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The evolution of Indian summer monsoon in 1997 and 1983

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Summary

During most El-Niño events the Indian summer monsoon rainfall has been below normal. El-Niño that occurred during 1997 was one of the strongest in the 20th century, but did not have an adverse impact on the Indian summer monsoon rainfall in 1997. This is despite the fact that most parameters observed in May 1997 suggested that the Indian summer monsoon rainfall may be below normal. This intriguing feature of the 1997 Indian summer monsoon rainfall has been examined by studying the evolution of various parameters from May to August. The behavior of the 1997 monsoon is related to its evolution during June and July, with westward migration of cloudbands from West Pacific that increased convection over Bay of Bengal. We find that there exists a significant correlation between convective activity over Bay of Bengal and winds over the Arabian Sea with the latter lagging convection over Bay of Bengal by about three days. The convective activity over Bay of Bengal induces stronger winds over the Arabian Sea and this in turn enhances advection of moisture into the Indian landmass and leads to increased precipitable water and strength of the monsoon. Using a simple thermodynamic model we show that increased precipitable water during July leads to increased rainfall. A similar behavior has also been noticed during the 1983 monsoon, with precursors indicating a possible poor monsoon but subsequent events changed the course of the monsoon.

1. Introduction

Numerous studies have shown that there is a strong association between the Indian summer monsoon rainfall and El-Niño (see, for example, Sikka, 1980; Rasmusson and Carpenter, 1983).

The Indian summer monsoon is usually below normal during an El-Niño year. In the recent past, the severe droughts in 1972, 1982 and 1987 were associated with El-Niño events in the Pacific Ocean. Given the strong association between Indian summer monsoon and El-Niño it is indeed intriguing that during the strongest El-Niño of the 20th century (1997–98), the rainfall over the Indian region was marginally above normal (Fig. 1) at 103% of its long-term average. In contrast, we find that during 1987, another year with a moderate El-Niño, there was a severe failure of the Indian monsoon. Some studies have been attempted to understand the behavior of the 1997 monsoon. Asnani (2001) has studied the 1997 monsoon and its relationship with El-Niño using Sea Surface Temperature (SST), Southern Oscillation Index (SOI) and Outgoing Longwave Radiation (OLR). He notes that while rainfall during early June was below normal, it picked up substantially from the 3rd week of June and remained nearly normal through rest of the season. Krishna Kumar et al. (1999) have argued that the association between El-Niño and the Indian summer monsoon rainfall became progressively weaker during the decade of 1990–2000. They attribute the weaker link between equatorial Pacific Ocean and the Indian monsoon to the reduction of snow cover over Eurasia. Chang et al. (2001) have suggested that Atlantic circulations have a role to play in the weakening of the

Fig. 1. The precipitation anomaly during **a** June–Sept 1987; **b** during June–Sept 1997; **c** during June–Sept 1983; and **d** June–Sept mean for 1979–1998 from Xie and Arkin (1997) precipitation dataset

relationship between Indian monsoon rainfall and El-Niño. They argue that the effect of ENSO on the monsoon is disrupted by increased meridional temperature gradient caused by the eastward extension of warmer Eurasian temperatures which in turn is affected by poleward shift of the jet stream over the North Atlantic. Shen and Kimoto (1999) suggest that intraseasonal variability of the monsoon system in 1997 was responsible for the above-normal rainfall over India. Their study indicates that the transient component of moisture transport was much larger than normal, leading to positive rainfall

anomalies over India. Slingo and Annamalai (2000) studied the relationship between El-Niño and Indian monsoon in the specific context of the 1997 monsoon and found that the modulation of the local Hadley circulation over the maritime continent may play an important role. Their analysis shows that the suppression of convection over the maritime continent and the equatorial Indian Ocean was marked in 1997. This caused the tropical convergence zone over the Indian subcontinent and West Pacific to be more active, particularly in July and August. They suggest that while El-Niño of 1982 and 1987 caused

suppression of Walker circulation, the intense El-Niño of 1997 may have resulted in the Hadley circulation over the maritime continent shifting to a different regime. Monsoon being a complex nonlinear system it is indeed possible that more than one mechanism (or a combination of these) could be responsible for this behavior.

