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THE INFLUENCE OF THE INDIAN OCEAN DIPOLE MODE ON PRECIPITATION OVER THE SEYCHELLES

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ABSTRACT

Correlation and composite analysis are applied to study the atmospheric–oceanic mechanisms related to precipitation on the largest island of the Seychelles archipelago, Mahé, in the equatorial western Indian Ocean (EWIO). Significant relationships are found to exist between precipitation and a reversal in zonal wind in the equatorial Indian Ocean (IO), cooler sea surface temperatures (SSTs) in the eastern and southern IO and convergence over Eastern Africa. The observed SST and zonal wind anomalies affecting rainfall in the EWIO are also characteristics of the dipole mode, an Indian Ocean event of internal variability measured by the dipole mode index (DMI). The September–October–November DMI is significantly correlated to December–January–February precipitation in the EWIO, explaining up to 20% of the variance. The analysis suggests an additional influence on variability of rainfall over the EWIO by the sea surface temperatures of the southwest Indian Ocean. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: precipitation; western Indian Ocean; dipole mode; Seychelles

1. INTRODUCTION

Studies conducted on the climatic mechanisms of the Indian Ocean (IO) have previously focused on the oceanic response to the El Niño Southern Oscillation (ENSO) phenomenon (Cadet, 1985; Nicholson, 1997) and the monsoon (Shukla and Misra, 1977; Rao and Goswami, 1988). More recently, investigators have observed a separate, distinct climate anomaly inherent to the IO. Saji *et al.* (1999) noted the occurrence of several IO events during 41 years of observation from 1958 to 1998. These IO events, termed Indian Ocean dipole mode events (IOD), reveal a pattern of internal variability with anomalously low sea surface temperatures (SSTs) off Sumatra and Indonesia and high SSTs in the equatorial western Indian Ocean (EWIO) (Saji *et al.*, 1999). The SST anomalies are accompanied by an increase in rainfall in east Africa, droughts in Indonesia and a reversal in the west to east zonal wind direction (Clark *et al.*, 2003; Black *et al.*, 2003). The Oceanic Tropical Convergence Zone (OTCZ), a large-scale zone of convection over the southern equatorial IO, is normally responsible for the heavy rainfall regions in the IO. In a dipole mode event, however, rainfall over the OTCZ decreases and is compensated by increased rainfall further to the west (Saji and Yamagata, 2003). The strength of the occurrence of the IOD is measured by the dipole mode index (DMI), defined as the difference in the SST anomalies between the western and eastern parts of the IO (Saji *et al.*, 1999).

Recent studies have focused on establishing and presenting the seasonal evolution of the IOD event as an independent phenomenon to ENSO (e.g. Webster *et al.*, 1999; Saji *et al.*, 1999) and have looked at the possible impacts of the IOD on the global climate (Saji and Yamagata, 2003). This study, however, aims to explore the EWIO response to the IOD. In particular, an attempt is made to determine the degree to which

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variations of rainfall on the island of Mahé can be attributed to the IOD. If a significant relationship exists, lagged mechanisms may be used to predict rainfall on Mahé a season in advance. This study uses rainfall data collected between 1974 and 2001 from the Seychelles Islands, scattered between 4 °S and 11 °S latitude and 45 °E and 56 °E longitude. More specifically, this study examines rainfall on the island of Mahé, located at 4 °S latitude and 55 °E longitude. Rainfall patterns can impact economic activities in the Seychelles, e.g. manufacturing and construction, tourism and transportation. Therefore, using the IOD event to understand and forecast rainfall variability could provide useful insight for managing the regional environment and minimizing losses of the affected economic sectors.

2. METHOD: DATA, ANALYSIS AND LIMITATIONS

Historical rainfall data was available from 21 rain gauges throughout the Seychelles with the majority of the gauges located on the granitic islands. Of the 115 islands that comprise the Seychelles, the granitic islands lie within the relatively shallow Seychelles plateau at 4 °S of the equator, while the low-lying coralline islands lie beyond the plateau up to 10 °S of the equator. The altitude of the gauges varies significantly, from sea level to over 850 m; over a third of the gauges are located over 700 m above sea level. The majority of the Seychelles population lives on the largest granitic island of Mahé, on and around the narrow coastal strip. As with many other rainfall records from around the world, the Seychelles rain gauge data has a number of gaps corresponding to missing data. After grouping the gauge records according to the correlation between records, one group of gauges was selected in order to study the influence of IOD events on precipitation of the Seychelles. This data set had the most complete record historically and was located near sea level and, thus, was felt to be the most representative of the climate as experienced by the majority of Seychellois. These data had an annual rainfall average of 2443.0 mm/year with a standard deviation of 79.92 mm/year.

