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sphere/Eurasian continent. Hence the recent ENSO-monsoon changes may be just a part of natural climate variability.

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Is there an Indian Ocean dipole, and is it independent of the El Niño - Southern Oscillation?

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The papers by Saji et al. (1999) and Webster et al. (1999) describe an equatorial Indian Ocean sea surface temperature (SST) dipole pattern (IOD) which they claim modulates rainfall in East Africa and Indonesia, and operates independently of the global-scale El Niño - Southern Oscillation (ENSO) (Tourre and White, 1997). The concept of possible independence of Indian Ocean SST variability from ENSO has been shaped by research focusing on climatic events during the 1990s (eg. Behera et al., 1999; Murtugudde et al., 2000). However, in an earlier paper Nicholls (1989) describes a different IOD pattern of variability related to Australian winter rainfall, and argues that this pattern operates largely independently of ENSO. In this paper we demonstrate clearly that with consideration of the evolution of ENSO events, the varying lag correlations between IOD and ENSO indices, and using seasonally-stratified data, the apparent ENSO independence disappears from both IODs.

IOD SST patterns and indices were identified by Saji et al. (1999) and Webster et al. (1999) using a mixture of Empirical Orthogonal Function (EOF) and correlation techniques, oceanic and atmospheric observations and dynamics. However, Saji et al. (1999) fail to take account of the spatiotemporal evolution of ENSO events when using a standard EOF analysis of data in a non-temporally stratified form. They mistakenly assume that the EOF 1 and 2 modes in their results are distinct phenomena, being ENSO and an independent IOD signal. Although these EOFs are orthogonal at zero lag, they are confounded and have considerable shared variance as their time series correlate significantly with one another at leads and lags of around 9-10 months. Such problems have been highlighted further using EOF Varimax rotation (Tourre and White, 1995) and in two recent papers focusing on various EOF (non-rotated and rotated) and Principal Oscillation Pattern (POP) examinations of the IOD question (Dommenget and Latif, 2001; Baquero-Bernal and Latif, 2001). These studies indicate that the two nodes of the IOD are not significantly anti-correlated in time, and the IOD structure is part of ENSO. The lack of consistent anti-correlation between eastern and western IOD nodes is also seen when the data are detrended and ENSO influences are removed (Nicholls and

