Variability in the Tropical Southwest Indian Ocean and Influence on Southern African Climate

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Abstract This study considers satellite era reanalysis products to characterize inter-annual variability in the SW Indian Ocean and influence on the climate of southern Africa. Decorrelation of temperature from a buoy area (8°S, 55°E) is found to vary by season; widespread in the first half of the year and almost zero in the second. This leads to an analysis of the annual cycle and inter-annual variability via wavelet filtered principal components. Contrasts between SODA and GODAS reanalysis products reveal the former exhibits higher amplitude annual to inter-annual variability. Good agreement is found for sub-surface temperature in the SW Indian Ocean thermocline ridge, with rhythmic fluctuations of 2.5-5 yr period. When an ocean Rossby wave crest arrives in the southwestern part of the basin, increased SST and local convective rainfall alters the large-scale circulation. The NW monsoon becomes active and moisture that would normally be exported to southern Africa is retained in the SW Indian Ocean. Daily data from a mooring at 8°S, 55°E reveals intra-seasonal pulses at 15-50 days in Nov.-Mar. season. Intercomparisons with satellite and reanalysis data reveal a cool bias in NCEP during the SE monsoon. Hovmoller analysis highlights how surges in NW monsoon winds relate to heat fluxes and rossby wave patterns. A case study is made to contrast Dec.-Mar. 2011 vs 2012, the former having negative sea surface height anomalies, the latter being positive. Regional wind responses to SW Indian Ocean heat anomalies contribute to a 15% change in seasonal rainfall and maize production in South Africa.

Keywords Southwest Indian Ocean; Inter-annual variability; Southern Africa; Climate

1 Introduction

The Indian Ocean interacts with a strong Asian monsoon and a weaker African monsoon through its circulation and heat content. The eastern Indian Ocean is characterized by zonal winds and sea surface temperatures (SST) > 28°C, while the west Indian Ocean exhibits a meridional circulation and cooler SST. Research has identified the key air-sea interactions (Webster et al., 2000), sub-surface processes (Schott et al., 1994; Field, 1997; Hacker et al., 1998; Reppin et al., 1999; Taylor et al., 2001; Send et al., 2001) and parameterizations suited to Indian Ocean models (Halkides and Lee, 2011). There is consensus on the mechanisms driving equatorial semi-annual (Wyrtki, 1973; Knox, 1976; McPhaden, 1982) and 30-day fluctuations (Weller et al., 1998; Webster et al., 1998, 2000; Bhat et al., 2001; Sengupta et al., 2001). But the interaction of Pacific El Niño Southern Oscillation (ENSO) and local forcing of the east-west temperature dipole is still debated (Saji et al., 1999; Webster et al., 1999; Behera et al., 2006; Yeshanew and Jury, 2007; Luo et al., 2007; Izumo et al., 2010). The dipole pattern may affect the entire tropical Indian Ocean and is strongly expressed on a zonal dome or ridge in the thermocline which occurs on 4º-12º S between 45º-90º E. In-situ observations have been used to link the processes involved (Jury and Harrison, 1999; Roemmich and Owens, 2000; Ehrlich et al., 2002); and data from an array of moored buoys covering the tropical Indian Ocean is now available (McPhaden et al., 2009). Interannual oscillations of SST in the southern tropics are governed by wind-forced Rossby waves that undulate westward on the well known thermocline ridge (McCreary et al., 1993; Sengupta et al., 2001; Xie et al., 2001; Huang and Kinter, 2002; Jury and Huang, 2004; Nagura and McPhaden, 2010). Coupled models have been evaluated to determine their ability to represent this feature and its impacts (Behera et al., 2006). Rather small adjustments of the thermocline
ridge can induce large responses in the overlying atmosphere (Yamagata et al., 2003) that sustain regional climate anomalies of interest here.

This paper provides an analysis of the SW Indian Ocean thermocline ridge and addresses the following scientific questions: How well does the new RAMA buoy array represent ocean-atmosphere coupling? What is the amplitude and phase of the annual cycle? What is the amplitude and frequency of inter-annual variability in the satellite era? What are the characteristics of intra-seasonal pulsing? And, how do Rossby wave troughs and crests affect the austral summer climate?

