Impact of the upper tropospheric cooling trend over Central Asia on the Indian summer monsoon rainfall and the Bay of Bengal cyclone tracks

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The Indian summer monsoon rainfall had three-decade long alternate dry and wet epochs during the 150 years from 1840 to 1989. The dry epochs had frequent drought monsoons affecting agriculture, power generation and the overall economy of the country. A high percentage of severe cyclones in the Bay of Bengal moved northwards during the dry epochs causing disasters in Bangladesh, Myanmar and the Indian states of Odisha and West Bengal. These dry epochs have been shown to be associated with the cold phase of the Atlantic multidecadal oscillation in sea-surface temperature. Using the available tropospheric temperature (re-analysis) data since 1948, the recent dry epoch during 1960–89 which had 10 monsoon drought years was found to have cold upper tropospheric temperature anomaly over Central Asia. This cold anomaly region has also experienced a long-term cooling trend. Extrapolating the naturally occurring epochal nature of the ocean–atmosphere system into the future, we fear that the epoch 2020–49 is likely to be another dry one, and the cooling trend over the Asian continent is likely to make it even more severe in its impact than 1960–89. This article presents details of an ocean–atmosphere instability that generates frequent drought monsoons during dry epochs which needs urgent research.

Keywords: Cooling trend, cyclone tracks, summer monsoon, upper troposphere.

THE recent severe Indian monsoon droughts of 1982, 1987, 2002 and 2009 had an adverse impact on agriculture, energy generation and the overall economy of the country. However, these droughts did not create famine conditions, as the Government had taken action to have enough stock of food grains for public distribution. This was not the case for drought monsoons of earlier years[1]. Following the drought monsoon of 1899, the famine was widespread and severe. It was not merely a food famine, but also one of fodder and water. Cattle died by the millions. In more recent times during the drought monsoon of 1972, arrangements had to be made by the Indian Government to import 2 million metric tonnes of food grains.

During the dry epoch 1960–89, there were 10 monsoon drought years (1965, 1966, 1968, 1972, 1974, 1979, 1982, 1985, 1986 and 1987). The just earlier wet epoch 1930–59 had only two drought monsoons (1941 and 1951). Such three-decade long epochs of alternating dry and wet monsoons have been observed since the 1840s, when India began to take rainfall measurements. If this natural cyclicity of period about 60 years which is found linked to the global sea-surface temperature (SST) anomalies, particularly the well-known Atlantic multidecadal oscillation (AMO) continues, India may have to face yet another epoch of frequent monsoon droughts during 2020–2049. Indications are that due to the observed cooling trend of the upper tropospheric temperature over continental Asia, the frequency and severity of droughts expected during 2020–2049 is likely to be higher than that of the recent dry epoch 1960–1989. The atmospheric circulation (winds) over South Asia is also found to have parallel multidecadal oscillation which has influenced the tracks of the cyclones of the Bay of Bengal (BoB), resulting in higher proportion of north-moving cyclones during dry epochs. In BoB, north-moving cyclones have longer lifetime over the sea and therefore are able to reach higher intensities than west-moving cyclones. In view of the shallow bathymetry of the coastal areas of north BoB, north-moving cyclones have the potential to create very high storm surges and the consequent heavy loss of life and property.

Dry and wet epochs in Indian summer monsoon rainfall

According to the India Meteorological Department (IMD), if the Indian summer monsoon rainfall (ISMR) during the four monsoon months of June to September is deficient by 10% (about one standard deviation) of its long-term average, it is declared as a drought monsoon. Using data

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from a network of 306 climatological raingauge stations well distributed over India, scientists at the Indian Institute of Tropical Meteorology (IITM), Pune have derived an ISMR series for the period 1871 to the current year using the method developed by Parthasarathy and Mooley[2]. This series is updated every year and provided in the IITM website (www.tropmet.res.in). A prominent decadal variability in ISMR, first reported[3] in the 1970s (Figure 1 *a*), gives the anomaly in units of its standard deviation for each year from 1871 to 2010. During the three-decade long dry epochs 1900–1929 and 1960–1989, India had monsoon droughts on average once in three years. In contrast, during the wet epochs 1870–1899 and 1930–1959, the frequency of droughts had been once in 10–20 years only. Using the available network with a smaller number of raingauge stations[4], it was found that 1840–1869 was a dry epoch. Thus, during the 150 years from 1840 to 1989, there were regular 30-year epochs alternating between dry and wet. In dry (wet) epochs, the decadal mean ISMR is lower (higher) than the long-term mean[5].

Parallel epochal changes are seen in an index derived from SST of the Atlantic Ocean, i.e. AMO (Figure 1 *b*)[6]. During the dry (wet) epochs of ISMR, AMO is negative (positive). Goswami *et al.*[7] have given a hypothesis regarding the link between AMO and ISMR. A multi-century simulation[8] using a fully coupled atmosphere–ocean–sea ice general circulation model was able to reproduce the general characters of the observed linkage between AMO and ISMR; a positive AMO favours more rainfall over India from July to October. A recent study has shown that ISMR on the decadal scale is better related to the global SST gradient between the tropics and the northern hemisphere mid-latitude oceans than to the AMO[9].

