# The Strongest IOD in the Satellite-Era: Processes and Impacts


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## Introduction

The Indian Ocean Dipole (hereafter IOD) is a natural mode of interannual climate variability[1] that originates from coupled ocean-atmosphere interactions in the equatorial Indian Ocean[2;3]. Its distinguishing spatial signature is a dipole structure that can be observed in many climatic variables towards the peak phase of the event. Once initiated, the mode persists from early boreal summer to late winter. Exhibiting a significant biennial tendency, positive and negative phases of the IOD tend to occur in consecutive years.

Climate of the Indian Ocean is strongly affected by the IOD. Deficit rainfall spans a wide region from southern Indonesia to southern Australia[4] during positive IOD events, which is counterbalanced by excessive rains over a wide region spanning India to equatorial East Africa[5]. SST and sea surface height are lower than normal in the eastern equatorial Indian Ocean and higher than normal in the western equatorial Indian Ocean. Consequently, the impacts of IOD are not limited to rainfall, but also significantly affect the biogeochemical and physical environments of the Indian Ocean.

Further, through atmospheric teleconnections its impacts influence rainfall and temperature over far-flung regions such as over Japan, South and North America and southern Europe. It also has a significant effect on equatorial Pacific sea surface temperatures through atmospheric Kelvin wave mediated processes, and has been hypothesized to generate super El Ninos, interacting with coupled ocean-atmosphere processes in the Pacific[6].

## The 2019 IOD event

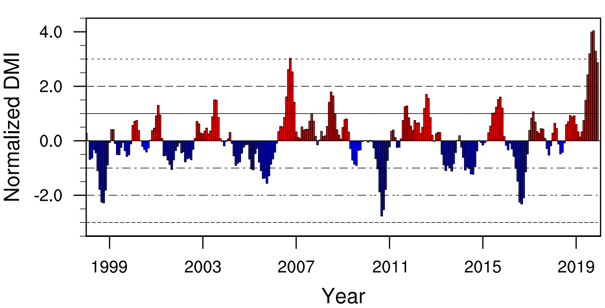


**Figure 1.** Monthly anomalies of the Dipole Mode Index (DMI) from Jan 1999 to Dec2019.

The strongest IOD event of the satellite-era (post 1978) occurred in 2019. Fig. 1 is a time series of monthly values of the Dipole Mode Index (DMI) from Jan 1999 to Dec 2019. The DMI is an index for the IOD, and is calculated as a difference of SST anomalies over the western tropical Indian Ocean (60°E–80°E, 10°S–10°N) and the eastern tropical Indian Ocean (90°E–110°E, 10°S–Equator). The SST dataset used here is from satellite observations in the microwave channel (source: http://www.remss.com/measurements/sea-surface-temperature).

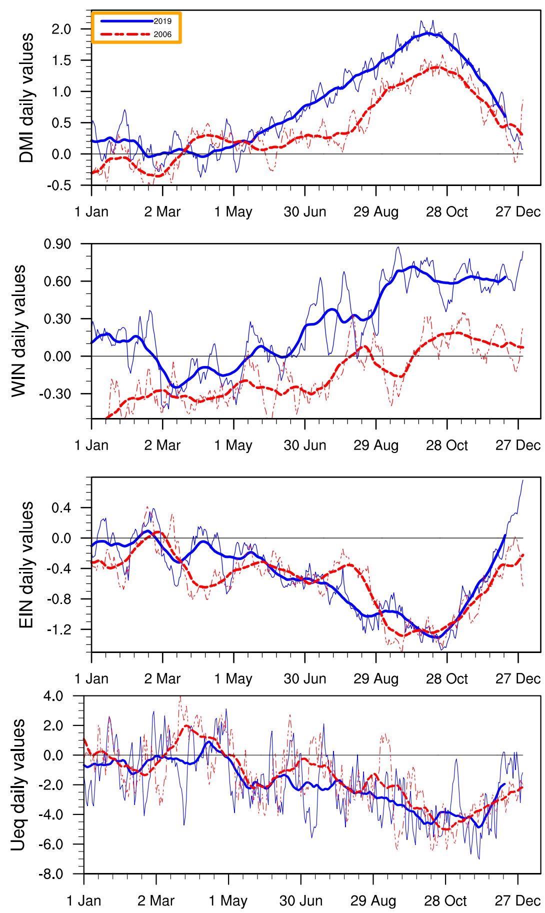


**Figure 2.** From top to bottom: Daily evolution of anomalies of DMI, western Indian ocean SST anomalies, eastern Indian Ocean SST anomalies, and surface zonal wind anomalies over the equatorial Indian Ocean from 1 January to 31 December. The blue lines are for the 2019 event, and the red ones for the 2006 event.

