# Easterly flow in the tropical Indian Ocean and climate variability over south-east Africa

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### Abstract

The relationship between African rainfall and zonal wind anomalies in the adjacent tropical Indian Ocean is investigated. Comparisons are made using a December to March rainfall index for Africa south of 20°S and east of 25°E. Cases are selected when the zonal 850 hPa wind anomaly in the area 5° to 20°S, 40 to 90°E exceeds ± 1 standard deviation. During wet (dry) summers, low-level winds are more easterly (westerly). The easterly flows surge at certain times, bringing intra-seasonal 'pulses' of convection from the tropical Indian Ocean to south-east (SE) Africa during austral summer. National Center for Environmental Prediction (NCEP) reanalysis composites are constructed and structural features are analysed by subtracting the dry westerly cases from the wet easterly cases. Composite differences of zonal easterly flow extend through the troposphere in the 5° to 20°S band. Convection is reduced over the tropical South Indian Ocean whilst increased over SE Africa. Differences between east and west regimes are evident in the velocity potential and outgoing longwave radiation (OLR), indicating a convective sink near 15°S, 75°E over the South Indian Ocean. Composite sea surface temperatures (SST) are significantly above normal in the latitude band 25° to 35°S, and below normal in the tropics to the north. Precursor patterns are investigated to determine the origins of this climate mode.

## Introduction

Much of the summer rainfall over Africa south of the Zambezi River (~ 15°S) is produced by quasi-stationary troughs (Harrison, 1986; Levey and Jury, 1996). The convection is often focused along a NW-SE oriented band by a Rossby wave in the subtropical upper westerly flow. Prior to the convective event, a period of low-level easterly flow from the tropical Indian Ocean is necessary to build up moisture as illustrated in Fig. 1 (D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995). Widespread rainfall occurs over many days at near-monthly intervals during the November to March season (Makarau, 1995; Levey and Jury, 1996). Each convective spell brings ~100 mm of rainfall and contributes about 20% of the seasonal total, so an understanding of their coupling to the surrounding monsoon circulations would be useful.

A number of studies have described the meteorological structure of multi-day rainfall events (Taljaard, 1987; Matarira and Jury, 1990; Lindesay and Jury, 1991; Lyons, 1991; D'Abreton and Lindesay, 1993; Jury et al., 1993) based on statistical inferences from model-interpolated weather data. Across south-eastern (SE) Africa and the south-western (SW) Indian Ocean the wet spells appear to be pulsed at frequencies which are consistent with the passage of tropical waves during austral summer (Hayashi and Golder, 1992). Transient waves of the tropical Indian Ocean were studied by Jury et al. (1991) through hovmoller analysis of satellite imagery in the 10° to 20°S band over the period 1970 to 1984. 50% of years between 1971 and 1984 exhibited westward moving convective disturbances with a mean speed of 2 $m \cdot s^{-1}$ and wavelength of 3 500 km giving an average period of 20 d. Other years had quasi-stationary or eastward-moving disturbances. Characteristics of the background circulation with respect to the potential for easterly waves have not been investigated. Here we look specifically at this issue. We investigate whether tropical easterly inflows are sourced from a divergent centre in the Indian Ocean and analyse the regional structure and ocean-atmosphere environment.

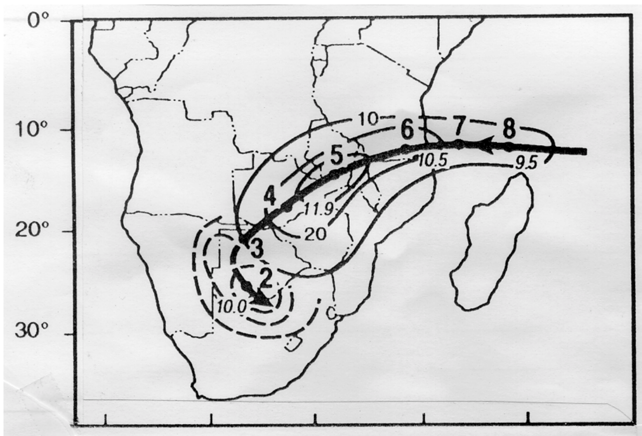


***Figure 1***
*Mean water vapour trajectory for rainy spells over the interior of SE Africa from D'Abreton and Tyson (1996)*

