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A theoretical investigation of the tropical Indo-Pacific tripole mode

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The El Niño-Southern Oscillation (ENSO) phenomenon in the tropical Pacific has been a focus of ocean and climate studies in the last few decades. Recently, the short-term climate variability in the tropical Indian Ocean has attracted increasingly more attention, especially with the proposition of the Indian Ocean Dipole (IOD) mode. However, these phenomena are often studied separately without much consideration of their interaction. Observations reveal a striking out-of-phase relationship between zonal gradients of sea surface height anomaly (SSHA) and sea surface temperature anomaly (SSTA) in the tropical Indian and Pacific Oceans. Since the two oceans share the ascending branch of the Walker cells over the warm pool, the variation within one of them will affect the other. The accompanied zonal surface wind anomalies are always opposite over the two basins, thus producing a tripole structure with opposite zonal gradients of SSHA/SSTA in the two oceans. This mode of variability has been referred to as Indo-Pacific Tripole (IPT). Based on observational data analyses and a simple ocean-atmosphere coupled model, this study tries to identify the characteristics and physical mechanism of IPT with a particular emphasis on the relationships among ENSO, IOD, and IPT. The model includes the basic oceanic and atmospheric variables and the feedbacks between them, and takes into account the inter-basin connection through an atmospheric bridge, thus providing a valuable framework for further research on the short-term tropical climate variability.

ENSO, IOD, IPT

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The El Niño-Southern Oscillation (ENSO) is the most important interannual oscillation in the Earth's climate system. It is characterized by large sea surface temperature anomaly (SSTA) in the tropical eastern Pacific (Rasmusson et al., 1982), often measured by Niño3.4 index (SSTA averaged over 5°S–5°N, 170°E–120°W), but the impact of ENSO is far beyond the Pacific. For instance, significant negative correlation is found between Niño3.4 and the zonal gradient of SSTA in the equatorial Indian Ocean (Nigam et al., 1993; Nicholson, 1997; Yu et al., 1999), indicating a strong coupling between the two tropical ocean basins.

Observed interannual variations in the tropical Indian Ocean have long been attributed to the influence of the tropical Pacific ENSO (Allan et al., 2001; Hastenrath, 2002). However, Saji et al. (1999) pointed out that even in non-ENSO years such as 1961–1962, 1967–1968, and 1994–1995, the tropical Indian Ocean exhibited significant SSTA and sea surface wind anomaly (SSWA) of its own. Their composite analyses of these events indicate that strong SST cooling appears off Sumatra during summer, with anomalous southeasterly winds aloft, while the tropical central Indian Ocean warms up. This SSTA dipole pattern reaches its maximum strength in autumn, with the warm pole shift-

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ing to the western Indian Ocean.

By considering this phenomenon a climate mode intrinsic to the Indian Ocean, Saji et al. (1999) called it Indian Ocean Dipole (IOD), and characterized it with the SSTA difference between the west (10°S–10°N, 50°E–70°E) and east (10°S–0°, 90°E–110°E) tropical Indian Ocean. The concept of IOD has attracted attention of many investigators, and a series of follow-up studies, based on both data analysis and numerical modeling, provided further evidence of the existence of IOD (Ashok et al., 2001; Yamagata et al., 2003). Nevertheless, because IOD is highly correlated to ENSO when seasonally stratified, it is still argued that IOD is merely a response to ENSO rather than an independent mode (Anderson, 1999; Allan et al., 2001; Hastenrath, 2002).

Chen et al. (2008) and Chen (2011) analyzed the relationship between ENSO and IOD based on multi-variable empirical orthogonal function (MEOF) modes of the tropical Indo-Pacific. The dominant mode appears to have a tripole pattern in both SSTA and sea surface height anomaly (SSHA), with one pole over the western Pacific-eastern Indian warn pool and the other two opposite poles in the eastern Pacific and western Indian Oceans (Figure 1). When the warm pool region exhibits cold (warm) SSTA and low (high) SSHA, the tropical eastern Pacific and western Indian Oceans show warm (cold) SSTA and high (low) SSHA. The Indian Ocean part of this mode is quite similar to IOD, whereas the Pacific part of it is comparable to ENSO pattern. This mode is referred to as Indo-Pacific Tripole (IPT) and is considered an intrinsic mode of the tropical Indo-Pacific climate variability.