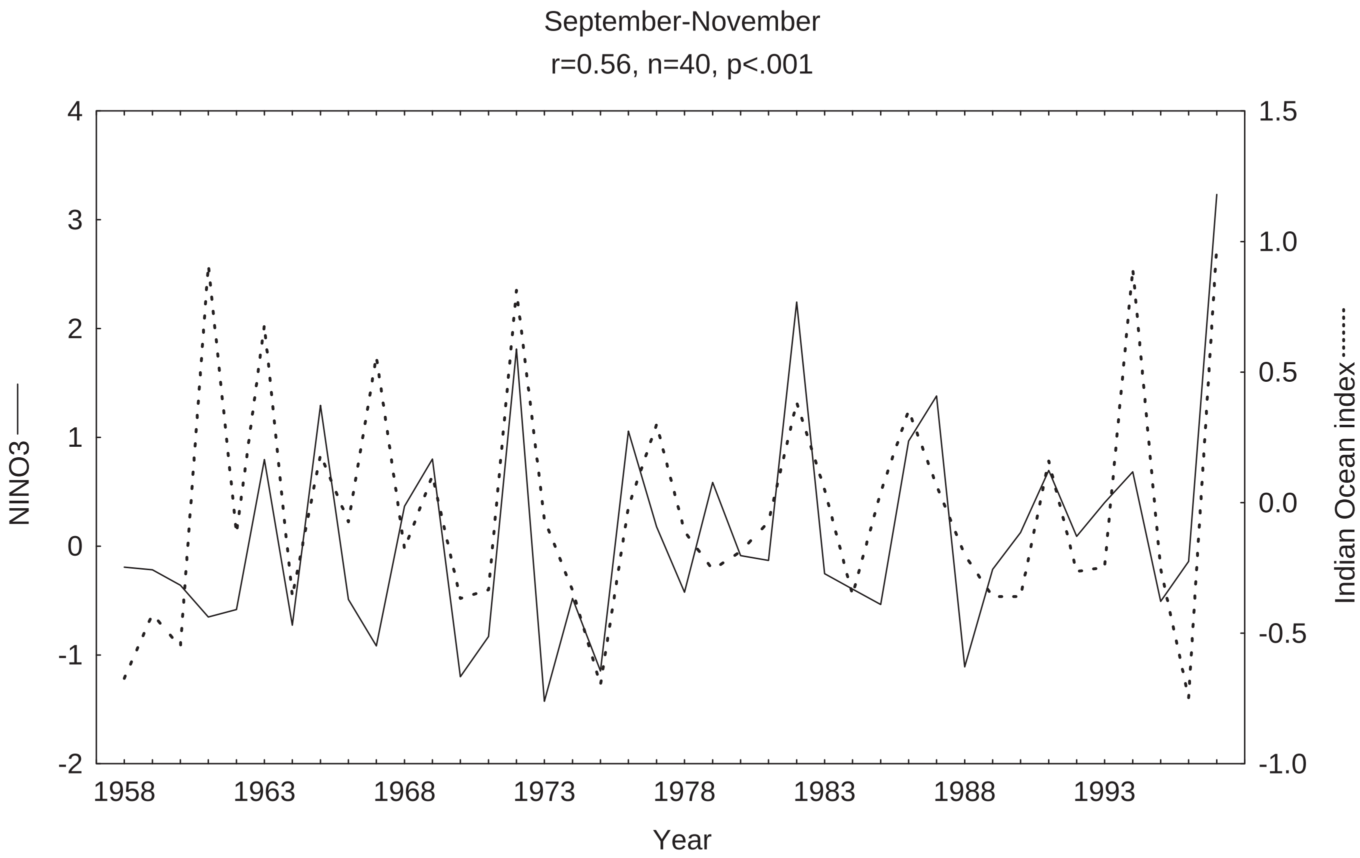

Figure 1: September-November Saji et al. (1999) IOD and Niño 3 SST indices, post 1957 (r=+0.56).

Drosdowsky, 2001). Nevertheless, the above EOF and correlation mistakes are still repeated in recent IOD papers (Behera et al., 2000; Behera and Yamagata, 2001; Iizuka et al., 2000).

Both Saji et al. (1999) and Webster et al. (1999) report insignificant correlations between their IODs and the Niño 3 region (5°N-5°S, 150°W-90°W) SST index of ENSO. A different picture emerges, however, if the correlations are calculated on monthly or seasonally-stratified values of the indices. Thus, the correlation between mean September-November values of the Saji et al. (1999) IOD index and Niño 3 is 0.52, using data from 1872-1997. The correlation using only the shorter post-1957 period examined by Saji et al. (1999) is 0.56.

Both of these correlations are highly statistically significant. Replacing the Saji et al. (1999) IOD index with the slightly different Webster et al. (1999) IOD index produces correlations only marginally different (and still very significant). Correlations between the Saji et al. (1999) IOD index and Niño 3 using March-May means are, however, weakly negative (and not statistically significant). These findings are confirmed in a similar correlation analysis using monthly-stratified data (Nicholls and Drosdowsky, 2001). An important aspect of this work is that removal of the long-term trend and the ENSO signal still fails to reveal distinct evidence of a regular IOD (Figure 2). A similar situation is observed across the Indian Ocean sector when the ENSO signal related to the Southern Oscillation Index (SOI) is removed during the peak of IOD activity (Mutai and Ward, 2000). The situation may be more akin to the Atlantic Ocean, where the meridional SST anomaly gradient, and not a dipole, is the important physical feature (Rajagopalan et al., 1998).