## Data and methods

Our study considers the principal components analysis of Mulenga (1998) on gridded summer rainfall departures (Hulme and Jones, 1993). In that work, areas with common fluctuations were identified over the period 1950 to 1992. A significant mode (PC4) occurs over Africa south of 20°S and east of 25°E. This area is agriculturally productive and yields a substantial food grain reserve following wet seasons (Lindesay, 1990). Seasonal rainfall extremes were noted and related to differences in the atmospheric circulation over the west Indian Ocean. Two common circulation patterns were identified based on the NCEP reanalysis zonal 850 hPa wind anomaly in the area 5° to 20°S, 45° to 85°E north-east of Madagascar exceeding ± 1 standard deviation. East flow years include:

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1961, 66, 69, 76, 77, 79, 81; west flows are: 1968, 71, 80, 83, 90, 92, and 95; seven of each type. The season considered is December to March and coincides with the NE monsoon season, when the inter-tropical convergence zone (ITCZ) lies south of the equator near 15°S from 25° to 50°E (Ho and Wang 2000). The easterly regime occurred more frequently in the 1960s and 1970s with a cooler tropical Indian Ocean, whilst the westerly regime has been more prominent in the 1980s and early 1990s during repeated El Niño warming events. The easterly regime appears to have become re-established since 1996. Table 1 lists the 850 hPa zonal wind anomaly in the area 10 to 15°S, 60 to 70°E. The intra-composite bias is limited according to grid point and field significance tests. Individual years do not significantly affect the composite patterns, according to sensitivity tests conducted by withdrawing more extreme years.

Meteorological differences between easterly and westerly composites are analysed for winds at 850 hPa and at upper levels, geopotential height at 700 hPa, OLR, SST, and velocity potential at lower and upper tropospheric levels. The dry-westerly fields are subtracted from the wet-easterly fields to infer differences between seasons when the tropical inflow is enhanced or suppressed. Zonally propagating circulation systems are analysed using climatological mean low-level meridional winds plotted in Hovmoller fashion in the latitude band 7° to 17°S across the Indian Ocean. Hovmoller plots of zonally propagating convective anomalies based on pentad OLR data for individual years are also considered.

Our analysis makes use of the NCEP reanalysis products available from the NOAA/ CIRES/ CDC website on the Internet. The data are at a resolution of 2°, four times a day averaged into monthly means. Kalnay et al. (1996) describe the reanalysis system in detail. Suffice to say that composite differences, consisting of 28 months for each flow regime, should be realistic, despite the known observational discrepancies around tropical Africa.

It is useful to consider the seasonal monsoon circulations of the SW Indian Ocean. Easterly near-surface winds prevail in the austral winter from April to November, according to historical averages. During austral summer, cross-equatorial flow recurves to create westerly winds from 5° to 10°S between December and March. The monsoon flow in this area north of Madagascar extends to a depth of 4 km or 600 hPa and is overlain by easterly winds aloft. This westerly flow, if persistent, can oppose the influx of Indian Ocean moisture to the continent. However, when the monsoon weakens or reverses, tropical moisture can extend across Madagascar and penetrate into SE Africa.

## Results

A comparison of area-averaged rainfall for the composite years is given in Table 1 together with austral summer values for the southern oscillation index and the quasi-biennial oscillation index (equatorial zonal wind at 30 hPa, U30). There is a distinct and symmetrical difference in rainfall over SE Africa for the easterly and westerly cases. Rainfall in the easterly regime averages about 1 standard deviation above normal, in the westerly regime it is as much below normal. D'Abreton and Tyson (1996) have shown that the area north of Madagascar is a source region for moist inflows to subtropical troughs over Southern Africa (Fig. 1), so this result is expected. Their results suggest that the inflow maintains a constant elevation, but undergoes an increase in the moisture content after crossing the east coast of Africa around 15°S. The increase is attributed to evapotranspiration and eddy heat fluxes along the densely forested eastern escarpment. The moist inflow is pulsed at intra-seasonal scales via easterly waves embedded within the mean flow as described in the composites below. Table 1 suggests that the relationship with ENSO phase is not well defined. The easterly inflow regime is favoured when equatorial stratospheric (30 hPa) winds are from the west.