The comparison of the Mahé rainfall and the DMI to other climatic indices, e.g. outgoing long-wave radiation (OLR), SSTs, surface zonal wind, surface vectoral wind and velocity potential, was possible using data from the National Centre for Environmental Prediction and the National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis project (Kalnay *et al*., 1996).

The relationships between rainfall and other climatic variables were studied using correlation and composite analysis. Composite analysis compared the 5 years of maximum seasonal rainfall against the 5 years of minimum seasonal rainfall. Composite analysis was employed in preference to the correlation method, as it makes no assumptions concerning the linearity of the relationship between the two variables (von Storch and Zwiers, 1999).

The errors in this study arise from the limitations of statistical analysis, from the collected rainfall data and from analyses performed with the NCEP/NCAR Reanalysis data. Obviously, correlation and composite analysis do not necessarily imply causation; an independent factor related to both variables could be responsible for any observed significant correlation or the correlation could simply arise by chance. The analysis that follows attempts to explain reasons why the established statistical relationships are indicative of physical processes and are not spurious. The main problem with time series from station data is its inhomogeneity. A change in the physical environment of the observing site, in the observing equipment, of the observing procedures and time or of the responsible personnel can cause changes in the collection of data. This may cause an error in calculating composite means, but in this case, the error was taken to be minimal by the quality control of the initial data. For example, spurious figures are cross-checked manually with readers at the stations. Unfortunately, some of the observed data sets used in this study were incomplete; this was overcome by using appropriate average values. For example, a missing rainfall value (mm/year) for December 1981 was corrected with the average value of December for that time series (e.g. 1975–2001). The NCEP/NCAR Reanalysis encounters many factors that can limit the accuracy of the analysis. For example, human errors have been made in the assimilation of data, mostly in input processing (Kistler *et al*., 2001). Though these limitations must be kept in mind, a comparison of climatic indices with rainfall data can still provide valuable information and insight into the climatic processes occurring.

3. RESULTS AND DISCUSSION

Monthly rainfall data, as shown in Figure 1, indicate that, typically, rainfall over the Seychelles is heaviest during the months of December–January–February (DJF); this study therefore focuses on this interval. A DJF 1975 season, for example, is here taken to represent rainfall values from December 1974, January 1975 and February 1975.

Outgoing long-wave radiation (OLR) measured by satellites represents the black-body radiating temperature of the atmosphere. In the tropics, values of OLR are known to respond strongly to variations in cloudiness and provide a useful indicator of precipitation Peixoto and Oort, 1992; Hastenrath, 1996; (Webster *et al.*, 1999). Figure 2 shows the correlation between heavy precipitation in the region of the Seychelles during the months of DJF with a large region of reduced OLR over the far west of the central IO. This suggests that

