Seasonal to decadal predictability and prediction of southern African climate

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Introduction

Southern Africa, broadly defined here as Africa south of the equator, is a region prone to pronounced flood and drought events and significant climate variability on a range of time scales. Some of this variability is thought to be forced remotely via ENSO (e.g., Nicholson and Entekhabi, 1986; Lindesay *et al.*, 1988; Mason and Jury, 1997; Nicholson and Kim, 1997; Reason *et al.,* 2000; Allan *et al.*, 2003) while some is related to variability in the neighbouring Indian and Atlantic Oceans (e.g., Hirst and Hasternrath, 1983; Lough, 1986; Ogallo *et al.*, 1988; Walker, 1990; Mason, 1995; Reason and Mulenga, 1999; Reason, 1999; Behera and Yamagata, 2001; Rouault *et al.*, 2003) or to local land surface processes (Zheng and Eltahir, 1998; Douville *et al.*, 2001). It should be stated at the outset that climate variability over southern Africa is complex with a multitude of forcing factors that interact with each other and wax and wane in their importance through the record. Landman and Mason (1997), Richard *et al.* (2000), Allan *et al.* (1996, 2003) amongst others all provide evidence of how the ENSO influence on southern Africa has varied while Mulenga *et al.* (2003) show that some dry seasons over northern South Africa may be directly related to ENSO whereas others show an influence from the subtropical and midlatitude Atlantic. In this paper, the focus is on possible relationships between the Atlantic Ocean and southern African climate and we begin by considering the annual cycle of SST, winds and moisture fluxes over this region.

1. Annual cycle

The potential influence of the Atlantic on southern African climate is mainly related to the variability in the Inter-tropical Convergence Zone (ITCZ) over the region, the South Atlantic anticyclone and, to lesser extent, the midlatitude westerlies. Compared to the eastern side of Africa and the neighbouring Indian Ocean, the annual cycle in ITCZ location over the Atlantic and neighbouring western Africa is far less pronounced. Throughout the year, the coherent structure of the Atlantic ITCZ migrates north and south, staying largely parallel to the equator across the basin with a slight inclination to the north in the eastern part of the basin (larger in some months than others). In austral autumn (April-May), the Atlantic ITCZ attains its southernmost position with its core reaching 5°S in the west, over the northeast coast of Brazil, but staying slightly north of the equator in the Gulf of Guinea region in the east. In austral winter (July-August), the Atlantic ITCZ moves furthest away from the equator to 8-10°N. Over neighbouring southern Africa, the ITCZ reaches its southernmost position in February when it lies across Madagascar, central Mozambique, and southeastern Zambia in eastern Africa. Over the latter region, there is a confluence with the Congo Air Boundary that separates moist tropical air over Angola / Congo from drier air over Namibia and Botswana. To the north of this confluence, the ITCZ stretches meridionally through Zambia and Congo before exiting out over the equatorial eastern Atlantic. Between February and April, the ITCZ moves northward over southern Africa while slowly reaching its southernmost position over the Atlantic near 5^{o}S as SST there reaches its maximum. In austral winter, the ITCZ over Africa is located well north of the equator.

Since Africa terminates at relatively low latitudes (near 34°S), the annual cycle in the location and intensity of the subtropical anticyclone and midlatitude westerly belt over the South Atlantic is far smaller than in the North Atlantic or Pacific. On average, the South Atlantic anticyclone shifts only 6° of latitude between the seasons and a significant semi-annual oscillation in this position is observed. The zonal shift in the anticyclone is about 13°, again with a semi-annual signal superimposed, and it tends to lie closer to southern Africa in spring. These seasonal fluctuations in the anticyclone drive changes in surface wind which then impact on SST, particularly in the upwelling zones along the southern Angolan, Namibian and South African coasts and, further north, in the Gulf of Guinea and the Atlantic cold tongue.

Over the tropical Atlantic, the underlying surface conditions in the two extreme seasons are quite different. In austral autumn, a relatively weak and broad region of marine convection, strongest in the western equatorial region, is located over a wide strip of warm SSTs with weak latitudinal gradients. In the winter, the band of ITCZ associated precipitation is sharp and stretches across the entire ocean basin with largest values in the east. The band of warm SST is relatively narrow surrounded by strong latitudinal gradients, particularly to the southeast, where the Atlantic cold tongue resides.