**TABLE 1**
**YEARS SELECTED FOR INCLUSION IN THE COMPOSITE**

| Year | Rain | SOI | U30 | Type | U850 m/s |
|---|---|---|---|---|---|
| 1961 | +1.0 | +.4 | -1.0 | East | -3.6 |
| 66 | +1.4 | -1.5 | +.7 | East | -2.4 |
| 68 | -.8 | +.3 | -1.5 | West | +2.2 |
| 69 | +1.2 | -.4 | +1.1 | East | -2.9 |
| 71 | -.5 | +1.3 | -.7 | West | +1.1 |
| 76 | +1.6 | +1.8 | +.5 | East | -2.5 |
| 77 | +1.1 | -.2 | -.7 | East | -1.8 |
| 79 | +.9 | -.3 | +.3 | East | -0.9 |
| 80 | -.9 | -.3 | -.5 | West | +1.7 |
| 81 | +.7 | -.5 | +.8 | East | -1.9 |
| 83 | -1.2 | -2.5 | +1.0 | West | +2.1 |
| 90 | -.9 | +.3 | -.5 | West | +2.3 |
| 92 | -1.2 | -1.4 | -1.4 | West | +3.7 |
| 95 | -1.0 | -.4 | +.8 | West | +1.6 |
| East - West+2.0 | | +.3 | +.7 std dep. | | |

Year refers to December to March season labelled according to the January month, Rain = standardised departure over Africa south of 20°S and east of 25°E, SOI = southern oscillation index, U30 = equatorial zonal wind anomaly at 30 hPa, Type is defined by U 850 hPa zonal wind averaged over the grid box 5 to 15°S, 50 to 75°E.

### Composite patterns

In Fig. 2 the east minus west differences are analysed for 850 hPa winds and 700 hPa geopotential height. The lower level pattern is used to select composite years for inclusion and illustrates a broad band of easterly flow in the area 5° to 20°S, 40° to 90°E to the north-east of Madagascar in the Indian Ocean. An anticyclonic circulation near 25°S, 60°E separates easterly flows in the tropics from westerlies to the south. Analysing the composite differences at higher levels one finds a deep easterly circulation over Madagascar. The lack of an opposing return flow at the upper levels means that the westward flux of mass from the Indian Ocean cannot be conceptualised as a zonal over-turning (Walker) circulation. Geopotential differences are positive (anticyclonic) to the east of Madagascar and negative in the equatorial and mid-latitude bands. The anticyclone guides easterly waves westward to Africa, drawing tropical air polewards across SE Africa and cool dry air equatorward over the South Indian Ocean, thereby suppressing tropical cyclone formation there (Jury, 1993).

In Fig. 3, variables describing the convective patterns and thermodynamic inputs from SST are analysed. The OLR differences indicate a suppression of convection across the tropical south Indian Ocean. OLR differences are > +10 W $m^{-2}$ in the area 0 to 30°S, 60 to 100°E, in years when the easterly wave-guide is present.