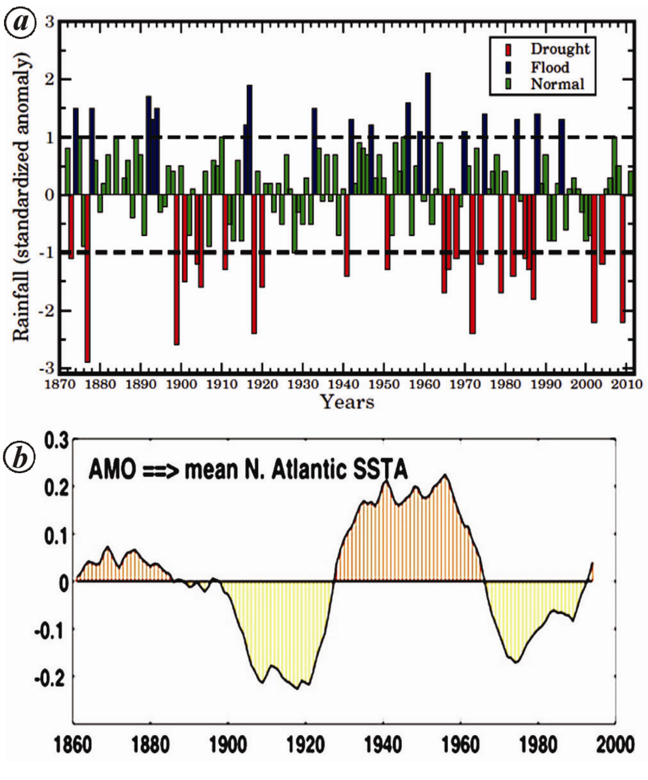

Figure 1. ***a***, Standardized anomaly of Indian summer monsoon rainfall of 1871–2010 with drought monsoons marked by red bars. ***b***, Atlantic multi-decadal oscillation in sea-surface temperature (SST) of 1860–2000 taken from Enfield *et al.*[6].

Decadal change in wind/temperature and cyclone tracks

Using NCEP/NCAR reanalysis data[10] available from 1948, it was shown by Joseph[11] that during 1965–1987 (part of the dry epoch which produced 10 droughts in ISMR), the upper tropospheric westerlies intruded equatorwards during the monsoon season as a wave number-3 trough over Asia (see figure 11 of Joseph[11]) when compared to 1950–1959, a decade of the wet epoch 1930–1959. Figure 2 *a* and *b* shows the 200 hPa wind anomaly and 300 hPa temperature anomaly of the decade 1970–1979 compared to the decade 1950–1959 for the monsoon season. The equatorward intrusion of westerlies over Asia is consistent with the cold temperature anomaly at 300 hPa over the Asian continent according to thermal wind

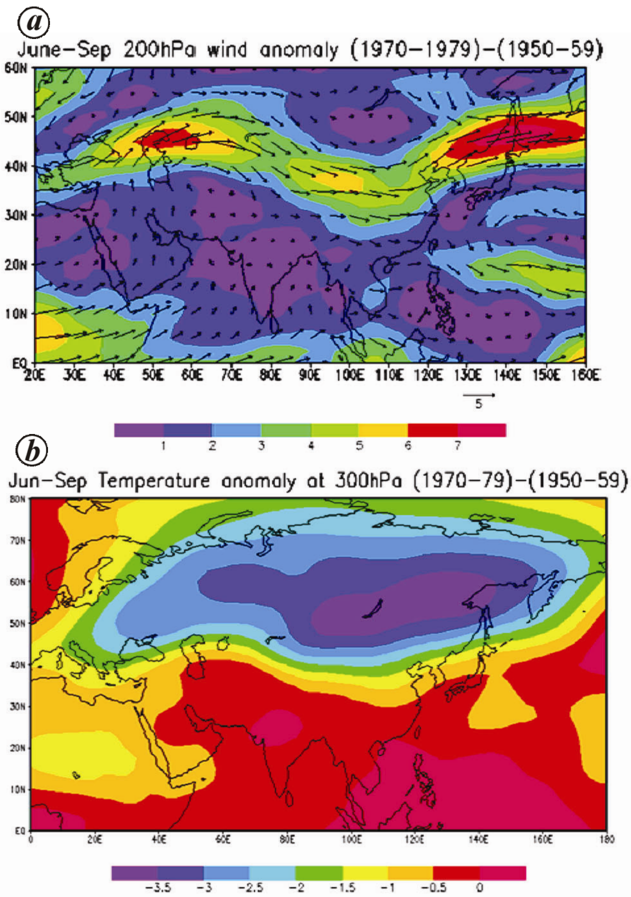

Figure 2. Difference (1970–1979) – (1950–1959) of mean June to September anomaly of 200 hPa wind (m/s; ***a***) and 300 hPa temperature (°C; ***b***).