The relationship between tropical SST, convection, and surface winds was studied by Mitchell and Wallace (1992). They emphasized the dominance of the first harmonic of the annual cycle in the pattern of ITCZ seasonal variability and proposed that the reasons for this behaviour lies in the response of the tropical atmosphere-ocean system to the variations of insolation in the presence of a north-south asymmetry of the distribution of land masses around the equator (particularly in the eastern boundary from which the trade winds are blowing). In particular, they note that it is the development of the massive convection centers over land (in the Atlantic case, the west African monsoon) during late boreal spring, early summer, that leads to the development of the cross equatorial flow in the east, which in turn forces equatorial upwelling and advection of cold water from the Southern Hemisphere and the development of the cold tongue. The development of the cold water leads to rise in sea level pressure over the equator, which further enhances the northward flow, which assists in the development of the monsoon. Over the ocean, the presence of warm water at ~7°N and the airflow from the south, contribute to the creation of a strong, and well-defined region of ITCZ convection. This positive feedback interaction between ocean and atmosphere is what keeps the marine ITCZ well to the north of the equator until well into austral spring, when the convection over land begins to move south of the equator.

A pronounced seasonal difference in rainfall patterns exists over southern Africa which is related to the annual cycle in the subtropical high pressure belt and the ITCZ. The annual cycle of rainfall based on the CAMS-OPI dataset (Janowiak and Xie, 1999) is presented as the percentage contribution of each season to the annual rainfall (Fig. 1.1). The southwestern Cape (SWC) region of South Africa is a mainly austral winter rainfall region, the south coast an all season rain region, whereas rainfall over most of the rest of subtropical southern Africa occurs mainly in the summer and is generated largely from convective thunderstorms (Harrison, 1984), driven for the most part by tropical-extratropical interaction and associated cloudbands. Over tropical southern Africa, the main rainy seasons shift towards bimodal in the east and late summer / autumn in the west. The Atlantic seaboard of southern Africa and the neighbouring hinterland contains the Namib, western Karoo and Kalahari deserts and is much drier than the eastern half of southern Africa.

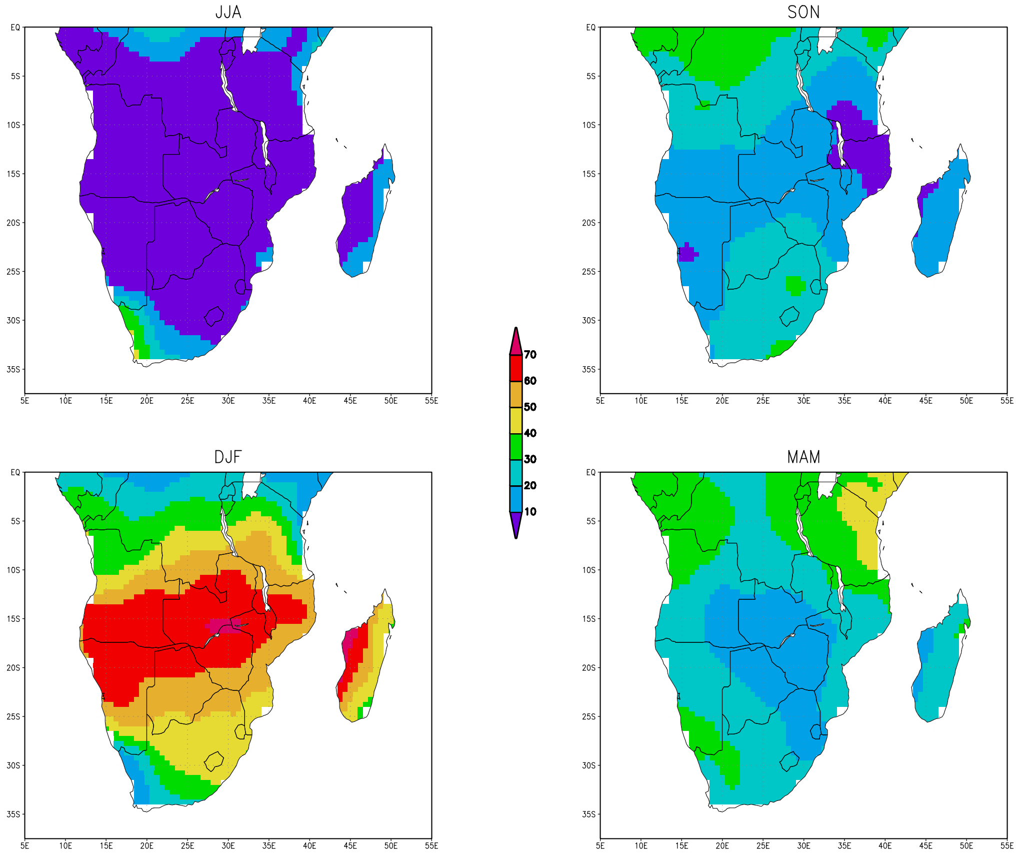

Figure 1.1: Seasonal rainfall as a percentage of the annual rainfall based on CAMS-OPI data for the period 1979-2003.