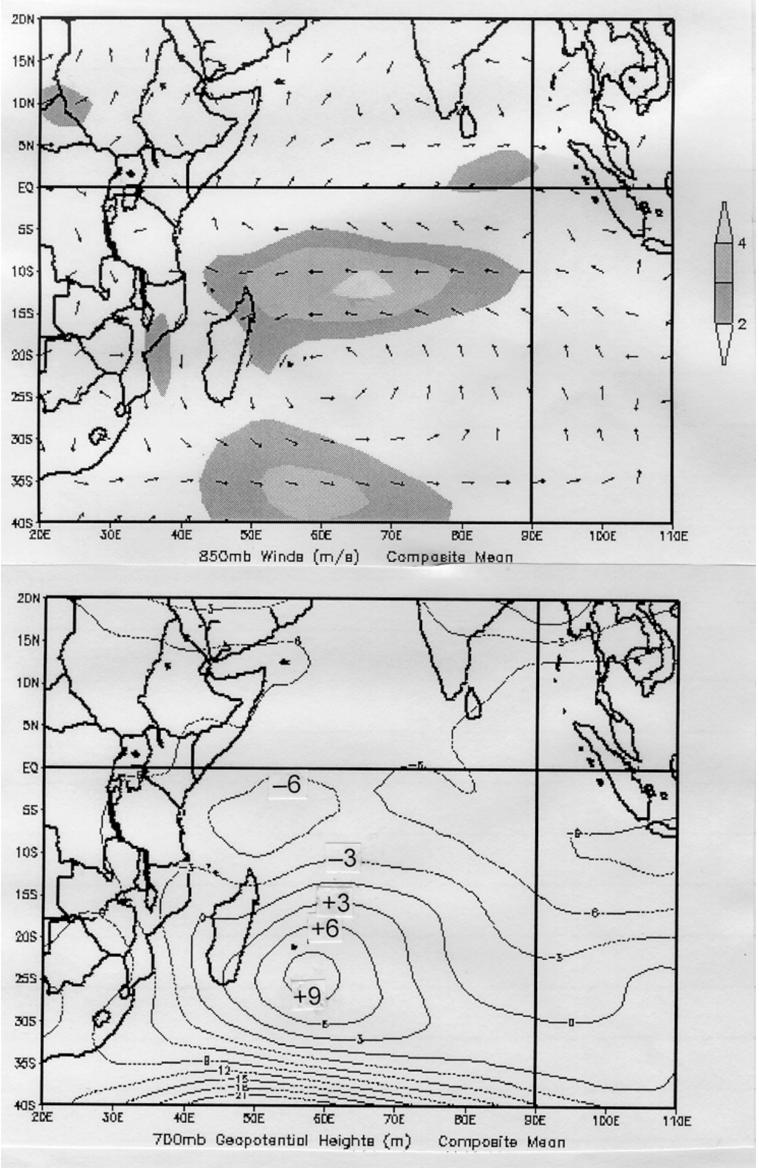



***Figure 2***
*Composite wet/easterly minus dry/westerly differences over SE Africa and the Indian Ocean for December to March period for winds (m·s$^{-1}$) at 850 hPa (a), and 700 hPa geopotential height gpm (b).*

The western edge of the subsident region is relatively sharp along 60°E, about half-way across the region occupied by the zonal wind anomaly. An area of enhanced convection (-OLR differences) lies in an axis extending from northern Madagascar toward eastern and southern Africa. Sea surface temperatures play a role in this scenario as identified in the lower panel. Poleward of the easterly wind regime and supporting the anticyclonic gyre, a warm anomaly of magnitude +1.0°C extends from 50 to 80°E along 30°S. Throughout the entire tropics, covering an area 2 x10$^{13}$ m$^2$, SST differences are of order -0.4°C, in agreement with the earlier results of Jury (1996). The meridional gradient of SST is more than 1°C weaker to the east of Madagascar resulting in reduced westerlies in the upper troposphere through the thermal wind mechanism: ($\partial T/\partial y \sim -\partial U/\partial z$) where T and U are layer-averaged temperature and zonal wind, respectively. The subtropical jet stream is displaced poleward, hence limiting the penetration of westerly shear in the tropics. This mechanism is well represented in the GCM study of Reason and Mulenga (1999) wherein a +1°C SST anomaly south of Madagascar induces a 2 to 5 m·s$^{-1}$ easterly wind anomaly at the 200 hPa level in the 5° to 25°S latitude band across Africa.

The vertical extent of the anomalous wind response to cooling (warming) of the central (southern) Indian Ocean is plotted in Fig. 4. Easterly anomalies extend through the troposphere from the surface to 100 hPa (15 km) in the 5° to 25°S latitude band over the longitudes east of Madagascar. The zonal wind differences are 2 to 5 m·s$^{-1}$ between east and west years. In the higher latitudes upper westerlies are more intense. The deep layer of easterly wind anomalies over the western tropical Indian Ocean creates a suitable barotropic environment for the westward propagation of convective waves. Fig. 5 illustrates the velocity potential (divergent component of the circulation), and reveals an intense centre of upper level inflow and low-level outflow over the south Indian Ocean. Lower-divergent (< 0) and upper-convergent cells are located at 15°S, 70°E with a radius of 3 x 10$^6$ m. These cells dominate the entire Indian hemisphere in this set of composites and can be described as a source region from which easterly waves advect.

SST and circulation patterns for the period August to November (not shown) provide an indication of antecedent conditions. Tropical Indian SSTs are < -0.3°C below normal leading into the easterly flow regime. This is the case everywhere except west of Malaysia (5°S, 100°E) where low-level westerly wind anomalies of +2 m·s$^{-1}$ and associated equatorial downwelling occur - SST differences there are +0.4°C. A deep anticyclonic circulation is located east of Madagascar in the precursor season.

