to 30 September rainfall in India using data of more than 300 raingauge stations well distributed over the whole country. We used this dataset kindly provided by IITM to study durations of strong and weak monsoon rainfall. Daily rainfall data for India as a whole for the period 1 June to 30 September 1901–1989 were prepared from grid data[20] and for the period 1990–2002 as updated by IITM from the ‘All India Weather Summary’ prepared by India Meteorological Department. Figure 7 is a bar diagram of the daily rainfall for the monsoon season during 1979 and 2002. The linear correlation coefficient between the daily 850 hPa zonal wind through the peninsular India box and the daily rainfall of India for the monsoon season (1 June to 30 September) of 1979 and 2002 is 0.83 and 0.69 respectively. We performed similar analysis for the monsoon seasons of five DRY years and five WET years for the 30-year period 1961–1990. The 1 June to 30 September rainfall of India during these ten years and their percentage deficiency or excess are given in Table 1. (The long-term mean monsoon rainfall for India of 1871 to 1990 used as base is 86.3 cm and its standard deviation is 8.7 cm.)[21] These are the years of five lowest (DRY) and five highest (WET) rainfall in the 30 years (1961 to 1990). Figure 8 *a* and *b* gives the scatter diagram of daily zonal wind and daily Indian rainfall of the DRY and WET composites.

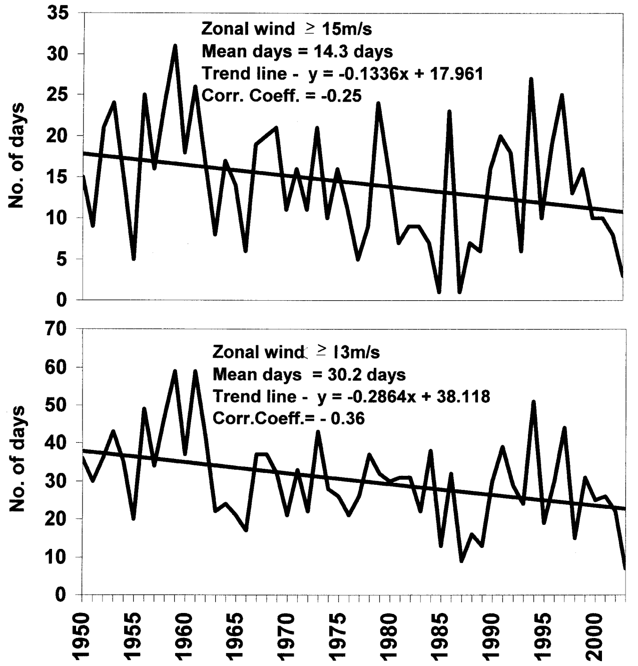

Figure 6. Number of days during monsoon season from 1 June to 30 September with mean zonal flow at 850 hPa level through box bounded by latitudes 10 and 20 N, and longitudes 70 and 80 E greater than or equal to 15 m/s (top) and 13 m/s (bottom) shown by wavy line. Linear trend line is marked. Number of active (strong) monsoon days has decreased by 49.5 and 45% for wind speeds 15 and 13 m/s respectively.

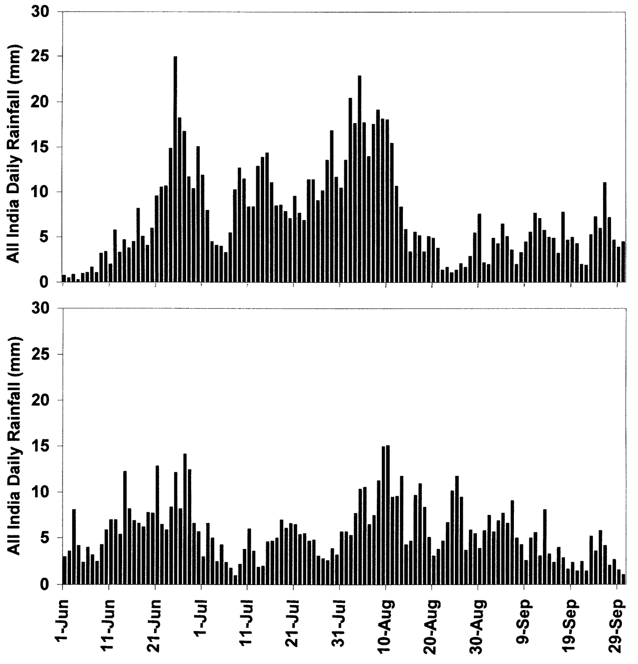

Figure 7. Daily all-India mean rainfall in mm for monsoon season during 1979 (top) and 2002 (bottom).