Winter rainfall over the SWC is frontal and is facilitated by the northward shift of the anticyclone over the South Atlantic and the development of a region of relative low pressure between it and the South Indian anticyclone that lies just to the south of the SWC. Substantial interannual variability exists and evidence exists that this may be related to South Atlantic SST gradients (Reason *et al.*, 2002 - Section 4). North of about 15^{o}S, the influence of the tropical South Atlantic may be important via westerly moisture flux associated with the Angola low. This region receives most of its rainfall in late summer (February-April).

The Angola low is a shallow heat low that develops from about October over southern Angola and northern Namibia and strengthens considerably from January onwards. A confluence zone stretches northeast towards the meridionally oriented ITCZ across central southern Africa. North of the low, there is a relatively weak low level moisture flux from the tropical southeast Atlantic over Angola. To the south, low level easterly moisture fluxes originating from the Indian Ocean, dominate most of subtropical southern

Africa in summer. In addition, the Angola low acts as the tropical source region for the tropical-extratropical cloudbands that bring most of the summer rainfall across southern Africa south of about 15°S. On occasion, easterly disturbances track west across subtropical southern Africa from the South Indian Ocean and merge with the low, typically leading to enhanced rainfall. Evidence exists (Rouault *et al.*, 2002) that modulations of the Angola low, related to tropical South East Atlantic SST, may significantly influence summer rainfall over large areas of southern Africa, particularly Angola and northern Namibia (Section 3) but also South Africa (Cook *et al.*, 2004).

Early studies of moisture flux and rainfall variability over South Africa (D'Abreton and Tyson, 1995) suggested that the Indian Ocean source of moisture for the summer rainfall area shifts between wet and dry years. NCEP reanalyses (Kalnay et al 1996) that have subsequently become available suggest that moisture sourced from the Indian Ocean feeds primarily into the ITCZ over Mozambique and the western Indian Ocean and that the South East Atlantic Ocean is also an important source of moisture for the southern Africa region (Fig. 1.2). The moisture sources and sinks in this figure are calculated from the divergent flow produced by the NCEP reanalysis model. This field, however, is classified as having second-order accuracy, suggesting that some level of error is possible in the moisture source/sink values. However, the importance of the South East Atlantic Ocean as a moisture source remains clearly evident for both DJF and JJA seasons.

Moisture flux is determined by atmospheric circulation. This is associated with the lower branch of the Hadley Cells in the tropics and with mid-latitude cyclones in the westerlies. The convergence of moisture in the ITCZ is clearly shown at about 10°S over the Indian Ocean and about 5°N over the Atlantic Ocean during DJF. In the austral winter the ITCZ shifts to the northern hemisphere and the South Atlantic Ocean remains a strong source of moisture. The southward flux of moisture over the South Atlantic Ocean is relatively strong compared to the other oceans in the Southern Hemisphere during both DJF and JJA (Fig. 1.2).

Further evidence of the relationship between rainfall variability in southern Africa and the large-scale circulation is shown with vertically integrated barotropic and baroclinic kinetic energy. Distinct contrasts between the characteristics of the daily archetype frequencies are found between wet and dry years (Tennant and Hewitson 2002). Typically barotropic kinetic energy is reduced and shifted polewards during wet summers and baroclinic kinetic energy breaks into two branches, with the northern branch over southern Africa. Similar associations have been found for the winter rainfall areas of the SWC. These are shown here as composites of the rate of conversion of eddy potential energy into eddy kinetic energy between wet and dry years (as defined in Tennant and Reason, 2004) (Fig. 1.3). During dry South African summers, this energy conversion is enhanced around 45°S over the South Atlantic Ocean. During dry winters in the SWC, a northward displacement of activity is shown in the western sector of the South Atlantic Ocean. Wiin-Nielsen (1962) described the energy cycle as eddy potential energy converting into eddy kinetic energy and then into zonal-mean kinetic energy. Northward displaced energy conversion in the South Atlantic Ocean would then contribute to enhanced zonal-mean kinetic energy downstream, i.e. in the African region, that would suppress rain-bearing systems over that region. It is of particular interest that these associations are located predominantly over the South Atlantic Ocean indicating the importance of the circulation in this region to rainfall in South Africa, and potentially, southern Africa.