2 Data and Methods

The analysis of marine climate variability in the tropical SW Indian Ocean (20°S-5°N, 40°-85° E) makes use of simple ocean data reanalysis v2.6 (SODA; Carton and Giese, 2008) and NCEP operational global ocean data assimilation system (GODAS; Behringer and Xue, 2004; Behringer, 2007) monthly fields of sub-surface temperature (T), salinity (S), currents (U, V), vertical motion W and wind stress (τX, Y) - which for SODA derives from the European Community Medium-range Weather Forecasts (ECMWF, Dee et al., 2011). The SODA data extend from Jan. 1979-Dec. 2008 at 0.3° x, y resolution while GODAS data cover the period Jan. 1980-Apr. 2012 at 1° x, 0.3° y resolution. The analysis focuses on depth-averaged layers known to be important for ocean-atmosphere coupling: T 5-150 m, S 5-30 m, U 5-15 m and W 100-200 m, labelled: T100, S20, U10, W150, respectively. A moored buoy with continuous data is available at 8º S, 55º E from Nov 2008 to May 2012 for T, S, U V currents, U V winds, rainfall, relative humidity (RH), and sea surface and air temperature (SST, Ta) via the PMEL website: www.pmel.noaa.gov/tao/rama/. Inter-comparisons are made with daily NOAA satellite SST (Reynolds et al., 2007), cMorph rainfall (Joyce et al., 2004) and NCEP reanalysis U wind and Ta (Kanamitsu et al., 2002). Wavelet spectral analysis is applied to buoy U wind and rainfall to determine the amplitude and frequency of intra-seasonal pulsing relative to annual and semi-annual cycles. Daily rainfall (Love et al., 2004) over southern Africa (20º-30º S, 20º-30º E) during the buoy data period was obtained from the IRI Climate Library and its wavelet spectra was analyzed. Cross-correlations were computed between the daily parameters. Although the record length is 1268, persistence in the marine environment and cycles of the monsoon tend to limit the degrees of freedom, so r > |0.41| is significant at 90% confidence.

To understand how SW Indian Ocean climate evolves in the buoy data period 2008-2012, GODAS monthly anomalies of wind stress, surface heat flux and sea surface height fields were analyzed as x,t hovmollers. Two phases of climate emerge: Dec.-Mar. 2011 cool SW Indian Ocean/wet southern Africa, and Dec.-Mar. 2012 warm SW Indian Ocean/dry southern Africa. The two years were contrasted to reveal coupling processes using monthly GODAS currents, vertical motion and sea surface height in the SW Indian Ocean, and monthly anomalies of NCEP 200 mb and 700 mb wind, 200 mb velocity potential, Climate Prediction Center (CPC) rainfall anomalies (Chen et al., 2002) and satellite vegetation fraction (Leptoukh et al., 2007)
over southern Africa. Reference is made to ‘NW’ and ‘SE’ monsoons that prevail over the thermocline ridge from Dec.-Mar. and Jun.-Sep. respectively. Although some daily time series are considered, the main focus is on inter-annual variability using monthly datasets.

3 Results

3.1 Observing system and decorrelation scale
The SW Indian Ocean observing system in 2012 (Figure 1a) consisted of >100 Argo profiling floats, -10 drifting buoys, a number of research ship cruises, and 9 moorings. The general clockwise rotation of currents maintains drifters at high density in most areas, except the Mozambique Channel. Of the 9 moorings, one had almost continuous records since 2008: 8ºS, 55ºE south of the Seychelles. Spatial decorrelation influence is calculated from SODA seasonal $T_{100}$ values in the buoy area and Hadley SST fields. Correlations above +0.5 in the first half of the year are widespread (Figure 1b), however in the second half values are near zero (Figure 1c). The difference suggests two factors: a) air-sea interactions acting independently from the sub-surface circulations, and b) the delayed influence of ENSO on the Indian Ocean dipole. The annual cycle of ocean variance provides insight to this particular issue (Figure 1d, e, f). While salinity anomalies exhibit maximum standard deviations in the NW monsoon season (Jan.-Jun., $\sigma_S>$0.04 1-50 m), SODA temperature and zonal current anomalies in the buoy area have most variance ($\sigma_T>$0.6C 50-100 m, $\sigma_U>$0.07 m/s 1-50 m) during and after the SE monsoon.