The major objectives of this paper is to understand the behavior of monsoon during 1997 and 1983, especially with reference to their evolution. We also highlight the relationship between the rainfall over Bay of Bengal and winds over the Arabian Sea and its impact on increasing rainfall over the Indian landmass through increased moisture advection. In Sect. 2, we discuss the datasets used in this study and in Sect. 3, we examine the conditions prior to the monsoon. In Sect. 4, we examine the evolution of monsoon during the monsoon months of June, July and August during 1997 and 1983. This study of evolution of the 1983 and 1997 monsoons is similar in spirit to the studies of the 1987 and 1988 monsoons by Krishnamurti et al. (1989), and Krishnamurti et al. (1990). Discussions and conclusions are presented in Sect. 5.

2. Data used in this study

In this study we have used winds, and precipitable water from NCEP/NCAR reanalysis (Kalnay et al., 1996). The Outgoing Longwave Radiation (OLR, a proxy for rainfall or organized convective activity) is from NOAA AVHRR. All India monsoon rainfall is from Parthasarthy et al. (1994) and the global monthly mean rainfall data used is the merged dataset of satellite observations and conventional observations (including rain gauge data) based on the algorithm of Xie and Arkin (1997). Daily rainfall for 1997 is from GPCP (Huffman et al., 2001). The relatively coarse resolution ($2.5^\circ \times 2.5^\circ$ of the NCEP/NCAR reanalysis and $1^\circ \times 1^\circ$ of the GPCP rainfall dataset) of these datasets precludes any analysis of meso-scale features.

3. Precursors to the summer monsoon of 1997

Many studies beginning with the pioneering work of Walker (1923) have suggested that values of

certain parameters in the months preceding the summer monsoon can be used as indicators of the strength of the Indian summer monsoon (Banerjee et al. (1978), Sikka (1980), Kung and Sharif (1980), Joseph et al., (1981), Pant and Parthasarthy (1981), Thapliyal (1984), and Parthasarthy et al. (1994)). Joseph and Srinivasan (2000) have shown that the pattern of 200 hPa meridional wind anomaly during the month of May could be used to predict the strength of the subsequent monsoon. Yang et al. (1996) have shown that prior to a strong monsoon the westerlies over subtropical Asian region are weaker. Thapliyal (1990) has shown that various parameters such as Himalayan snow cover at the end of May, South American surface pressure, Sri Lankan rainfall in May, Darwin surface pressure, Central Indian surface temperature during May can be used to predict the strength of the ensuing Indian summer monsoon. Based on these parameters, the India Meteorological Department (IMD) has developed a multi-parameter regression model used for generating long-range forecasts of the monsoon. Vernekar and Ji (1999) have shown that prior to a weak monsoon the circulation over the East Asian high is weaker and surface pressure anomaly over the Indian region is positive. Kripalani et al. (1999) have suggested that upper tropospheric/stratospheric geopotential heights over Siberian region could have signals which may indicate the strength of the ensuing summer monsoon. Harzallah and Sadourny (1997) have shown that strong monsoons are associated with low Eurasian snow-cover during the preceding winter, and warm SSTs in the Niño 3 and subtropical Atlantic region during the preceding autumn.

Let us examine the conditions prior to the 1997 summer monsoon. The upper level (200 hPa) westerlies during the preceding winter and spring over the Indian monsoon region (50°E – 80° and 10°N – 22°N) were stronger than normal (i.e., it indicated a relatively weaker monsoon, Yang et al., 1996). The surface pressure anomaly during May 1997 over the Indian was positive, indicating that the ensuing monsoon could be below normal (according to Vernekar and Ji, 1999).