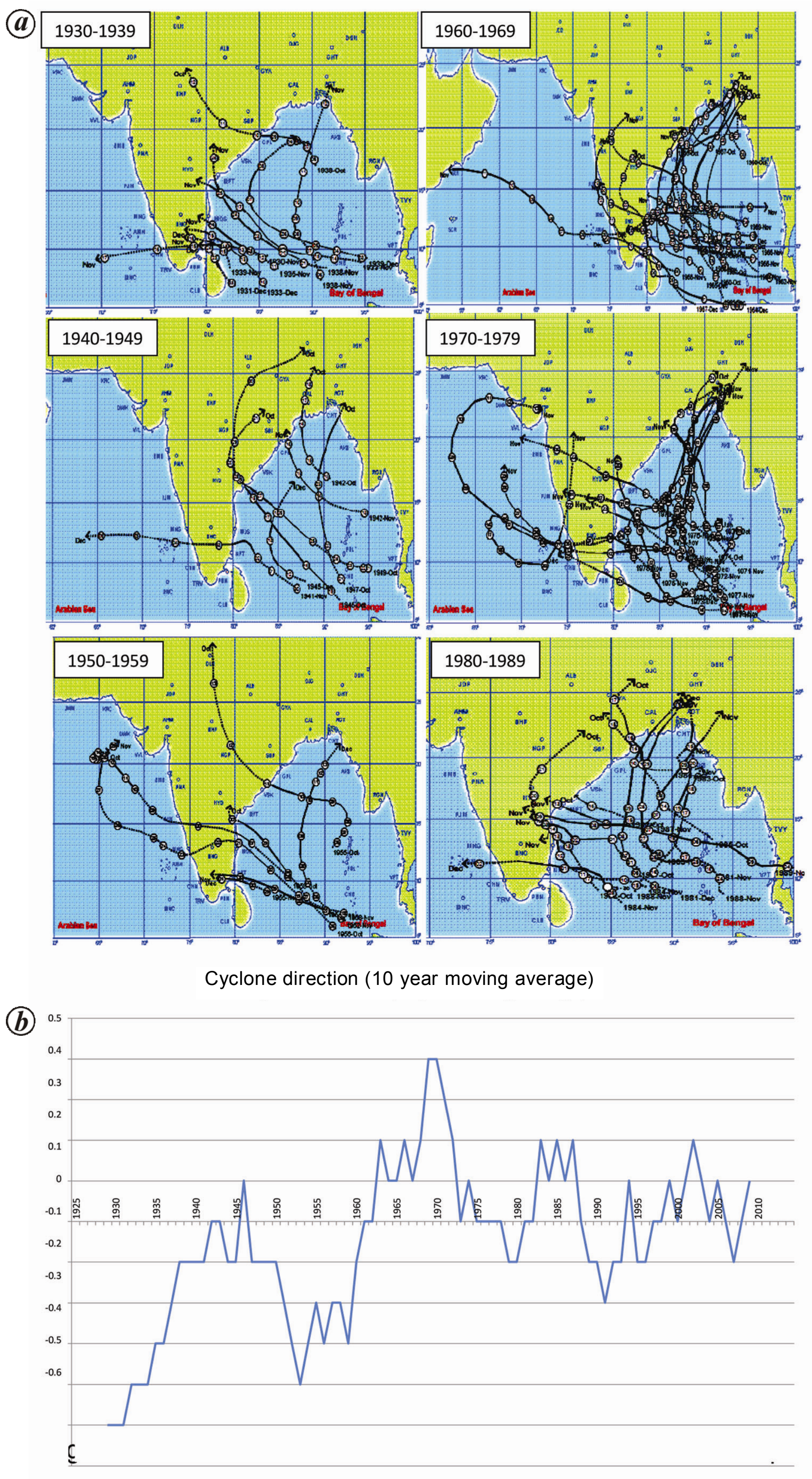

Figure 3. ***a***, October–December tracks of severe cyclones in the Bay of Bengal (BoB) during each decade of the wet epochs 1930–1959 (left panel) and dry epochs 1960–1989 (right panel). ***b***, Ten-year moving average of cyclone motion index for the period 1925–2013. In the October–December season, if all the severe cyclones in BoB move west (north), the index for that year is –1 (+1), and for all other years it is zero.

