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Variability in sea-surface temperature and winds in the tropical south-east Atlantic Ocean and regional rainfall relationships

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ABSTRACT: Variability in sea-surface temperature (SST) and winds in the Angola Benguela frontal zone (ABFZ) in the tropical south-east Atlantic Ocean has previously been shown to be important for regional fisheries and for seasonal rainfall anomalies over Angola/Namibia in austral summer and coastal West Africa in boreal summer. This study investigates intraseasonal variability in winds and SST over this region using QuikSCAT and tropical rainfall measuring mission (TRMM) satellite data for 1999–2004. Wavelet analyses reveal periods of relatively strong power in the 20–30 or 30–64 day frequency bands throughout the record but that there is substantial interannual variability in the occurrence of these intraseasonal oscillations. The implications of this variability for seasonal rainfall anomalies during the main rainy seasons in southern Africa (austral summer) and coastal West Africa (boreal summer) are discussed. Copyright © 2008 Royal Meteorological Society

KEY WORDS SST; tropical south-east Atlantic; African rainfall; winds

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1. Introduction

The Benguela Current upwelling system is one of four major subtropical eastern boundary-upwelling systems in the world ocean but is unique in that it is bounded at both its northern and southern extremities by warm water (in Figure 1, the ‘u’ symbol denotes the main centres of upwelling in the Benguela system). To the south of South Africa, warm rings are shed off the Agulhas Current retroflection region several times per year and track into the southern Benguela Current region whereas, to the north, the Angola Benguela frontal zone (ABFZ in Figure 1) separates the upwelling system from the tropical Angola Current waters. The location and intensity of this frontal zone appear to be related to the winds over the south-east Atlantic (Colberg and Reason, 2006).

Using a regional-ocean model driven by various wind-stress forcings, these authors showed that the location of the frontal zone is determined by opposing northward and southward flows near the coast. South of the front, the northward flow is mainly driven by geostrophic adjustment to coastal upwelling forced by the meridional windstress. The southward flow equatorward of the front is related to the southeastward flowing South Equatorial Countercurrent which, in turn, responds to the wind-stress curl over the tropical south-east Atlantic. These authors suggested that variability in winds over the south-east Atlantic Ocean not only affects the ABFZ but may also be linked with anomalous land-based convective rainfall over Angola and the Congo basin.

Typically, the ABFZ is located near 15–17 °S and extends several hundred kilometres seaward of the southern coast of Angola. Its location and the area immediately surrounding it is typically characterized by the largest standard deviation in sea-surface temperature (SST) in the South Atlantic Ocean (Florenchie *et al*., 2004) as this area is where the surface expression of the Benguela Niño generally occurs (Shannon *et al*., 1986; Florenchie *et al*., 2003). The large SST variability in this region during Benguela Niños is important for southern African rainfall (Rouault *et al*., 2003). Benguela Niños occur roughly every decade or so in late austral summer and manifest themselves as a strong SST anomaly off the coast of southern Angola/northern Namibia with a coherent and substantial subsurface temperature anomaly extending north along the thermocline towards the equator and then west across the equatorial Atlantic. These anomalies are typically generated by a large area of weaker trade winds in the equatorial south-west Atlantic Ocean that occurs a few months before the SST anomaly appears off the Angolan coast.

On seasonal time scales, the frontal zone tends to be strongest and located furthest south in austral summer and less pronounced and furthest north in winter (Colberg and Reason, 2006; Veitch *et al*., 2006). Over the Benguela system proper, there is also seasonality with strongest wind-driven upwelling occurring off central Namibia in austral winter and off southwestern South Africa in

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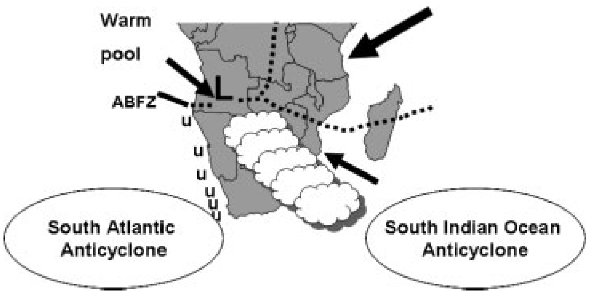


Figure 1. Schematic showing important features in the tropical south-east Atlantic region. The Angola Benguela Frontal Zone is marked by the solid line and labelled ABFZ. The major upwelling centres in the Benguela Current are marked by 'u'. The Angola low (marked L) and ITCZ (dotted lines) are present in austral summer as are the cloud bands. Low-level moisture fluxes for the austral summer are denoted by the arrows with their thickness giving an indication of their relative strengths.

austral summer, and reduced or no upwelling in the opposite season.

In addition to seasonal and decadal variations, the ABFZ is also characterized by substantial interannual and intraseasonal variability. It is the latter that forms the main topic of this study and this is analysed using 5 years of QuikSCAT wind and TMI SST data, only available since mid-1999. The period to the middle of 2004 is chosen since it contains a Benguela Niño event (Rouault *et al.*, 2003), a Pacific El Niño event (Reason and Jagadheesha, 2005) and years which were neutral with respect to either of these major modes of interannual climate variability. Although a 5-year record is too short to comprehensively analyse interannual variability, it is adequate to analyse the intraseasonal variability in the winds and SST over the region and how the nature of this shorter time-scale variability may vary from one year to the next.

Variability in the frontal zone and associated SST anomalies has been shown to be very important for both fisheries and rainfall and therefore there is considerable motivation for understanding this region better. The frontal zone marks the northern boundary of a very rich upwelling species-dominated coastal fishery. During Benguela Niño events, the frontal zone tends to be displaced southward following an intrusion of warm and saline tropical water sometimes as far south as 25 °S (Shannon *et al.*, 1986; Mohrholz *et al.*, 2001). As a result, fish distributions and abundance can be strongly impacted in the northern Benguela system (Boyer *et al.*, 2001; Boyer and Hampton, 2001). Benguela Niños and other strong warm SST events along the Angolan/northern Namibian coast typically lead to above average rainfall in the coastal region (Hirst and Hastenrath, 1983) and sometimes further inland (Rouault *et al.*, 2003). The latter authors suggested that the extent of the rainfall anomaly over southern Africa might be associated with the relationship of the regional atmospheric circulation anomaly, which typically occurs in the Angolan low region (marked L in Figure 1), to the low-level moisture fluxes emanating from the western Indian Ocean (arrows in Figure 1). In addition to southern African rainfall links, there is evidence that SST and winds in the ABFZ region are related to boreal summer rainfall over coastal West Africa (Reason and Rouault, 2006). The 1999–2004 period analysed here using QuikSCAT and TMI data was also interesting from a rainfall perspective as it contains several unusually wet seasons, a Benguela Niño event (2001) and a protracted drought over large areas of southeastern Africa (2002–2004).