The monsoon is influenced both by large-scale circulation and the conditions over the oceans around India. We examine the two variables viz. 200 hPa meridional winds (which would reflect

the conditions of the large-scale flow) and precipitable water (which would reflect conditions over the surrounding oceans), to highlight the conditions prevalent preceding the 1997 monsoon (i.e., during the month of May 1997).

3.1 Meridional winds during May 1997

Joseph and Srinivasan (2000) have shown that wave trains of large amplitude with wavelengths 50° E– 60° longitude (zonal wave number 6–7) are prominent in 200 hPa meridional wind anomalies during the month of May. There is, however a spatial phase difference of about 20° longitude between the weak and strong monsoons. We show the anomalies for 200 hPa meridional winds for the weak monsoon years of 1972 and 1987 (Fig. 2). It is interesting to note that this spatial shift between a good and bad monsoon year is unrelated to the phase of the ENSO e.g., while 1987 was a drought year that occurred during an El-Niño event, 1979 was a severe drought during a year in which there was no significant ENSO activity. Notice that during May preceding a weak monsoon, the Indian region has anomalous

southerlies while in a strong monsoon the anomalies are northerly. Now comparing the 200 hPa meridional wind anomaly pattern during 1997 (Fig. 3) with the previous years we notice that southerlies occur over the Indian region i.e., it is similar to that of a weak monsoon year (though it was a year with normal monsoon rainfall).

3.2 Precipitable water during May 1997

Srinivasan (2001), Zhang (1995), and Nanjundiah and Srinivasan (1999) have highlighted the importance of precipitable water in modulating tropical rainfall in observations and in model simulations. Precipitable water influences precipitation through the availability of moisture and through modification of vertical moist static stability. As most of the water vapour over the Indian subcontinent is advected from the surrounding oceans, precipitable water over these areas can be indicative of the strength of the ensuing monsoon. For this purpose we have examined the precipitable water during the pre-monsoon phase (the month of May) during extreme years when the monsoons were extremely

Fig. 2. The 200 hPa meridional wind anomaly during the month of May for years with below normal monsoon rainfall; top: May 1987, bottom: May 1979

Fig. 3. The 200 hPa meridional wind anomaly during the month of May 1997

Fig. 4. The precipitable water (kg m^{-2}) anomaly during the month of May for **a** May 1979; **b** May 1987

weak (1979, 1987, Fig. 4). The anomaly of precipitable water over the oceans around the Indian subcontinent for the month of May from NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) was negative for weak monsoon years.

This signal appears to be indicative of the strength of the ensuing monsoon, independent of the phase of the ENSO. The monsoon failure during 1979 was not associated with El-Niño. We find that during 1997 (Fig. 5) this anomaly was negative i.e., it was similar to that in May during weak monsoon years.

The conditions in May in 1997 indicated that it would be a weak monsoon. IMD's long term forecast based on the multi-parameter regression model of Gowardkar et al. (1989) indicated that the strength of the monsoon would be around 92% (with a possible error of 4%, i.e., it could be between 88% and 96% of the mean). The rainfall during the summer monsoon of 1997 was 103%.

Fig. 5. The precipitable water (kg m^{-2}) anomaly during the month May 1997

The 200 hPa meridional wind anomaly in July 1997 was very different from that in May 1997. In July, the meridional wind (Fig. 6a) was similar

Fig. 6. The 200 hPa meridional wind anomaly during **a** July 1997; **b** July 1988; and **c** July 1987

to that of July 1988 (a year of strong monsoon, see Fig. 6b) and different from the pattern during July 1987 (Fig. 6c). This is surprising since the 200 hPa meridional wind anomaly during May 1997 was closer to that in May 1987 and different from that of May 1988. This suggests that some events must have occurred during June which changed the manner in which monsoon evolved in 1997. We therefore examine the evolution of the 1997 monsoon.

