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# An Appraisal of Indian Ocean Dipole variability and its linkage with ENSO: Future perspective

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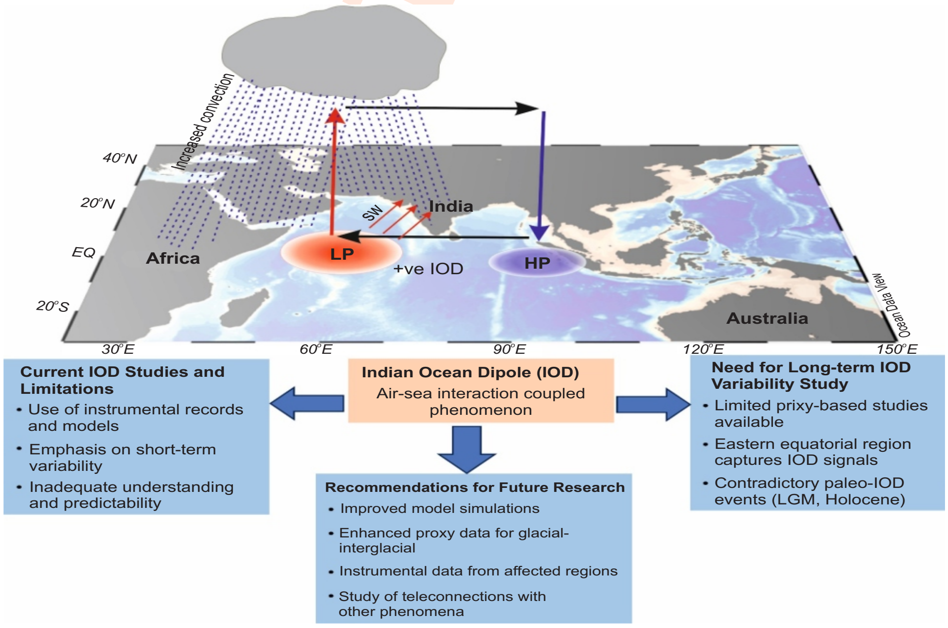
## Abstract

The Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon marked by anomalous equatorial Sea Surface Temperature (SST) variations, shaping global climate patterns. Numerous instrumental records and model simulations demonstrate the IOD mechanisms on a centennial scale. However, IOD trends, variability, and connection with other climatic phenomena are still debatable and need further study.

This study synthesizes instrumental and high-resolution proxy records to trace IOD variability from present to deep geological time scales, evaluating its role in the Indian Ocean climate dynamics and global teleconnections.Previous studies document that the eastern equatorial pole is sensitive to capture IOD signals and makes a shallower thermocline during positive IOD. Additionally, long-term proxy-based studies of IOD variability are limited and show conflicting results regarding IOD-like mean state during the Last Glacial Maximum (LGM) and the Holocene.

Predictions of IOD variability are still preliminary, with inconsistent accuracy and varied success. Therefore, more emphasis is needed to improve model simulations and enhance proxy data for the longer time scale (glacial-interglacial cycle) to improve IOD predictions. Furthermore, the study required the influence of the Pacific and Atlantic Oceans on the Indian Ocean Dipole (IOD) and the Indian monsoon.

**Key words:** El-Niño Southern Oscillation, Indian Ocean Dipole, Indian monsoon, Indonesian through flow, Walker circulations

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## Introduction

The dynamics of atmospheric and oceanic circulation are intricately linked, exerting a profound influence on global climate. However, variability in these circulations remains poorly understood, posing a significant challenge on climate science. A key phenomenon in this context is the Indian Ocean Dipole (IOD), a coupled ocean-atmosphere interaction driven by Sea Surface Temperature (SST) anomalies between the eastern and western tropical Indian Ocean. The strength of IOD events is quantified using the Dipole Mode Index (DMI), which measures the SST gradient between the eastern (90-110°E, 10°S–Eq) and western (50-70°E, 10°S-10°N) Indian Ocean (Webster *et al.,* 1999; Saji *et al.,* 1999). Indian Ocean circulation undergoes seasonal modulation due to monsoonal wind variations. The summer monsoon strengthens winds, enhancing rainfall and latent heat release over southern Asia. During this period, the Indian Ocean Equatorial Westerly (IEW) winds weaken, whereas strong winds during the monsoon transition seasons (April-May, October-November) trigger IOD events.