To date, very little work has been performed on the intraseasonal variability of the tropical south-east Atlantic Ocean and southwestern African region. Elsewhere in southern Africa though, several studies have documented the importance of better understanding the variability on this time scale for regional climate (e.g. D'Abreton and Lindesay, 1993; Levey and Jury, 1996; Pohl *et al.*, 2007). In terms of the tropical south-east Atlantic, Cook *et al.*, (2004) showed that synoptic rainy spells over South Africa tended to be related to the strength of the near-surface low-pressure system that develops over northern Namibia/southern Angola in austral summer (Angola low) and the winds over the tropical south-east Atlantic. This study also pointed to the intraseasonal scale as requiring further study. Risien *et al.*, (2004) analysed QuikSCAT winds for 1999–2000 along the Benguela coast from the south coast of South Africa to central Angola and found marked periods of stronger synoptic and intraseasonal activity which differed with latitude. Foltz and McPhaden (2004) considered Madden–Julian oscillations over the Atlantic and found strong signals over the southern tropics of the basin. More recently, Pohl *et al.*, (2007) highlighted the importance of Madden–Julian oscillations for southern African rainfall and presented some evidence of their signature in the Angolan region. Thus, taken together, these studies suggest that intraseasonal variability over the tropical south-east Atlantic region may be significant but remains to be investigated in detail. In addition to local linkages, Reason and Rouault, (2006) found evidence that the relationship between SST in this region and coastal rainfall over West Africa appears to change between the pre-monsoon (June) and monsoon (July–August) months further pointing to the need to better understand the intraseasonal scale.

Here, linkages of tropical south-east Atlantic conditions with Angolan/Namibian austral summer rainfall and West African rainfall on the intraseasonal scale are considered. In terms of the former, Figure 1 provides a schematic of important features for the region during summer. Convection in the previously mentioned Angola low region acts as the source for the tropical extra-tropical cloud bands that bring most of southern Africa's summer rainfall and tends to be strong and well developed (weak) during years with good (poor) rains (Cook *et al.*, 2004; Reason *et al.*, 2006). Onshore low-level moisture flux from the warm pool in the tropical south-east Atlantic (Figure 1) during the late summer and early autumn feeds into the Angola low and may enhance the regional rainfall although most of the moisture tends to come from the western Indian Ocean. This warm pool lies north of the ABFZ that marks the northernmost limit of the cold waters of the Benguela Current coastal upwelling system. In terms of the latter, strongest upwelling in austral summer occurs much farther south off the west coast of South Africa whereas in austral winter once the South Atlantic anticyclone has shifted further north, the central Namibian coast experiences the most pronounced upwelling.

During May and June, winds over the tropical south-east Atlantic strengthen and become more southeasterly (i.e. little or no onshore component towards Angola) leading to the replacement of the warm pool by an upwelling cold tongue and low-level moisture transport towards coastal West Africa. This cold tongue strengthens in July as the West African monsoon starts and the relationship between coastal West African rainfall and SST off Angola changes sign. Further details of the annual cycle of winds, SST and circulation over the tropical Atlantic can be found in Schott *et al*., (2005) or Reason *et al*., (2006); here the focus is on the intraseasonal scale.

2. Data and methodology

QuikSCAT wind data at 0.5° resolution spanning a 5-year period from August 1999 to July 2004 in the domain extending from −40 to 0 °S and 0 °E to the southern African coast (south-east Atlantic Ocean) were employed in this study. These data were derived from the SeaWinds Scatterometer onboard the NASA QuikSCAT satellite which was launched in June 1999. The original QuikSCAT data of 0.25° resolution and two passes per day were smoothed temporally to 2-day composites and spatially to 0.5° resolution. This smoothing is applied to fill spatial/temporal gaps as the swath sometimes misses a region of interest.

Given that the region is often covered by persistent marine stratocumulus cloud, microwave imaging SST is preferable to AVHRR data. Thus, SST data from the TMI satellite (Kummerow *et al*., 1998) are used in this study for the same 1999–2004 period as the winds. These data are also available at 0.25° horizontal resolution. Similar to the winds, the raw data are smoothed to a 2-day composite and to 0.5° resolution.

Since our interest is mainly on intraseasonal timescales, a 20–70 day bandpass filter that uses a Dolph–Chebyshev convergence window (Doblas–Reyes and Deque, 1998) is applied to both the wind and the SST data. The wind and SST anomaly time series were constructed by area-averaging both u and v components and subtracting respective monthly means calculated for the period 1999–2004, from each average (2-day average) over six regions in the south-east Atlantic. These six regions were chosen on the basis of a careful self-organizing map (SOM) analysis (Risien *et al*., 2004) which indicated that they have distinct synoptic, intraseasonal and seasonal wind characteristics from each other and that they are appropriate for the purposes of this study. These regions are 10–15 °S, 15.5–18.5 °S, 19–23.5 °S, 24–28.5 °S, 29–32.5 °S and 33–35 °S. They are bounded longitudinally by 0° longitude and the southern African coast. In this study, only the two regions near the ABFZ, important for Angolan/Namibian austral summer rainfall (Rouault *et al*., 2003) and coastal West African boreal summer rainfall (Reason and Rouault, 2006) are analysed.

To isolate intraseasonal wind variability and how the nature of this variability may change from one year to the next, wavelet analyses of the 20–70 day filtered wind and SST time series were performed. In this study, the one-dimensional complex Morlet wavelet, which is commonly used in geophysical studies (Weng and Lau, 1994), is utilized. The wavelet is a complex cosine wave modulated by a Gaussian function. The advantage of this type of wavelet is that its complex nature allows for detection of both time-dependent amplitude and phase for different frequencies present in the signal or time series.

Before performing the wavelet transform, the time series has to be padded with zeros at either end (Torrence and Compo, 1998). This padding is done to offset errors that occur at the beginning and end of the wavelet power spectrum due to the finite-length nature of the time series. The zeroes have to be removed afterwards. However, padding with zeroes introduces discontinuities at the endpoints. This region of the wavelet spectrum where the edge effects become important is the cone-of-influence (COI). In cases where the end-points are unimportant, the COI can be disregarded (Meyers *et al*., 1993).

Possible associations with regional rainfall are considered by using Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) mean pentad rainfall data (Xie and Arkin, 1997) together with indices of the Angola low and West African coastal rainfall. The CMAP rainfall data are precipitation estimates obtained from the merging of observations from rain gauges and rainfall estimates from satellite and are produced on a global grid with a horizontal resolution of 2.5° × 2.5°. The CMAP data set used here has previously been used in recent southern African studies (e.g. Usman and Reason, 2004; Reason *et al*., 2005; Tadross *et al*., 2005).

On the basis of Figure 1 and the literature previously cited, an index of the Angola low is appropriate to study potential relationships with southern African rainfall; this index is derived by averaging daily NCEP reanalysis OLR over 12.5–17.5 °S, 17.5–22.5 °E (Kalnay *et al*., 1996). For the West African coast, an index derived by averaging NCEP reanalysis daily OLR over 5–10°N, 0–10 °E, the region of strongest connection with the ABFZ (Reason and Rouault, 2006) is used. In both cases, respective monthly means are subtracted from the data. Note that OLR is usually used as a proxy for deep convection and rainfall in the tropics (Wang and Rui, 1990; Vincent *et al*., 1998), especially in areas where ground-based precipitation measurements are sparse such as Angola.

3. Wavelet analyses

After 20–70-day bandpass filtering as described in the previous section, wavelet analyses were performed on the QuikSCAT wind stress and TMI SST data. Figures 2–3 show the wavelet analysis for the along- and across-shore wind stress for the two cells in the ABFZ region, 10–15 °S, and 15.5–18.5 °S. Note that the data are strictly pseudo-stresses rather than stress (i.e. the product of the drag coefficient and the density has not been included to avoid having to make assumptions about the values of these two scalars). Also note that although the terms alongshore and across-shore are used, strictly these are the northward (u) and eastward (v) components. However, since the coastline is close to being oriented south–north, the difference between u and v and the true alongshore and across-shore components is small.