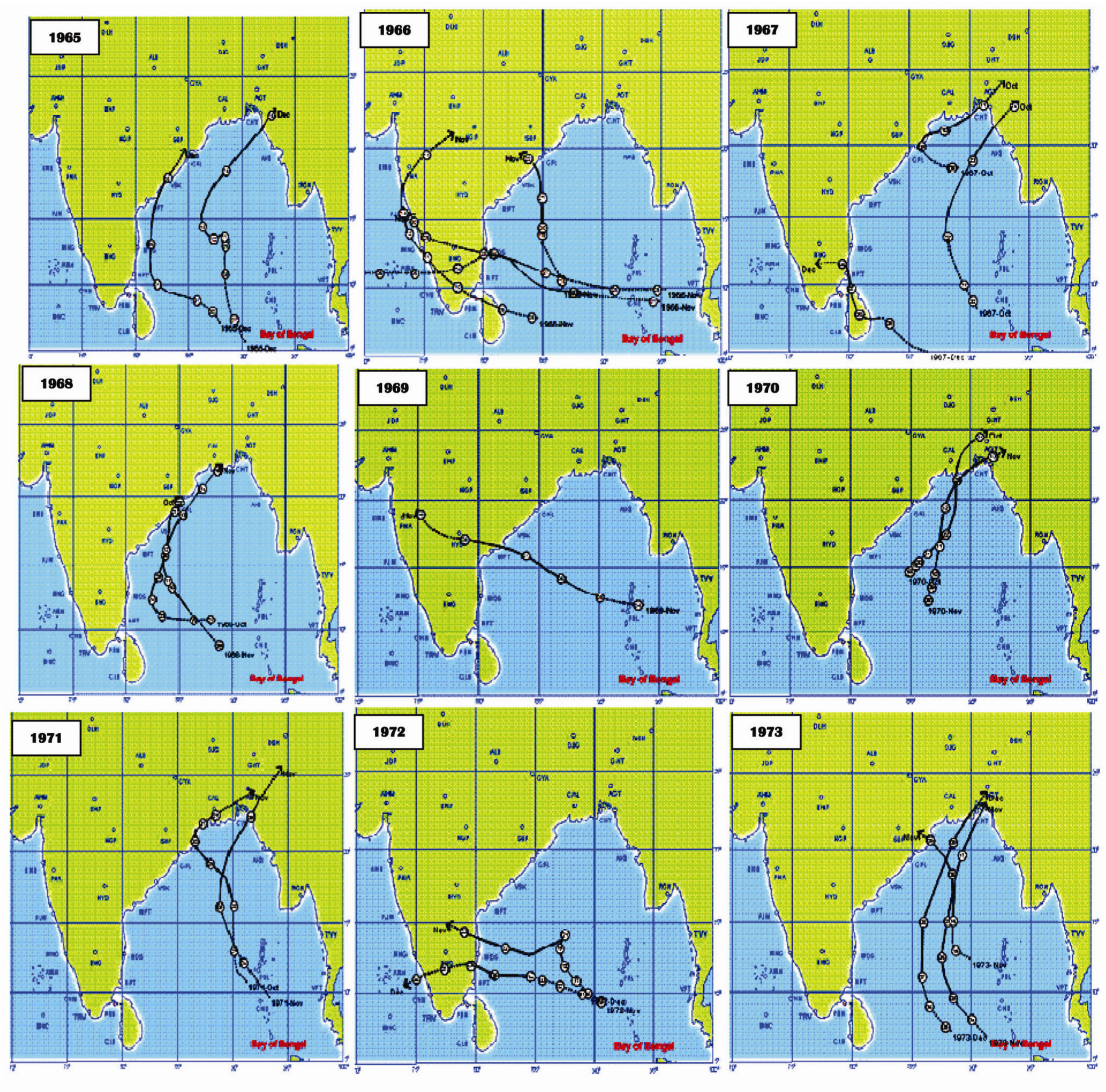

Figure 4. Tracks of October–December severe cyclones in BoB during each year from 1965 to 1973.

considerations. Similar equatorward intrusion of upper tropospheric westerlies in the following October–December season is the main cause for the large percentage of northward-moving Bay cyclones of that season in a dry epoch. Figure 3 *a* shows the tracks of severe cyclones (defined by IMD as a tropical cyclonic system with maximum sustained surface wind speed of 48 knots or more – one knot is 0.51 m/s) of the BoB during October–December, taken from the e-atlas of IMD (which gives cyclone tracks and other related information from 1891 to the current year; www.rmcchennaieatlas.tn.nic.in) for each decade of the wet epoch 1930–1959 and dry epoch 1960–1989. In the three dry decades, a high percentage of the cyclones had northward tracks, and Bangladesh, Myanmar and the Indian states of Odisha and West Bengal experienced many cyclone-related disasters. The cyclone of November 1970, which had landfall over Bangladesh and claimed 300,000 lives, is one among them. In the three decades of the wet epoch 1930–1959, Bay cyclones had mostly westward tracks.

To quantify the change in severe cyclone tracks, the following method is used. Most of the cyclones of BoB during October–December season have genesis south of lat 15°N. If such a severe cyclone has landfall south of lat 17°N (on the coast this point is close to Vishakapatnam), it is taken as a west-moving cyclone. If landfall is north of 17°N, it is taken as north-moving cyclone. Most of the October–December seasons have cyclones moving either west (represented by –1) or north (represented by +1). If in the season there are no cyclones, or if there are both west and north-moving cyclones, that season is represented by 0. A few severe cyclones had their genesis north of lat. 15°N. If their movement is westwards it is taken as west-moving and if northwards as north-moving, but such cases have been very few. Figure 4 provides examples of the above-mentioned cases of cyclone movement. Years 1969 and 1972 are each represented by –1, while years 1965, 1968, 1970, 1971 and 1973 each by +1. Year 1967 has one west-moving and one north-moving cyclone, both originating south of lat. 15°N and so the index for the year is 0. In the same year, there is an example of a cyclone having its genesis north of 15°N, and it is taken as a north-moving cyclone. Figure 3 *b* gives the ten-year moving average of this series. During the wet epoch 1930–1959, the ten-year moving average of this index is mostly negative showing that cyclone movement is predominantly westwards and during the dry epoch 1960–1989 cyclone movement is northwards. Cyclone movement during the decade 1990–1999 is westwards and 2000 onwards is northwards. Since BoB is a small ocean basin with land to the west, north and east, and is criss-crossed by merchant ships recording meteorological observations, we have reliable records in the e-atlas of the tracks of all the cyclones since 1925 whose data have been used. Satellite data have been used to track cyclones only from 1965.