Typically, IOD peaks in boreal summer (June-August) when a weakened IEW and a shallower thermocline in the Eastern Equatorial Indian Ocean (EEIO) reduce eastward heat transport. In contrast, IOD weakens during boreal fall (September-November), highlighting its strong seasonal dependence (Saji *et al.,* 1999; Hastenrath and Greischar, 1992; Yang *et al.,* 2015). The IOD has three phases, namely, positive, negative and neutral. The negative phase amplifies normal oceanic conditions, strengthening IEW winds and inducing warm water accumulation near western Indonesia. This leads to enhanced rainfall over this region and suppressed convection over East Africa. Conversely, the positive IOD phase strengthens equatorial easterlies, shifting the Walker Circulation westward (Fig. 3b). Moreover, this intense SST cooling in the eastern Indian Ocean through enhanced trade winds and thermocline feedback are critical to IOD evolution (Webster *et al.,* 1999; Annamalai *et al.,* 2003; Cai *et al.,* 2013). The Pacific Ocean plays a crucial role in IOD dynamics. The El Niño-Southern Oscillation (ENSO), a coupled ocean-atmosphere phenomenon in the central and eastern Pacific (Bjerknes, 1969), strongly interacts with the IOD, influencing monsoon variability across the Indian, African, and Australian regions (Saji and Yamagata, 2003).

Recent studies (Abram *et al.,* 2020) have reviewed IOD variability and its interactions with ENSO over short timescales. However, the connection of IOD with broader oceanic systems, such as the Agulhas leakage (Atlantic Ocean) and Indonesian Through flow (ITF) (Pacific Ocean), remains unresolved. Here in this research review, a comprehensive synthesis of proxy-based and modeling studies on IOD, particularly between the eastern (90-110°E, 10°S–Eq) and western (50-70°E, 10°S-10°N) Indian Ocean, with a focus on its long-term variability and climate implications has been presented. By identifying key research gaps, including unresolved interactions with the ITF and ENSO, a systematic appraisal of the previous studies, including authors contributions (Govil *et al.,* 2010, 2011, 2022; Khan *et al.,* 2023, 2024; Kumar *et al.,* 2025) has been provided, which will be helpful to identify research gaps and limitations related to IOD. The study also emphasizes long-term IOD variability and its impact on the global climate system. Here, the methods previously used to study the IOD, highlighting their limitations and suitability for analyzing different time scales has been discussed. The authors have also addressed conflicting theories about the IOD. The database of the PANGAEA platform (https://doi.pangaea.de/10.1594/ PANGAEA. 869100) and the earlier published records have been taken into consideration in this study.

## IOD Trend and Variability

**Proxies in the Eastern and Western Equatorial Indian Ocean:** Studies on marine sediment cores, analyzed using micropaleontological and geochemical proxies, from the eastern and western equatorial Indian Ocean suggest that SST anomalies are closely linked to positive and negative phases of the IOD and significantly influence the surrounding areas through coupled ocean-atmosphere teleconnections (Fig. 1). Reconstructions of past SST variability have been primarily derived from $\delta^{18}O$ records in fossil corals (Abram *et al.,* 2007, 2009), foraminiferal shells (Mohtadi *et al.,* 2007; 2010; Kwiatkowski *et al.,* 2015), and alkenone-based SST estimates (Li *et al.,* 2018) from the tropical eastern Indian Ocean upwelling regions off Java and Sumatra. These studies provide crucial insights into the mechanisms governing IOD variability. Multiple SST and $\delta^{18}O$ records from across the tropical Indian Ocean suggest that the core region of IOD activity lies within the south-eastern equatorial Indian Ocean, approximately between 3° and 7°S (Abram *et al.,* 2015).

The eastern Indian Ocean, particularly the western coast of Sumatra, is highly sensitive to IOD fluctuations and serves as a critical region for detecting both positive and negative IOD signals. Positive IOD phases are characterized by a significant cooling of SST and thermocline shoaling, primarily driven by enhanced cross-equatorial winds, suppressing precipitation over the Indo-Pacific region (Webster *et al.,* 1999; Abram *et al.,* 2007). Coral-derived geochemical records spanning the past 6,500 years indicate that the extreme positive IOD event of 1997 resulted in SST cooling of more than 2°C near Sumatra (Abram *et al.,* 2007, 2009), whereas instrumental observations suggest an average SST cooling of less than 1°C during $20^{th}$-century positive IOD events (Saji and Yamagata, 2003; Qiu *et al.,* 2012).

