Monsoon and EQUINOO: validation of the educated guess for the season of 2019

The summer monsoon of 2019 was rather unusual in terms of the all-India rainfall, with 32.8% deficit in June followed by rainfall being 4.6%, 15.4% and 52.3% above average for July, August and September respectively, resulting in the June–September rainfall being 10% above average (http://imdpune.gov.in/), on the borderline of excess rainfall. In an earlier study[1], we had analysed the performance of monsoon in June and July, and the important factors determining the interannual variation, viz. the El Niño Southern Oscillation (ENSO) and the Equatorial Indian Ocean Oscillation (EQUINOO). The warm (cold) phase of ENSO, i.e. El Niño (La Niña) is unfavourable (favourable) for the Indian summer monsoon rainfall. EQUINOO involves an oscillation between the positive phase (which is favourable for monsoon)[2], characterized by enhanced convection over the WEIO, the western equatorial Indian Ocean, and suppressed convection over the EEIO, the eastern equatorial Indian Ocean, and a negative phase characterized with opposite signs of the convection anomalies. We showed that the large deficit in June could be attributed to the El Niño[1]. The El Niño weakened continuously thereafter and hence it was expected that EQUINOO would play an important role in determining rainfall during rest of the season. The phase of EQUINOO was positive from June to early August, and we suggested that above average rainfall in July was a consequence of the dominating impact of EQUINOO vis-à-vis El Niño. On the basis of our understanding of the genesis and sustenance of the positive phase of EQUINOO, and analysis of the observations until 10 August, we made an educated guess that the positive phase of EQUINOO would be sustained and intensified in the remaining part of the season and hence that the seasonal rainfall would be above normal. Here we assess this by analysing the observations during the rest of the season.

We use an index for EQUINOO based on outgoing longwave radiation (OLR, downloaded from https://www.esrl.noaa.gov/psd), which is defined as the difference between the OLR of the EEIO and OLR of the WEIO[3]. With the OLR of the WEIO being negatively correlated with that of the EEIO, suppression of convection over one region tends to lead to enhancement over the other. In 2019, a positive phase of the EQUINOO occurred in May, June and July with more intense suppression of convection over the EEIO in May and July, whereas the El Niño steadily weakened from May to July (Figure 1). As a measure of convection over a specific region on a daily scale, we have used a convective index (CI) which is the sum of 200 Wm^{-2}-OLR (Wm^{-2}) for all the grids in that region for which this quantity is positive, i.e. can be considered to have convection[4]. The variation of CI over the WEIO and the EEIO until early August in 2019 is shown in Figure 2 *a* (figure 10 of Gadgil *et al.*[1]). It is seen that the convection over the EEIO dominated that over the WEIO in April, but it was suppressed during late April to early May, recovered a little thereafter, but remained subdued until the last week of June and was even further suppressed in July. The convection over the WEIO increased in mid-May and remained high until the end of July (Figure 2 *a*). Thus, a positive phase of the EQUINOO was generated in May and was sustained in June and July 2019. A possible mechanism for the genesis of positive phase was suggested by Francis *et al.*[4], who pointed out that a severe cyclonic storm in April–May over the Bay of Bengal can lead to suppression of convection over the EEIO, which in turn can lead to enhancement of convection over the WEIO; hence genesis of a positive phase of the EQUINOO. The cyclones are relatively short-lived and suppression of convection over the EEIO associated with these cyclones does not last for more than a few days. However, in association with the enhancement of convection over the WEIO, equatorial wind anomalies become easterlies, enhancing the convergence over the WEIO. This atmospheric feedback can further enhance the convection over the WEIO and keep the EEIO convection suppressed. With such a positive atmospheric feedback, convection over the EEIO can remain suppressed for several weeks leading to sustenance of the positive phase of the EQUINOO. The genesis of positive phase of the EQUINOO in May 2019 can be attributed to such a cyclonic storm, called '*Fani*', which occurred over the Bay of Bengal from 27 April to 3 May and its sustenance till the end of July to the positive atmospheric feedback. The evolution of the EQUINOO in this period is similar to that in the monsoon seasons of 2003 and 2008 (ref. 1). However, in those cases the positive phase of the EQUINOO aborted in early August. Our aim was to assess the possibility of the positive phase sustaining in August and September 2019 (ref. 1).