An earlier analysis of 1999–2000 QuikSCAT alongshore winds for this region suggested the presence of a relative peak near 40 days (Risien *et al.*, 2004) in both cells. Energy at roughly this timescale is apparent in Figure 2 (bottom) during 1999–2000 but more obviously in mid-2001, mid-late 2002, and early 2003 for the 10–15 °S cell which lies to the north of the ABFZ. Substantially higher frequency variability (20–30 days) is also apparent, particularly during the summer of 1999/2000 (a very wet summer), 2002 and late 2003/early 2004. Although there are differences in magnitude, periods of relatively strong energy at a certain timescale in the alongshore wind stress more or less match those in the across-shore wind stress.

Several of the stronger features apparent in Figure 2 can also be identified in Figure 3, the corresponding plots for 15.5–18.5 °S over the ABFZ. As for Figure 2, the waxing and waning of different periods of intraseasonal

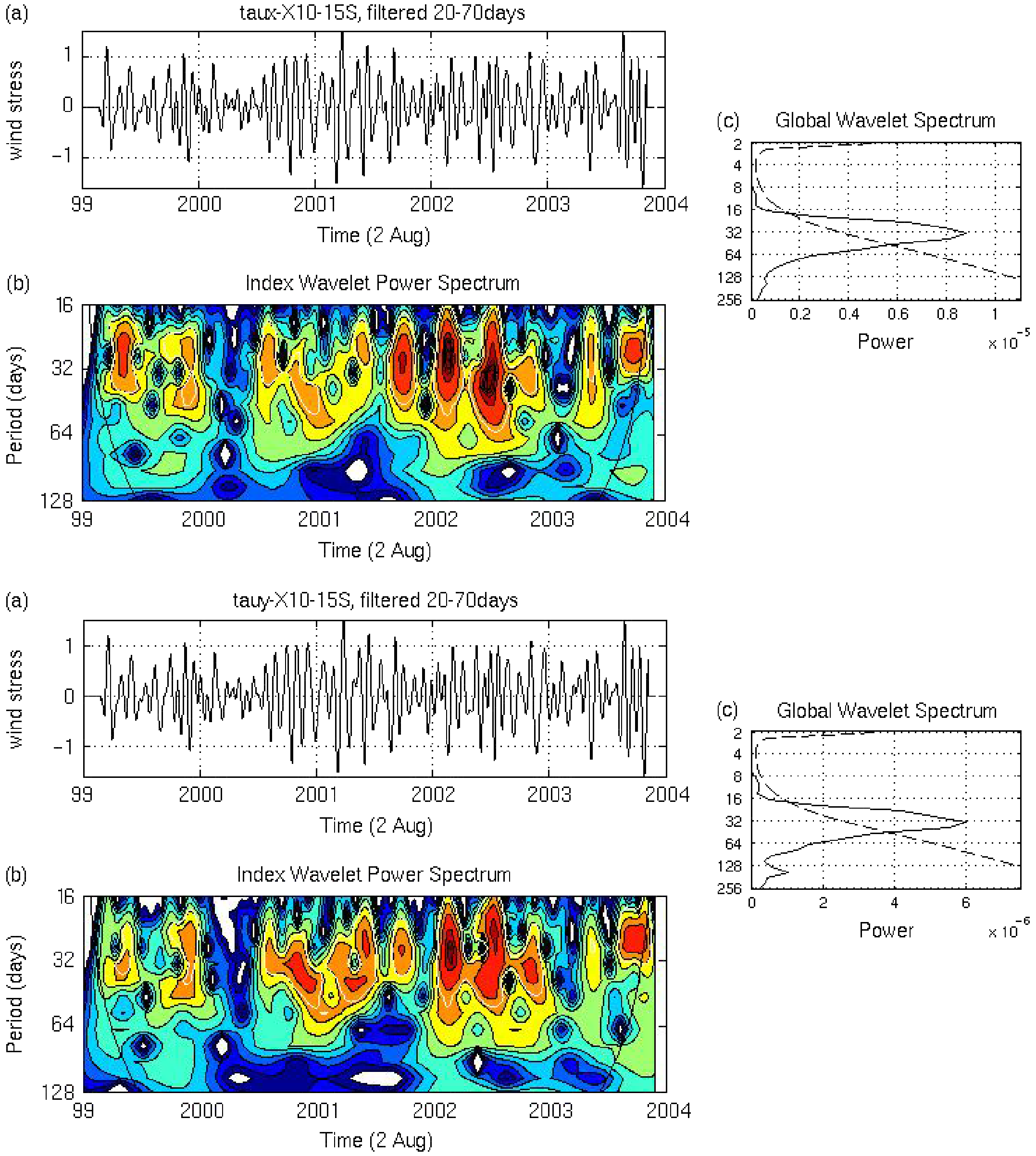


Figure 2. Bandpass filtered (20–70 days) wavelet spectrum for the averaged coastal-wind pseudo-stress at 10–15 °S for August 1999–August 2004. Upper (lower) panel shows the across-shore (alongshore) component. This figure is available in colour online at www.interscience.wiley.com/ijoc

