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Invited review

The Indian Ocean Zonal Mode over the past millennium in observed and modeled precipitation isotopes

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ABSTRACT

The Indian Ocean Zonal Mode (IOZM) has gained considerable attention in the past decade due to its role in causing widespread flooding and droughts in the continents and islands surrounding the Indian Ocean. The IOZM has also been observed to vary on a low-frequency (multi-decadal) basis, making its behavior important to understand both for mid-range 21st century climate prediction and for paleoclimate studies. Despite efforts to reconstruct the IOZM using corals and other high-resolution proxies, nonstationarities in the response of paleoclimate proxies to the IOZM have also been noted, raising the possibility that the IOZM may be difficult to reconstruct or to predict in the long-term. It is therefore critical to assess the low-frequency component of the IOZM in observed, modeled, and paleoclimate data from the Indian Ocean region in order to identify nonstationary behavior and to assess its role in low-frequency climate variations.

We present an analysis of low-frequency and nonstationary behavior in the IOZM on multi-decadal to centennial timescales using a combination of modeled, observed, and proxy reconstructions of $\delta^{18}O/\delta D_{precip}$. In order to assess multiple timescales of low-frequency variability, we focus on two key time periods: the historical period (1870–2003), and the past millennium (1000 C.E.-present). We find significant nonstationarities in the relationships between the IOZM, precipitation amount, and $\delta^{18}O_{precip}/\delta D_{precip}$ during the historical period. These relationships vary on a multi-decadal basis in our model and in observed/reanalysis datasets. Air-sea interactions in the Indo-Pacific Warm Pool and teleconnections to the Pacific Ocean, as well as the phase of the IOZM itself, may contribute to this nonstationary behavior.

We examine the potential ramifications of nonstationary IOZM behavior using a synthesis of spatially distributed proxy archives of $\delta^{18}O_{precip}/\delta D_{precip}$ from both sides of the IOZM region spanning the past millennium. Our findings indicate that during the past millennium, a strong IOZM-like connection exists in the proxy data network, with anti-correlation between East Africa and Indonesia. However, the links are spatially limited and in some cases timescale-dependent. Nonlinear behaviors in these links suggest that the IOZM may be difficult to detect on a consistent basis in proxy records from the past millennium. Based on our modeling results, the inconsistent links in the IOZM proxy network may arise from temporally and spatially variable relationships between the IOZM, precipitation, and $\delta^{18}O_{precip}/\delta D_{precip}$. We conclude that the IOZM's potential to influence the climate of the Indian Ocean region is inconsistently reflected in proxy data, and that due to the changing strength of the IOZM/$\delta^{18}O_{precip}/\delta D_{precip}$ relationship, its spatial "footprint" may be restricted on multi-decadal to multi-centennial timescales.

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1. Introduction

1.1. The Indian Ocean Zonal Mode

The Indian Ocean Zonal Mode (IOZM; also known as the Indian Ocean Dipole; Table 1) is an important mode of interannual rainfall variability in the circum-Indian Ocean region (Saji et al., 1999). IOZM events occur during boreal Fall (September–December;

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Table 1
List of abbreviations.

IOZM	Indian Ocean Zonal Mode
IOZM+(−)	IOZM positive (negative)
SST	Sea Surface Temperature
EEIO	Eastern Equatorial Indian Ocean
WEIO	Western Equatorial Indian Ocean
OND	October–December
SOND	September–December
ENSO	El Niño-Southern Oscillation
DMI	Dipole Mode Index
ZWI	Zonal Wind Index
LS	Link Strength

SOND) every 2–7 years, causing pronounced rainfall anomalies in East Africa, western Indonesia, Australia, and India (e.g., Ashok et al., 2001; Black et al., 2003). Under normal conditions, a strong gradient in sea surface temperature (SST) between the warmer Eastern Equatorial Indian Ocean (EEIO) and the cooler Western Equatorial Indian Ocean (WEIO) causes weak westerly winds along the equator, contributing to the normal Indian Ocean Walker Circulation, with rising air and deep atmospheric convection over Indonesia and descending air and dry conditions in East Africa. During IOZM positive (IOZM+) events, a breakdown of the normal SST gradient and equatorial wind field leads to anomalously dry conditions in western Indonesia while enhancing the October–December (OND) rainy season in East Africa (Fig. 1). The event ceases when the normal boreal summer monsoon circulation develops, cooling the WEIO and relaxing anomalous easterly winds (Webster et al., 1999; Schott and McCreary, 2001).