Webster et al. (1999) assert that the intensity of the dipole is independent of the very strong El Niño event during 1997. September-November values of the IOD, Niño 3 SSTs, the SOI and Darwin mean sea level pressure (MSLP) do not support this conclusion (Figures 1 and 3). The strength of the 1997 IOD index is consistent with the very strong 1997 El Niño. There are years (1961, 1967, 1994) when the IOD intensity is substantially diffeent from what could be expected given the Niño 3 index for that year (Figure 1). However, the 1961 and 1994 IOD events do show responses to the SOI and Darwin MSLP (Figure 3), and occur during 'protracted' La Niña and El Niño episodes respectively (Allan and D'Arrigo, 1999; Allan, 2000; Reason et al., 2000; Allan et al., 2001), when an IOD pattern is found in conjunction with enhanced Niño 3.4 to 4 SST anomalies. The 1967 IOD develops during the onset of a La Niña event, as noted by Saji et al. (1999).

Other evidence supports the interdependence of ENSO and the IOD. Graham and Goddard (1999) find a peak correlation of 0.75 at a 3 month lead between Niño 3.4 (5°N-5°S, 170°W-110°W) SSTs and a central equatorial Indian Ocean SST index (0-15°S, 50°E-80°E) of the western node of the IOD. Mutai et al. (1998) show highly signifi-