Paleoceanographic reconstructions further suggest that extreme positive IOD events were prevalent during the mid-Holocene (5.5-4.3 ka and before 6.8 ka) (Abram *et al.,* 2009) whereas the late Holocene (after 4.3 ka) experienced a greater frequency of negative IOD events. However, contrasting findings by Kwiatkowski *et al.* (2015) suggest a dominance of negative IOD conditions during the mid-Holocene (8-3 ka) and a shift towards more frequent positive IOD events in the late Holocene. The coupling between SST and thermocline variability is closely

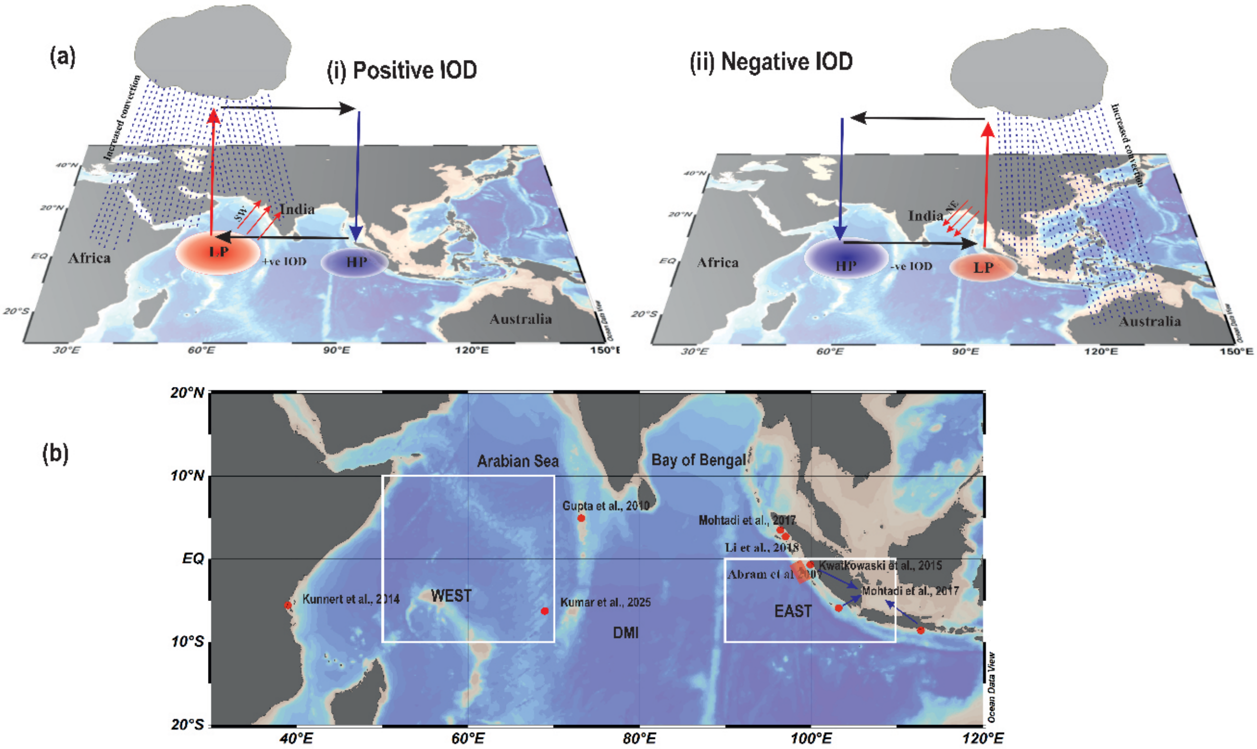


**Fig. 1:** (a) The schematic diagram shows Ocean-atmosphere anomalies (shading) and Walker circulation (arrows) associated with the positive and negative phases of IOD. (The source file is freely available on the website: http://www.bom.gov.au/climate/iod/; Australian Bureau of Meteorology, and it was further modified by the authors of this study) and (b) Map showing the core locations from previous proxy-based studies in the eastern (Abram *et al*., 2007; Mohtadi *et al*., 2007, 2010; Kwiatkowski *et al*., 2015; Li *et al*., 2018) and western (Gupta *et al*., 2010; Kuhnert *et al*., 2014; Kumar *et al*., 2025) regions of IOD variability. The white box indicates the areas of the eastern and western poles used to define the Dipole Mode Index (DMI).

associated with the atmospheric dynamics, where strong IOD events are linked to deep thermocline adjustments, whereas weak IOD events are primarily driven by surface wind forcing (Abram *et al.,* 2007). The IOD also exhibits a strong correlation with the Indian Ocean Walker Circulation, which was more pronounced during the Last Glacial Maximum (LGM), resulting in a deeper thermocline and enhanced precipitation in the eastern tropical Indian Ocean (negative IOD), while the late Holocene saw a reversal of these conditions (Mohtadi *et al.,* 2017). Furthermore, long-term records extending up to 300 ka reveal that SST, thermocline depth, and upwelling intensity in the tropical eastern Indian Ocean exhibit complex interactions. Wang *et al.* (2018) observed that thermocline water temperatures near southern Sumatra remained relatively unaffected by glacial-interglacial cycles, suggesting that local wind forcing exerts a dominant control over upwelling intensity in this region.

