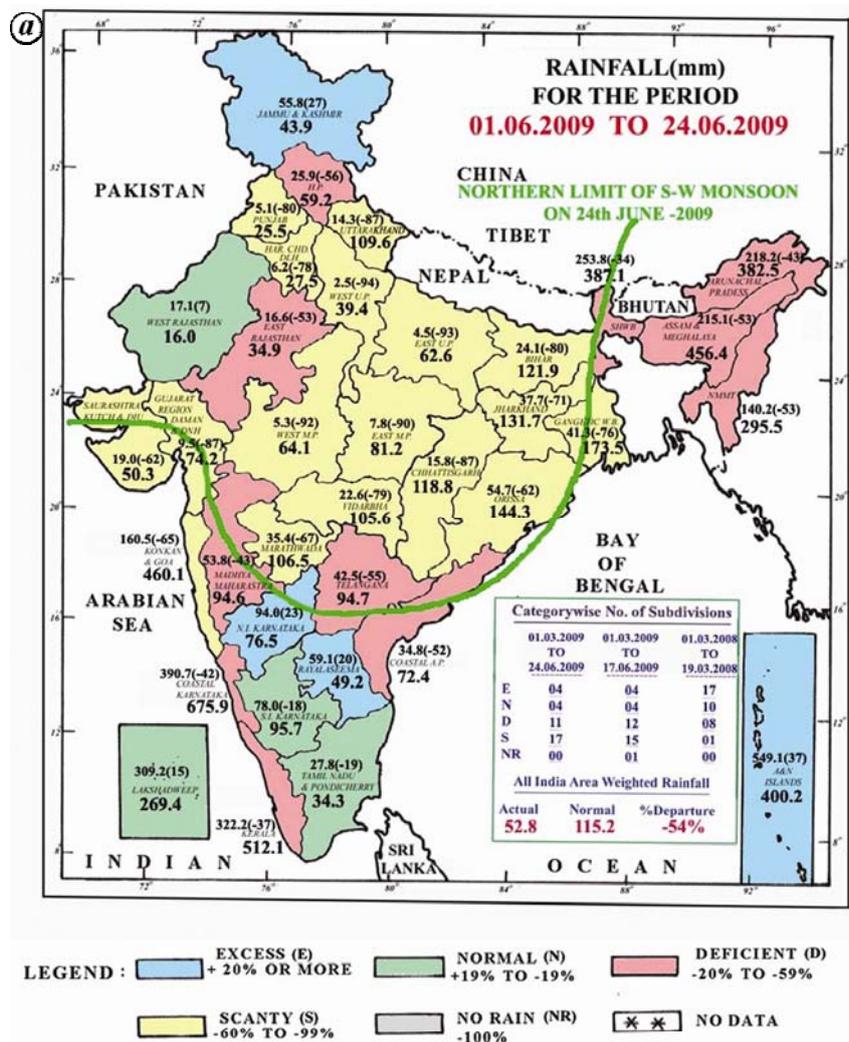


The aberrant behaviour of the Indian monsoon in June 2009

After an early onset over Kerala on 23 May 2009, further advance of the monsoon over the Indian region was delayed by about two weeks with the monsoon restricted to the west coast and southern peninsula until 24 June (Figure 1a)¹. This resulted in a massive deficit in the all-India rainfall of 54% of the long term average for this period. The deficit in the all-India rainfall for the month of June in 2009 (48%) was close to the lowest recorded rainfall (50% in June 1926) since 1871. This deficit could not be made up in the rest of the season (Figure 1b) and the deficit in the all-India summer monsoon (June–September) rainfall is 23%¹, which is comparable to the most severe droughts in the last 100 years (24% in 1972 and 22% in 2002). The impact of this drought (defined as a season with deficit in the all-India June–September rainfall of more than 10% of the long-term average) has been felt across the entire country, not only by the farmers but also the urban population who felt the pinch in rising prices, and water and power shortages.