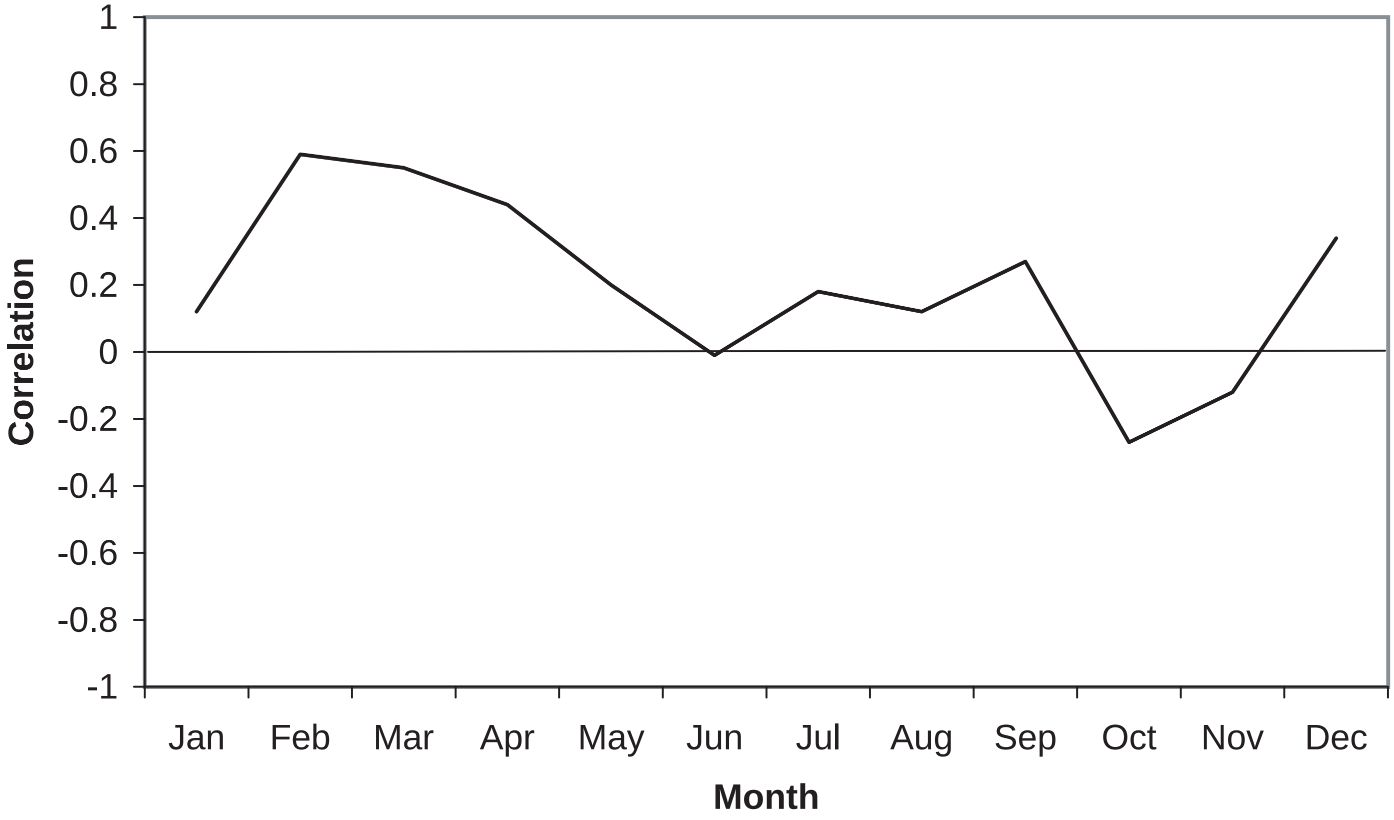

Figure 2: Correlations between east and west equatorial Indian Ocean SST, after detrending and removal of ENSO influence (Niño 3 effect removed).