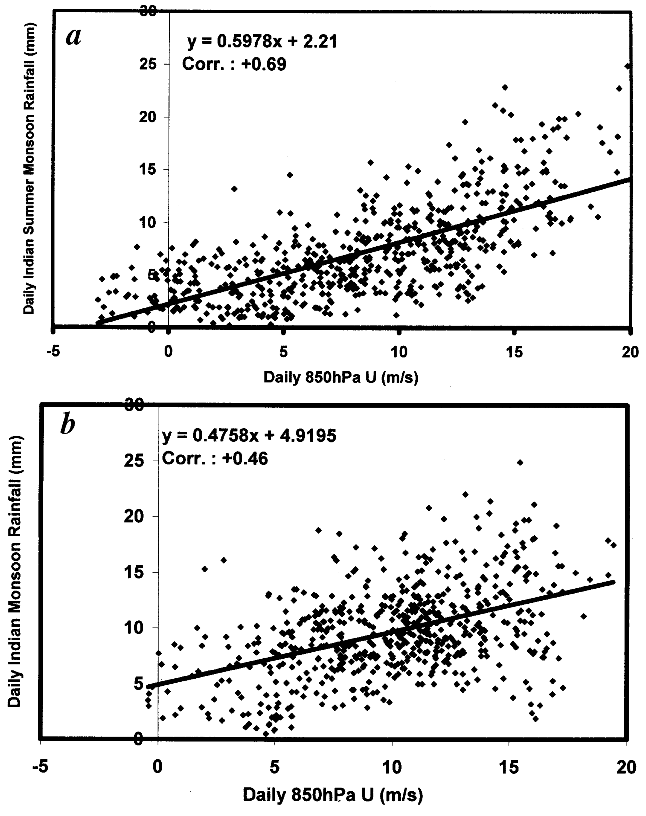

Figure 8. Scatter diagram between daily zonal flow at 850 hPa through box 10–20 N and 70–80 E and daily all-India rainfall during (***a***) five DRY monsoons 1965, 1972, 1979, 1982 and 1987 and (***b***) five WET monsoon 1961, 1970, 1975, 1983 and 1988. Straight line is linear regression line whose equation is also shown.

The linear correlation coefficients between daily wind and rainfall are also shown. The correlations are highly significant (each one with 610 pairs of data). The correlation is higher for DRY years.

We examined whether the long-term trend seen in the zonal wind through peninsular India is seen in the daily all-India rainfall also. From Figure 8 *a* and *b*, it is seen that break (weak) monsoon as defined by 850 hPa zonal wind corresponds to all-India daily rainfall of about 8 mm and less per day, and active (strong) monsoon corresponds to all-India daily rainfall of about 12 mm per day and more. It is seen that there is strong and significant increasing trend in the number of break (weak) monsoon days and significant decreasing trend in active (strong) monsoon days as defined by rainfall in monsoon seasons from 1950 to 2002. The increase in weak monsoon days is by about 45.4% and the decrease in strong monsoon days is 77.8% using this rainfall index.

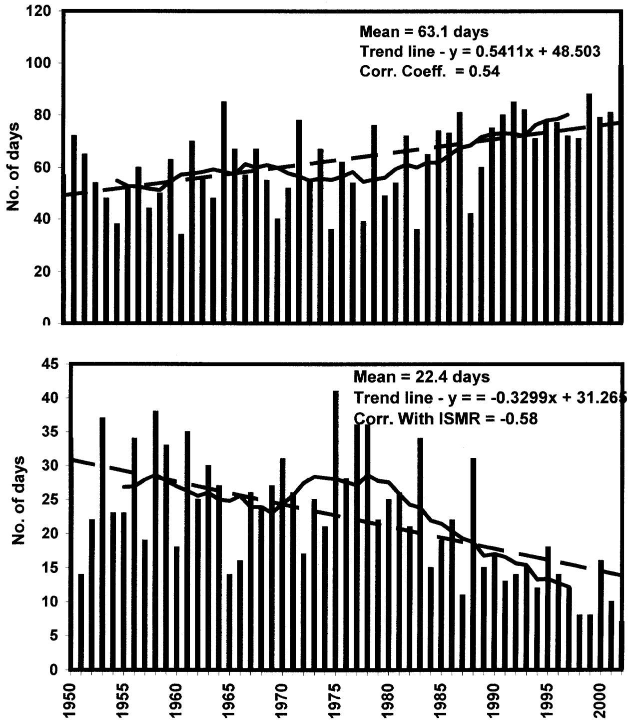

Figure 9. Number of days during monsoon season from 1 June to 30 September with daily all-India rainfall less than or equal to 8 mm/day (top) and greater than or equal to 12 mm/day (bottom) during the period 1950 to 2002. Linear trend is marked by broken line and 11-year moving average by continuous line. Number of days with rainfall greater than or equal to 12 mm/day (active monsoon days) has decreased by 77.8% and that with rainfall less than or equal to 8 mm/day (break monsoon days) has increased by 45.4%.