Inter-annual variability of ISMR and cyclone tracks

Some studies[9,11] (and references therein) have shown that during the dry epoch when upper tropospheric westerlies were more equatorward over South Asia, wave number 6 stationary Rossby wave trains were superposed on these westerlies, with opposite spatial phases for the wave during monsoon seasons with deficit (drought) and excess rainfall. This wave was named Asia-Pacific wave (APW) by Joseph and Srinivasan[12], who hypothesized that the spatial phase of the wave depended on the location of the convective heating anomalies, which in turn depended on the location of warm SST anomalies. Figure 5 *a* and *b* provides the composites of 200 hPa meridional wind anomalies showing APW of the five driest and five wettest years of the dry epoch 1960–1989. This wave was also found modulating the spatial distribution of total atmospheric ozone[13]. During monsoon seasons of drought years such a wave trough intrudes into northwest India, which is one of the causes for monsoon drought[14,15]; the very next wave trough to its east (close to Japanese islands) is found to steer a large percentage of the typhoons of the Pacific Ocean northwards during drought monsoon seasons[16]. There is an interesting negative feedback process hypothesized[9,11] to occur in a dry epoch, which was proposed in the 1980s (refs 17–19). One or two consecutive drought monsoons are followed by warm SST anomaly in the tropical Indian Ocean which persists till the following monsoon, resulting in normal or excess rainfall. The excess rainfall cools the Indian Ocean SST and brings back the atmospheric circulation conditions for causing another drought monsoon. This negative feedback process between monsoon and ocean, and the excitation of APW are hypothesized to be the cause for the occurrence of frequent drought monsoons during a dry epoch. A slightly different hypothesis was framed for the phenomenon known as tropospheric biennial oscillation[20], a critique of which may be found in ref. 9.

In the study by Joseph[17], the warm SST anomaly in the Indian ocean following the two consecutive drought monsoons of 1965 and 1966 was found to cause an anticyclone to form in the upper troposphere of north Indian Ocean, presumably due to the increased convective heating of the atmosphere. Thus, there in an association with the warm SST anomaly (see Figure 6 *a* taken from Joseph[17]). The upper tropospheric easterlies associated with that anticyclone steered the Bay cyclones of October–December 1966 season westwards. Similar westward motion of the Bay cyclones of October–December season may be seen in 1969 and 1972, associated with similar

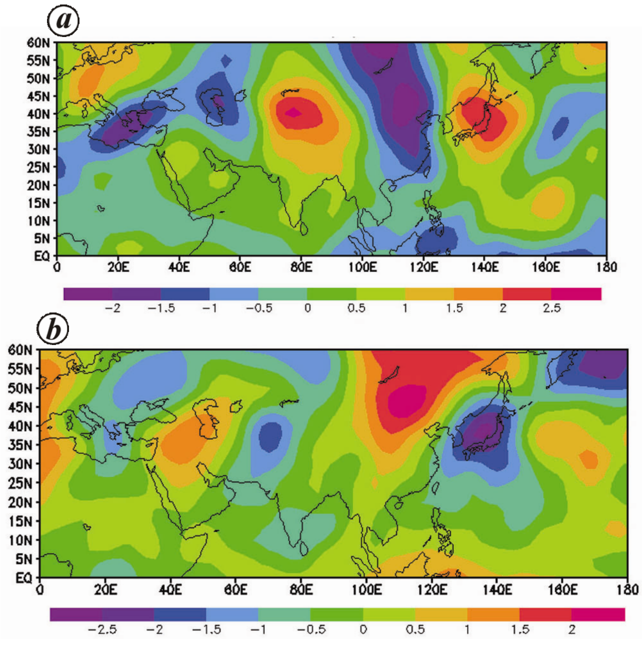

Figure 5. ***a***, June–September meridional wind anomaly composite of (***a***) drought years 1965, 1972, 1979, 1982 and 1987, and (***b***) excess rain years 1961, 1970, 1975, 1983 and 1988.