In addition to its direct effects on East African and Indonesian precipitation, the IOZM has the ability to effect large changes in regional hydrology through its connection with the Indian monsoon and the El Niño-Southern Oscillation (ENSO) (Ashok et al., 2001; D'Arrigo and Smerdon, 2008; Ummenhofer et al., 2011). Both an IOZM+ event and an El Niño event necessitate anomalous cooling in the Indo-Pacific warm pool and weakened vertical ascent and convection over Indonesia, and in some but not all years the two co-occur (Saji et al., 1999; Saji and Yamagata, 2003a), possibly triggered by ENSO-induced zonal shifts in Walker cell anomalies (Fischer et al., 2005). IOZM+ events can also be triggered by meridional Hadley cell perturbations in the absence of ENSO dynamics (Fischer et al., 2005), and numerous other studies have established that the IOZM's interannual fluctuations are distinct from ENSO and should be considered a separate Indian Ocean phenomenon (e.g., Saji and Yamagata, 2003b; Behera et al., 2006; Schott et al., 2009).

While the IOZM operates independently from ENSO, teleconnections to the Pacific Ocean can play an important role in triggering and enhancing IOZM events via local air-sea interactions, ocean dynamics, and atmospheric teleconnections (Li et al., 2003; Behera et al., 2006; Gnanaseelan and Vaid, 2010). Interannual to decadal variability in Pacific SSTs can induce stronger/more frequent IOZM+ events by preconditioning the EEIO with a shallower thermocline (Annamalai et al., 2005; Schott et al., 2009). This preconditioning is associated with changes in the Indonesian Throughflow as well as an atmospheric teleconnection to equatorial winds over the Indian Ocean (Annamalai et al., 2005). Air-sea interactions in the warm pool are also integral to the generation and termination of IOZM events (Cai et al., 2013 and refs therein). SST variability in the EEIO induces a positive feedback with wind speed and evaporative heat loss, further enhancing cold anomalies. However, cool SSTs also suppress clouds and convection, warming the EEIO via increased shortwave radiation (Cai et al., 2013).

In addition to pronounced interannual variability, the IOZM also exhibits low-frequency variability. The power spectrum of observed IOZM SSTs exhibits a spectral peak at ~10 years (90% significance level), suggesting that periodicity at decadal and potentially longer timescales is intrinsic to the IOZM system (Ashok et al., 2004a, 2003). Twentieth century SST observations reveal multi-decadal modulations of the IOZM, with periods of time characterized by more frequent/intense IOZM negative (IOZM-) events (~1880–1920), more frequent/intense IOZM positive

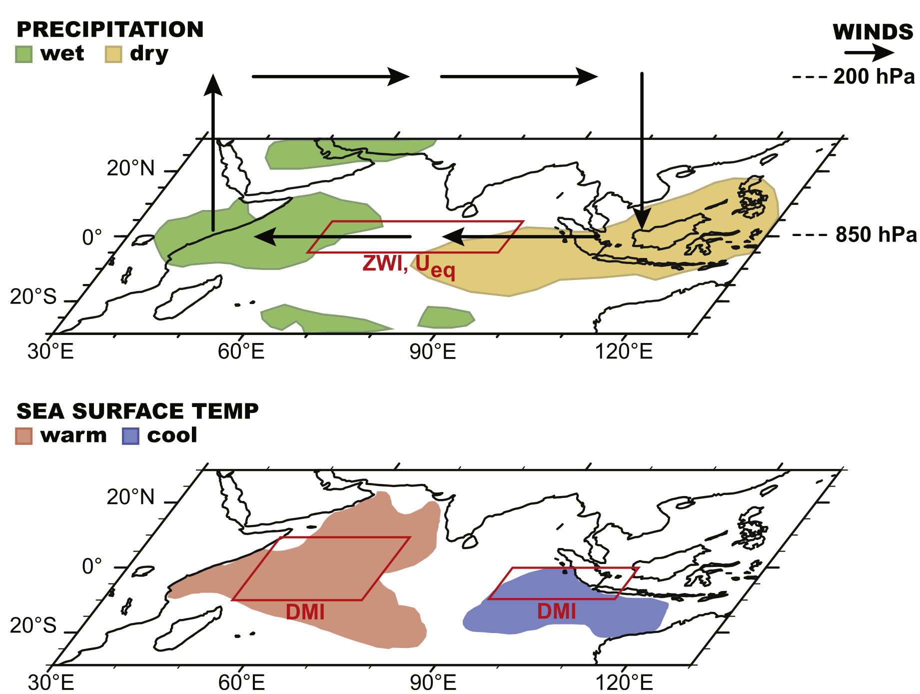

Fig. 1. Schematic illustration of the anomalous components of wind, precipitation, and sea surface temperature observed during an IOZM positive event. Adapted from Saji et al. (1999), Saji et al. (2006), and Schott et al. (2009). Red boxes outline the regions used to calculate the Zonal Wind Index, U_{eq}, and the Dipole Mode Index, discussed in text.

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