In the post-1950 SST record, IOD events of strength similar to the 2019 event have been detected in 1961, 1963, 1967, 1972, 1982, 1994, and 2006. This pattern of occurrence suggests a decadal modulation of IOD amplitude, as pointed out in previous studies[7].

A comparison with the previous strong event of 2006 (red lines) using daily anomalies smoothed with a 31-day running mean (Fig. 2) highlights a few features of interest. There is a strong phase-locking of IOD indices to the annual cycle. One sees that both events start with an abnormal cooling of the eastern Indian Ocean and abrupt setup of easterly wind anomalies over the equator around early May. The cool SST anomalies and equatorial easterlies continuously increase in amplitude, and their progression is only lightly disturbed by intraseasonal fluctuations till the events reach their peaks in late October. Further, we can see that the abnormal warming of the western equatorial Indian Ocean is lagged by about one or two months, resulting in the dipole structure of SST existing only around the peak phase of the IOD cycle.

## Impacts of the 2019 IOD

The 2019 IOD event strongly affected societies and ecosystems in the Indian Ocean rim countries. The impact locations and types were consistent with previous analyses[8]. Note that the impacts reported below were aggregated from newspaper reports, and do not represent a data driven account of IOD impacts during 2019.

Perhaps one of the largest humanitarian crises driven by IOD occurred in equatorial East Africa, where millions of people were affected through unusually heavy rains and associated floods. Several hundreds of East Africans have lost their lives, and there is an imminent threat of the resurgence of infectious diseases such as Malaria and Rift Valley Fever. This was preceded by severe heatwaves in Zimbabwe and other southern African regions. On the other side of the Indian Ocean, severe drought and hot temperatures caused Australia's wheat output to drop 45.6% in 2019 from a record high in 2017. In Indonesia, haze from uncontrollable forest fires caused cancellation of flights, closure of schools, and respiratory health problems in the country and its neighbours. The fires also drastically reduced forest cover and the resulting habitat loss poses grave threats to the survival of rainforest dwelling species such as orangutans, tigers, and sunbears. Severe floods in India and Pakistan during the southwest monsoon resulted in losses of life, infrastructure, and agricultural productivity. India a top exporter of onions banned their export after excessive rains damaged crops and reduced harvest. *Meanwhile in Japan, the summer brought record-breaking heat, prompting much of the nation and its media to wonder whether the 2020 Tokyo Olympics will be adversely affected by similar weather conditions.* The extreme bush fires during 2019 and early 2020 over Australia is likely an impact of the 2019 IOD event. Bush fires of such intensity have followed other IOD events in the past[5]. The forest fires in southern tropical South America were also likely driven by IOD induced drought and hot weather during boreal summer and fall[9].

## Impacts of IOD on the equatorial Pacific SST

In terms of ocean-atmosphere dynamics, one of the interesting impacts of IOD is on the equatorial Pacific. As the eastern Indian Ocean cools down during an IOD event, convective activities rapidly weaken over this region leading to negative diabatic heating anomalies in the mid-troposphere of the eastern Indian Ocean. These diabatic heating perturbations results in a readjustment of the atmospheric circulation that extends to the equatorial Pacific through the effect of atmospheric Kelvin waves.

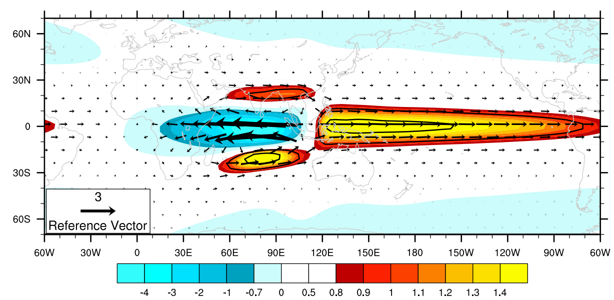


**Figure 3.** Simulation of surface wind anomalies forced by a negative heating source over the equatorial eastern Indian Ocean. The simulations were carried out using linearized primitive equations conditioned on a zero background mean flow.