4. Evolution of the 1997 and 1983 monsoons

We show in Fig. 7 the evolution of daily Kinetic Energy (KE) at 850 hPa and precipitable water (pwat) during the 1997 and 1987 monsoons over

the Indian region (70°E – 90°E , 10°N – 30°N). We notice that during early June precipitable water was lower in 1997 than during 1987 and the winds were weaker too. It is also noteworthy that precipitable water showed a gradual increase in 1997 while it peaked in early June during 1987 followed by a reduction in its magnitude. We find that till 16th June the precipitable water vapour in 1997 was below that in 1987. There was a rapid increase in precipitable water vapour around 16th June 1997 and after that the precipitable water in 1997 remained higher than that in 1987 up to the middle of August. What synoptic event contributed to the dramatic increase in precipitable water around 16th June 1997? The daily Outgoing Longwave Radiation (OLR) from NOAA-AVHRR from 1st to 20th June 1997 (Fig. 8)

Fig. 7. The evolution of precipitable water (pwat , kg m^{-2}) and kinetic energy (KE , $\text{m}^2 \text{s}^{-2}$) during the 1997 (dashed lines) and the 1987 (solid lines) monsoons over the Indian region (70°E – 90°E 10°N – 30°N). 5 day smoothing applied to both KE and pwat

Fig. 8. Daily variation of OLR averaged between 7.5°N and 17.5°N during May–June 1997. Contours are drawn at 200, 220, and 240 Wm^{-2}

shows that there was a westward migrating deep cloudband from the Western Pacific region which arrived in Bay of Bengal on 6th June 1997. A little later there was a northward migrating

cloudband from 10°S that reached the Bay of Bengal on 16th June. Both these events caused copious rainfall over Bay of Bengal. We find that during this event around 15th June, precipitation

Fig. 9a. Convective activity over the Indian Region between 15–20 June 1997 (mm day⁻¹); **b** 850 hPa zonal wind (dashed line, m sec⁻¹) over Arabian Sea (60° E–70° E, 15° N–20° N) and precipitable water (dotted line, kg m⁻²) over the land region (75° E–80° E, 15° N–20° N); **c** 850 hPa wind over Arabian Sea and rainfall over Bay of Bengal (87.5° E–92.5° E, 15° N–20° N)

over Bay of Bengal (Fig. 9c) increased followed by increase in winds over the Arabian Sea (with a lag of about 2–3 days). This suggests that convective events over Bay of Bengal influence winds over the Arabian Sea. This can be verified by looking at the correlation between daily rainfall over Bay of Bengal (BoB, 87.5° E–92.5° E, 15° N–20° N from GPCP daily rainfall data) and the 850 hPa zonal KE over Arabian Sea (AS, 60° E–70° E, 15° N–20° N, from NCEP/NCAR

Fig. 10. Correlation between zonal KE over Arabian Sea (60° E–70° E, 15° N–20° N) and rainfall over Bay of Bengal (87.5° E–92.5° E, 15° N–20° N) during June and July 1997

reanalysis). This is shown in Fig. 10. We find that rainfall over the Bay of Bengal is strongly correlated with winds over the Arabian Sea, with the latter lagging the precipitation over the Bay of Bengal by about 3 days (Fig. 10). The maximum correlation is about 0.52 significant at over 99% (tested using the randomization technique of Sokal and Rohlf, 1981). This correlation between winds over the Arabian Sea and rainfall over Bay of Bengal is also seen in 1998 and 1999 (the years for which daily rainfall datasets are available).

The relationship between winds over Arabian Sea and convective activity over Bay of Bengal can be understood in terms of the simple transient model of Heckley and Gill (1984). The convective activity over Bay of Bengal acts as an off-equatorial heat source and in response to this, westerlies to the west of the heat source (i.e., the Arabian Sea region) intensify. They have also shown that typical response time between the initiation of heating and reaching a state of maximum response (or in their case the near steady-state value) is around 2–3 days. Mawson and Cullen (1992) using a “dry” (i.e., a model without the moisture conservation equation) primitive equation model have also shown that the large-scale flow field around the Indian region responds with a lag of about 5 days to the monsoon heat source.