However, a drought was not expected from the predictions generated by the leading centres in the world using complex models of the coupled ocean–atmosphere system. Models had generally predicted above average rainfall for June–July–August (JJA) over most of the Indian region, which is almost the opposite to what was observed. So for assessing the chance of a drought, we have to rely either on past history or on the links with phenomena which can be predicted, such as El Niño and Southern Oscillation (ENSO)². In addition to ENSO, the inter-annual variation of the Indian summer monsoon rainfall (ISMR) is linked to the Equatorial Indian Ocean Oscillation (EQUINOO) also^{3,4}. Gadgil *et al.*^{3,4} showed that each drought (excess rainfall season) during 1958–2003 was associated with unfavourable (favourable) phases of either ENSO or EQUINOO, or both. The worst droughts are associated with unfavourable phases of both the modes. For example, the severe drought of 2002 was associated with negative phases of ENSO and EQUINOO. For June 2009 also, ENSO and EQUINOO were both unfavourable but the magnitudes of the indices were not as large as in 2002. Yet, while the all-India rainfall



NOTES:
 (a) Rainfall figures are based on operational data.
 (b) Small figures indicate actual rainfall (mm), while bold figures indicate normal rainfall (mm). Percentage departures of rainfall are shown in brackets.

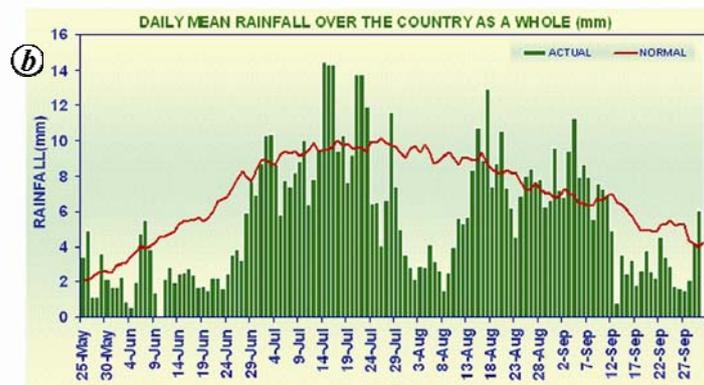


Figure 1. a, Actual rainfall (in mm) for the period 1–24 June 2009 for each meteorological subdivision. Climatological rainfall (in mm) is also shown in bold face. Northern limit of the south-west monsoon as on 24 June 2009 is shown as green curve. Source: www.imdpune.gov.in. b, Daily variation of all India rainfall (in mm) during 25 May–30 September 2009. Source: www.imd.gov.in.

of June 2002 was 7% in excess, that of June 2009 was 48% deficit. This suggests that one or more additional unfavourable factors contributed to the deficit of June 2009. Clearly, for understanding the drought of 2009, the factors that led to the massive deficit of rainfall in June have to be identified.

In this note, we present in brief, the results of a study⁵ aimed at identifying the factors which could have led to the unusual behaviour of the monsoon in June 2009. We consider first the special features of the monsoon of June 2009 in the light of what we know about the nature of variability of the Indian summer monsoon.

The monsoon is a manifestation of the seasonal variation of the tropical convergence zone (TCZ) which appears as a prominent zonal cloud band in satellite imagery, in response to the seasonal variation of the solar radiation. Large-scale rainfall over the Indian region during the summer monsoon is associated with a TCZ which is established over the Indian monsoon zone north of the peninsula, generally by July. June is the month in which the onset phase of the monsoon occurs. This phase commences with the onset over Kerala in late May or early June and culminates with the establishment of a TCZ over the Indian monsoon zone (north of the peninsula) in July. The onset phase comprises one or more northward surges of the rainbelt across the peninsula. These are seen as northward propagations of cloud bands in satellite imagery, stretching from the Arabian Sea across the Indian region to the Bay of Bengal⁶. The onset phase also involves synoptic systems such as lows and depressions moving westward from the Bay across the Indian monsoon zone towards Rajasthan⁷. Such westward and northward propagations are seen throughout the summer monsoon season^{6,7}. Thus the TCZ over the monsoon zone is maintained by the northward propagations of the oceanic TCZ and propagations of systems generated over the Bay of Bengal and the Arabian Sea onto the Indian region. Hence the convection over the surrounding oceans is critical for the TCZ over the monsoon zone and the variability of the large scale monsoon rainfall is linked with the variability of convection/precipitation over the surrounding seas and the equatorial Indian Ocean.