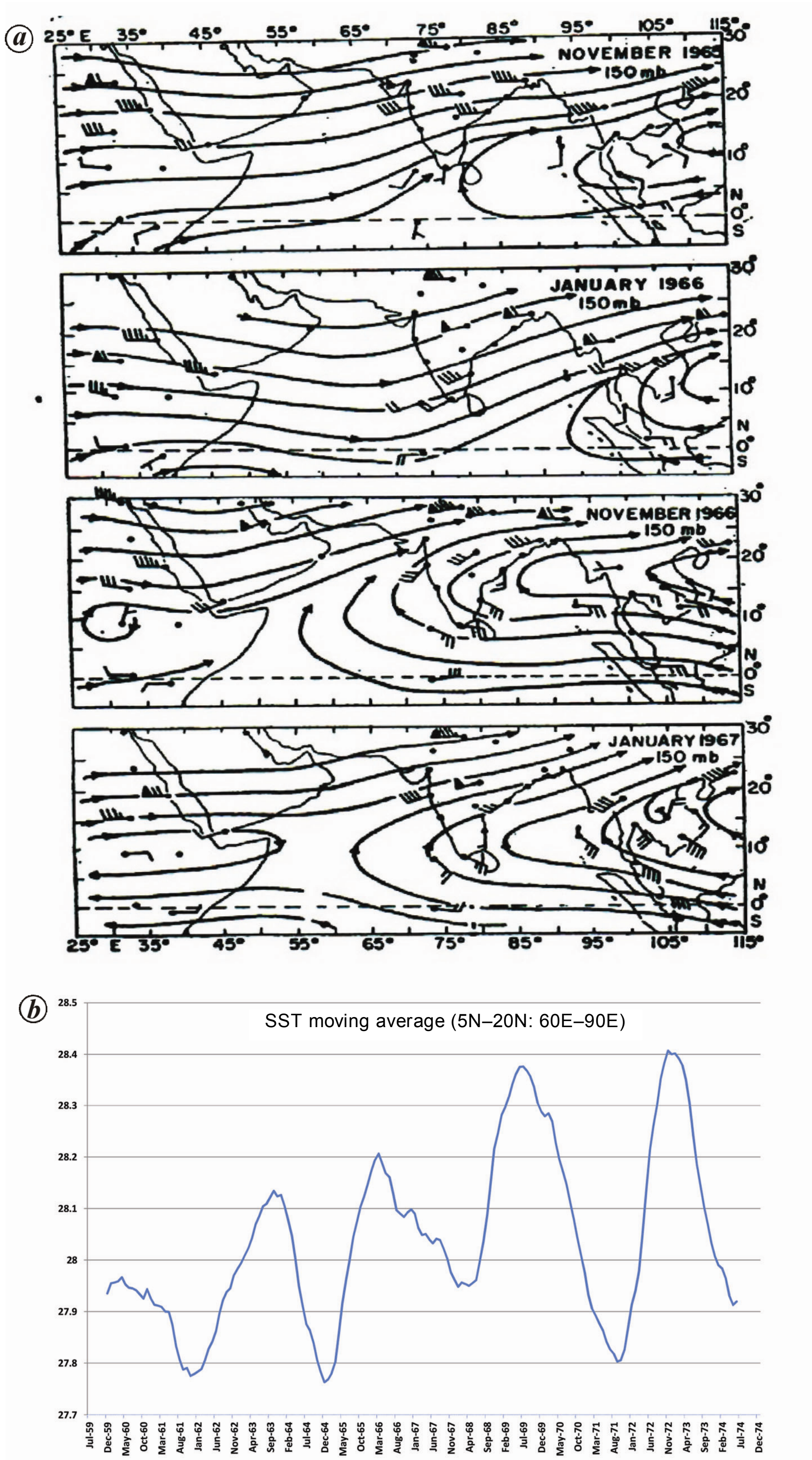

Figure 6. ***a***, Monthly station mean wind at 150 hPa and streamlines taken from ref. 17 showing the change from a westerly regime in November 1965 to an easterly regime in November 1966 over BoB. ***b***, Twelve-month moving average of the mean SST of north Indian Ocean between lat. 5–20°N and long. 60–90°E.

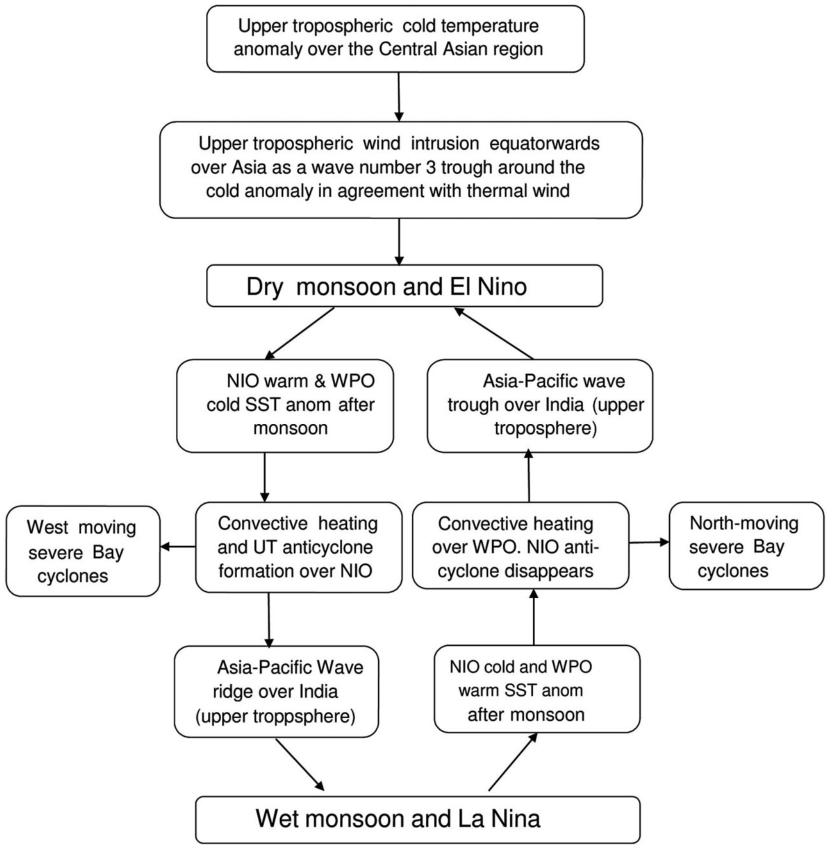

Figure 7. Schematic diagram showing the ocean–atmosphere instability that produces frequent drought monsoons when upper tropospheric westerly winds move equatorwards over South Asia.