This suggests that convective activity (a heat source) over the Bay of Bengal (Fig. 9a,c)

Fig. 11. Pentad differences of precipitable water (kg m^{-2}) between June 1997 and June 1987

caused the winds to increase over Arabian Sea (Fig. 9a, b) strengthening the low-level westerly jet which in turn caused enhanced advection of moisture into the Indian region. The (pentad) differences of pwat over the Indian region between June 1997 and June 1987 is shown in Fig. 11. We notice that in the first three pentads the precipitable water is below the corresponding value for June 1987. The precipitable water increases from the pentad of 11 June–15 June 1997. It becomes much larger during the pentad of 16–20 June (coinciding with the westward propagating event) and remains higher than the corresponding 1987 value during the rest of the month. The increase in precipitable water after 16th June increases the strength of the monsoon as seen by the increase in 850 hPa kinetic energy over the Indian region (Fig. 7). Asnani (2001) has

also noted that while monsoon rainfall was below normal during the first two weeks of June, it increased substantially during the 3rd week and remained normal during rest of the season.

A single synoptic event during the 1997 monsoon season appears to have changed the course of the monsoon. This may be somewhat surprising. Was this a unique feature of the 1997 monsoon or did such a phenomenon occur in other years? We consider another year in which the precursors indicated a possible weak monsoon but was one of the strongest monsoons viz., 1983.

4.1 The 1983 monsoon

The Indian summer monsoon rainfall (June–September) in 1983 was about 950 mm (about 100 mm or 12% above normal, Fig. 1). We find that as in 1997, the precipitable water in the month of May 1983 had a negative anomaly in the Indian region (Fig. 12) suggesting a possible weak monsoon. Surface pressure anomaly during May 1983 was positive. Vernekar and Ji (1999) have shown that a positive surface pressure anomaly during the pre-monsoon period indicates a weak monsoon. The 200 hPa meridional wind (Fig. 13) anomalies showed a shift of wave-trains the phase of which was similar to that 1987 and indicated the possibility of a poor monsoon.

The precipitable water and kinetic energy in 1983 during early and mid-June (Fig. 14) was lower than that during the corresponding period in 1987. However, precipitable water showed a rapid increase during the middle of June. During this period we notice the occurrence of a westward migrating cloudband (Fig. 15) from the

Fig. 12. Anomaly of precipitable water (pwat, kg m^{-2}) during May 1983

Fig. 13. The 200 hPa meridional wind anomaly during May 1983

Fig. 14. The evolution of precipitable water (pwat , kg m^{-2}) and kinetic energy (KE , $\text{m}^2 \text{s}^{-2}$) during the 1983 (dashed lines) and the 1987 (solid lines) monsoons over the Indian region (70°E – 90°E 10°N – 30°N). 5-day smoothing applied to both KE and pwat

Fig. 15. The variation of OLR during 1983, averaged between 7.5°N – 17.5°N . Contours are drawn at 200, 220, and 240 W m^{-2}

West Pacific region into the Bay of Bengal. This increased convective activity over the Bay of Bengal which in turn caused a strengthening of the westerly jet over the Arabian Sea. The

increased winds over the Arabian Sea (lagging the convective activity over Bay of Bengal by about 2–3 days) increased the moisture convergence into the Indian landmass and caused an

Fig. 16a. Convective activity over the Indian region between 6–10 June 1983; **b** 850 hPa zonal wind (dashed line) over Arabian Sea (55° E–65° E, 10° N–15° N) and precipitable water (dotted line) over the land region (75° E–80° E, 10° N–15° N)

increase in precipitable water (Fig. 16) and kinetic energy over the Indian region (Fig. 14). Thus the evolution of the 1983 Indian summer monsoon was similar to that of 1997.