Satellite derived outgoing longwave radiation (OLR) is considered as a proxy

for rainfall in the tropics, because areas with low OLR are associated with high cloud tops and hence deep convection. The variation of the convective zone (delineated as the region of low OLR) at 85°E over the Bay of Bengal during the summer monsoon of 2009 is compared with that during a typical monsoon season (viz. 2008) in Figure 2a and b. A prominent feature of the variation in 2008 is a series of northward propagations from south of the equator to north

of 25°N beginning with one in the first half of June. After this propagation, which was associated with the advance of the monsoon, the convection persisted over the region 15–27°N for over a month, except for a short gap of three days. However, in 2009, the convection disappeared from the northern latitudes (viz. 15–27°N), 2–3 days after the first northward propagation in late May. During 1–24 June 2009, the convection over the Bay appeared intermittently over the

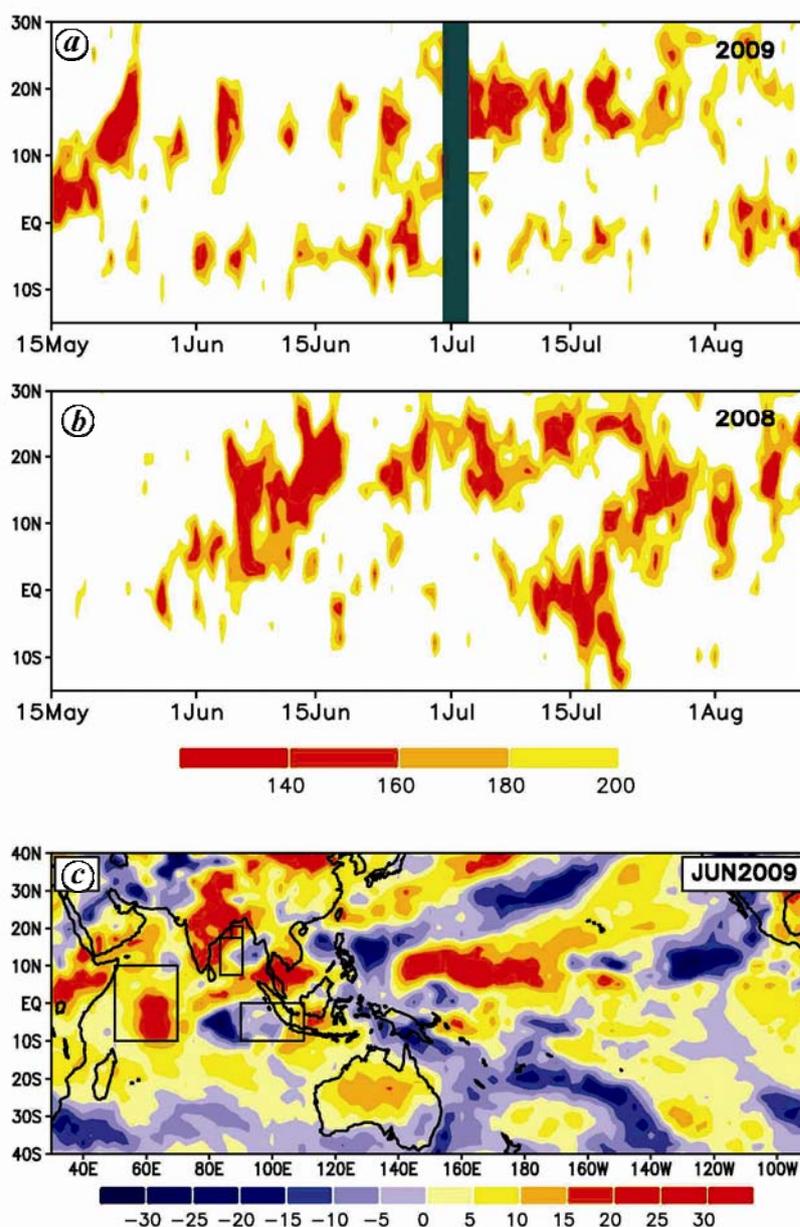


Figure 2. a, Daily variation of latitudinal belt with low outgoing longwave radiation (OLR, Wm^{-2}) measured by NOAA satellites (<http://www.cdc.noaa.gov>) at 85°E for the period 15 May–12 August 2009. b, Same as above, but for the period 15 May–12 August 2008. c, OLR anomaly (Wm^{-2}) pattern for June 2009.