3.2 Annual cycle
Analysis of the mean annual cycle in the buoy area reveal a number of important features in SODA and GODAS reanalysis. The near-surface salinity remains low (34.6-34.8) from January to May under the influence of the NW monsoon. A shallow, fresh, stable layer changes temperature readily depending on the surface heat budget and advective processes (Chirokova and Webster, 2006): mean daily short-wave radiation peaks near 330 W/m² from October to March while currents tend to recirculate waters clockwise. Salinity is higher (35.1) in July-November (Figure 2a) following the retreat of the SE monsoon and ITCZ. The GPCP rain rate in the buoy area varies from >5 mm/day from Dec.-Feb. to <1.5 mm/day in Jun.-Sep. season. Upper layer temperature and vertical motion exhibit semi-annual cycling. $W_{150}$ is generally upward especially in Mar.-May and to some extent Oct.-Dec. (Figure 2b), partly due to cyclonic shear imparted by winds and currents. $T_{100}$ lags vertical motion being cooler in Dec.-Jan. and Jun.-Jul., and warmer in March and October transition months. Wind stress exhibits a singular annual cycle consisting of highest (lowest) $\tau_Y$ ($\tau_X$) values occurring in the Jun.-Sep. monsoon season (Figure 2c), that deepen the mixed layer from 20 m in the first quarter to 45 m in the third quarter of the year (cf. Foltz et al., 2010). Currents are relatively low in the middle of a cyclonic gyre (cf. Figure 1a). Zonal currents are near zero in Feb.-Mar. when meridional currents are northward (Figure 2d). Zonal currents are westward (~0.2 m/s) from June to December. Differences in the two ocean reanalysis are mainly that GODAS is warmer and saltier in the Feb.-Sep. period with weaker westward currents. For most variables, except wind stress, the annual cycle amplitude is greater in SODA. Halkides and Lee (2011) provide a similar analysis and inter-comparison with an ocean model (ECCO).

3.3 Principal components and inter-annual analysis
An analysis of the dominant principal component modes in satellite era SODA reanalysis $T_{100}$ support earlier findings that the cool thermocline ridge 6º-12ºS, 50º-80ºE is, in fact, the dominant inter-annual feature (Figure 3a). It is linked to zonal wind stress in the central basin (Figure 3b, c), wherein equatorial wind surges impart shear and vertical motion that induce temperature oscillations (Trenary and Han, 2012) with spectral energy from 2.5 to 5 yr (Figure 3d). Considering N-S and E-W sections, the dominant inter-annual temperature mode exhibits a loading maximum at 8º-10º S, 60º-67º E, 50-250 m (Figure 3e, f). The reduction of loading values at the surface suggests that air-sea interactions are somewhat disconnected from and secondary to sub-surface conditions modulated by slow Rossby waves and attendant currents and vertical motions. The dominant mode explains 36%-54% of variance compared with 10%-17% for secondary modes.

Now, focusing on the buoy area, SODA and GODAS inter-annual filtered data reveal cross-correlations indicating consistent representation of year-to-year changes. Both show $T_{100}$ oscillations at 4 yr in the
1980s, 3 yr in the 1990s and 5 yr in the 2000s (Figure 4a). In GODAS the 1998 El Niño – Indian dipole event was of higher amplitude; while the rhythm of the two $T_{100}$ series was incoherent during 2001-2003. The changes of inter-annual rhythm reflect the Indian Ocean dipole and interaction with ENSO. $S_{20}$ tended to decline from 1985-1999 with slow oscillations in SODA. After the major El Nino event in 1998 near-surface salinity increased. The amplitude of salinity fluctuations was lower in GODAS (Figure 4b) and the uptrend after 1998 was diminished. An interesting feature of wind stress was biennial oscillations (Figure 4c, 4d) embedded within linear trends that were upward for tauY (more southerly) and downward for tauX (more easterly). Vertical motion tended to lead temperature but most local ocean parameters were weakly associated with $T_{100}$ in SODA (Table 1a). Ocean currents displayed organized fluctuations in the zonal component, while meridional currents had weak oscillations (Figure 4e, f) consistent with location inside a gyre. Inter-annual fluctuations in vertical motion were flatter in GODAS (Figure 4g).