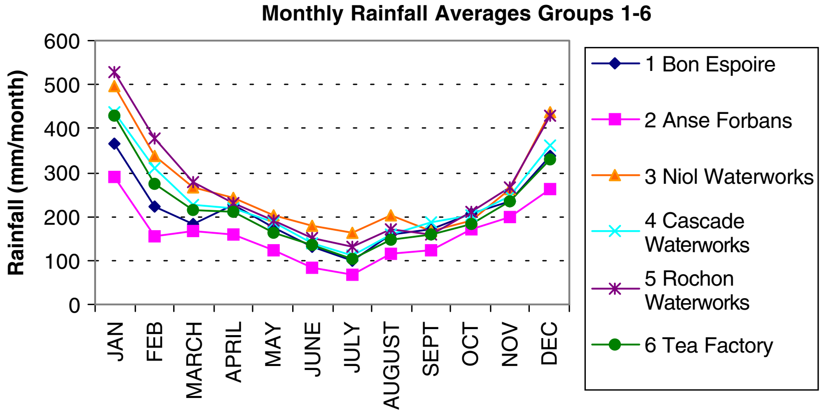

Figure 1. Monthly rainfall averages for groups 1–6 on Mahé

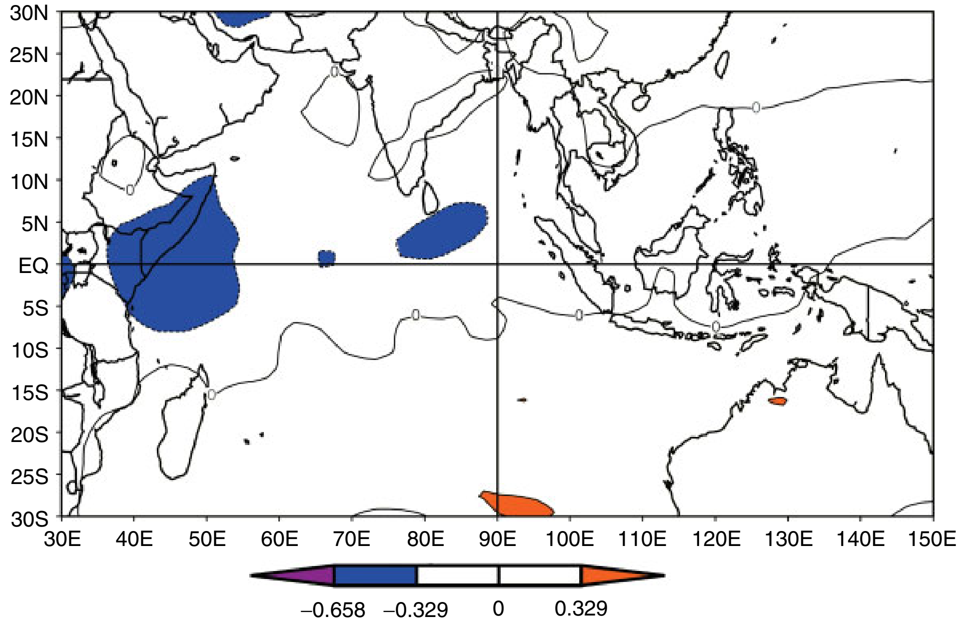

Figure 2. 1975-2001: DJF surface OLR monthly correlation with DJF Seychelles rainfall. This figure is available in colour online at www.interscience.wiley.com/ijoc

the rainfall variations over Mahé are part of a larger scale signal over the EWIO. Correlations are significant at the 95% level for all values of $r \leq -0.329$ and $r \geq 0.329$.

To study precipitation processes, it is necessary to examine the atmospheric–oceanic interaction affecting the climate system. The quantification of oceanic and atmospheric interaction is often represented by sea surface temperature anomalies. Figure 3 shows a significant negative correlation between SSTs off the coast of southwest Indonesia and rainfall over the Seychelles. Correlations are significant at the 95% level for all values of $r \geq 0.329$ and $r \leq -0.329$. Owing to the small spatial area showing significance, these results must be interpreted with caution.

Cooler SSTs off western Indonesia and northwest Australia are expected to be accompanied by higher atmospheric pressure at the surface, relative to the EWIO, and produce an easterly zonal wind regime. In the equatorial IO, surface winds predominantly blow from west to east (Peixoto and Oort, 1992; Hastenrath, 1996). However, high rainfall rates in the Seychelles are associated with a reversal in surface zonal wind, as shown with correlation and composite analysis in Figures 4 and 5. While a clear easterly anomaly in the central IO is shown in the composite analysis, it was not possible to test the significance of these results due to the small number of years used in the analysis. The Seychelles are located at the cusp between the easterly oceanic anomaly and a small westerly anomaly extending from eastern Africa.

Velocity potential is indicative of whether a region is experiencing large-scale convergence or divergence; positive (negative) values indicate convergence (divergence). Composite analysis shown in Figure 6 reveals large-scale convergence at the surface over the Seychelles. While the significance of these results cannot be verified due to the limited number of years of the analysis, the relationship between rainfall in the EWIO and velocity potential is confirmed with correlation analysis, depicted in Figure 7. Correlations are significant at the 95% level for all values of $r \geq 0.329$.

The preceding relationships, established between rainfall in the EWIO and SST and zonal wind anomalies, are also characteristics of the dipole mode. As previously mentioned, the IOD is associated with cool SST anomalies over the eastern IO while the western tropical ocean warms. The pressure gradient created from the SST differences in the eastern and western IO causes the normal westerly surface winds to weaken and reverse direction (Webster *et al*., 1999; Saji *et al*., 1999). The IOD first appears off the coast of Sumatra