region between 10°N and 20°N. However, each spell was only about 3–4 days, and no northward propagations occurred in this period. No low pressure systems were generated over the head Bay and the westward propagation across the monsoon zone, which is characteristic of the onset phase of the monsoon, did not occur. Over the Indian longitudes of 70°E and 80°E also, there were only short spells of convection over the region between 10°N and 20°N (not shown) and the monsoon rains were restricted to the region south of 20°N, and as a result, there was a large deficit in the rainfall over the northern parts of the country. This suggests that the massive deficit in the all-India rainfall for this period is a consequence of the suppressed convection over the Bay of Bengal. Clearly, the question to be addressed is: why was convection over the Bay not sustained during 1–24 June?

We note that in this period, convection occurred frequently over the equatorial Indian Ocean east of 80°E in the 0°–10°S belt, whereas convection over this region occurred for very few days in June 2008. The OLR anomaly pattern for June 2009 (i.e. difference between the OLR for June 2009 and the average June OLR) shown in Figure 2c, also implies that convection is enhanced (negative OLR anomaly) over the eastern and central equatorial Indian Ocean and suppressed over a large part of the rest of the region including entire Indian region and western equatorial Indian Ocean. Thus the phase of EQUINOO in June 2009 was unfavourable. It appears that the developing El Niño may not have had much impact on the June 2009 rainfall over India, since the enhancement of convection over the central Pacific, which is an important characteristic of El Niño, is not seen in the OLR anomaly pattern for June 2009 (Figure 2c).

A special feature of the Indian longitudes is the occurrence of TCZ over the warm waters of the equatorial Indian Ocean intermittently throughout the summer monsoon⁶. There is a competition between the oceanic TCZ and the TCZ north of 15°N associated with the large scale monsoon rainfall, with weak spells of the latter generally coinciding with the active spells of the oceanic TCZ and vice versa⁶. The competition between convection over the Bay and the convection over the equatorial Indian Ocean on the subseasonal scale is manifested as a sig-

nificant negative correlation between the pentad mean OLR of the Bay and that of the eastern equatorial Indian Ocean (EEIO) and central equatorial Indian Ocean (CEIO)⁵. Hence active spells of the monsoon are associated with enhanced convection over the Bay and sup-

pressed convection over the EEIO and CEIO^{8,9}. The variation of the convection over the Bay vis-a-vis that over the CEIO and EEIO in June 2009 suggests that in this competition, the convection over the EEIO and CEIO had an edge over that of the Bay in this period. We suggest that