Table 1. Monsoon (1 June to 30 September) rainfall in India as derived by Parthasarthy *et al.*[21] for the DRY and WET years and its percentage departure from the long-term mean

Year	Rainfall (cm)	Percentage departure
WET years		
1961	103.34	18.1
1970	95.15	10.3
1975	97.48	12.9
1983	96.78	12.2
1988	97.31	12.7
DRY years		
1965	71.81	–16.8
1972	66.13	–23.3
1979	71.74	–16.9
1982	74.51	–13.7
1987	70.69	–18.1

Modelling studies using global models of atmosphere and ocean are needed to know the cause of the decreasing (increasing) trend observed in the lengths of strong (weak) monsoon spells during the monsoon season from 1950 to 2002. A recent observational study has shown that during the last 100 years, monsoon depression frequency had a strong decreasing trend[22]. The frequency now is less than half the frequency of depressions at the beginning of the twentieth century. The decrease in monsoon depression frequency fits in well with the observed long term changes in the duration of strong and weak monsoon spells. (A strong LLJ through peninsular India and the Bay of Bengal is favourable for the genesis of monsoon depressions[3] and monsoon depressions do not form in break or weak monsoon conditions.).

After a long period (1988 to 2001) of good monsoon (June to September) rainfall for India as a whole[17,22], we had two monsoon droughts recently in 2002 and 2004. As a result of the weakening of monsoon current through peninsular India, will we get frequent monsoon droughts in the coming years? This is an important question for India. It is found that the linear correlation coefficient between the mean 850 hPa zonal flow through the box bounded by latitudes 10 and 20 N and longitudes 70 and 80 E for the whole monsoon season and the Indian Summer Monsoon Rainfall (ISMR) as derived by Parthasarthy *et al.*[21], and the series as extended by IITM and given in their website for the season 1 June to 30 September, for the period 1950 to 2002 is 0.65, which is high and statistically very significant. Similarly, the linear correlation coefficient between the meridional flow of the LLJ across the equator at 850 hPa through the box bounded by latitudes 5 S and 5 N and longitudes 35 and 55 E during a monsoon season and ISMR for the same period is 0.64, which is also high and statistically significant. Both these flows, zonal and meridional, are important for monsoon rainfall in India. The multiple correlation coefficient between the zonal and meridional flows and ISMR is 0.72, which explains about 50% of ISMR variability. The meridional flow brings to India moisture produced over the south Indian Ocean and Arabian Sea through the LLJ and the zonal flow through India gives the dynamics for monsoon rainfall of India.

Figure 10 *a* gives variation of mean 850 hPa meridional wind through the box 5S–5N and 35–55 E. Figure 10 *b*