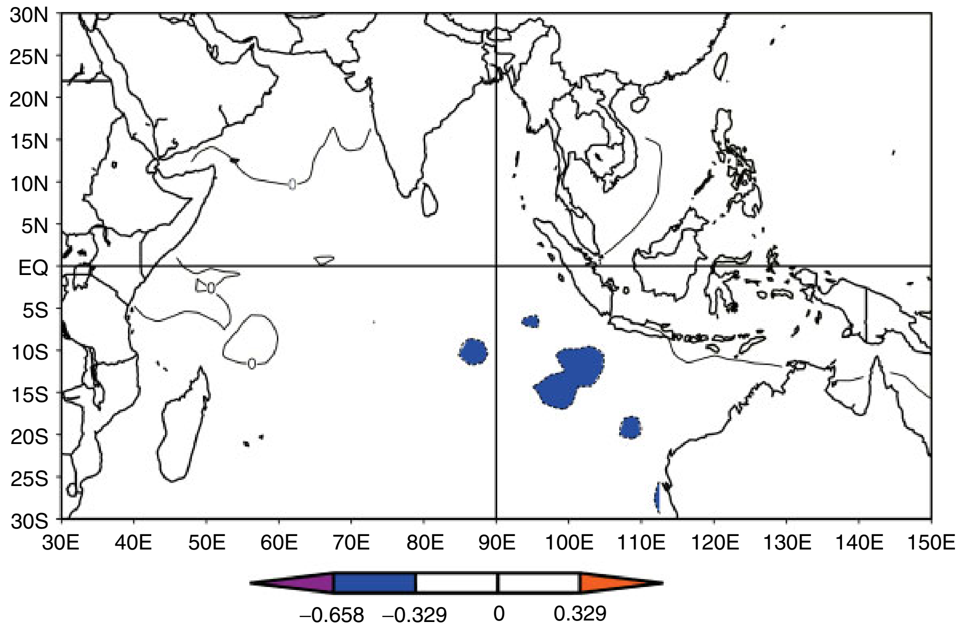

Figure 3. 1975–2001: DJF SST monthly correlation with DJF Seychelles rainfall. This figure is available in colour online at www.interscience.wiley.com/ijoc

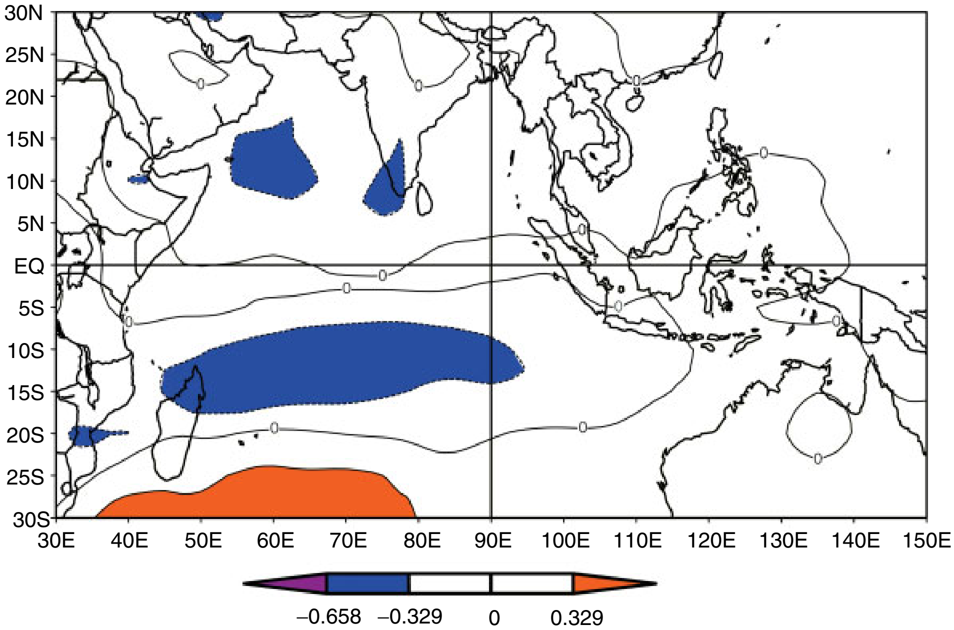

Figure 4. 1975–2001: DJF zonal wind monthly correlation with DJF Seychelles rainfall. This figure is available in colour online at www.interscience.wiley.com/ijoc

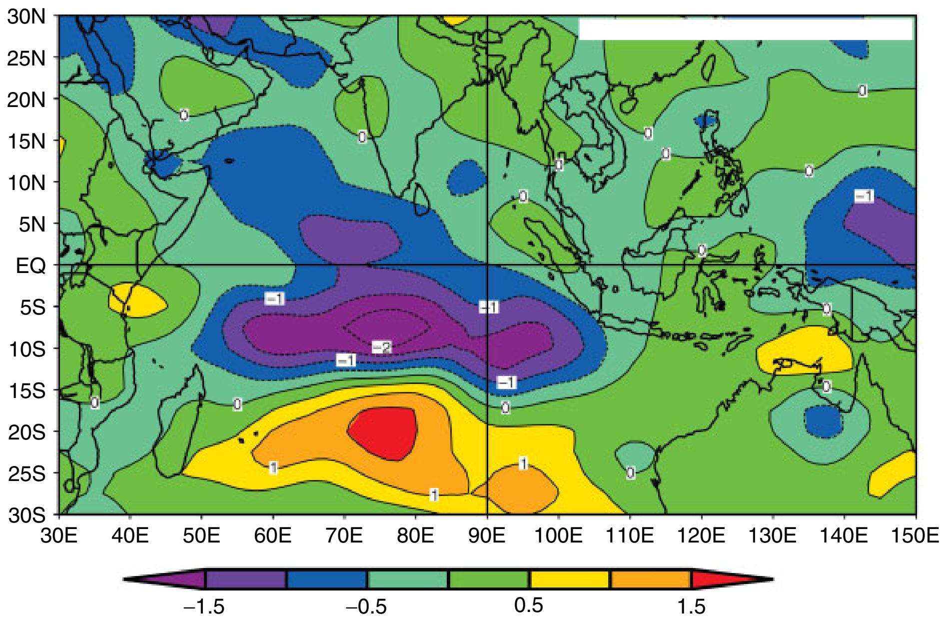

Figure 5. 1975–2001: DJF zonal wind composite analysis. This figure is available in colour online at www.interscience.wiley.com/ijoc