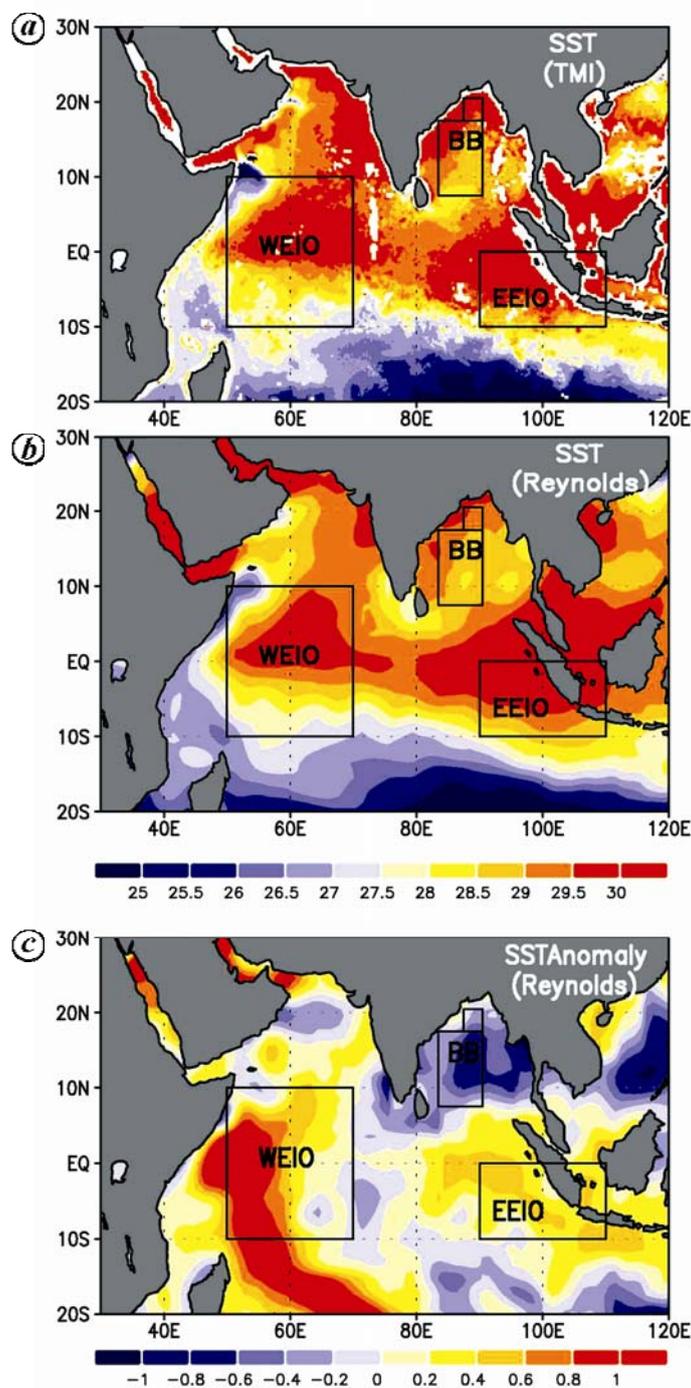


Figure 3. Sea surface temperature (SST, °C) patterns for the month of June 2009 from (a) NOAA optimal interpolated SST data (Reynolds SST, <http://www.cdc.noaa.gov>) and (b) TRMM/TMI SST data obtained from <http://www.ssmi.com/>. (c) NOAA optimal interpolated SST anomaly (°C) pattern for the month of June 2009.