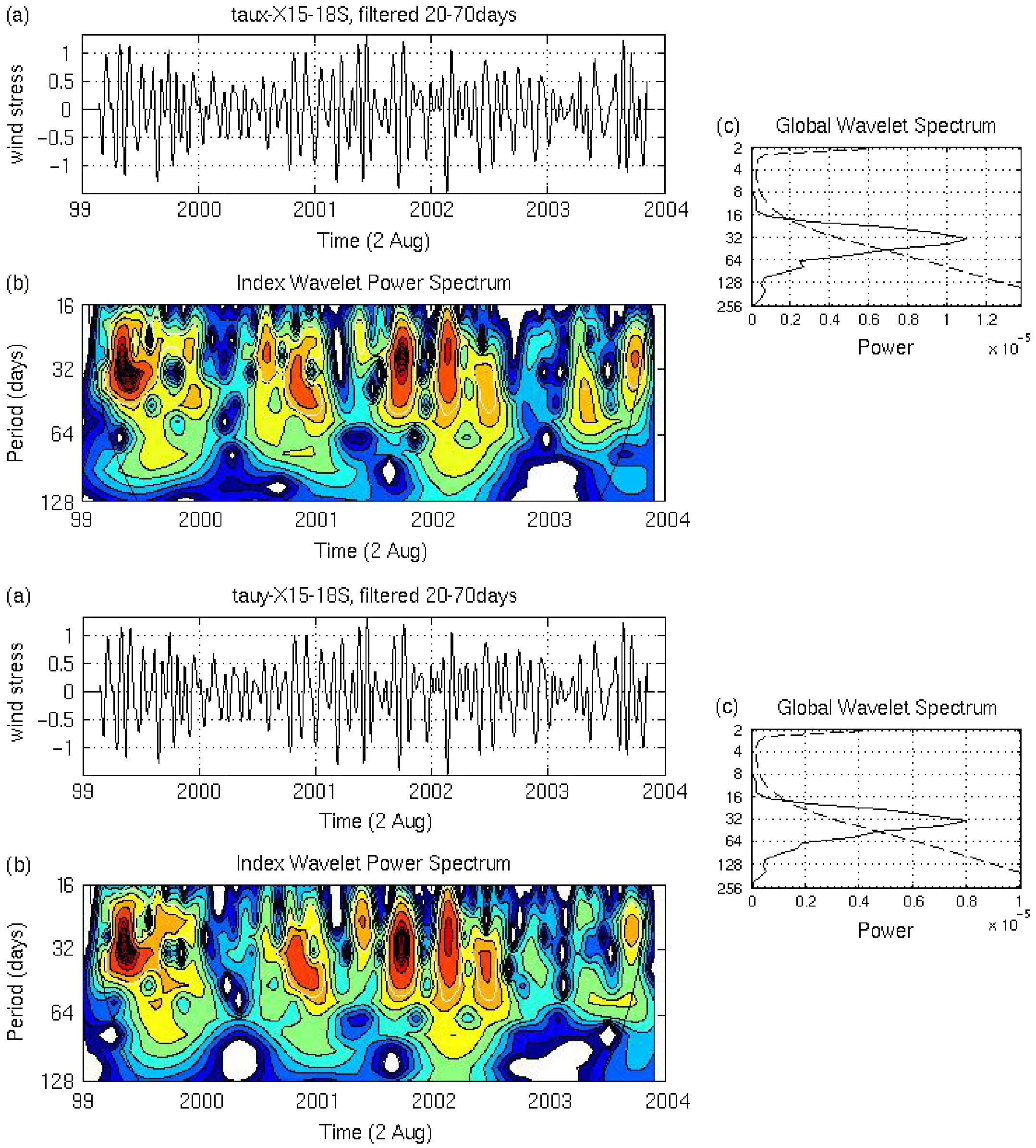


Figure 3. As for Figure 2 except for 15.5–18.5 °S. This figure is available in colour online at www.interscience.wiley.com/ijoc

variability through the 5-year record indicates that the relative peaks previously obtained by Risien *et al.* (2004) using 1999–2000 data need to be viewed with some caution since they appear to differ slightly from one year to the next (Figure 3). Similar to the 10–15 °S cell, these authors also found a relative intraseasonal peak near 40 days; however, Figure 3 indicates that such a peak is not obvious during certain periods such as late 2000/early 2001 or early 2003, for example. Further south, the central Benguela region did not show such a peak whereas the cells in the southern Benguela system near 32–35 °S did (Risien *et al.*, 2004), thus suggesting that the wind-stress variability over the ABFZ region is decoupled from the region immediately to its south at this time scale.

Although it is not immediately obvious that the wavelet analyses for the SST and the wind stress are related to each other in the 10–15 °S cell (*cf* Figures 2 and 4), some of the stronger features do appear to occur at about the same time. For example, the low frequency peak in the 40–70 day range in the SST data during the middle of 2001 and in late 2002/early 2003 is reflected in the alongshore wind-stress results and to lesser extent in the across-shore wind stress plot for these periods. There are generally less obvious connections at higher frequencies, and it is apparent that there is little evidence of much energy in the 20–35 day range in the SST (Figure 4) in contrast to that apparent in this range in the wind analyses (Figure 2). This result is not unsurprising given that the differences in heat capacity between the media mean that the response time of the upper ocean to a change-in-surface forcing (e.g. wind stress) is longer than the time the lower atmosphere takes to adjust to a change-in-surface heat flux. If the wavelet time series are correlated, then it is found that the strongest results occur at a 6-day lag of SST behind the local winds with $r = 0.4$ (alongshore) and $r = -0.3$ (across-shore), both significant at 99%.

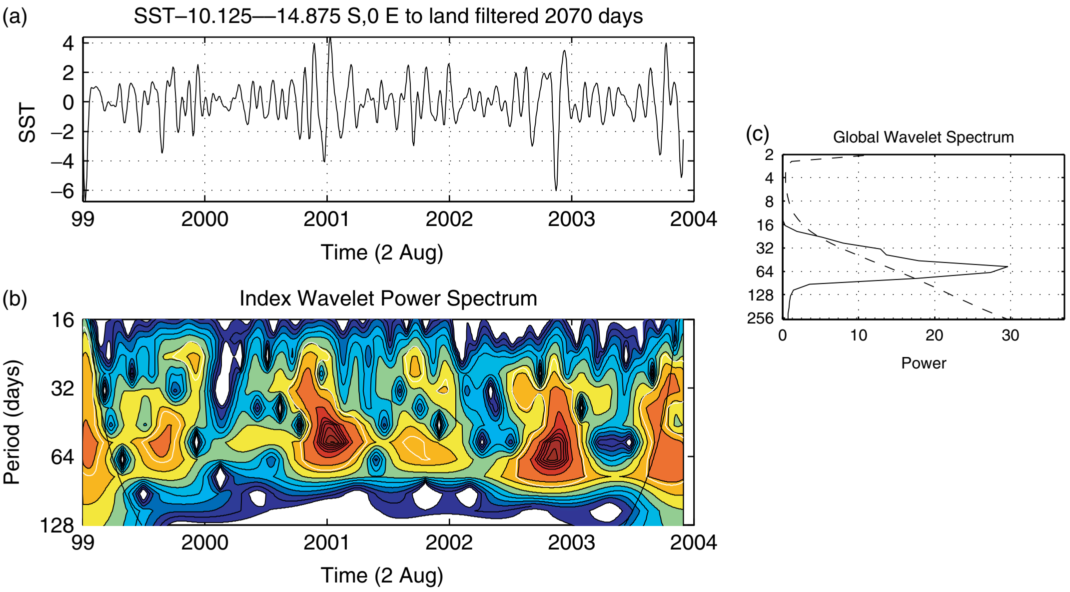


Figure 4. As for Figure 2 except SST. This figure is available in colour online at www.interscience.wiley.com/ijoc

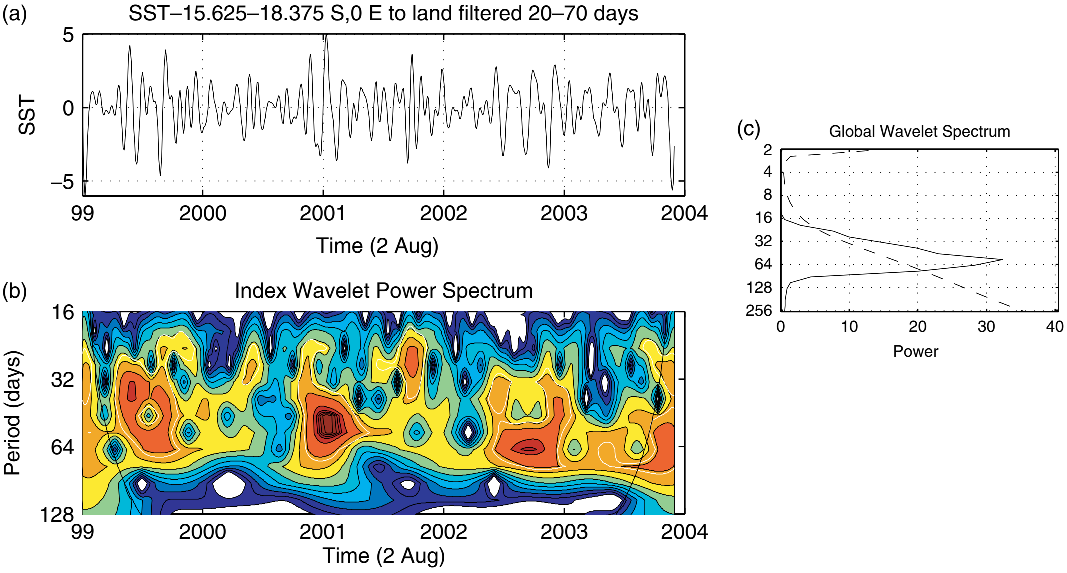


Figure 5. As for Figure 3 except SST. This figure is available in colour online at www.interscience.wiley.com/ijoc

Examination of Figure 5, the SST wavelet analysis at 15.5–18.5 °S confirms the relatively little energy in the higher frequency part of the band. Comparison with Figure 3 also indicates that there are periods of lower-frequency variability (greater than 35 days) evident in the SST which match to some extent those in both the alongshore and across-shore wind stresses. The clearest examples are late 1999/early 2000 and early-middle 2001. In this band, the correlations with the wind stresses are very similar to those found further north ($r = -0.4$ for across-shore wind stress leading SST by 8 days, $r = 0.4$ alongshore wind stress leading SST by 6 days, also significant at 99%).