during the month of June and intensifies in the following months, peaking around October (Saji *et al.*, 1999). Therefore, while the IOD is strongly correlated to a SST dipole anomaly in the IO during the months of September, October and November (SON), only a weak correlation exists between SSTs and the DMI during the months of DJF (Figures 8 and 9). Similarly, the easterly zonal wind anomaly associated with the IOD is

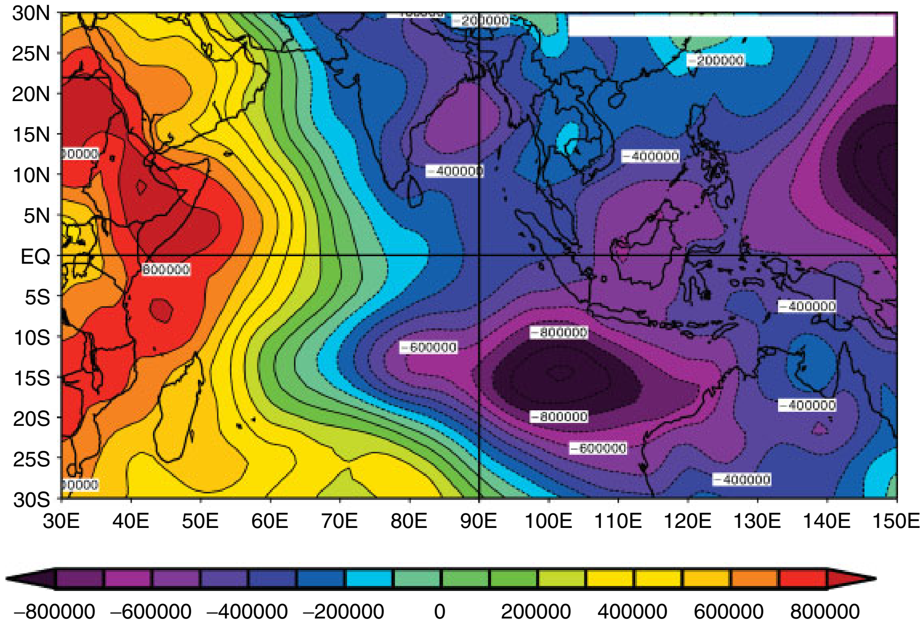

Figure 6. 1975–2001: DJF velocity potential composite analysis. This figure is available in colour online at www.interscience.wiley.com/ijoc

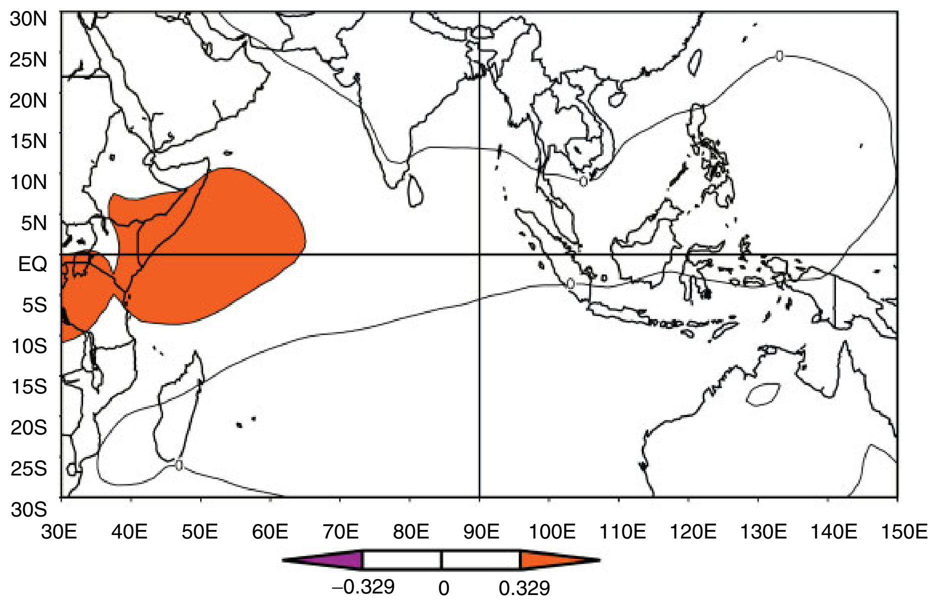

Figure 7. 1975–2001: DJF velocity potential monthly correlation with DJF Seychelles rainfall. This figure is available in colour online at www.interscience.wiley.com/ijoc

strongest during the months of SON and weaker, yet still significant, during DJF (not shown). Correlations are significant at the 95% level for all values of $r \leq -0.26$ and $r \geq 0.26$.