Table 1b lists cross-correlations for monthly GODAS parameters in the buoy area over the period 1980-2011; noteworthy inter-annual relationships include local rainfall and currents (r=−0.40), $T_{100}$ and tauX (r=−0.45), $U_{10}$ and tauX (r=+0.55), and $V_{10}$ and $W_{150}$ (r=+0.73). Intercomparison of SODA and GODAS versions of SW Indian Ocean variability is presented in Table 1c. Among the variables, $T_{100}$ was best inter-related (r=+0.67) followed by tauX (r=+0.63) and tauY (r=+0.60). SODA tauX (from ECMWF) shows high cross-correlation with all GODAS parameters in the buoy area, leading with salinity (r=+0.76). Analysis of wavelet spectral power (not shown) reveals that SODA time series exhibit distinct periods near 2.5 and 5 yr for $T_{100}$ and tauX, and a singular 4 yr period for $U_{10}$, while GODAS displays a narrower range 2.5-3 yr for $T_{100}$ and $U_{10}$, and 3.5 and 5 yr periods for tauX.

Climatic conditions were studied using inter-annual filtered GPCP rainfall anomalies at the buoy and over southern Africa (Figure 4h). The two series are weakly related (r=−0.27) possibly due to ENSO influence, while southern Africa rainfall and buoy-area $T_{100}$ are inversely related (r=−0.44; Table 1a) indicative of links in regional climate (Morioka et al., 2012). SW Indian Ocean rainfall is positively related with $T_{100}$ (r=+0.35 to +0.36) and negatively with GODAS salinity (r=−0.44). $U_{10}$ is related with $S_{20}$ (r=+0.33 to +0.37) suggesting advective effects from the west-salty, east-fresh gradient across the SW Indian Ocean. The uptrend in SW Indian Ocean rainfall (r=+0.04 mm day$^{-1}$/yr) may relate to rising SST in the period 1979-2008 (Xie et al., 2010).

Table 1 Cross-correlation of filtered time series in buoy area (cf. Figure 4), where swR is GPCP rainfall and saR is southern Africa rainfall; with insignificant values omitted

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Table 1 Cross-correlation of filtered time series in buoy area over the period 1980-2011

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Table 1 Cross-correlation of filtered time series in buoy area over the period 1980-2011
To link variability of the SW Indian Ocean to African climate, correlations are analyzed between SODA Dec.-Mar. $T_{100}$ at the buoy and Dec.-Mar. rainfall using GPCP and ECMWF fields 1979-2008 (Figure 4i, j). Both show similar patterns with significant negative correlation over Africa south of 15°S, and positive correlation over equatorial east Africa/west Indian Ocean. Negative values $<-0.5$ form a NW-SE axis over the Kalahari plateau (Namibia, Botswana, South Africa). Positive values $>+0.5$ extend across Kenya and Tanzania, consistent with earlier findings on the influence of the Indian Ocean dipole and ENSO on African rainfall (Behera et al., 2005).

3.4 Moored buoy 8°S, 55°E and intra-seasonal features

The daily data from tropical ocean moorings provide valuable insights on intra-seasonal variability and vertical structure. Temperatures decrease from a mean value of 27.5°C ($\pm$ 1.19) at 20 m to 13.4°C ($\pm$ 0.53) at 180 m (Figure 5a). In the period Nov. 2008-Nov. 2011, the annual cycle was rather weak and comparable to the rising trend. Salinity exhibited a large annual cycle in 10-20 m depths from a peak $>$36.2 in 2009 to a minimum of 34.3 in early 2012. The $T_{100}$ linear trend was $+0.002 ^\circ C$/day and the $S_{20}$ trend was $-0.0004$ ppt/day in period of buoy data. Salinity changes at 60 m and 100 m were minimal (Figure 5b). SST was consistently above Ta due to evaporation (RH -80%) and its variability was low. The annual cycle was $-5 ^\circ C$ (Figure 5c) and there was a semi-annual pattern except in late 2011. Wind components displayed a large annual cycle, varying from $>5$ m/s southeasterly in austral winter to northwesterly in austral summer when the equatorial trough prevailed with mean rain rates up to 5 mm/hr (Figure 5d). In the 2010-2011 season the NW monsoon peaked from early January to mid-February with mean zonal wind of 0.65 m/s; in contrast NW winds prevailed from early December to mid-March in 2011-2012 with a mean zonal value of 2.38 m/s. The daily incoming shortwave radiation rose to a peak $>300$ W/m$^2$ from October to March (Figure 5e), in advance of the NW monsoon winds. Downward spikes of radiation corresponded with NW wind and rain, and coincided with spells of northeast-ward currents at the end of the monsoon season in Mar.-Apr. (Figure 5f) likely due to entrainment around the equatorial jet. Table 2 presents intra-seasonal cross-correlations between the various daily buoy time series in the period Nov. 2008 to May 2012. The expected correlations are noted: SST and Ta (+0.90), U and V wind ($-0.65$), radiation and RH, rain ($-0.47$, $-0.41$). Although NW winds coincide with locally warmer conditions; it is surprising that buoy rainfall is unrelated to Ta and winds.