Many of the composite differences in the precursor season exceed the historical inter-annual standard deviation, hence prediction of the easterly wave regime may be possible. Consideration of years listed in Table 1 suggests a decadal rhythm, with the 1960s and 70s experiencing an upsurge in easterly anomalies, and the 80s and early 90s dominated by the westerly regime. As the ENSO influence is obscure in these analyses, it is not clear what mechanism underlies this low-frequency modulation, also found in the 18 year rainfall cycle over southern Africa (Tyson, 1986).

## Wave motions

We have outlined conditions in the background circulation which favour the enhancement or suppression of easterly flows in the tropical Indian Ocean. In this section we investigate the wave motions at higher frequencies using daily filtered eddy meridional winds in hovmoller (longitude-time) format for the 7.5° to 17.5°S latitude band. Zonally propagating waves modulate the meridional component of flow between the ITCZ and the subtropical anticyclone.

A regular westward propagation of eddies within the mean flow is found (Fig. 5) and suggests that the trade winds ‘surge’ at certain intervals. This seasonally phase-locked signal is consistent with filtered daily rainfall records at Mauritius and is unlikely to be an artifact of the NCEP model. A number of eddies (-V’ component) translate from 100°E to 60°E every 10 to 25 d between November and March. The waves travel westward at a mean speed of 2.5 m·s$^{-1}$, in agreement with the earlier results of Jury et al. (1991). On average, the easterly waves dissipate near Madagascar,