In the western Indian Ocean (Arabian Sea), positive IOD events are associated with increased stratification and reduced upwelling. This IOD-related reduction in upwelling results from strengthened Walker circulations, similar to those observed during the global warming hiatus. Coral proxy records provide evidence of the impact of the global warming hiatus on IOD-related upwelling, particularly in 1999 (Watanabe *et al.,* 2019). The tropical Indian Ocean SST has shown significant warming during the late twentieth century, suggesting a future trend towards more frequent positive IOD-like conditions. On orbital timescales, climate variations are influenced by changes in the seasonal and latitudinal distribution of solar insolation, which, in turn, drive shifts in the position of the Intertropical Convergence Zone (ITCZ) (Schneider *et al.,* 2014). The first SST reconstructions from the Central Indian Ocean over the past 137,000 years suggest a cooling of approximately 2.1°C during the Last Glacial Maximum (LGM), while conditions during Marine Isotope Stage 5e were comparatively warmer than present (Saraswat *et al.,* 2005).

Furthermore, comparisons with high-latitude and western Pacific climate records reveal similar climatic trends (Saraswat *et al.,* 2005). Holocene climatic variations in the Western Indian Ocean have been inferred from thermocline temperature reconstructions using $\delta^{18}O$ and magnesium/calcium (Mg/Ca) ratios in planktic foraminifera shells. These studies indicate that the Mid-Holocene global climate anomalies were driven by external forcing rather than internal climate variability within the Indian Ocean. Anomalous rainfall patterns over Indonesia and

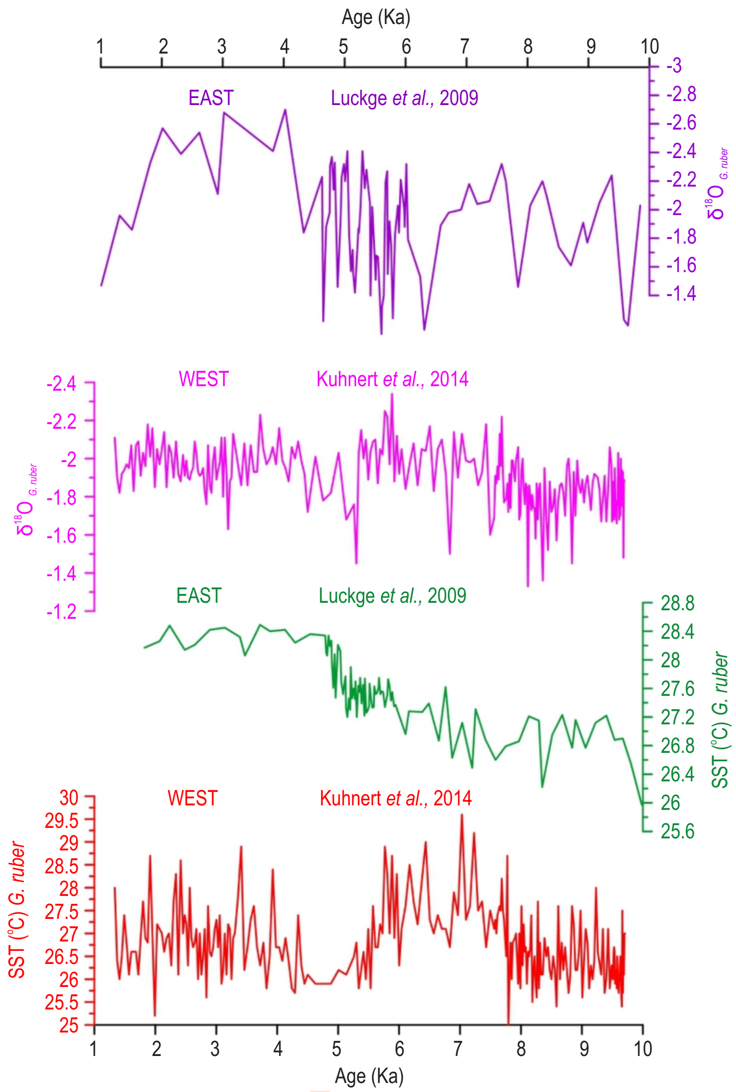


**Fig. 2:** Holocene sea surface temperature (SST) and $\delta^{18}O$ records from the eastern and western Indian Ocean (Kuhnert *et al.,* 2014; Lückge *et al.,* 2009) reveal a relatively weak east–west gradient between 10 ka and 6 ka. However, this gradient strengthens significantly after 6 ka, indicating the development of more pronounced zonal oceanographic and climatic contrasts during the mid to late Holocene.

unusual SST distributions further support this hypothesis. In the Western Indian Ocean, a ~2°C temperature decline during the Mid-Holocene (Fig. 2) contributed to an increased mixed-layer thickness and strengthened Walker circulations (Kuhnert *et al.,* 2014). Additionally, Gupta *et al.* (2010) demonstrated that the IEW, IOD, and eastward equatorial currents (Wyrtki jets) are interconnected and modulated by the Indian, East African and Australian monsoon systems. Their findings also indicate the presence of a positive IOD phase during the mid-Brunhes epoch (300–250 ka) (Gupta *et al.,* 2010).