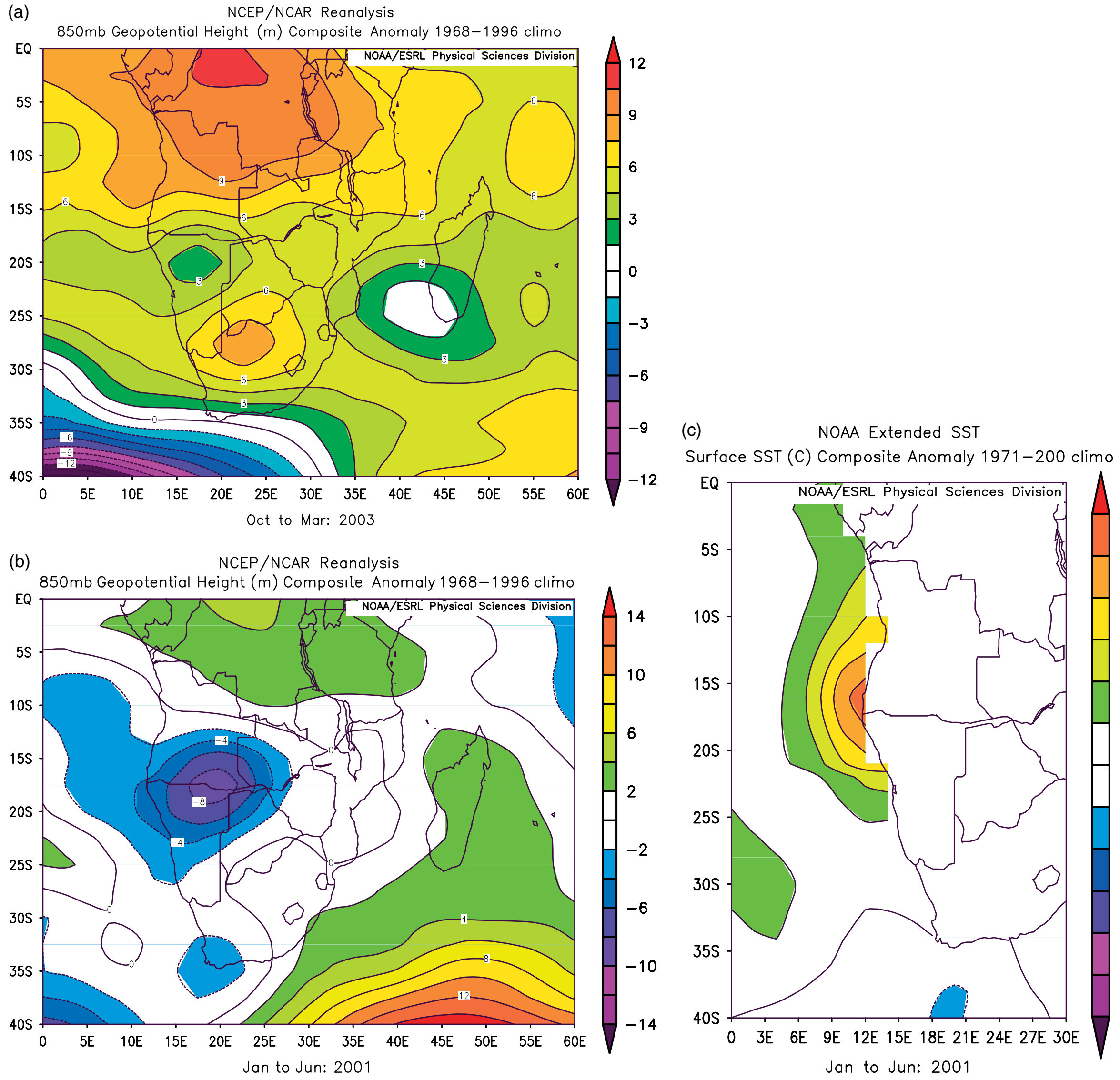
Note that a positive correlation exists with the alongshore wind stress at both 10–15 °S and 15.5–18.5 °S because these regions generally lie over and north of the ABFZ (the equatorward boundary of the Benguela Current upwelling system), and do not experience upwelling of cool water. Further south (20–34 °S), stronger alongshore wind stresses (and associated negative curl) lead to cooler SST through offshore Ekman transport and upwelling and hence the correlation would be negative in the central and southern Benguela Current region. Over, and north of the ABFZ region focussed in this study, numerical model results (Colberg and Reason, 2006) indicate that stronger alongshore winds increase the upper-ocean convergence between the southward-flowing South Equatorial Counter Current/Angola Current that lies to the north of the ABFZ, and the northward-flowing coastal upwelled jet that lies to the south of the ABFZ. As a result, warmer SST occurs off the Angolan coast when the alongshore winds are stronger.

Model results (Colberg, 2006) indicate that this dynamical process dominates over any wind-driven change to the surface-heat flux. On the other hand, a negative correlation exists with the across-shore wind stress at both 10–15 °S and 15.5–18.5 °S because a stronger wind stress in this direction has little impact on the currents mentioned above but leads to more evaporative heat loss from the sea surface and hence surface cooling.

4. Discussion

The early-middle 2001 and late 2002/early 2003 periods of low-frequency variability in both wind stresses and SST noted above for each region correspond to a Benguela Niño event (Rouault *et al.*, 2003) and the mature phase of an El Niño event (Reason and Jagadheesha, 2005) respectively. Austral summer and autumn following the first appearance of warming in the tropical Pacific, or mature phase, is when the El Niño signal is most pronounced in the tropical south-east Atlantic (Colberg *et al.*, 2004). Consistent with El Niño conditions, a persistent high-pressure anomaly over much of tropical southern Africa, extending over the neighbouring south-east Atlantic, and a weaker Angola low were evident during late 2002/early 2003 at the same time as the strong low-frequency variability in the wavelets of the SST and wind stresses during this period (Figure 6(a)). The early-middle 2001 period was also characterized by a persistent circulation anomaly in the lower atmosphere over the Angolan region (in this case cyclonic – Figure 6(b)) and warm SST anomalies (Figure 6(c)) in the frontal zone (the Benguela Niño) which may be reflected in the strong power in the lower frequencies in the wind stress and SST wavelet analyses then.