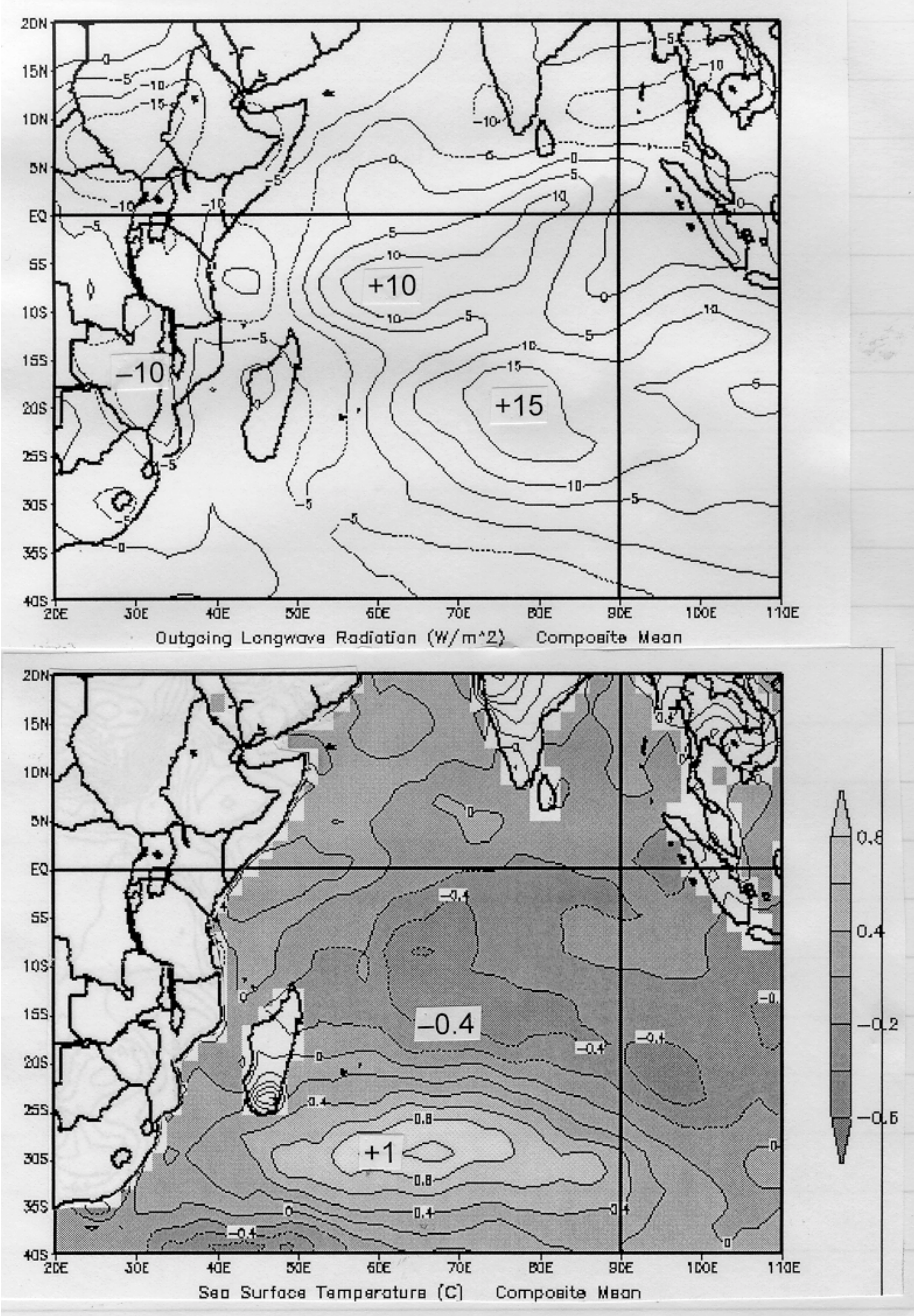



***Figure 3***
*Composite wet/easterly minus dry/westerly differences as in Fig. 1 but for OLR W m$^{-2}$ (a), and SST°C (b)*

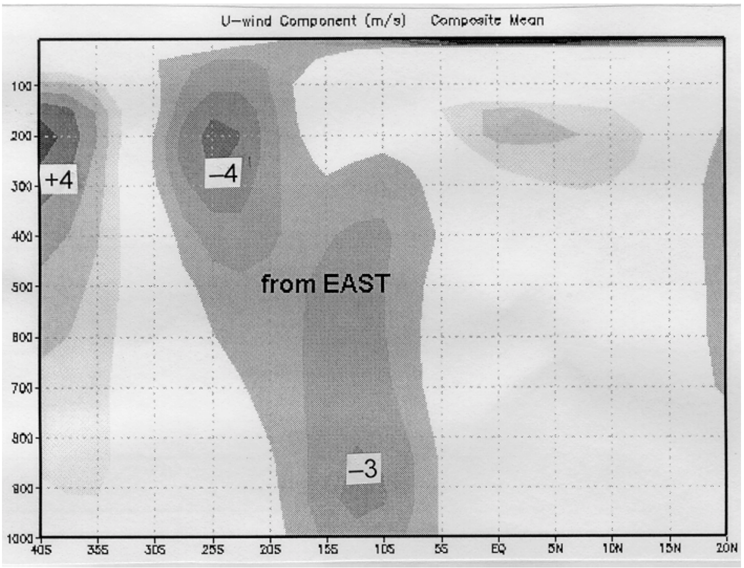
where a standing wave over the steep orography is found. However in some years when climatic conditions are suitable, easterly waves penetrate further westward.