A factor which played a role in the termination of the positive phase of the EQUINOO in 2003 and 2008 was sea surface temperature (SST) of the WEIO. It is well known that for deep convection (generally indicated by monthly OLR < 240 Wm^{-2}) to occur over the tropical oceans, SST has to be above a threshold of about 27.5°C (refs 5, 6). Vinayachandran *et al.*[7] have shown that SST of the WEIO is primarily determined by the air–sea fluxes. Hence with enhanced convection and winds over the WEIO, SST in 2003 cooled rapidly from May onwards with values reaching below the threshold in August. With this, convection over the WEIO ceased, and since the EEIO was warmer than the threshold, convection over the EEIO was enhanced, implying termination of positive phase of the EQUINOO (figure 8 of Gadgil *et al.*[1]). Figure 2 *b* shows the variation of observed SST in the WEIO and the EEIO until early August 2019 along with the climatological mean SST (figure 10 of Gadgil *et al.*[1]). From June to mid-July 2019, SST of the EEIO was slightly higher than that of the WEIO, but both were above the threshold; so clearly dynamical factors played a role in suppressing convection over the EEIO. During June–July when convection was sustained over the WEIO, SST decreased rapidly (Figure 2 *b*) and became colder than the climatology and SST threshold towards the end of July. Had this cooling continued, like in the cases of 2003 and 2008, the convection over the WEIO would have ceased. However, this decrease was arrested in early August and SST began to increase again. The question we addressed was: would SST of the

WEIO continue to increase and remain above the threshold and make possible the sustenance of the positive phase of the EQUINOO?

We tried to answer this by considering the case of 2007, in which SST of the WEIO decreased rapidly till July but more slowly in August, remained above the threshold throughout the season and the positive phase of the EQUINOO was sustained[1] (figure 8 of Gadgil *et al.*[1]). Effy *et al*. (pers. commun.) have shown that the lower rate of decrease of SST in July–August 2007 was a result of less-efficient vertical processes. They showed that this was due to the deepening of isothermal layers with the arrival of two downwelling Rossby waves from the EEIO, one reflected from the eastern boundary when the downwelling Kelvin wave (triggered by the westerly wind burst in April over the central equatorial Indian Ocean, CEIO) encountered the eastern boundary, and another as a direct response of an easterly wind burst over the CEIO. Based on analysis of satellite-measured sea-level anomaly data and *in situ* temperature data collected by RAMA mooring at 0°N, we showed that, in 2019, as in 2007, the oceanic response to the westerly wind burst over the CEIO during the third week of April was an eastward-propagating downwelling Kelvin wave and reflected downwelling Rossby wave, which propagated westward[1]. We further suggested that this Rossby wave would have arrived at the WEIO by the end of July and deepened the isothermal layers in the WEIO. Since the cooling was arrested in late July, we suggested that SST of the WEIO would increase and be maintained above the threshold and convection over the WEIO would be sustained in the remaining part of the season, leading to rapid cooling of the EEIO compared to climatology due to the associated easterly wind anomalies[1].

Specifically we had made an educated guess that 'with this favourable east-west gradient in SST in the equatorial Indian Ocean, it is possible that the convection over the western parts of the equatorial Indian Ocean will be enhanced and that over the EEIO will remain suppressed in the coming weeks. In addition, with the positive SST anomalies in the central Pacific, there has been intermittent convection near the date-line. This anomalous convection also suppresses the convection over the EEIO dynamically. Hence, unlike in the aborted EQUINOO cases of 2003 and 2008, when there was no significant convection over the central Pacific, it is expected that EQUINOO development may strengthen in the second part of the monsoon season in 2019. This will be favourable situation and could lead to an above normal rainfall for the season as a whole'[1].