In addition, we further compared the previous east-west SST and $\delta^{18}O$ records over the past ~10 ka, which reveal clear spatial and temporal variations in Holocene oceanographic and climatic conditions. In the eastern region, the $\delta^{18}O$ record (Luckge *et al.,* 2009) shows greater variability, particularly around 5-6 ka (Fig. 2), suggesting a significant hydroclimatic shift likely associated with changes in monsoon intensity or freshwater influx, potentially due to shifts in the Intertropical Convergence Zone (ITCZ). Conversely, the western $\delta^{18}O$ record (Kuhnert *et al.,* 2014) is relatively stable (Fig. 2), suggesting more consistent salinity and temperature conditions, potentially influenced by open-ocean dynamics and reduced terrestrial input. However, the western SST record displays high-frequency variability throughout the Holocene, especially between 6-8 ka, indicating dynamic surface ocean conditions that could be linked to periodic upwelling or current fluctuations (Kuhnert *et al.,* 2014).

The temporal alignment of major changes around 5-6 ka (Fig. 2) in both regions points to a possible regional climatic transition during the mid-Holocene, though expressed differently due to local environmental settings. Furthermore, the data reveal a relatively weak east-west zonal gradient in both SST and $\delta^{18}O$ between 10 ka and 6 ka, which strengthens after 6 ka (Kuhnnert *et al.,* 2014; Lückge *et al.,* 2009) (Fig. 2). The pronounced east-west contrast in SST and $\delta^{18}O$ after 6 ka suggests an increasing influence of IOD-like dynamics. This zonal asymmetry reflects enhanced ocean-atmosphere interactions during mid to late Holocene. It was found that most IOD-related studies are restricted to the eastern pole. However, only three proxy-based studies in the WEIO are related to IOD variability. Unfortunately, these studies are not located in the western pole (100N-100S and 50º-70ºE). Further study is needed to examine the long-term proxy records from the eastern and western regions, and their comparison is needed for capturing drastic positive-negative IOD signals.

**IOD prediction using instrumental data:** The tropical Pacific and Atlantic Oceans exhibit internal modes of variability that influence global climate. Similarly, independent modes of variability have been identified in the Indian Ocean, distinct from ENSO, based on the observational data over the past 40 years (Saji *et al.,* 1999; Webster *et al.,* 1999). Coupled atmosphere-ocean dynamics, driven by zonal winds and baroclinic waves, generate interannual subsurface (thermocline) variability in the tropical Indian Ocean, characterized by the Indian Ocean Dipole (IOD) (Rao *et al.,* 2001; Shikha and Valsalva, 2018). Intense IOD events modulate subsurface hydrography in the Equatorial Indian Ocean (EIO) through Kelvin and Rossby wave propagation, as captured by model simulations during 1994, 1997 and 2006. The 2006 IOD event exhibited anomalous conditions south of the equator whereas the 1994 and 1997 events showed a westward extension across the equator (Vinayachandran *et al.,* 2002, 2007). Recent studies utilizing satellite and ARGO data indicate that anomalous SST patterns during positive IOD phases in 1994, 1997 and 2006 were essential for upwelling-favorable coastal winds along Sumatra (1ºS-3ºS) (Kämpf and Kavi, 2019).

Phytoplankton size structure, influenced by oceanic physical conditions, is a proxy for reconstructing past IOD variability (Brewin *et al.,* 2012). Remote sensed SST observations provide a robust tool for tracking daily DMI variations (Dwivedi *et al.,* 2012). Model simulations suggest that the mid-Holocene climate experienced frequent and intense IOD events (Iwakiri *et al.,* 2019). ENSO and IOD events correlate negatively with rainfall over Pakistan, Afghanistan and Iran. IOD significantly influences Indian monsoon rainfall along the monsoon trough and south-western coastal regions, while ENSO exerts a broader impact. Additionally, positive IOD events show strong inverse partial correlations with precipitation over Australia's Indo-Pacific, western and southern regions (Ashok *et al.,* 2001, 2003).