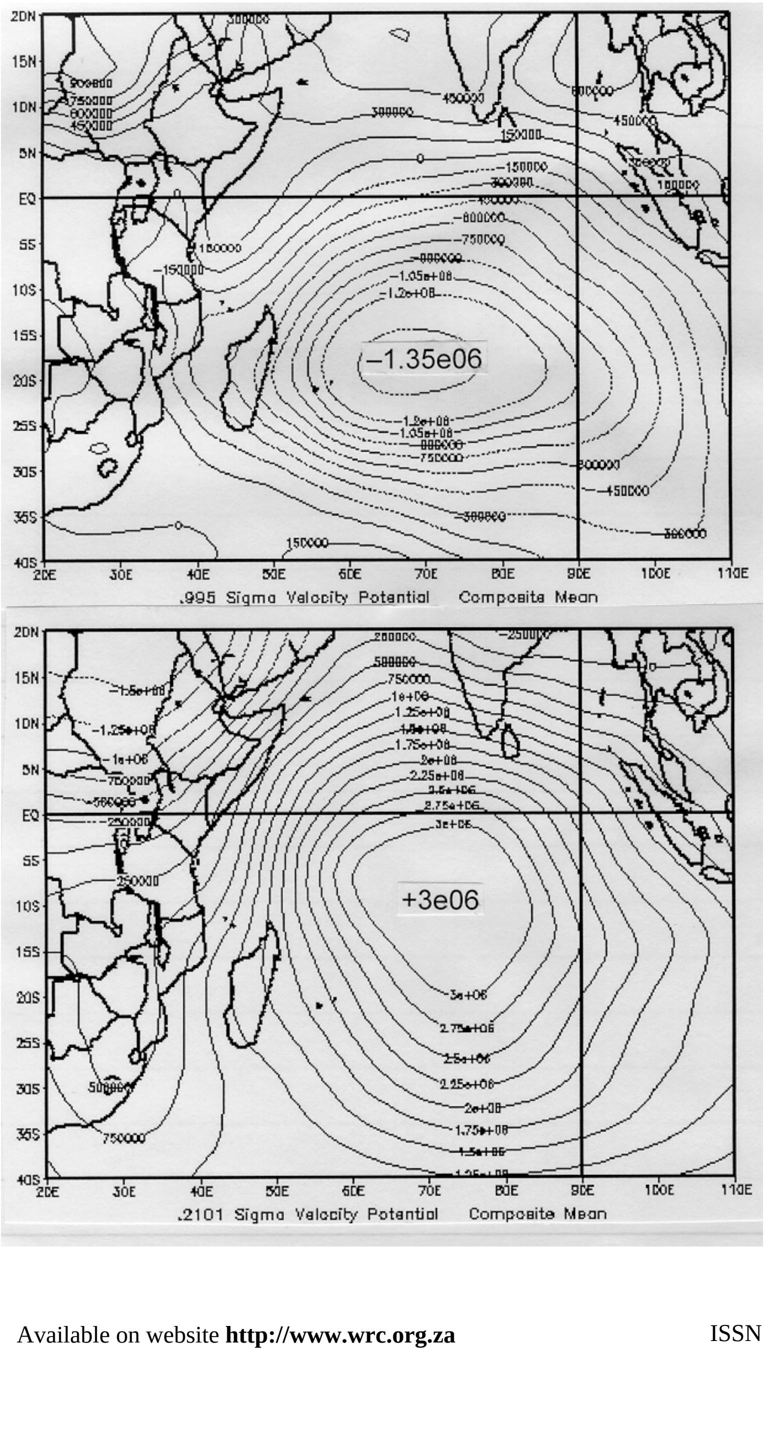
## Discussion and conclusion

A comparison of pentad OLR anomalies for easterly and westerly regimes was made in Jury et al. (1991). In the easterly case, the convective troughs and their attendant ridges propagate westward into SE Africa along 10°-15°S. The propagation speed across the Indian Ocean from 80° to 20°E is 3.3 to 4.1 m·s$^{-1}$, consistent with the background flow (Fig. 4). In the easterly case, the convective anomalies develop further west than usual, and travel along a path that is further equatorward, so sliding past northern Madagascar and into SE Africa along the Zambezi River valley as illustrated in Fig. 1. The intra-seasonal surges enhance the moisture supply over Southern Africa and contribute to latent heat release in quasi-stationary troughs over the continent - the main source of rainfall. In the westerly regime, continental moisture is depleted and an eastward propagation of convective weather systems may occur, often coupled to equatorial Kelvin waves as outlined by Vincent et al. (1998).

In this study it is demonstrated that summer rainfall over SE Africa increases when easterly flow is present off northern Madagascar in the tropical Indian Ocean. Our composite reveals deep easterly flow differences in the band 5° to 20°S. Convection is reduced over the South Indian Ocean (0 to 30°S, 60° to 110°E) whilst increased over SE Africa. Differences between wet and dry years are evident in the velocity potential and OLR which indicate a centre of subsident outflow at 15°S, 75°E. SST in the latitude band 25° to 35°S are higher in easterly flow years and couple with a deep anticyclonic anomaly in the wind field which transfers moist convection westward to SE Africa. SST in the tropics are below normal, hence the poleward thermal gradient is reduced and the associated subtropical jet stream shifts polewards to 40°S. In the tropics around the latitudes of Madagascar, deep easterly flow anomalies of 2 to 5 m·s$^{-1}$ develop when SST increases (decreases) to the south (north). The observational results here correspond well with the numerical modelling study of Reason and Mulenga (1999).

In the precursor season (August to November) SST fields indicate that warming in the sub-tropics is weak and may lag the atmosphere through air-sea interaction processes as described in Reason (1999). Over the central basin, below-normal sea temperatures are found in contrast to warmer conditions off the coast of Malaysia. Westerly 850 hPa wind differences are found over the equatorial band particularly near 90°E. In the upper levels the tropical flow is easterly and at higher latitudes the flow differences are westerly. The easterly anomalies are related to the anticyclone and warmer SST in the south. In this scenario convective surges from the Indian Ocean remain in the 7°




to 15°S latitude band and are less likely to recurve poleward near Madagascar. Hovmoller analyses indicate that seasonally phase-locked, transient waves propagate westward across the South Indian Ocean every 10 to 25 d fueling widespread convection over SE Africa.