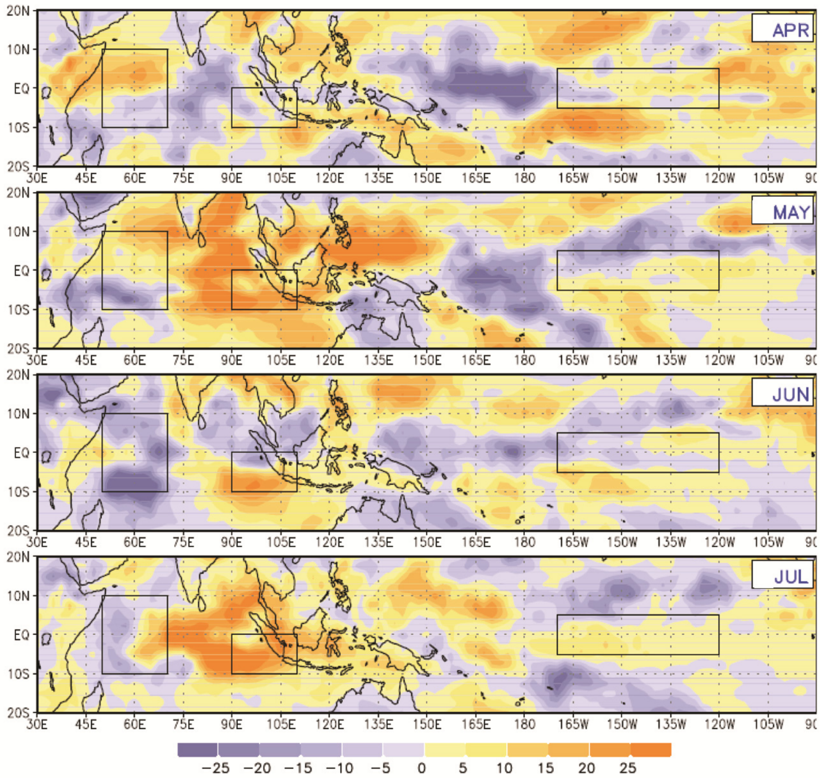

Figure 1. OLR anomaly patterns for April, May, June and July 2019. Boundaries of the regions WEIO and EEIO are shown for each case.

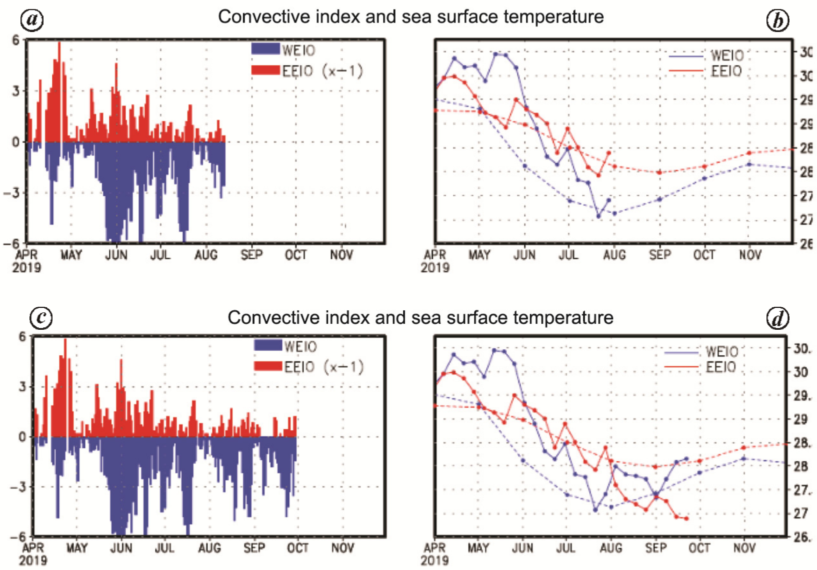

Figure 2. ***a***, Variation of convective intensity (CI) over EEIO and WEIO (with sign reversed). ***b***, SST of WEIO (blue) and EEIO (red) for available data from 1 April until 10 August 2019, climatology shown as dashed lines (figure 10 of Gadgil *et al.*[1]). ***c***, ***d***, Same as ***a***, ***b***, but for the period until 30 September 2019.