Further, accurate IOD prediction is crucial to mitigate these effects but remains highly challenging. For over two decades, researchers have been working on forecasting IOD at seasonal scales (Saji *et al.,* 1999; Iizuka *et al.,* 2000; Shinoda *et al.,* 2004; Luo *et al.,* 2007; Doi *et al.,* 2016). The IOD, like other basin-scale air-sea coupled phenomena including the Atlantic Niño/Niña, El Niño-Southern Oscillation (ENSO), and ENSO Modoki, has strong teleconnections to mid-latitudes, significantly impacting global climate patterns (Zebiak, 1993; Alexander *et al.,* 2002; Behera and Yamagata, 2003; Ashok *et al.,* 2007; Weng *et al.,* 2007). Heat budget studies highlight that model-generated dipole mode events critically depend on tropical air-sea interactions, which are heavily influenced by ocean dynamics (Luo *et al.,* 2007). IOD prediction remains a formidable challenge. Previous studies have been limited to seasonal forecasts, with a maximum lead time of four months (Shinoda *et al.,* 2004; Luo *et al.,* 2007; Doi *et al.,* 2016). Climate model systems, particularly SINTX-F1 and SINTX-F2, have demonstrated predictive capability (Luo *et al.,* 2007). These models have successfully forecasted extreme IOD events such as the positive phases in 2006 and 2007 and the negative phase in 2010 (Luo *et al.,* 2008).

Historical predictions show mixed accuracy. In 1994 and 2005/06, the models captured extreme positive and weak negative IOD events, respectively (Luo *et al.,* 2007). They also correctly predicted warm SST anomalies in the Western Indian Ocean during 1983, 1987, 1991, 1997/98 and 2003, as well as cold anomalies in 1985, 1989, 1996 and 1999 (Luo *et al.,* 2007). More recently, Feba *et al.* (2021) made a breakthrough in multi-year IOD prediction, extending lead times to at least two years. They identified the strongest signals in the Southern Ocean at 300-800 m depths, with positive temperature anomalies in this region correlating with positive IOD events 8-10 years later and *vice versa* for negative events (Luo *et al.,* 2007; Feba *et al.,* 2021).

Advancements in Coupled General Circulation Models (CGCMs) are essential to improve long-range IOD forecasts. Incorporating surface and subsurface temperature data from the Indian and other oceans, both of which influence IOD development, will enhance predictive accuracy. Additionally, since atmospheric conditions play a crucial role, analyzing wind patterns over the Eastern Indian Ocean (EIO) will further refine IOD forecasting.

## Global impact of IOD

Simulation studies indicate that the IOD significantly influences the meridional monsoon zonal tropospheric circulation, shaping Indian Summer Monsoon Rainfall (ISMR). Previous research lacked clarity on this relationship, but recent findings show that 73% of positive IOD events enhance ISMR, while 67% of negative IOD events reduce it (Saji *et al.,* 1999; Webster *et al.,* 1999). A positive IOD strengthens the monsoon by intensifying convergence over the Bay of Bengal, whereas a negative IOD weakens it (Ashok *et al.,* 2001). Notably, the simultaneous occurrence of a positive IOD and El Niño in 1994 had a pronounced impact on India and the Bay of Bengal (Guan and Yamagata, 2003). Beyond India, IOD modulates monsoons in Africa and Australia, influencing regional hydroclimates. Positive IOD phases weaken the Walker circulation while