The dynamics of IPT mode is closely related to the atmospheric Walker circulation (Chen et al., 2008; Chen, 2011). Because the two Walker cells over the equatorial Pacific and the Indian Oceans share the same ascending branch over the warm pool region, any variations in one ocean basin will affect the other through the atmospheric bridge. In particular, when El Niño occurs in the tropical Pacific, the associated anomalous surface westerly will weaken the Pacific Walker cell and the convection over the warm pool, which then weakens the Walker cell over the tropical Indian Ocean. Through the positive feedback between SSTA and SSWA (Bjerknes, 1969), SST cooling (warming) will develop in the tropical eastern (western) Indian Ocean, thus leading to an IPT pattern over the whole tropical Indo-Pacific region.

Chen (2011) further discussed the three "pure" IOD events invoked by Saji et al. (1999). It is found that although there was no full-blown El Niño in these three years, a weak warming pattern appeared in the tropical western and central Pacific. This could be explained within the IPT framework. During these IOD years, the Walker cell over the tropical Indian Ocean was weakened first, which led to reduced strength of the Pacific Walker cell through atmospheric bridge. Then the positive feedback between SSTA and SSWA took place, leading to a SST warming in the tropical Pacific. However, since the eastern Pacific SST is

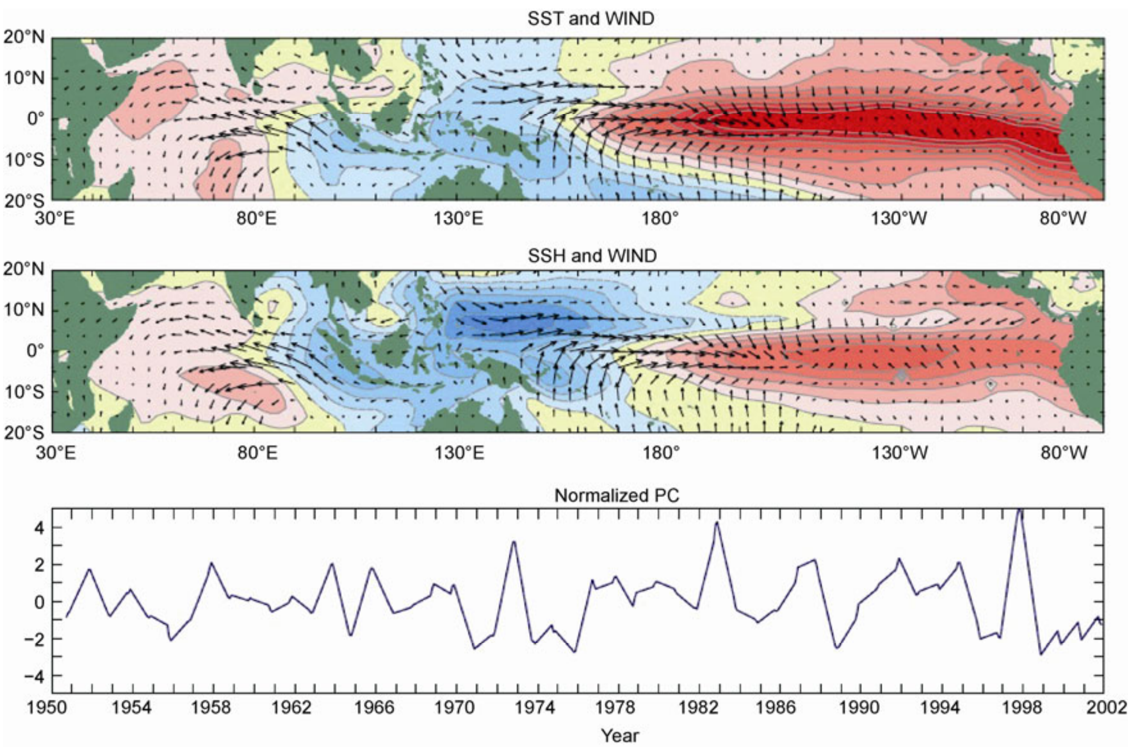

Figure 1 Indo-Pacific Tripole as depicted by the first mode MEOFs of SST, SSH and surface wind stress calculated using SODA dataset for September-October-November (SON) over the period 1950–2001. The upper two panels are spatial patterns of SST and SSH with wind stress superimposed, and the lower panel is normalized time series (principal component) of the mode (Chen et al., 2008, Figure 8).