Fig. 3 shows a schematic of this teleconnection process based on simulations with a linear atmospheric model conditioned on a state of zero background mean flow. In this simulation, a perturbation of diabatic heating was applied only to the eastern Indian Ocean. Surface wind anomalies simulated by the model are seen to not only affect the Indian Ocean (compare bottom panel of Fig. 2), but also extend over to the east to cover the entire equatorial Pacific.

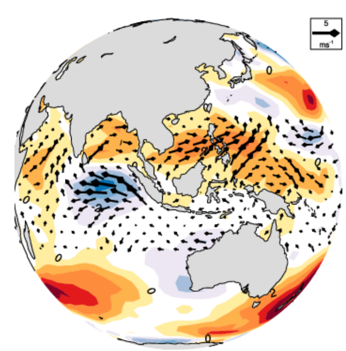

**Figure 4.** Observed wind anomalies in the Indian and far-western Pacific oceans during boreal summer of 2019.

In the real atmosphere, where the mean flow is non-zero, the solutions are modified[6] to resemble the observed wind anomalies during an IOD event. Fig. 4 shows the surface wind anomalies over the tropical Indian and far-western Pacific oceans in August during the 2019 IOD event. Although the entire Pacific Ocean is not shown, we ask the reader to appreciate that the IOD forced winds are confined to the far-western Pacific (the reader may consult similar, but more comprehensive figures in Hameed et al 2018[6]).

Do these western Pacific wind anomalies excited by IOD have an impact on equatorial Pacific Ocean SSTs? Hameed et al (2018)[6]'s ocean simulations have suggested that these do indeed impact the Pacific SSTs.

There are two distinct processes associated with the wind's influence on SST. The first process is that of horizontal advection of oceanic temperature at the edge of the Pacific warm pool. This results in the SST front at the edge of the warm pool slowly extending east. This impact depends on the location of the IOD-induced wind anomalies, which are not only influenced by the strength of diabatic heating anomalies over the eastern Indian Ocean, but also by the nature of the mean flow in the western Pacific (work under preparation).

A more stronger impact is through propagation of oceanic Kelvin waves forced by the winds over the western Pacific. Hameed et al (2018)[6] have shown that these lead to significant warm anomalies over the eastern Pacific during positive IOD events. Such SST anomalies have occurred during past IOD events. For example, both the 1994 and 2006 IOD events developed during a period where Pacific SST was close to normal or even negative in the eastern Pacific. Following the development of IOD activity, SST warming developed and persisted till the end of the event.

It should be noted that during the IOD development phase, the seasonal cooling of eastern Pacific SST is prominent. Although the SST anomalies forced by IOD over the tropical Pacific are significant (upto a degree C), these do not impact atmospheric convection over the eastern Pacific. This is because the mean SST is very low over this region, and a rise of 1 degree does not raise it above the convective threshold. Thus, IOD induced SST anomalies over the Pacific, while significant, are not accompanied by atmospheric convection as during El Nino. These findings are consistent with the observed nature of ocean-atmospheric state over the Pacific during the IOD events of 1994 and 2006.

## Questions for future examination

The 2019 IOD event was one of the well observed and sampled events in the short history of climate science. It is likely that detailed analyses of the event can provide not only a better understanding of the physics underlying an IOD event and that of processes shaping its impacts, but may also yield a deeper understanding of the workings of our climate system. It is likely that many of IOD's impacts are not fully known due to the relative sparsity of historical data and the short record of IOD events. This situation may be partly remedied with well-planned numerical experiments using models of various complexities. Further, we may need to carefully analyze historical SSTs from the Indian Ocean to uncover the temporal behaviour of IOD, especially its cyclical and secular trends.

We are currently developing an international consortium to better understand the processes and impacts underlying IOD events, in particular the 2019 event. We hope that many in the Japanese climate research community will join our efforts. Please bookmark our group's homepage (http://enformtk.u-aizu.ac.jp) for further updates.

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