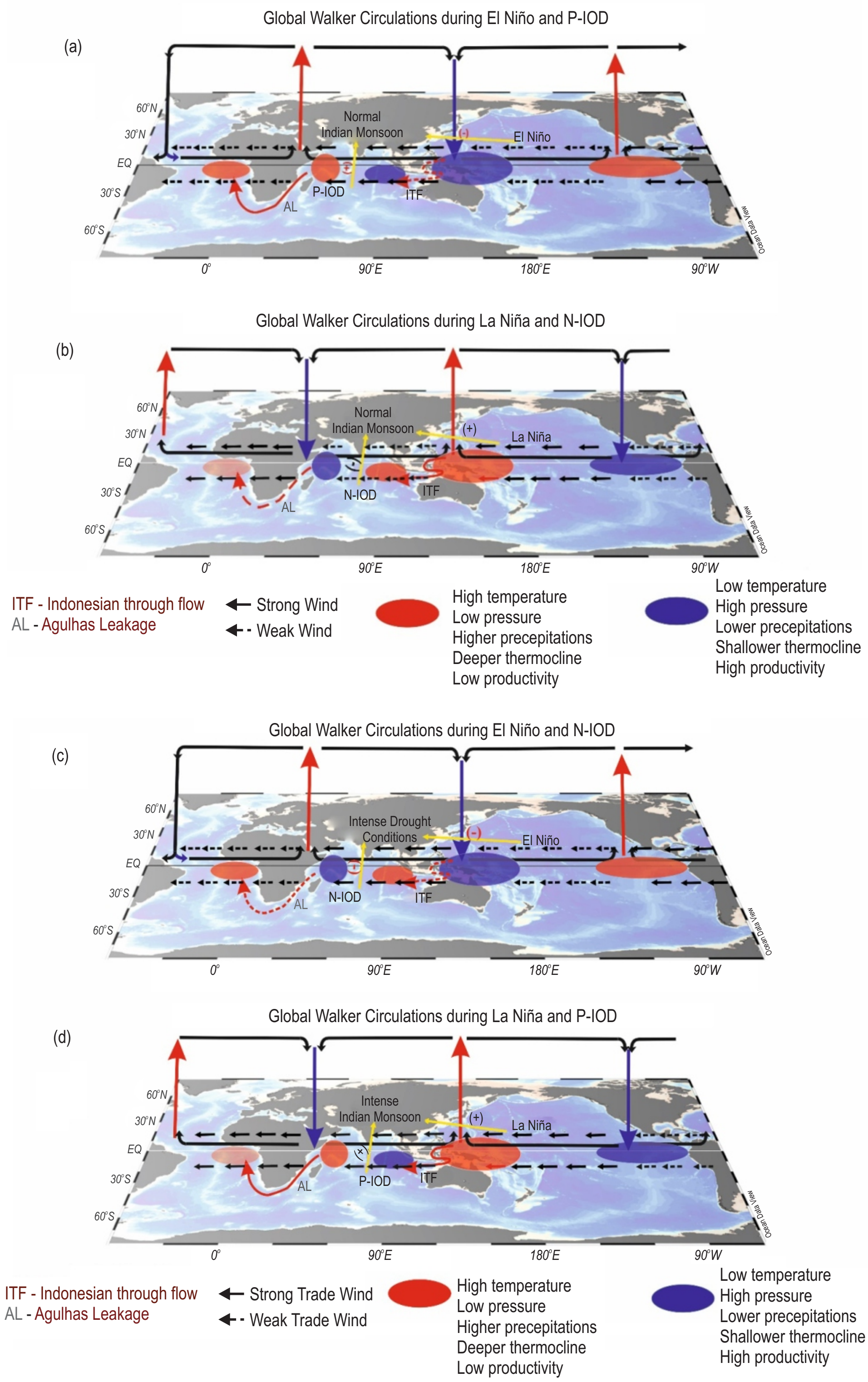


**Fig. 3:** The schematic diagram shows the heat distributions between the Pacific, Indian, and Atlantic Oceans due to the global Walker circulations (arrows) and teleconnection phenomena. (a) El Niño weakens the Pacific and Atlantic Ocean trade winds and strengthens the Indian Ocean (+ve IOD). (b) La Niña strengthens the Pacific and Atlantic Ocean trade winds and weakens the Indian Ocean (-ve IOD). (c)El Niño weakens the Pacific and Atlantic Ocean trade winds, and negative IOD weakens the Indian Ocean trade winds.(d) La Niña strengthens the Pacific and Atlantic Ocean trade winds, and positive IOD strengthens the trade winds in the Indian Ocean. (The source file is freely available on the website NOAA Climate.gov, drawing by Fiona Martin, and the authors of this study further modified it).

temporarily strengthening the Hadley circulation, enhancing rainfall over East Africa (Tierney *et al.,* 2013; Blau and Ha, 2020).

In contrast, Australia experiences drier conditions, rising temperatures, and increased wildfire risks, especially in the southeast (Cai *et al.,* 2009). The standard rotational model suggests that positive IOD events induce cold SST anomalies in western Indonesia, generating high pressure over mainland Australia and suppressing rainfall (Ashok *et al.,* 2003). Long-term reconstructions of Indo-Pacific rainfall variability, based on isotopic analysis of plant waxes, highlight two periods of intensified precipitation linked to extreme negative IOD phases (~8-6.5 ka and 2-1 ka) (Niedermeyer *et al.,* 2014). However, these findings contrast with reconstructions by Abram *et al.* (2009) and Kwiatkowski *et al.* (2015), suggesting an inverse relationship between EEIO SST anomalies and western Indian Ocean precipitation patterns.

**Relations among the IOD, ITF, ENSO and Atlantic Niño:** The equatorial Pacific, Atlantic and Indian Oceans influence global climate variability through atmospheric bridges, ocean circulation and teleconnections (Wang, 2019). The Pacific Ocean affects the Indian Ocean via ENSO, Walker circulation, and the ITF, which plays a crucial role in heat distribution and interannual ocean circulation by propagating equatorial waves linked to both ENSO and IOD (Fig. 3). Under normal conditions, the tropical Pacific and Atlantic Oceans exhibit warm (west) and cold (east) mean SST due to intensified Hadley cell circulation and trade winds. ENSO disrupts this pattern by weakening trade winds, altering SST distribution in the Pacific (McPhaden *et al.,* 2006), while a similar process triggers the Atlantic Niño in the tropical Atlantic (Zebiak *et al.,* 1993). Although ENSO and IOD are independent phenomena (Saji *et al.,* 1999), ENSO can amplify IOD events by modulating Walker circulation in the Indian Ocean (Behera *et al.,* 2006). ENSO influences IOD formation and intensity in years of co-occurrence, with the Indian Ocean's thermocline dynamics responding to atmospheric forcing, particularly during the positive IOD phase (Venzke *et al.,* 2000; Alexander *et al.,* 2002). ENSO impacts the Indian Ocean through the atmospheric bridge, reversing the Walker cell during El Niño, leading to strong subsidence over the western Pacific and the equatorial Indian Ocean (Klein *et al.,* 1999; Venzke *et al.,* 2000) (Fig. 3).