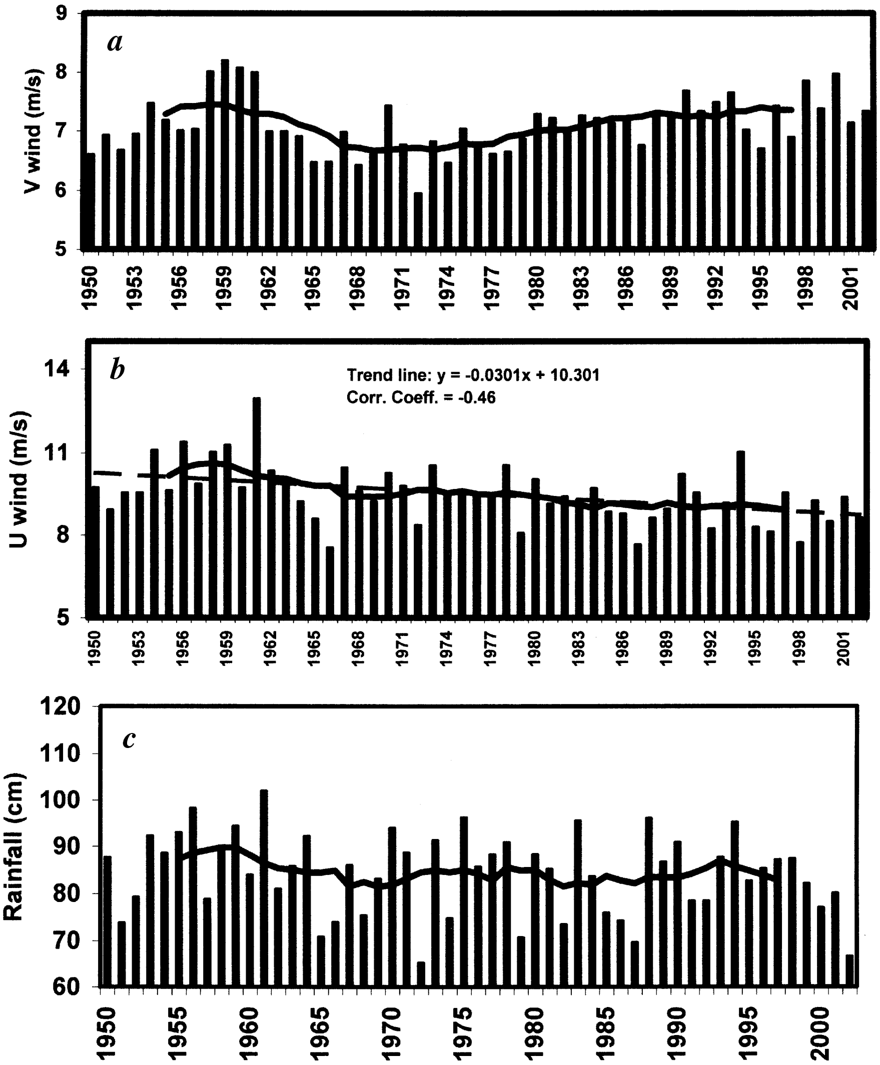

Figure 10. ***a***, Meridional wind flow through box 5 S–5 N, 35–55 E for each monsoon season during 1950 to 2002 shown by bars along with 11-year moving average. ***b***, Zonal flow through box 10–20 N, 70—80 E for the same period with linear trend line and 11-year moving average. ***c***, Indian Summer Monsoon Rainfall and its 11-year moving average for 1950–2002.

gives variation of zonal wind through the box 10–20 N and 70–80 E for each monsoon season from 1 June to 30 September for the period 1950 to 2002. During this period when the zonal flow through peninsular India had a decreasing trend, the meridional flow through the box 5 S–5 N, 35–55 E had decadal variations. ISMR had only decadal variations and no long-term trend (Figure 10 *c*). Coupled with the weakening of the zonal current passing through peninsular India, if the meridional flow crossing the equator also begins to weaken, it is feared that India may have frequent monsoon droughts in the future. Meridional flow has reached a plateau now and it is likely to slow down during the coming decades.

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1. Joseph, P. V. and Raman, P. L., *Indian J. Meteorol. Geophys.*, 1966, **17**, 407–410.
2. Findlater, J., *Quart. J. R. Meteorol. Soc.*, 1969, **95**, 362–380.
3. Sikka, D. R., *Pure Appl. Geophys.*, 1977, **115**, 1501–1529.
4. Webster, P. J., Magana, V. O., Palmer, T. N., Shukla, J., Tomas, R. T., Yanai, M. and Yasunari, T., *J. Geophys. Res. C*, 1998, **103**, 14451–14510.
5. Annamalai, H., Slingo, J. M., Sperber, K. R. and Hodges, K., *Mon. Weather Rev.*, 1999, **127**, 1157–1186.
6. Sperber, K. R., Slingo, J. M. and Annamalai, H., *Q. J. R. Meteorol. Soc.*, 2000, **126**, 2545–2574.
7. Krishnamurthy, V. and Shukla, J., *J. Climate*, 2000, **13**, 4366–4377.
8. Goswami, B. N. and Ajaya Mohan, R. S., *J. Climate*, 2001, **14**, 1180–1198.
9. Annamalai, H. and Slingo, J. M., *Climate Dyn.*, 2001, **18**, 85–102.
10. Krishnan, R., Zhang, C. and Sugi, M., *J. Atmos. Sci.*, 2000, **57**, 1354–1372.
11. Gadgil, S. and Joseph, P. V., *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*), 2003, **112**, 529–558.
12. Joseph, P. V. and Sijikumar, S., *J. Climate,* 2004, **17**, 1449–1458.