Rainfall over the Seychelles during the peak IOD months of SON is weak and shows no significant relationship to the IOD. However, the coupling of the ocean with the atmosphere serves as a physical basis for seasonal forecasting up to several months in advance (Murphy *et al.*, 2001) owing to the relatively slow

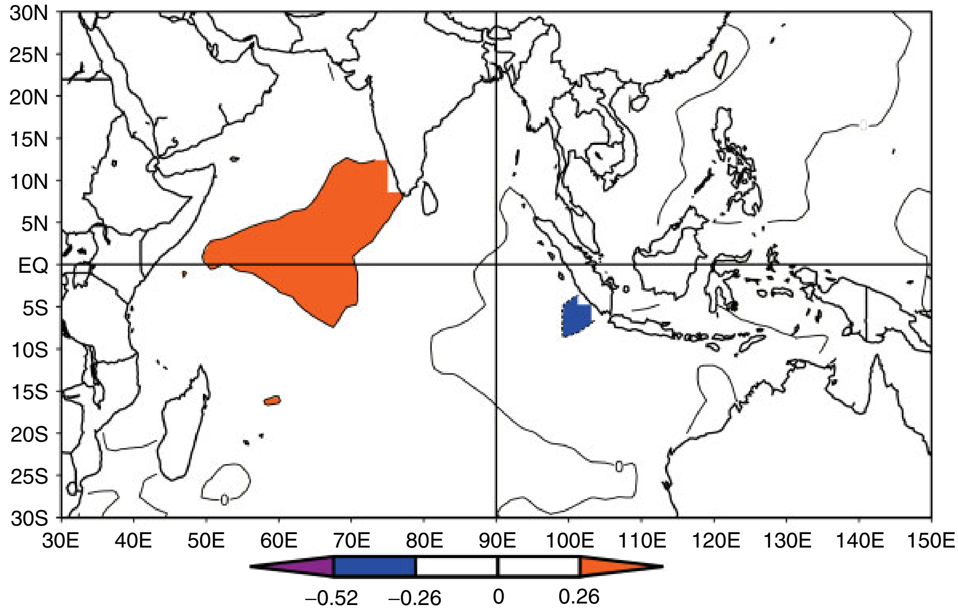

Figure 8. 1958–1999: DJF SST monthly correlation with DJF DMI. This figure is available in colour online at www.interscience.wiley.com/ijoc

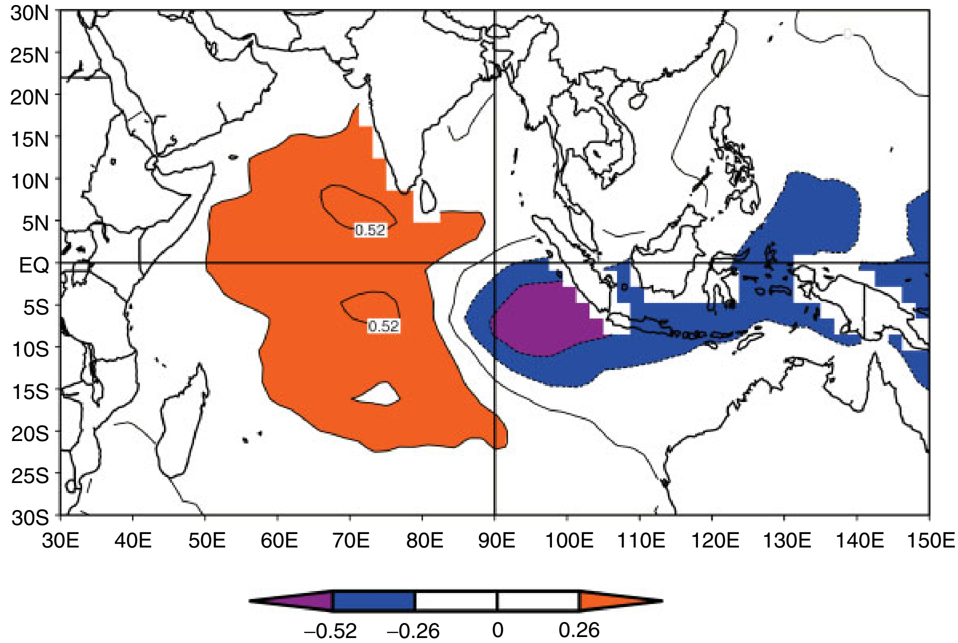

Figure 9. 1958–1999: SON SST monthly correlation with SON DMI. This figure is available in colour online at www.interscience.wiley.com/ijoc

evolution and high persistence of SSTs and the predictable manner of the atmospheric response (Todd *et al*., 2002). Therefore, lagged relationships between Seychelles DJF rainfall and SON climatic indices in the IO might be used to predict Seychelles rainfall.