warm SST anomalies in the north Indian Ocean and Bay upper tropospheric anticyclone and easterly winds. In the remaining years of the period 1965–1973, Bay cyclones of October–December moved northwards (Figure 4). Thus during a dry epoch there are both west- and north-moving cyclones, but in a wet epoch most of the cyclones move westwards only. Figure 6 *b* provides the 12-month moving average SST of a representative area of the north Indian Ocean (5–20°N, 60–90°E) for the period 1960–1974. Westward motion of the Bay cyclones occurred when the SST of the north Indian Ocean reached maxima in a cycle period of three years. Thus, during the dry epochs there is large interannual variability in ISMR, the upper tropospheric winds over the north Indian Ocean and in Bay cyclone tracks of the October–December season. The SST variation in the north Indian Ocean of 1960–1974 is similar (and with temporal phase different only by a few months) to the SST variation in a three-year cycle in the El Niño warm anomaly area of the equatorial Pacific Ocean (figures 5 and 13 of Pan and Oort[21]), which shows the involvement of El Niño in the interannual changes to the atmospheric circulation over South Asia and north Indian Ocean. Thus, the interannual variability observed during a dry epoch is a planetary-scale ocean–atmosphere instability (negative feedback) phenomenon occurring when the upper tropospheric winds move to lower latitudes over Asia, allowing the monsoon heat sources to better interact with the westerlies and produce APW. Figure 7 provides the details of this ocean–atmosphere instability phenomenon that produces frequent drought monsoons in a dry epoch. This phenomenon requires focused research efforts, including modelling studies by the global scientific community.

Climate change in upper tropospheric temperature

Abish *et al.*[22] studied the change in the upper tropospheric temperature (at 300 hPa) during the recent six decades and found large climate change in temperature in the mid-latitude belt between 30° and 60° in both the northern and southern hemispheres (see figures 1 *e* and 3 *e* of Abish *et al.*[22]). Figure 8 *a* shows the change in temperature for the monsoon season, decades 2000–2009 minus 1950–1959. While over Asia there was cold anomaly in the same area as seen in Figure 2 (bottom), the rest of the world had warm anomalies in the mid-latitude belt between 30° and 60° lat. A strong upper tropospheric cooling trend was found in East Asia during July and August around 300 hPa (ref. 23). Accompanying this summer cooling the upper level westerly jetstream over