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<tr>
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Note: Values below 0.30 are omitted.

The intercomparisons between buoy daily data and reference estimates from NOAA satellite and NCEP reanalysis are given in Figure 6. The closest fit is for SST ($r^2 = 93\%$), the trend line is almost 1:1 with little bias due to assimilation. The zonal winds are next closest with a $r^2$ fit of 86% and a curved trend close to 1:1. A small scatter is noted for easterly winds, whereas weak westerly flow tends to be under-represented in NCEP. The largest bias is found for air temperature, where NCEP is too cold in the lower range $-24 ^\circ C$. The Ta $r^2$ fit is 75% and bias tends to be small in the upper range $>28 ^\circ C$. A weak intercomparison is found for rain rate as expected ($r^2=47\%$), yet there is little bias and scatter for convective events $>1$ mm/hr.

Wavelet spectral analysis was applied to zonal winds and rainfall at the buoy (Figure 7a, 7b). Significant intra-seasonal pulsing at 15-50 days is confined to the NW monsoon season from Nov.-Mar. in each of the four years. Annual and semi-annual cycling exhibits higher spectral power yet similar levels of significance. In most NW monsoon seasons there is a dominant intra-seasonal frequency, however in 2011-2012 there were two spectral peaks. A similar analysis was applied to southern African daily rainfall (Figure 7c, 7d) that reaches a maximum in Nov.-Mar. season and is nearly absent in austral winter. Intra-seasonal oscillations were significant in the range 15-30 days from 2009-2011 with peak events $>10$ mm/day, but were much weaker in early 2012 with daily rainfall below 10 mm/day. The diminished intra-seasonal
amplitude over southern Africa contributed to dry conditions there, and could be related to a stronger, long-lived NW monsoon in the SW Indian Ocean.

3.5 Hovmoller plots in SW Indian Ocean

Environmental anomalies are studied using monthly GODAS data 2009-2012 averaged 4º-12º S as longitude-time plots (Figure 8). Wind stress anomalies were found to start off rather weak in early 2009 but became southeasterly in the western basin coincident with negative heat flux anomalies from Oct. 2009 to May 2010. NW wind stress anomalies developed in the central basin in mid-2010 and strengthened in the western basin in early 2011, coincident with a westward propagating positive sea surface height (SSH) anomaly indicative of a Rossby wave ‘crest’. Negative SSH anomalies denoting an upwelling Rossby wave ‘trough’ propagated westward from the central basin from January 2011 in conjunction with negative heat flux anomalies. It is noteworthy that SSH undulations associated with the Rossby waves exceeded 0.3 m from 60º-85º E and flattened westward due to basin geometry. By mid-2011 NW wind anomalies and positive heat flux anomalies developed over the western basin and spread eastward in early 2012. Strong NW monsoon pulses in early 2012 coincided with the arrival of a second Rossby wave crest. The mean phase speed of the Rossby wave train was -20 km/day or 0.25 m/s westward, consistent with those embedded in the annual cycle (White, 2000; Meehl et al., 2003; Johnson, 2011), but faster than Rossby waves associated with ENSO (Jury and Huang, 2004, Yeshanew and Jury, 2007). SST anomalies in the thermocline ridge were +0.6ºC in Dec. 2010 - Mar. 2011, and -0.4ºC in Dec. 2011 - Mar. 2012 during the La Niña event. Thus 2011 and 2012 exhibited contrasting conditions that warrant case study analysis.