Cool SSTs observed in SON in the southern IO and off southwestern Indonesia are significantly correlated to rainfall over the EWIO in DJF (Figure 10). Again, the total surface area covered with a significant correlation is relatively small and must therefore be interpreted with caution. Composite analysis in Figure 11 reveals a similar trend, but the limited number of years in the composite analysis does not allow us to comment on its likely significance. The strength of the SST anomaly of the IOD, shown in Figure 9, is not shared with the SST anomalies associated with enhanced Seychelles rainfall. It is interesting to note, that Seychelles rainfall seems to be affected by a cooling of SSTs not only in the eastern IO but also by a cooling the southwest IO.

Similarities in relationships between climatic mechanisms and the DM and EWIO precipitation lead us to examine the relationship between precipitation in the EWIO and the DM. Figure 12 shows the evolution of the DJF DMI, the SON DMI and precipitation in the WIO between 1975 and 1999. The strong dipole mode years of 1982 and 1994 do not correspond with higher-than-average precipitation in the Seychelles in the respective seasons, 1983 and 1995. The lower-than-expected rainfall may be explained by the interference of other large-scale climatic mechanisms during those years, i.e. El Niño. Regression analysis shows that SON and DJF rainfall on Mahé exhibits no relationship with ENSO (r-square values of 0.009 and 0.005 respectively). On the contrary, SON DMI shares a positive relationship with SON ENSO with an r-square value of 0.49. The strong dipole mode event of 1997 does correspond to high rainfall levels experienced in Mahé, which can be explained both by the DMI and the heavy monsoon rainfalls noted in 1997. Correlation analysis shows that the DMI during the months of SON is significantly correlated to DJF rainfall with $r = 0.45$ (the 95% significance level is at 0.35). We can conclude that the IOD explains nearly 20% of the variance of precipitation in the western IO. While this discovery is significant, it is not sufficient to forecast precipitation a season in advance and suggests the influence of other climatic factors on rainfall variability in the EWIO. The use of coupled models may allow the IOD to be predicted a season in advance (Wajsowicz, 2004). In conjunction with the observed IOD-rain relation, this suggests that a one-season lead forecast for climate variability associated with IOD is plausible.

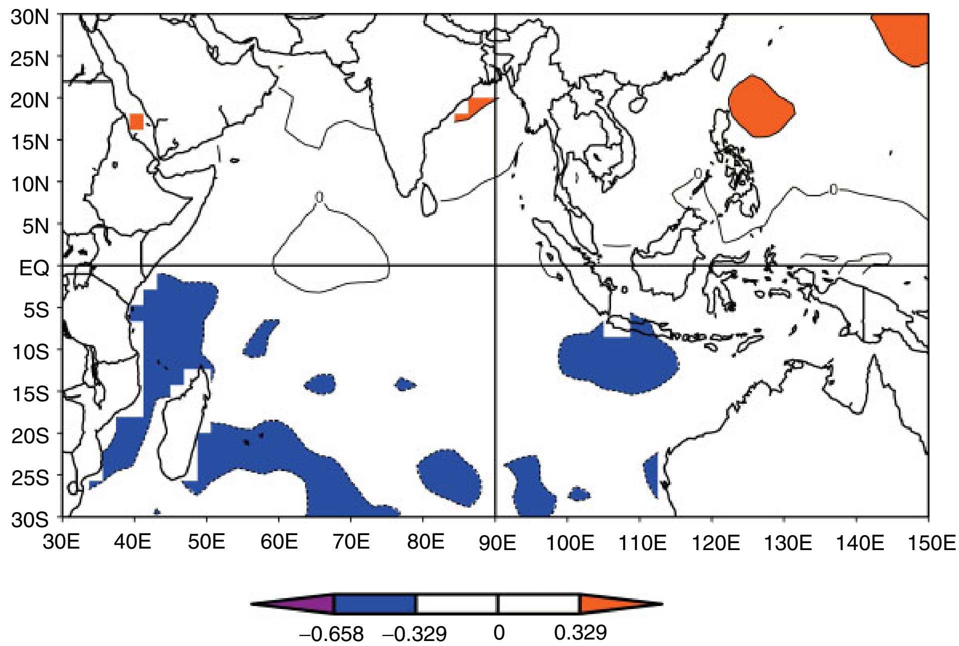

Figure 10. 1975–2001: SON SST monthly correlation with DJF Seychelles rainfall. This figure is available in colour online at www.interscience.wiley.com/ijoc