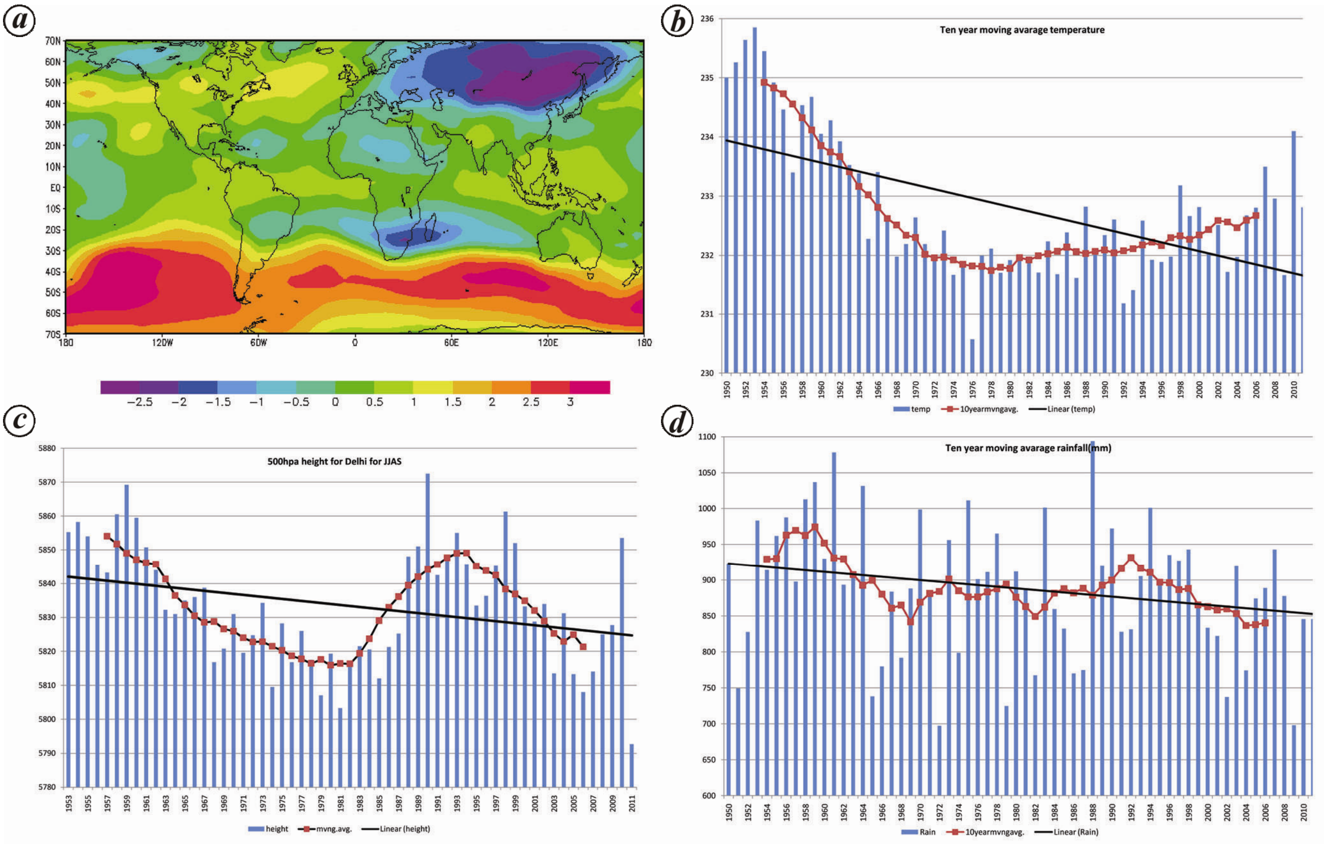

Figure 8. ***a***, Mean June–September temperature (°C) anomaly, (2000–09) minus (1950–59) at 300 hPa. ***b***, Bars showing June–September mean temperature of each year averaged over the box 40–60°N; 70–140°E. Red line shows ten-year moving average and blue line shows the linear trend. ***c***, June–September mean geopotential height of 500 hPa surface of Delhi, India. Red line shows ten-year moving average and blue line shows the linear trend. ***d***, Indian summer monsoon rainfall of June–September of 1950 to 2011. Red line shows ten-year moving average and blue line shows the linear trend.

East Asia was found to shift southwards. Figure 8 *b* gives the temperature of the atmosphere at 300 hPa averaged for the monsoon season over a box bounded by lat. 40°N and 60°N and long. 70°E and 140°E (the core region of the cold anomaly) for each year of the period 1950–2011. The ten-year moving average shows the coldness (decadal variation) of the dry epoch 1960–1989. The linear cooling trend is also marked.

Flohn[24] used the thickness of the 1000–500 hPa layer of the atmosphere to study the climate change in atmospheric circulation (see figure 4 of Flohn[24]), which shows a major change from the 1950s to 1960s. Figure 8 *c* gives the June to September average of the altitude of the 500 hPa surface over Delhi, India, as observed by the radiosonde ascents of the period 1953–2011 (data taken from the Monthly Climatic Data of the World, a publication of NOAA, Ashville, USA). The ten-year moving average clearly shows the dry epoch 1960–1989. The wet decades 1950–1959 and 1990–1999 are also clearly seen in the data with high 500 hPa altitude. There is a long-term trend of decreasing 500 hPa altitude. The linear trend marked shows the effect on the atmospheric circulation caused by atmospheric cooling over Central Asia. It may be noted that the NCEP/NCAR re-analysis data (which have some influence from the model used in the re-analysis) and the pure observational data (500 hPa radiosonde measurements) give the same type of decadal variation and climate change (decreasing trend).

Extrapolation to the epochs 1990–2019 and 2020–2049

The 300 hPa temperature was warm over Asian mid-latitudes during the wet decade 1950–1959, which had only one drought monsoon. It was warm also during the decade 1990–1999, which did not have even a single year of drought in the ISMR. The epoch 1990–2019 was expected to be a wet one, extrapolating the natural cyclicity of the ocean–atmosphere system of the earlier 150-year period. But during the decade 2000–2009 there were three droughts (monsoons of 2002, 2004 and 2009). During the first part of the following decade, the years 2014 and 2015 had monsoon droughts. Thus the frequent drought scenario has reappeared after the first decade of the expected wet epoch. The cooling trend of the Asian upper troposphere over Central Asia is believed to have caused this. The upper troposphere cooling trend is expected to continue in the near future decades. The natural cyclicity of the ocean–atmosphere system that gave rise to the observed dry and wet epochs for a century and a half expected to continue and cause a dry epoch during 2020–2049. The observed cooling trend could make the upper troposphere over Central Asia even colder during 2020–2049 accompanied by more intense equatorward intrusion of upper tropospheric westerlies over South Asia compared to the dry epoch 1960–1989. We therefore expect more frequent and intense monsoon droughts during 2020–2049 than what we experienced during 1960–1989 and a large percentage of severe cyclones of the BoB is expected to move north.

Summary and conclusion

Dry epochs, when frequent drought Indian monsoons and north-moving BoB severe cyclones occurred, were periods when the phase of AMO was cold. During the 150-year period 1840–1990, there were alternating 30 year dry and wet epochs. Extrapolating this natural cyclicity of the ocean–atmosphere system, the three decades 2020–2049 are likely to have frequent disastrous droughts in the ISMR and a large percentage of the severe cyclones of BoB are likely to have northward tracks, adversely affecting the coastal region of north BoB. The upper troposphere of the mid-latitude region of Asia is found to have a cold anomaly in a dry epoch (decadal variability). This region is also experiencing a long-term cooling trend. It is feared that this cooling trend over the Asian continent is likely to make the expected dry epoch 2020–2049 more severe in its impact than the dry epoch 1960–1989. The South Asian region to be affected by droughts and cyclones has a high population density. There is urgent need for the global scientific community to take up further studies, including modelling to understand the ocean–atmosphere instability (negative feedback) on both regional and global scales as described in this article.

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