Historical events, such as strong IOD in 1997, coinciding with a powerful ENSO, highlight this interaction. While about 50% of IOD events coincide with ENSO, others occur independently (Saji and Yamagata, 2003), possibly driven by anomalies in Hadley and Walker circulations (Vinayachandran *et al.,* 2009). Notably, IODs associated with ENSO tend to emerge in winter and spring, whereas those in summer and fall are often ENSO-independent (Tozuka *et al.,* 2008). Beyond the Indian Ocean, teleconnections extend to the Atlantic via the atmospheric bridge and Agulhas leakage (Wang *et al.,* 2019). The Atlantic Niño, a coupled ocean-atmosphere phenomenon, influences the Indian monsoon and global climate variability (Kucharski *et al.,* 2008, 2009). The IOD can also impact the Atlantic by generating warm SST anomalies in the equatorial basin, triggering the Atlantic Niño (Zhang *et al.,* 2021).

Furthermore, we present a conceptual graphic illustration highlighting the interconnected roles of the Atlantic and Pacific Oceans in modulating Indian monsoon variability (Fig. 3). When ENSO occurs with a positive IOD (Fig. 3a), or La Niña with a negative IOD (Fig. 3b), their opposing influences on the Indian monsoon tend to cancel each other out, often resulting in near-normal rainfall. In contrast, a positive IOD combined with La Niña strengthens the monsoon, increasing the likelihood of heavy rains and flooding (Fig. 3d). On the other hand, the combination of a negative IOD and El Niño can significantly weaken the monsoon, leading to severe drought conditions (Fig. 3c).The ISMR extremes during ENSO events are primarily driven by asymmetric changes in zonal and meridional gradients in surface pressure (Ps). In contrast, non-ENSO-related ISMR extremes result from zonal gradients in zonally symmetric Ps anomalies (Chakraborty and Singhai, 2021). This distinction highlights the differing atmospheric dynamics governing monsoon variability under ENSO and non-ENSO conditions.

## Recommendations for future study

Despite significant advancements in understanding atmospheric-ocean coupled phenomena such as the Indian Ocean Dipole (IOD), El Niño-Southern Oscillation (ENSO), and Atlantic Niño, a major research gap persists in reconstructing their long-term behavior, particularly concerning the IOD. Current climate models project an increase in extreme positive IOD events and a weakening of negative phases; however, their predictability remains limited due to the scarcity of instrumental records and insufficient focus on present-day variability. Furthermore, the complex interplay between IOD and ENSO, especially their opposing impacts on mixed-layer and thermocline dynamics across ocean basins, is not yet fully understood.

Planktic foraminifera, with their depth-stratified habitat preferences and isotopic sensitivity, serve as valuable proxies for reconstructing past sea surface temperatures, thermocline depth, and vertical ocean structure (Hemleben *et al.,* 1989; Ravelo and Fairbanks, 1992; Govil *et al.,* 2010, 2011, 2022). However, more regionally distributed high-resolution palaeoceanographic data, especially from both the eastern and western poles of the Pacific and Indian Oceans, are required to accurately capture the spatial heterogeneity of IOD and ENSO influences. Future research should focus on developing multi-proxy records by utilizing paired isotopic signatures from species such as *Globigerinoides ruber* and *Neogloboquadrina dutertrei* to effectively track vertical thermal gradients and mixed-layer dynamics (Ravelo and Fairbanks, 1992; Mulitza *et al.,* 1997; Khan *et al.,* 2023, 2024; Kwiatkowski *et al.,* 2015; Ford *et al.,* 2018). In addition to isotopic analyses, the relative abundance of these foraminiferal species serves as a valuable proxy for reconstructing variations in mixed-layer and thermocline depth (Podder *et al.,* 2021; Khan *et al.,* 2023).Such reconstructions across the late Quaternary would provide critical insights into the evolution of IOD and ENSO systems and improve the reliability of climate models and long-term forecasts.

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**Authors' contribution: P. Govil and B. Kumar:** Conceptualized, collected the information and wrote the manuscript. **D. Verma and H. Khan:** Assisted in data collection and interpretation. All authors read and approved the final manuscript.

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