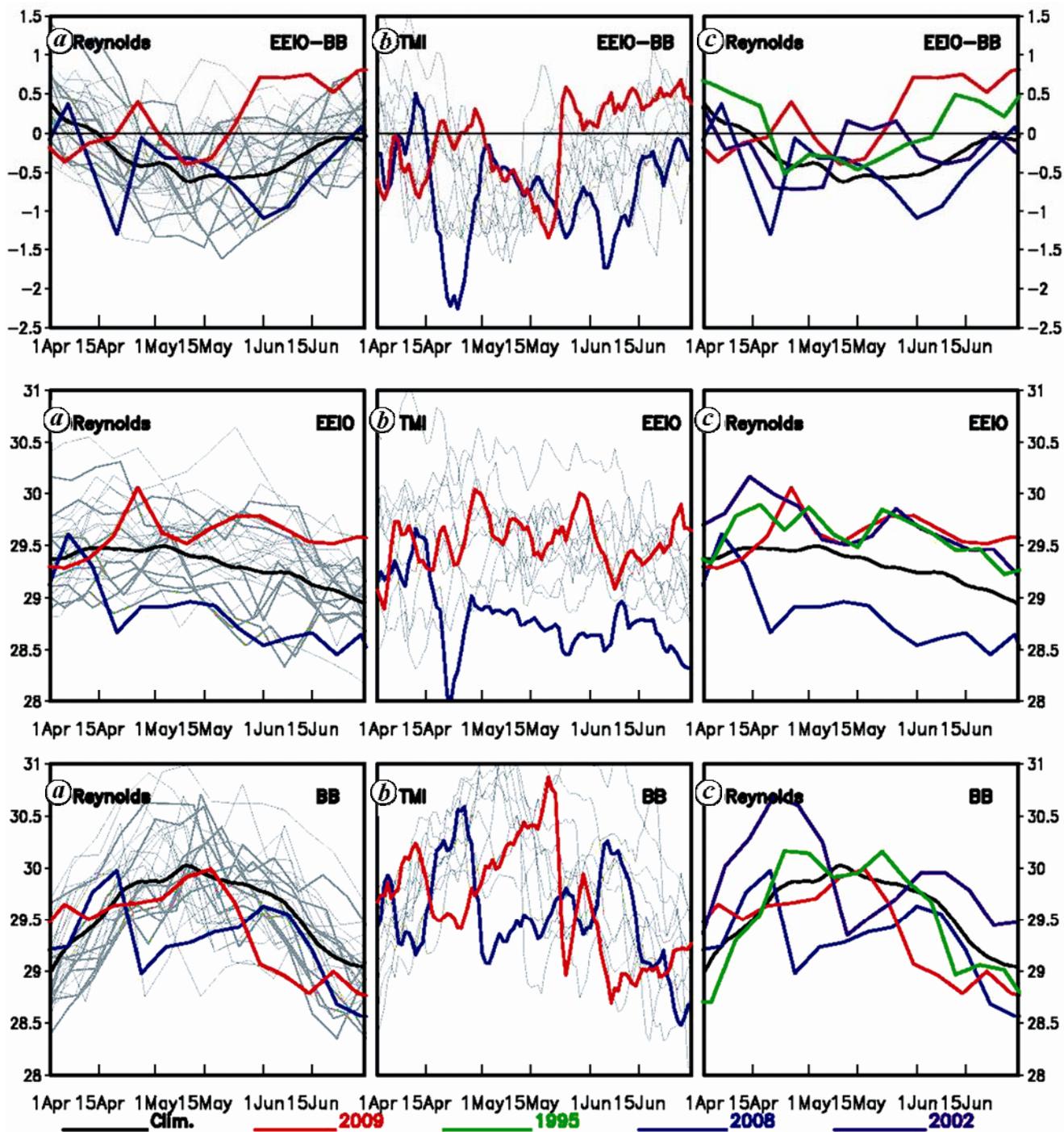


Figure 4. Timeseries of SST (°C) averaged over the Bay of Bengal (bottom panels), EEIO (middle panels) and the difference in SST between EEIO and BB (top panels). Weekly mean NOAA optimal interpolated SST time series for each year during the period 1982–2009 are shown in the left side panels (a), that for selected years are shown in the right panels (c) and daily mean TMI SST for the period 1998–2009 are shown in the middle panels (b). Colour code: red for 2009, blue for 2008, green for 1995 and purple for 2002. The black curves in the left and right panels are the climatological SST time series.

this unusual behaviour in June 2009 can be attributed to a special feature of the sea surface temperature (SST) pattern over the Bay and the equatorial Indian Ocean.

The patterns of the SST and the SST anomaly for June 2009 are shown in Figure 3. It is seen that whereas the Bay is colder, the equatorial Indian Ocean is

much warmer than average. Note that, whereas in the intense positive or negative phases of Indian Ocean Dipole (IOD) events^{10,11}, there is a large gradient

between the SST of the EEIO and the western equatorial Indian Ocean, in June 2009 almost the entire equatorial belt is warm. The evolution of the SST over the Bay and the EEIO (regions shown in Figure 3) as well as the difference between the SST of the EEIO and the Bay, are shown in Figure 4 for each year for which data are available (i.e. 1982 onwards for Reynolds' data (Figure 4a and c) and 1998 onwards for TRIMM data (Figure 4b)). In Figure 4a, the years 2009 and 2008 and the climatological mean are specially marked in different colours. The evolution of SST from Reynolds data for a few selected years, viz. 1995, 2002, 2008, 2009 and the climatological mean are shown in Figure 4c. Note that for almost all the years, the Bay is warmer than EEIO in June and the difference between the SST of the Bay and EEIO is largest for 2008. On the other hand, in June 2009 the Bay is cooler than the EEIO and the magnitude of the difference between the SST of EEIO and the Bay is very large (almost one degree). In fact, whereas the EEIO during June 2009 is the warmest, the EEIO in June 2008 is the coldest. Note that the EEIO-BB difference in June 2009 is near the maximum of the envelope of the curves for the period for which data are available. We note that occurrence of such a negative gradient in SST between the Bay and EEIO is a rare event. The only other year in which the Bay was cooler than EEIO for several days in June is 1995 (Figure 4c). Convection over the Bay was suppressed during that period also and the all-India rainfall for June 1995 was 24% below normal.