13. Joseph, P. V., *Mausam*, 1990, **41**, 291–296.
14. Rajeevan, M., *Mausam*, 1993, **44**, 109–111.
15. Kalnay, E. *et al.*, *Bull. Am. Meteorol. Soc.*, 1996, **77**, 437–471.
16. De, U. S., Lele, R. R. and Natu, J. C., Breaks in southwest monsoon. India Meteorological Department Report No. 1998/3, 1998.
17. Gadgil, S., Srinivasan, J., Nanjundiah, R. S., Kumar, K. K. and Munot, A. A., *Curr. Sci.*, 2002, **83**, 394–403.
18. Kalsi, S. R., Hatwar, H. R., Subramanian, S. K., Rajeevan, M., Jayanthi, N., Shyamala, B. and Jenamani, R. K., Various aspects of unusual behaviour of monsoon-2002, India Meteorological Department, Synoptic Meteorology No. 2/2004, 2004, p. 97.
19. Rodwell, M. J. and Hoskins, B. J., *J. Atmos. Sci.*, 1995, **52**, 1341–1356.
20. Kripalani, R. H., Singh, S. V. and Arkin, P. A., Large-scale features of rainfall and outgoing long-wave radiation over Indian and adjoining regions. *Contrib. Atmos. Phys.*, 1991, **64**, 159–168.
21. Parthasarthy, B., Munot, A. A. and Kothawale, D. R., All-India monthly and seasonal rainfall series: 1871–1993. *Theor. Appl. Climatol.*, 1994, **49**, 217–224.
22. Joseph, P. V. and Xavier, P. K., Meteorology beyond 2000. In Proceedings of Indian Meteorological Society: TROPMET-99 Symposium, 1999, pp. 364–371.

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Benthic recovery four years after an El Niño-induced coral mass mortality in the Lakshadweep atolls

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The reefs of the Lakshadweep suffered a mass mortality of coral in 1998, in the wake of an El Niño event of unprecedented severity. In 2002, we conducted a broad-scale benthic survey of six atolls in this group to check if there were geographic trends in recovery patterns across the archipelago. Four years after the mass mortality, live coral cover was relatively low on most atolls, and thin algal turfs dominated the benthos. Clear benthic differences were apparent between eastern and western aspects of reefs, pointing to the importance of local hydrodynamic conditions in determining recovery rates. Where recovery was the most apparent, it was dominated by fast-growing and bleaching-resistant coral genera. Despite the apparent lack of recovery at many sites, the reef system did not show signs of having suffered a 'phase shift' to a macroalgal state. High herbivorous fish abundance was likely responsible in controlling macrophyte levels, and may be crucial for further benthic recovery in these reefs.

Keywords: Benthic recovery, coral bleaching, El Niño, Lakshadweep, mass mortality.

THE El Niño event of 1997–98 raised sea surface temperatures (SSTs) significantly above seasonal averages, causing large-scale coral mortality in tropical reefs[1]. Under stress, the chemical pathways that sustain the symbiotic relationship between algal zooxanthellae and their coral hosts are seriously compromised, and corals expel zooxanthellae, turning pale and then bleaching white[2]. While bleaching may be a routine response to minor stresses, when unfavourable conditions are protracted, corals may bleach en masse, and eventually die[3]. The effect of the 1997–98 ENSO on reefs was unprecedented in intensity, duration and extent; anomalous temperatures rose to previously unrecorded levels, causing mass bleaching of coral in reefs across the tropics at scales never encountered before. Many reefs recovered relatively quickly from this disturbance, but at several locations, corals were not able to recover and sustained considerable reductions to their populations[1,4–7].

Forecasts of climate data suggest that the 1997–98 El Niño presages an environment where SST anomalies will increase in intensity and frequency, resulting in recurrent and widespread coral bleaching and mortality events, possibly every year[8,9]. It is unclear how long reefs will continue to be able to maintain ecological function under such sustained pressure. As the dominant structural element in reefs, the loss of coral could result in major changes in benthic topography and flow-on consequences for other species, including fish. Additionally, the loss of coral could benefit opportunistic species like fleshy macroalgae, which often rapidly overtake benthic substrate, radically altering functional states, and potentially precluding the re-establishment of corals in these areas[10–12]. Once precipitated, these changes in functional state, called phase shifts, can be remarkably difficult to reverse[13,14]. Human communities in the developing tropics depend heavily on reefs for food security as well as a range of other ecosystem services[15], and the reduced function of reefs could potentially have a large impact on these economies[16].

Many reefs in the Indian Ocean were severely affected by the anomalous SST event of 1997–98. Coral mass bleaching and mortality were reported in various locations, including the East African coast, the reefs of continental India, Sri Lanka, and from several oceanic islands[1,17–20]. Reefs in the northern Indian Ocean atoll chain were particularly badly affected: for instance, reefs in Chagos and Maldives experienced large-scale bleaching of coral, with as much as 90% post-bleaching mortality in many of them[21–23].

As part of a broader assessment of bleaching impacts on Indian coral reefs, the first author (R.A.) surveyed shallow-

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