3.6 Case Study: Dec.-Mar. 2011 vs. 2012

In early 2011 a Rossby wave trough had propagated into the western basin (Figure 9), with widespread rising motion -0.5 m/day. Negative sea surface height anomalies were strongest (~0.3m) in the thermocline ridge near 70ºE and westward currents along 15ºS prevailed. In contrast, vertical motion was weak or sinking in early 2012 and westward currents along 15ºS diminished. A SSH anomaly of +0.1 m was located in the thermocline ridge near 65ºE. The tropical cyclone season was noted to be more active in 2012 with two intense TC: 18-23 Jan. and 9-21 Feb. and 164 fatalities, compared with 2011 with one intense TC from 9-18 Feb. and no fatalities, according to the regional center (Meteo-France Reunion).

The meridional overturning circulation and temperature exhibit significant differences in N-S depth section (Figure 9c). In the Dec.-Mar. 2011 season upwelling prevailed in the latitudes 8º-14ºS causing the 20ºC isotherm to lift to 50 m, forming a marked thermocline ridge. The equatorial sub-surface overturning circulation reflected a dual rotor and rising motion. In the Dec.-Mar. 2012 season, meridional currents were southward from 10-200 m 8º-10ºS which flattened the thermocline, so the 20ºC isotherm remained below 80 m. Equatorial upwelling below 150 m was also diminished in Dec.-Mar. 2012.

The large-scale atmospheric conditions are mapped in Figure 10a. The upper atmospheric velocity potential pattern exhibited divergent (easterly) anomalies over southern Africa in Dec.-Mar. 2011. In contrast, the following year saw a shift in upper divergence to the SW Indian Ocean. Upper wind anomalies rotated cyclonically around this center of action, reinforcing sinking motion over southern Africa in Dec.-Mar. 2012.

The low-level wind anomalies in Dec.-Mar. 2011 were northerly over Mozambique, representing a pushing action and numerous cloud bands developed over the Kalahari plateau (Figure 10b). In contrast, westerly 700mb wind anomalies were drawn across Africa toward the tropical SW Indian Ocean in Dec.-Mar. 2012, inferring a pulling action. The reduced influx of moisture from the Mozambique Channel caused rain to diminish over South Africa. The Dec.-Mar. satellite vegetation fraction (Figure 10c) went from 29% in 2011 to 25% in 2012 and maize production dropped from 13.4 to 11.4 M T <agritrade.cta.int/Agriculture>. In this manner the alternating Rossby wave trough/crest pattern in the SW Indian Ocean induced wet/dry summers in southern Africa.

4. Conclusions

This study considered in-situ observations and ocean reanalysis products in the SW Indian Ocean to understand how marine variability impacts the regional climate. The collection of drifting profilers
and a mooring array, along with satellite and ship data provides inputs to operational ocean models that represent basin-scale phenomena linking the thermocline dipole and regional atmospheric circulation. The decorrelation scale of $T_{100}$ from the buoy area (7°-9° S, 54°-56° E) was found to vary by season: widespread in the first half of the year when a fluctuating halocline is observed and almost zero in the second half when a fluctuating thermocline prevails. This observation led to an investigation of the annual cycle and inter-annual variability via wavelet filtered principal components. SODA and GODAS reanalysis products were compared; the former exhibits higher amplitude for both annual cycle and inter-annual variability. A consistency was found for sub-surface temperature in the SW Indian Ocean thermocline ridge, with rhythmic fluctuations of 2.5 to 5 yr period. However the relationship between $W_{150}$ and $T_{100}$ was weak in agreement with Halkides and Lee (2011).

When an ocean Rossby wave crest arrives in the SW basin, increased SST and local convective rainfall alters the large-scale circulation. The NW monsoon becomes active and moisture that could be exported to southern Africa is retained in the SW Indian Ocean. The daily data from the mooring at 8°S, 55°E revealed intra-seasonal cycling at 15-50 days in Nov.-Mar. season. Intercomparisons with satellite SST revealed a close fit, but NCEP Ta had a cool bias during the SE season. The daily data from the mooring at 8°S, 55°E revealed that intra-seasonal oscillations in austral summer are anti-phase over the SW Indian Ocean and southern Africa.