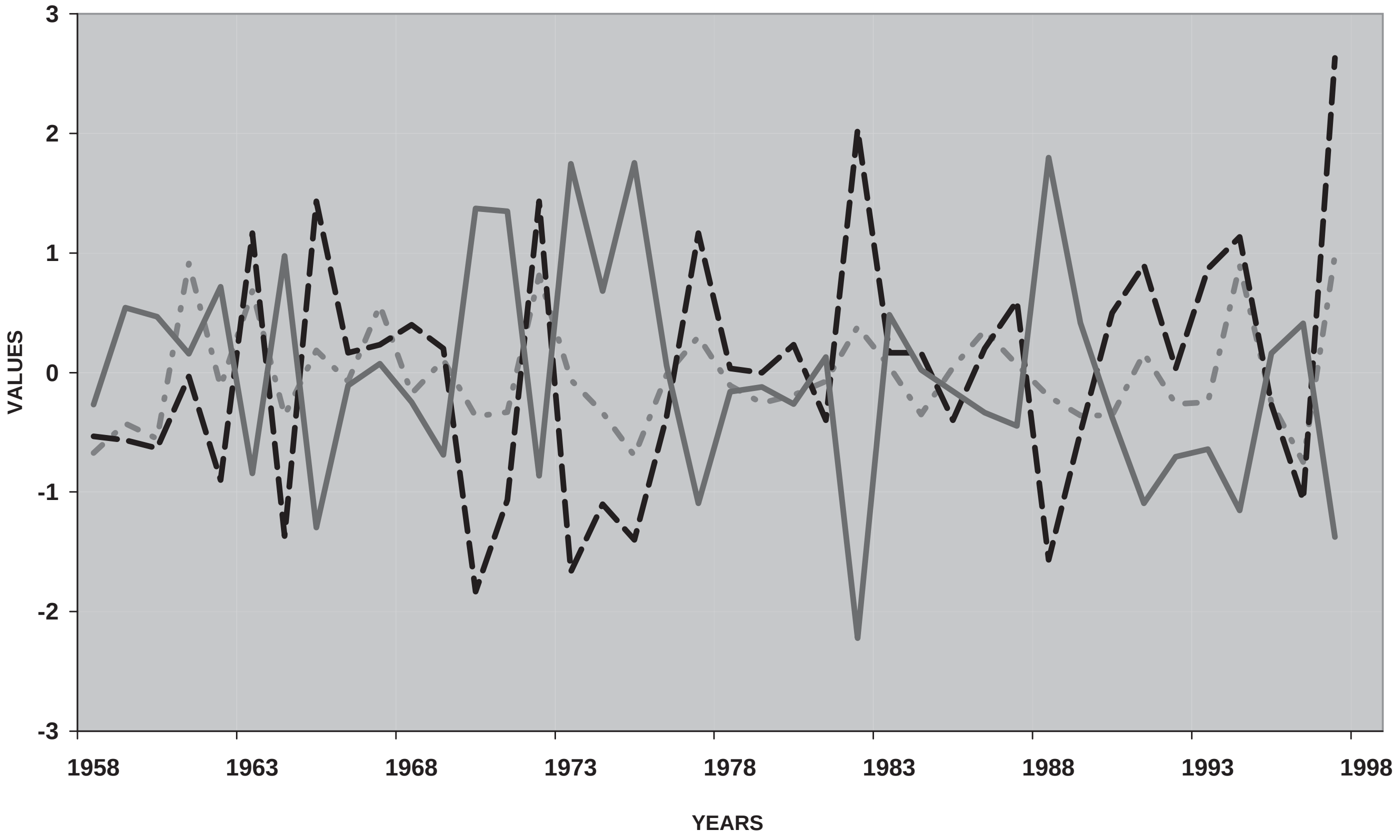

Figure 3: September-November Saji et al. (1999) IOD (dashed dotted) versus the SOI (divided by 10, solid, r=-0.56) and Darwin MSLP (dashed, r=+0.69), 1958-1997.

cant correlations between July-September Niño 3.4 and Niño 4 (5°N-5°S, 160°E-150°W) SSTs and October-December East African rainfall occurring in conjunction with an IOD. Chambers et al. (1999), Stone et al. (1996) and Wright et al. (1985) provide evidence that, taken together, supports significant relationships between ENSO and East African rainfall during IOD events. Reason et al. (2000) and Allan et al. (2001) have analysed composites of the evolution of atmospheric and oceanic variables over the Indian Ocean for both strong ENSO events and 'protracted' ENSO episodes. IOD patterns are again clearly evident during the evolution of both of these ENSO types. In fact, the IOD composites of Saji et al. (1999) have been shown to be synchonous with El Niño events when examined across the full Indo-Pacific basin (Hendon, 2000, per. com.). Such ENSO-IOD structures can also be produced (Figure 4, page 14/15) on the NOAA WWW site (http://www.cdc.noaa.gov/Composites/). Velocity potential anomalies for the IOD composites in Figure 4 show simply the rearrangement of the Walker Circulation across the Indo-Pacific basin that occurs during the evolution of El Niño events (Hobbs et al., 1998).

Saji et al. (1999) and Webster et al. (1999) propose local coupled mechanisms to explain the IOD. However, Chambers et al. (1999) explain the IOD by local wind forcing that is strongly correlated to the SOI. An IOD-like structure in SST anomalies is explored by Baquero-Bernal and Latif (2001) using a control integration with a coupled ocean-atmosphere general circulation model (GCM), a coupled run in which ENSO is suppressed, and one run in which the ocean GCM is replaced by a mixed layer model. These experiments quantify the contributions of ENSO and ocean dynamics to SST variability in the tropical Indian Ocean. The results show that ocean dynamics are not important to this type of IOD-like SST variability. It is forced by surface heat flux anomalies integrated by the thermal inertia of the oceanic mixed layer, which reddens the SST spectrum. These experiments find no evidence for an IOD generated by ocean dynamics that is independent of ENSO. However, several other GCM studies (Behera et al., 2000; Iizuka et al., 2000; Vinayachandran et al., 2001) continue to interpret and analyse their results based on the IOD concept detailed by Saji et al. (1999), or extended by Behera and Yamagata (2001). Although other recent research has somewhat questioned the IOD independence of ENSO (e.g., Li and Mu, 2001; Mu and Li, 2001), the underlying assumption that an independent IOD mode exists still continues to be perpetuated.