## Acknowledgements

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***Figure 4 (left top)***
*Composite wet/easterly minus dry/westerly differences plotted in vertical cross section over the latitudes 40°S to 20°N, averaged over the longitudes 50° to 75°E. Shaded region with easterly anomalies is identified.*

***Figure 5 (left bottom)***
*Composite wet/easterly minus dry/westerly differences as in Fig. 1 but for lower velocity potential $10^5\ m^2 \cdot s^{-1}$ (a), and upper velocity potential $10^6\ m^2 \cdot s^{-1}$ (b)*

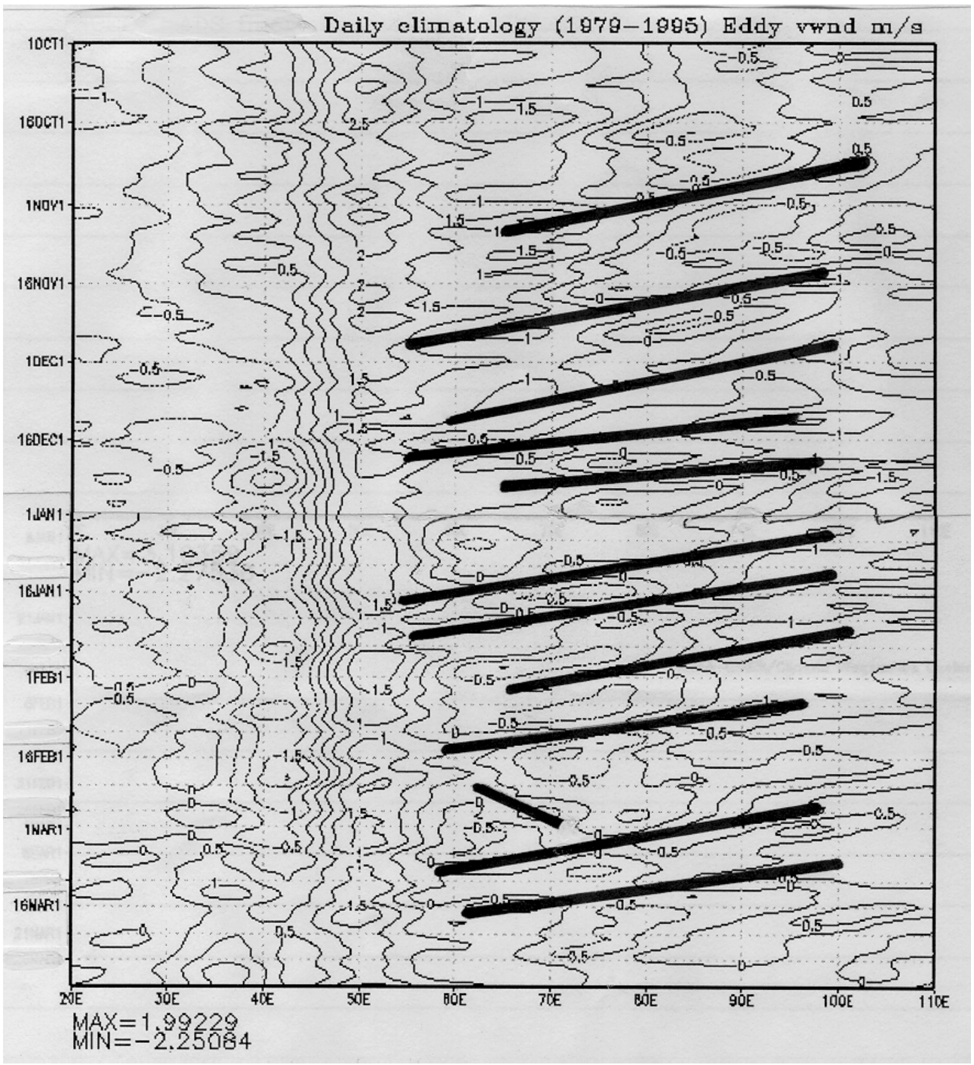


***Figure 6***
*Hovmoller plot of climatological mean eddy meridional wind averaged over the latitude band 7 to 17°S. Westward propagating circulation systems which are seasonally phase locked are identified by bold lines.*


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