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Figures:

Figure 1: a) Observing system in the SW Indian Ocean as of 2012; Argo profiling drifters - dots; moored array - squares (moorings on 80°E line excluded); SODA mean 10 m currents overlain. Correlation between SODA T 100 in buoy area (square in c) and had-SST in b) Jan.-Jun. and c) Jul-Dec seasons, 1979-2008. Mean annual cycle of standard deviation of SODA sub-surface anomalies for d) temperature (°C), e) salinity (ppt), and f) zonal current (m/s), with high values shaded.
Figure 2 Mean annual cycle in buoy area (7°-9° S, 54°-56° E) from SODA (thick) and GODAS (thin): a) 100 m temperature (°C) and 20 m salinity (ppt, upper), b) GPCP rainrate (mm/day, upper) and 150 m vertical motion (m/day), c) meridional and zonal wind stress (N/m²) and mixed layer depth (m), and d) 10 m meridional (upper) and zonal currents (m/s).
Figure 3 a) PC1 loading pattern of 5-150 m temperature (36% of variance). b) Smoothed PC1 time scores for temperature and zonal wind stress. c) PC1 loading pattern of zonal wind stress (49%). d) Wavelet spectral analysis for temperature PC1 score. e) PC1 loading pattern for temperature in the east-west plane using data averaged 6º-12º S (54% of variance), f) as in e) but in the north-south plane using data averaged 58º-63º E (42%); all from SODA2.6 reanalysis, detrended, standardized and 12-month filtered. Sections (e, f) are along dashed lines in a).
Figure 4 Inter-annual filtered time series in buoy area for SODA and GODAS (thin lines g- prefix): a) 100 m temperature b) 20 m salinity, c) zonal wind stress (N/m²) and SODA trend (thin dashed), d) meridional wind stress and SODA trend (thin dashed), e) 10 m zonal currents (m/s), f) 10m meridional currents, g) 150 m vertical motion (m/day), h) GPCP rainfall anomalies over buoy-area: swR, and southern Africa: saR (boxes in i). Correlation between SODA T_{100} and rainfall in Dec–Mar season for i) GPCP and j) ECMWF, 1979-2008. Arrow in a) refers to buoy data period.
Figure 5 Time series from moored buoy at 8°S, 55°E in the period 21 Nov 2008 to 12 May 2012: a) temperature, b) salinity, c) SST and RH (%), d) zonal wind (m/s) and rain (mm/day), e) meridional wind and incoming radiation (W/m²), f) zonal and meridional currents (cm/s). Arrow in b) highlights key feature.
Figure 6 Intercomparison of daily buoy data and: a) satellite SST (°C), b) NCEP U wind (m/s), c) NCEP Ta (°C), and d) satellite rain rate (mm/hr, log-scale, values <0.1 omitted); each with trend line, equation and fit.
Figure 7 Wavelet spectral analysis of daily buoy data (cf. Fig. 5d): a) zonal wind and b) rainfall, with values below 80% confidence masked, cone of validity given. c) Daily area-averaged southern Africa rainfall (mm/day) and d) wavelet spectrum. Dashed line at 0.1 highlights period of 36 days. Arrows in c, d) highlight key features.
Figure 8 Hovmoller plots averaged 4°-12° S from GODAS: a) wind stress (N/m²) and heat flux anomalies (W/m² upward positive), and b) sea surface height anomalies (m) over the buoy data period. Time is upward on the y-axis; dashed lines in b) refer to rossby wave crests and trough.
Figure 9 Ocean analysis from GODAS for Dec.-Mar. 2011 (left) and Dec.-Mar. 2012 (right): a) 10 m currents and 150 m vertical motion shaded blue rising, b) sea surface height anomaly; c) N-S depth section averaged 55°-67° E of meridional current/vertical motion vectors, and temperature (shaded). W exaggerated 1000-fold in c).
Figure 10 Atmospheric analysis over southern Africa for Dec.–Mar. 2011 (left) and Dec.–Mar. 2012 (right): a) NCEP 200 mb wind and velocity potential anomaly ($\times 10^6$), b) NCEP 700 mb wind and CPC rainfall anomaly, c) satellite NDVI vegetation fraction from 0.1 white to 0.8 dark green; value inside maize belt labelled. ‘Push’ ‘pull’ labels over Mozambique in b) highlight wind response.