Consider the possible impact of a warm EEIO relative to the Bay. Organized convection occurs over tropical oceans only if the SST is above the threshold of about 27.5°C (refs 12 and 13). For example, during positive IOD events, the cooling of EEIO leads to SST going below the threshold and the convection

over EEIO is suppressed. If the SST is higher than the threshold, whether convection occurs or not is determined by the dynamics, i.e. occurrence of low level convergence¹³. We expect regions over which SST is maximum to be dynamically favourable for convection. During June to September, the SST of the Bay is always above the threshold and that of EEIO below the threshold only during positive IOD events. Generally in May–June, the SST of the Bay is higher than that of EEIO and convection is favoured over the Bay. However, in June 2009, the high SST of the EEIO and CEIO relative to that over the Bay appears to have given an edge to the TCZ over the EEIO and CEIO in the competition with the TCZ north of 10°N over the Bay. The TCZ/cloud systems over the Bay are, therefore not sustained for longer than 3–4 days and no propagations occurred.

The large deficit in rainfall over the Indian region in June 2009 was associated with suppression of convection over the Bay of Bengal. We suggest that the unfavourable SST gradient between the Bay and EEIO led to suppression of convection over the Bay. This hypothesis is supported by the observations for the only other year in which such a gradient in SST occurred in June, viz. 1995. The convection over the Bay was also suppressed in June 1995 and there was a large deficit in the all-India rainfall. This hypothesis has to be tested with models which can simulate the subseasonal variation of the TCZs over the Indian longitudes realistically.

1. India Meteorological Department; <http://www.imd.gov.in>
2. Cane, M., Zebiak, S. E. and Dolan, S. C., *Nature*, 1986, **321**, 827–832.
3. Gadgil, S., Vinayachandran, P. N. and Francis, P. A., *Curr. Sci.*, 2003, **85**, 1713–1719.
4. Gadgil, S., Vinayachandran, P. N., Francis, P. A. and Gadgil, S., *Geophys. Res. Lett.*, 2004, **31**, L12213.

5. Francis, P. A. and Gadgil, S., *J. Earth Syst. Sci.* (submitted).
6. Sikka, D. R. and Gadgil, S., *Mon. Weather Rev.*, 1980, **108**, 1840–1853.
7. Ding, Y. and Sikka, D. R., In *The Asian Monsoon* (ed. Wang, B.), Springer-Verlag, New York, 2006, pp. 131–201.
8. Gadgil, S. and Joseph, P. V., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 2003, **112**, 529–558.
9. Rajeevan, M., Gadgil, S. and Jyoti Bhate, Active and Break Spells of the Indian monsoon, NCC Research Report No. 7/2008, National Climate Centre, India Meteorological Department (available at <http://www.imdpune.gov.in>) 2008.
10. Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T., *Nature*, 1999, **401**, 360–363.
11. Webster, P. J., Moore, A. M., Loschnigg, J. P. and Leben, R. R., *Nature*, 1999, **401**, 356–360.
12. Gadgil, S., Joseph, P. V. and Joshi, N. V., *Nature*, 1984, **312**, 141–143.
13. Graham, N. E. and Barnett, T. P., *Science*, 1987, **238**, 657–659.

ACKNOWLEDGEMENTS. It is a pleasure to acknowledge perceptive comments of Prof. J. Srinivasan and three reviewers which led to considerable improvement in the paper. We thank INCOIS, MoES, New Delhi for financial support.

Received 21 August 2009; revised accepted 13 September 2009

P. A. FRANCIS¹
SULOCHANA GADGIL^{2,*}

¹Indian National Centre for Ocean Information Services,
Ministry of Earth Sciences,
Ocean Valley, IDA Jeedimethla P. O.,
Hyderabad 500 055, India
²Centre for Atmospheric and Oceanic Sciences,
Indian Institute of Science,
Bangalore 560 012, India
*For correspondence.
e-mail: sulo@caos.iisc.ernet.in