Figure 7 plots the corresponding wavelet analysis for the Angola low OLR index defined in Section 2. The


(a) NCEP/NCAR Reanalysis
850mb Geopotential Height (m) Composite Anomaly 1968–1996 climo
Oct to Mar: 2003

(b) NCEP/NCAR Reanalysis
850mb Geopotential Height (m) Composite Anomaly 1968–1996 climo
Jan to Jun: 2001

(c) NOAA Extended SST
Surface SST (C) Composite Anomaly 1971–200 climo
Jan to Jun: 2001

Figure 6. NCEP re-analysis anomaly of (a) 850 geopotential height (contour interval 1.5 m) for the October 2002–March 2003 period, (b) 850 geopotential height (contour interval 2 m) for the January–June 2001 period, and (c) SST for this period (contour interval 0.3 °C). This figure is available in colour online at www.interscience.wiley.com/ijoc

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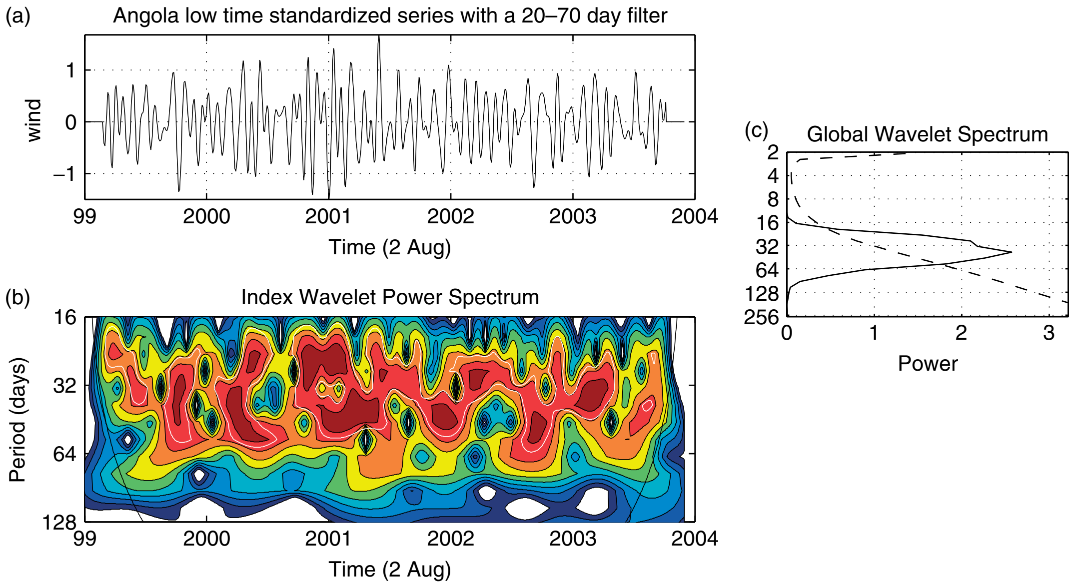

Figure 7. As for Figure 2 except the Angola low index. This figure is available in colour online at www.interscience.wiley.com/ijoc

2000–2001 period is marked by strong power across a range of timescales whereas 1999 shows mainly relatively high frequency power and 2002–2004 tends to show more at lower frequencies. The higher-frequency energy in 1999 seems to match with that evident in the across-shore wind stress for 10–15 °S at this time (Figure 2 top) whereas energy near 40–60 days in 2001 and late 2002/early 2003 is reflected to some extent in both wind-stress components but more in the alongshore (Figure 2 bottom). Correlating the indices leads to $r = 0.44$ with the alongshore wind stress leading the Angola low index by 4 days (significant at 99%) and $r = -0.30$ when the across-shore wind stress leads the Angola low index by 2 days. Similar results are obtained when the wind stresses at 15.5–18.5 °S are correlated with the Angola low index. Given that the Angola low index is a measure of convective rainfall over the neighbouring land, these results suggest that variability in this index and that in the wind stresses over the nearby ocean are linked since low-level moist air off the tropical south-east Atlantic feeds into the low.

Reason and Rouault (2006) found relationships between boreal summer seasonal rainfall over coastal West Africa and SST, evaporation and winds over the tropical south-east Atlantic the preceding boreal spring. Consistent with those seasonal results, the across-shore wind stresses are correlated strongest ($r = 0.41$ for 10–15 °S and $r = 0.40$ for 15.5–18.5 °S, $p < 0.05$ in both cases) with the index of the West African coastal rainfall (defined in Section 2) when the wind stresses lead by 86 days or almost one season. This result suggests that the relationship found by Reason and Rouault (2006) using monthly NCEP winds and monthly CRU rainfall data for 1948–2002 that increased West African coastal rainfall is linked with stronger southeasterly winds in the ABFZ region also holds for the more recent period in the higher temporal resolution QuikSCAT wind and NOAA OLR data. Slightly weaker correlations result between the alongshore wind stress and this index. From late 2001 onwards, the corresponding wavelet analysis of the West African rainfall index (Figure 8) shows periods of strong power in the roughly 30–60 day band that matches up to some extent with features in the across-shore winds at 10–15 °S, and to lesser extent, the alongshore winds. Prior to late 2001, stronger power in the West African index tends to exist at higher frequencies.

Over this West African region, the 2003, and 2004 summer seasons were somewhat drier than those earlier in the 1999–2004 period studied here and this appears related to anticyclonic conditions, enhanced subsidence (Figure 9(a)) and reduced meridional wind over the tropical south-east Atlantic (Figure 9(b)). As shown in Reason and Rouault, (2006), summer rainfall in coastal West Africa is related to SST in the ABFZ region and the southeasterly winds extending from this region towards the West African landmass as the monsoon develops after late June over the Sahel and the savannah region extending south from the Sahel. These weaker winds over the south-east Atlantic not only exist during the boreal summer rainy season but also during the preceding boreal spring (Figure 9(c) consistent with the coastal rainfall in summer showing strongest correlations with conditions of the previous season off Angola (Reason and Rouault, 2006).

5. Summary

The ABFZ is a major marine ecosystem boundary and marks the equatorward limit of the Benguela Current upwelling system. To its north, are the warmer saltier waters of the Angola Current. Analysis of 5 years of QuikSCAT data over the ABFZ region indicates strong intraseasonal variability in both the alongshore and across-shore component of the wind stresses and changes

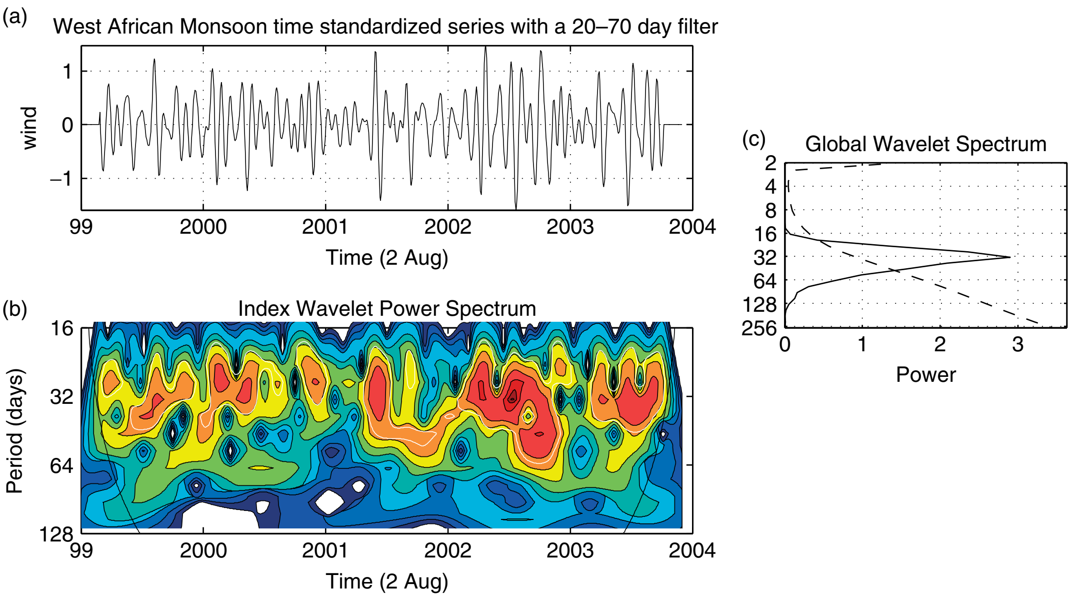

Figure 8. As for Figure 2 except West-African convection index. This figure is available in colour online at www.interscience.wiley.com/ijoc