This note is not intended to suggest that no other climatically driven signals exist in Indian Ocean SSTs other than those attributed to ENSO. However, it does indicate that the IOD feature reported in the literature is an integral part of ENSO evolution. Thus, every effort must be made to take account of the full ENSO-related climatic signal in analyses seeking to investigate other phenomena in the Indian Ocean domain.

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Regime Shifts in the 20th Century Found in the Northern Hemisphere SST Field

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1. Introduction

A 'regime shift' is characterized by an abrupt transition from one quasi-steady climatic state to another, and its transition period is much shorter than the lengths of the individual epochs of each climatic state. In the present study, we investigate when regime shifts occurred and what was the difference in climatic states before and after the shifts, using the wintertime sea surface temperature (SST) field in the Northern Hemisphere. The relationship between changes in the SST field and those in the atmospheric circulation is also investigated. Complete details of our results are given by Yasunaka and Hanawa (2001).

2. Dominant variations of the winter Northern Hemisphere SST field

First, in order to detect organized patterns of the SST variations in the Northern Hemisphere, we adopted an empirical orthogonal function (EOF) analysis. Figure 1 (page 16) shows the standardized time coefficients of the first two EOF modes, and the distributions of regression and correlation coefficients of the winter mean SST anomalies with the standardized time coefficients of EOF modes. It is found that the dominant modes correspond well to the specific atmospheric circulation patterns. That is, the first mode resembles the response to the activity of the Pacific/North American (PNA) pattern, and is similar to SST changes in El Niño/Southern Oscillation (ENSO) and so-called Pacific Decadal Oscillation (PDO). The second mode has high correlation with the activity of the Arctic Oscillation (AO). EOF analyses to each oceanic basin separately are also made and the robustness of these modes has been confirmed.

3. Detection of regime shifts

In order to identify the years when regime shifts occurred in the SST field, we carefully inspected the time series of original gridded SST data and those of the EOF modes. If the years of the regime shifts detected by both of the two time series are same, then we can say that the significant and systematic regime shifts occurred in these years. The difference between the 5-year means before and after the given year is used as a measure of shifts. As a result, seven regime shifts were detected during the period from the 1910s to the 1990s: 1914/15, 1925/26, 1945/46, 1957/58, 1970/71, 1976/77 and 1988/89, as shown by arrows in Fig. 2. It was also found that all these regime shifts could be found in both or one of the first and the second SST-EOF modes.

Figure 3 shows the SST difference between the 1971-76 regime and the 1977-88 one, that is, the periods before and after the 1976/77 regime shift. It reveals the changes in an intensity of the Aleutian Low (AL) and the corre-

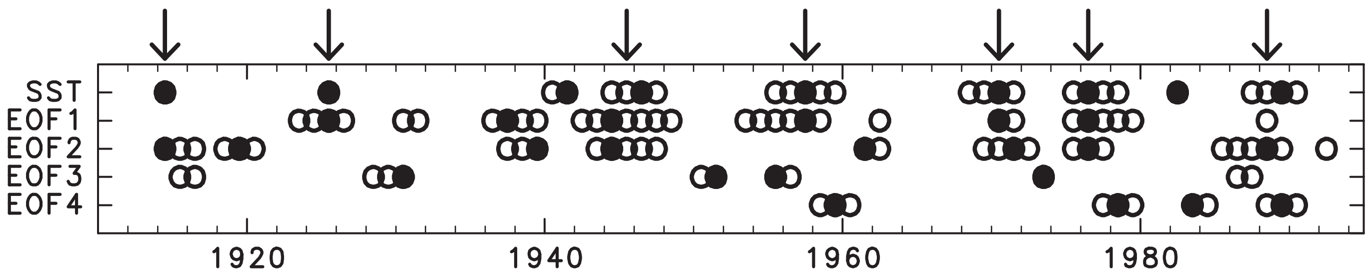

Fig. 2: Years when significant shifts occurred in the SST field and the first four EOF modes. Closed circles denote the year showing the maximum shift in a cluster of significant shift years (open circles). The years shown by arrows are those designated as regime shifts at the present study.