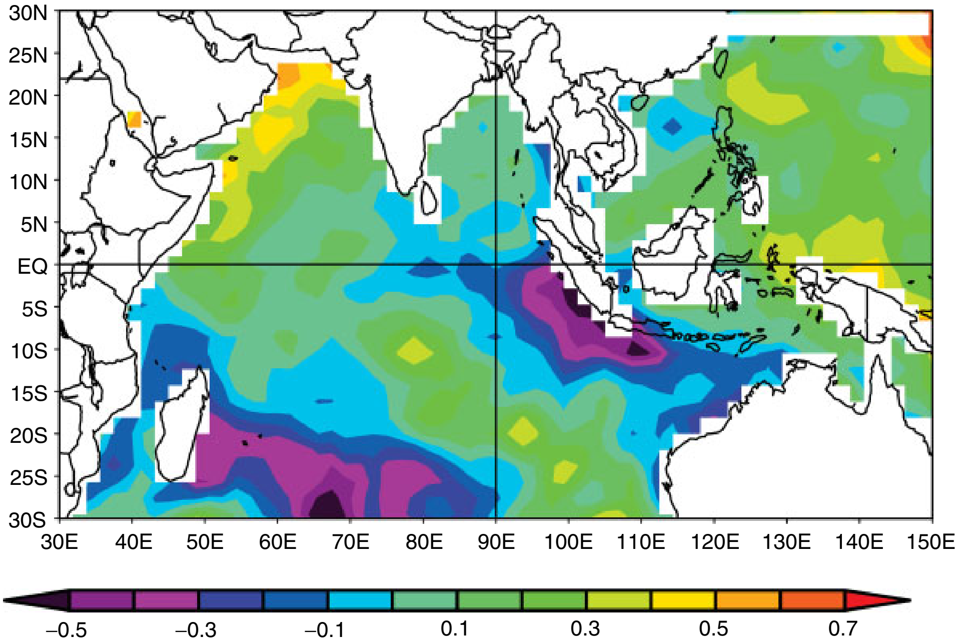

Figure 11. 1975–2001: SON SST composite analysis. This figure is available in colour online at www.interscience.wiley.com/ijoc

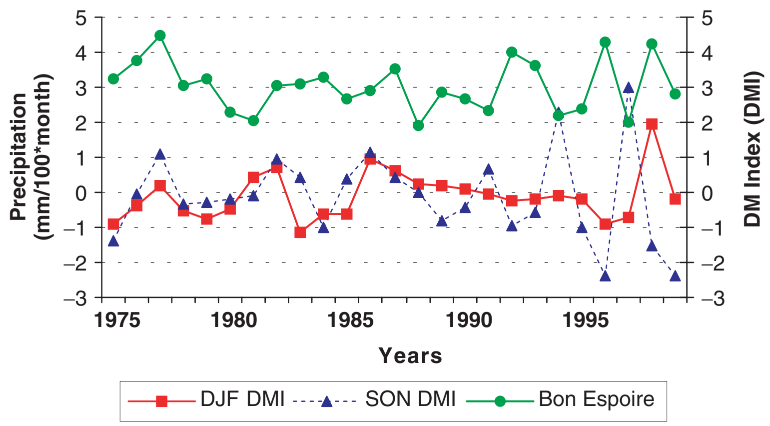

Figure 12. Annual evolution of the SON DMI, DJF DMI and precipitation in the western IO

4. CONCLUSIONS

In this study, the variation of monthly rainfall totals during the months of DJF was compared with the variation of selected climatic parameters. Mahé precipitation shares a significant relationship with cooler SSTs off southwest Indonesia, a reversal in zonal winds in the IO and convergence over Mahé at the sea surface. The DMI series was compared to the same climatic indices as the Seychelles rainfall. The DJF DMI is significantly correlated to cooler SSTs off Sumatra and a zonal wind anomaly in the IO. These correlations are much stronger during the months of SON, the peak months of the IOD.

Relationships between SSTs and Mahé precipitation at a lag of 3 months indicate the potential for seasonal forecasting. In particular, significant negative correlations exist between SON SSTs in southwest Indonesia and the southwestern IO and DJF WIO precipitation. The SON DMI and DJF Seychelles rainfall are significantly correlated. This relationship is significant but not always strong, explaining only up to 20% of the variance. It is suggested that some of remaining variance in Seychelles rainfall might be explained by variations in SST in the southwest IO.

Further studies using a climate model are required to determine the physical relationship between SSTs in the southwest IO and the eastern equatorial IO, with rainfall over the EWIO. While the findings in this study have their limitations, further study will continue to advance the understanding of the complex atmospheric–oceanic interactions affecting precipitation in the EWIO and hopefully provide a basis for seasonal forecasting of rainfall over the Seychelles.

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