in the nature of this intraseasonal variability between one year and the next. Although a 5-year record is too short to comprehensively analyse the interannual variability in the regional SST and wind stresses, it is adequate to analyse the intraseasonal variability focussed on herein and how the nature of this shorter time-scale variability may vary from one year to the next. SST data, taken from the TMI satellite, were analysed for the same regions (10–15 °S and 15.5–18.5 °S) and found to display similar time scales of variability. Some of the variability in the wind stress over the tropical south-east Atlantic may be linked to fluctuations in convection over the Angola heat low region or coastal West Africa. The results presented here indicate that there is substantial intraseasonal variability in SST, wind stress and rainfall over the region and extend previous work which has mainly focussed on interannual or interdecadal variability.

Idealized experiments with a regional ocean model (Colberg and Reason, 2006) have shown that both the location and the intensity of the ABFZ are sensitive to the wind stress over the south-east Atlantic. The regional wind-stress curl appears to mainly determine the location of the ABFZ whereas the strength of the southerly wind stress to its south is important for the intensity of the front. Thus, variability in the wind stress analysed here likely influence characteristics of the ABFZ that are important for both regional fisheries and rainfall. The rainfall relationships exist not only over the immediate southern African region but also over coastal West Africa far to the north. In the latter case, they are related to changes in the low-level meridional wind-transporting moisture from the tropical south-east Atlantic towards this landmass.

In southern Africa, southern Angola, and northern Namibia experienced well above-average austral summer rainfall during the 1999/2000 and 2003/2004 seasons. In the latter case, most of the area to the east and south experienced dry to a bit less than average summer rainfall, whereas for 1999/2000, the wet conditions extended over most of subtropical southern Africa. Previous analyses of rainfall variability in this region (e.g. Rouault *et al.*, 2003; Reason and Jagadheesha, 2005) have pointed to a stronger Angola low being associated with good rains. Low-level moisture over tropical southern Africa emanates from the tropical western Indian Ocean, the tropical south-east Atlantic and the Congo rainforest with a moisture convergence region extending from the Angola low northeastwards towards the meridional arm of the ITCZ that is located over northeastern Zambia/the eastern Congo/western Tanzania border region (Reason *et al.*, 2006). Despite the low-level moisture convergence patterns over the region being complex and the tropical south-east Atlantic tending to be a relatively less-dominant moisture source than the Indian Ocean for southern African rainfall (Rouault *et al.*, 2003; Reason *et al.*, 2006), it is worth noting that the wetter 1999/2000 and 2003/2004 summers correspond to periods of relatively high power in the zonal wind stress off the Angolan and northern Namibian coast (Figures 2 and 3 top panels). In addition, NCEP re-analysis winds indicate stronger westerly low-level winds off the tropical south-east Atlantic and into the Angola low during these two summer periods (not shown) reinforcing the suggestion that the wetter than average conditions during 1999/2000 and 2003/2004 over southern Angola and northern Namibia may have been associated with increased zonal winds over the 10–15 °S and 15.5–18.5 °S ABFZ region and enhanced moisture advection towards the land.

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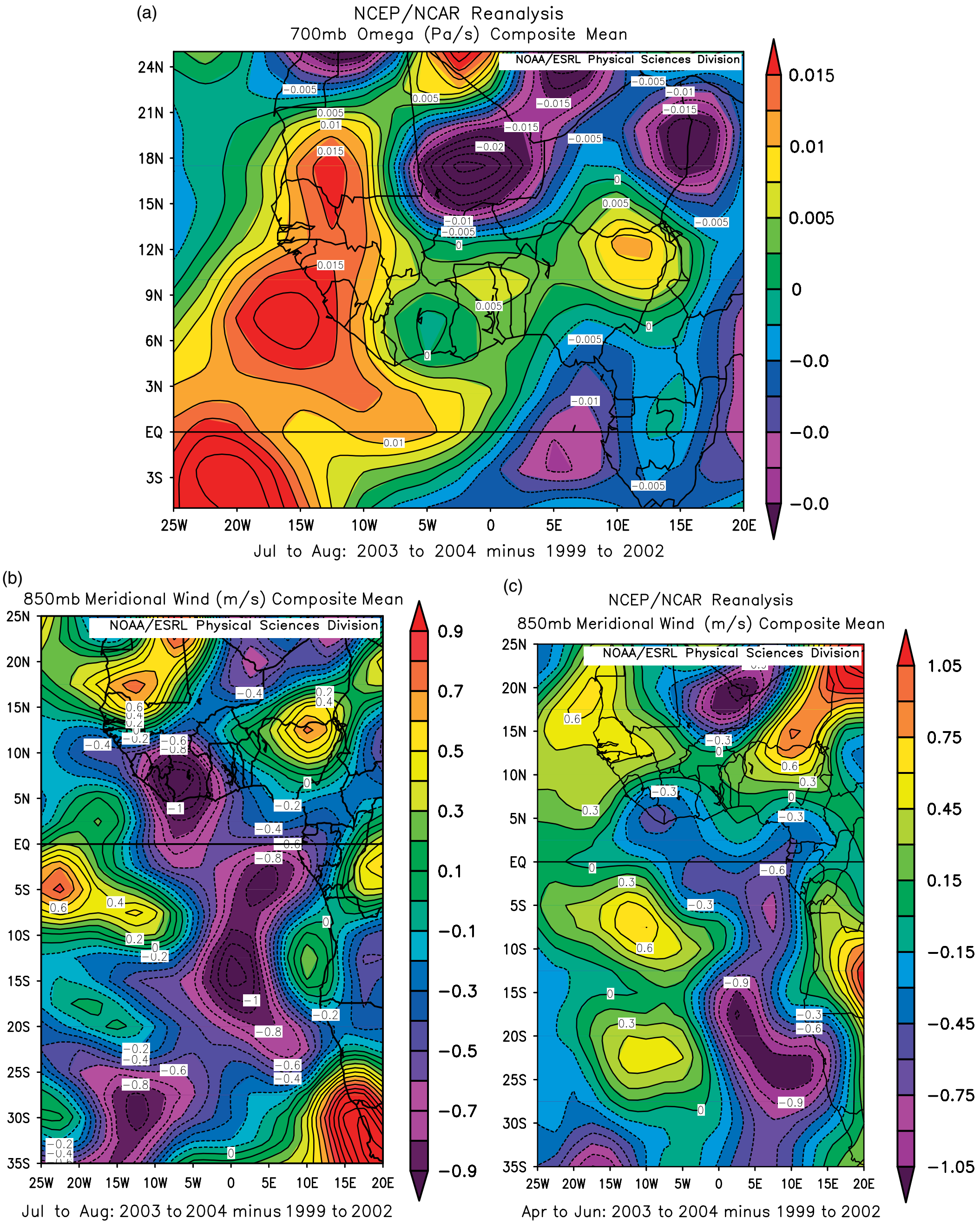

Figure 9. NCEP re-analysis difference plot of July–August 2003–2004 minus July–August 1999–2002 for (a) omega at 700 hPa (positive values indicate relative subsidence and contour interval is 0.0025 Pa s^{-1}), (b) 850 hPa height meridional wind (contour interval is 0.1 m s^{-1} and (c) same as (b) but for previous April–June season (contour interval is 0.15 m s^{-1}). This figure is available in colour online at www.interscience.wiley.com/ijoc

Oregon State University for assistance with obtaining the QuikSCAT data. Some plots were done online at the NOAA/NCEP Climate Diagnostics Center website.