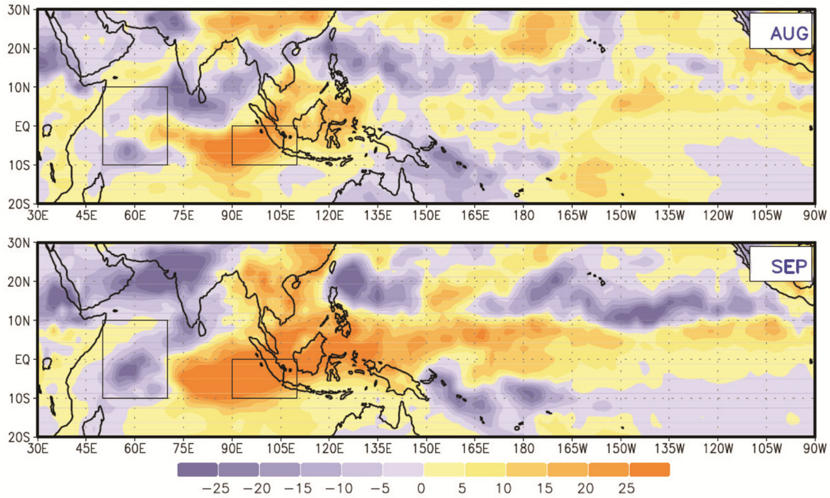

Figure 3. OLR anomaly patterns for August and September 2019.

The OLR anomaly patterns for August and September demonstrate clearly that the positive phase of the EQUINOO was sustained until end of the summer monsoon and became very strong in September (Figure 3). The large negative OLR anomaly over the Indian region and the link to the convection over the WEIO are also clearly seen in the figure. The variation of CI and SST of the WEIO and the EEIO till the end of September 2019 (Figure 2 *c* and *d*) can be compared with that until 10 August (Figure 2 *a* and *b*). Thus, the observations for the latter part of the season show that SST and the EQUINOO have evolved just as we had expected, clearly demonstrating the accuracy of our educated guess.

Our educated guess was based on the understanding of the role of intense convection over the Bay in April–May on the genesis of the positive phase of the EQUINOO, role of the feedback between convection over the WEIO and the zonal circulation over the equatorial Indian Ocean in sustenance of the positive phase of the EQUINOO for several weeks thereafter and finally the role of ocean/atmosphere processes in determining the mixed layer temperature of the WEIO. Hence, it is necessary that the physical processes we have proposed in this study are represented well in the ocean/atmosphere models to improve their skill to predict the EQUINOO. In retrospect, it would be educative to study the role of ocean dynamics and air–sea coupling during the years such as 2003 and 2008, and determine processes that lead to termination or continuation of the EQUINOO, particularly the role of preconditioning by the oceans which may carry valuable potential for prediction. In order to achieve improvement in the skill of predictions of EQUINOO, it is also necessary to unravel the mechanisms which may be important in determining the evolution of SST and EQUINOO in other years with differing intensity of ENSO and pre-monsoon convection over the Bay with the analysis of data for at least last 15 years for which excellent ocean data are also available. It is necessary to ensure that the processes so identified are represented in the models by more modelling studies, if necessary. Only with significant improvement in the skill of prediction of EQUINOO and its links with the monsoon, can the ultimate goal of improvement in the skill of predictions of the monsoon be achieved.

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