5. Discussions and summary

We have shown that the evolution of the Indian summer monsoon in 1997 and 1983 had similar features (schematically shown in Fig. 17). In both years the patterns of integrated water vapour and meridional wind in May indicated that seasonal mean monsoon rainfall may be below normal. The course of the monsoon changed in 1997 and 1983 on account of the migration of tropical convective systems from west Pacific

Fig. 17. Schematic of events leading to intensification of monsoon in mid-June during 1997 and 1983

into the Bay of Bengal in the middle of June. The intense rainfall in the Bay of Bengal during the middle of June acted as a heat source that led to an increase in the westerly winds in the Arabian Sea (with a lag of about 3 days). The higher westerly winds increased the advection of moisture from the Arabian Sea to the Indian land-mass. The evaporation was also higher due to the above normal SST in the Arabian Sea region during the months of June and July 1997. The above normal SST is related to the difference in phase of the 1997 El-Niño vis-a-vis the El-Niño of 1987. Typically during an El-Niño the warming of the Indian Ocean is noticeable only by October. However, during the 1997 El-Niño significant warming of the northern Indian Ocean (~about 1.0°C over the Arabian Sea during the

Fig. 18. Sea-surface temperature anomalies ($^{\circ}\text{C}$, from the climatological mean of 1979–1998) during **a** June 1997; and **b** June 1987

month of June 1997) occurred during the month of June (Fig. 18). As a consequence evaporation was much higher over the Arabian Sea region (by about 40 W m^{-2} vis-a-vis 1987). The higher evaporation in turn increased the moisture flow into the subcontinent, increasing the precipitable water (pwat) over this region. The importance of evaporation over Arabian Sea and its subsequent transport into the Indian landmass has also been highlighted by Rao et al. (1981).

The precipitable water over India was higher than normal in July 1997 and July 1983. The precipitable water averaged over India was 52 kg m^{-2} in July 1983 and 1997 while it was 48 kg m^{-2} in July 1987. Srinivasan (2001) has used the energy and moisture budget in an atmospheric column to show that the monthly mean rainfall and the monthly mean integrated water vapour in tropical continent are related as follows:

$$P = E + \frac{Q_{\text{net}} P_w}{(85 - P_w)}, \quad (1)$$

where P = rainfall, E = evaporation, Q_{net} = net radiation at the top of the atmosphere and P_w = total precipitable water (integrated water vapour). The second term in the right-hand side of the above equation is the moisture convergence term. This term depends upon the net

radiation at the top of the atmosphere and the integrated water vapour. From the above equation, we can infer that when monthly mean integrated water vapour increases by 1 kg m^{-2} , the monthly mean rainfall can increase by around 0.25 mm day^{-1} (depending upon the value of P_w and Q_{net}). The integrated water vapour in July 1997 was around 4 kg m^{-2} higher than in July 1987. This should have increased the moisture convergence by about 1 mm day^{-1} (from the above equation). The evaporation in July 1997 was about 1 mm/day higher than that in July 1987 (from NCEP reanalyses). The observed All India monsoon rainfall was 8 mm day^{-1} in July 1997 while it was 5.5 mm day^{-1} in July 1987. Hence the All Indian monsoon rainfall in July 1997 was 2.5 mm day^{-1} higher than in July 1987. The estimate of the increase in rainfall from the above equation is 2 mm day^{-1} which is close to the observed increase. Hence an increase in integrated water vapour over India on account of advection of moisture from Arabian Sea can increase the monthly mean rainfall by around 25%. Can a single synoptic event over Bay of Bengal alter the seasonal mean monsoon rainfall over India? Recently Rodwell (1997) has shown that a single synoptic event can alter the seasonal mean monsoon rainfall over India. He has argued

that the intrusion of dry mid-latitude air from the southern hemisphere (through the Somali jet) can reduce the seasonal mean monsoon rainfall over India by 4 to 5%. This occurs on account of the reduction in the advection of moisture from the Arabian Sea. Rodwell (1997) has also shown that a single convective event that occurred during 12–14 July 1994 had an impact on the seasonal mean monsoon rainfall.

Our study suggests a possible mechanism by which the monsoon strength may increase. Other studies such as Chang et al. (2001) have concentrated on global conditions which caused the 1997 monsoon to behave in an anomalous fashion. It is possible that there could be linkages between the synoptic scales (analyzed in our paper) and the global conditions (analyzed by others).

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