References

Boyer DC, Hampton I. 2001. An overview of the living marine resources of Namibia. *South African Journal of Marine Science-Suid-Afrikaanse Tydskrif Vir Seewetenskap* **23**: 5–35.

Boyer DC, Boyer HJ, Fossen I, Kreiner A. 2001. Changes in abundance of the northern Benguela sardine stock during the decade 1990–2000, with comments on the relative importance of fishing and the environment. *South African Journal of Marine Science-Suid-Afrikaanse Tydskrif Vir Seewetenskap* **23**: 76–84.

Colberg F. 2006. An analysis of variability in the South Atlantic. PhD thesis. University of Cape Town, South Africa, 196.

Colberg F, Reason CJC. 2006. A model study of the Angola Benguela Frontal Zone – sensitivity to atmospheric forcing. *Geophysical Research Letters* **33**: L19608, 10.1029/2006GL027463.

Colberg F, Reason CJC, Rodgers K. 2004. South Atlantic response to ENSO induced climate variability in an OGCM. *Journal of Geophysical Research* **109**: C12015, Doi 10.1029/2004JC002301.

Cook C, Reason CJC, Hewitson BC. 2004. Wet and dry spells within particular wet and dry summers in the South African summer rainfall region. *Climate Research* **26**: 17–31.

D'Abreton PC, Lindesay JA. 1993. Water vapour transport over southern Africa during wet and dry early and late summer months. *International Journal of Climatology* **13**: 151–170.

Doblas-Reyes FJ, Deque M. 1998. A flexible band pass filter design procedure applied to midlatitude intraseasonal variability. *Monthly Weather Review* **126**: 3326–3335.

Florenchie P, Lutjeharms JRE, Reason CJC, Masson S, Rouault M. 2003. The source of Benguela Niños in the South Atlantic Ocean. *Geophysical Research Letters* **30**: 12-1–12-4.

Florenchie P, Reason CJC, Lutjeharms JRE, Rouault M, Roy C. 2004. Evolution of interannual warm and cold events in the south-east Atlantic Ocean. *Journal of Climate* **17**: 2318–2334.

Foltz GR, McPhaden MJ. 2004. The 30–70 day oscillations in the Atlantic. *Geophysical Research Letters* **31**: L15205, Doi: 10.1029/2004GL020023.

Hirst AC, Hastenrath S. 1983. Atmosphere-ocean mechanisms of climate anomalies in the Angola-tropical Atlantic sector. *Journal of Physical Oceanography* **13**: 1146–1157.

Kalnay E, *et al*. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437–471.

Kummerow C, Barnes CW, Kozu T, Shiue J, Simpson J. 1998. The Tropical Rainfall Measuring Mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology* **15**: 809–817.

Levey K, Jury M. 1996. Composite intraseasonal oscillations of convection over southern Africa. *Journal of Climate* **9**: 1910–1920.

Meyers SD, Kelly BG, O'Brien JJ. 1993. An Introduction to wavelet analysis in oceanography and meteorology: with application to the dispersion of Yanai waves. *Monthly Weather Review* **121**: 2858–2866.

Mohrholz V, Schmidt M, Lutjeharms JRE. 2001. The hydrography and dynamics of the Angola-Benguela Frontal Zone and environment in April 1999. *South African Journal of Science* **97**: 199–208.

Pohl B, Richard Y, Fauchereau N. 2007. The influence of the Madden Julian oscillation on southern African summer rainfall. *Journal of Climate* **11**: 2659–2674.

Reason CJC, Jagadheesha D. 2005. A model investigation of recent ENSO impacts over southern Africa. *Meteorology and Atmospheric Physics* **89**: 181–205, Special Issue on Regional Climate, DOI 10.1007/s00703-005-0128-9.

Reason CJC, Rouault M. 2006. Sea surface temperature variability in the tropical southeast Atlantic Ocean and West African rainfall. *Geophysical Research Letters* **33**: L21705, 10.1029/2006GL027145.

Reason CJC, Hachigonta S, Phaladi RF. 2005. Interannual variability in rainy season characteristics over the Limpopo region of southern Africa. *International Journal of Climatology* **25**: 1835–1853.

Reason CJC, Landman W, Tennant W. 2006. Seasonal to decadal prediction of southern African climate and its links with variability of the Atlantic Ocean,. *Bulletin of the American Meteorological Society* **87**: 941–955.

Risien C, Reason CJC, Shillington F, Chelton DB. 2004. Variability in satellite winds over the Benguela upwelling system during 1999–2000. *Journal of Geophysical Research* **109**(C3): C03010, Doi10.1029/2003JC001880.

Rouault M, Florenchie P, Fauchereau N, Reason CJC. 2003. South East Atlantic warm events and southern African rainfall. *Geophysical Research Letters* **30**: 8009, Doi:10.1029/2003GL014840.

Schott F, Hazeleger W, Carton J, Johns W, Kushnir Y, Reason CJC, Xie S-P. 2005. The Tropical Atlantic Climate Experiment. World Climate Research Programme CLIVAR report, Geneva, 47.

Shannon LV, Boyd AJ, Brundrit GB, Taunton-Clark J. 1986. On the existence of an El Niño-type phenomenon in the Benguela system. *Journal of Marine Science* **44**: 495–520.

Tadross M, Hewitson BC, Usman MT. 2005. The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe. *Journal of Climate* **18**: 3356–3372.

Torrence C, Compo GP. 1998. A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society* **79**: 61–78.

Usman MT, Reason CJC. 2004. Dry spell frequencies and their variability over southern Africa. *Climate Research* **26**: 199–211.

Veitch J, Florenchie P, Shillington FA. 2006. Seasonal and interannual fluctuations of the Angola Benguela Frontal Zone (ABFZ) using 4.5 km resolution satellite imagery from 1982 to 1999. *International Journal of Remote Sensing* **27**(5–6): 987–998.

Vincent D, Fink A, Schrage JM, Speth P. 1998. High- and low-frequency intraseasonal variance of OLR on annual and ENSO timescales. *Journal of Climate* **11**: 968–986.

Wang B, Rui H. 1990. Synoptic climatology of transient tropical intraseasonal convection anomalies. *Meteorology and Atmospheric Physics* **44**: 43–61.

Weng H, Lau K-M. 1994. Wavelets, period doubling, and time–frequency localization with application to organization of convection over the tropical western Pacific. *Journal of the Atmospheric Sciences* **51**: 2523–2541.

Xie P, Arkin PA. 1997. Global precipitation: a 17 year monthly analysis based on gauge observations, satellite estimates and numerical model outputs. *Bulletin of the American Meteorological Society* **78**: 2539–2558.