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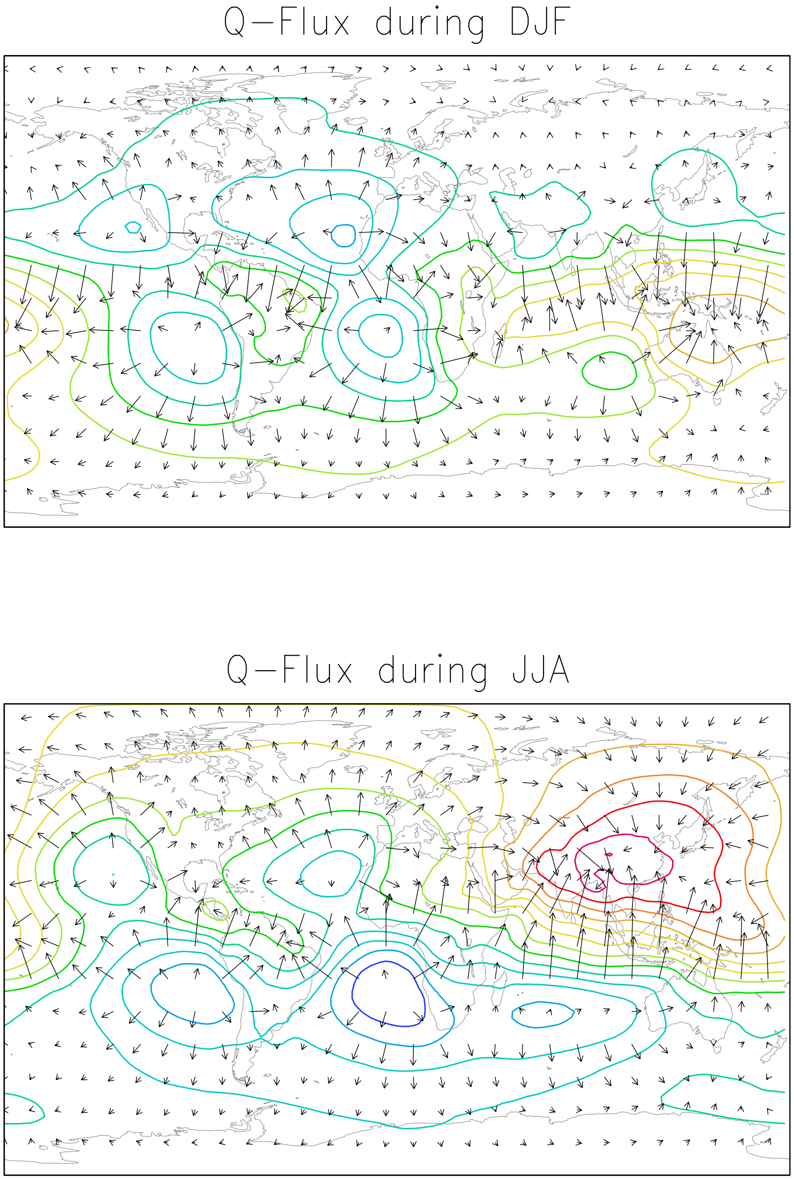
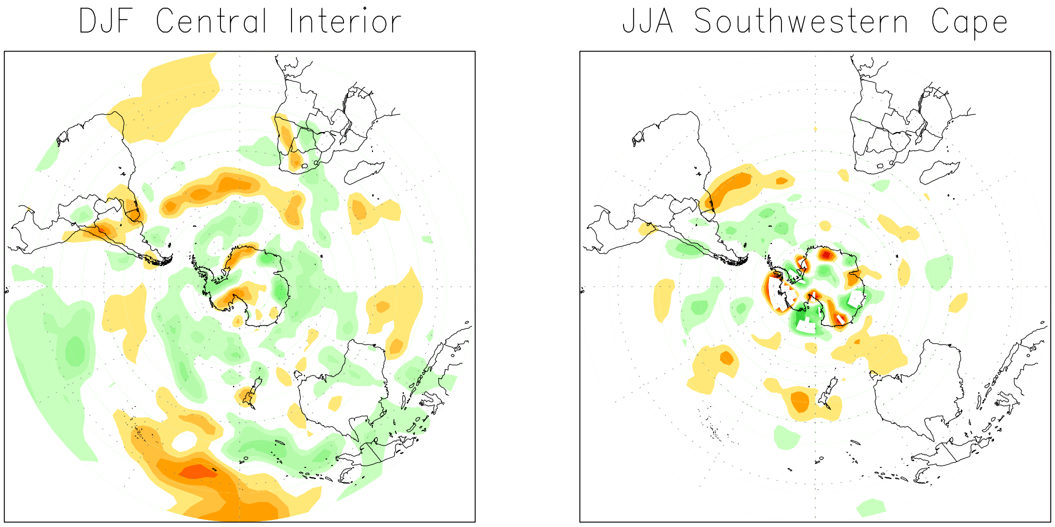


Figure 1.2: Average vertically integrated moisture flux and velocity potential for the austral summer (top) and winter (bottom) based on 6-hourly NCEP reanalysis data for the period 1979-2003.



DJF Central Interior

JJA Southwestern Cape

Figure 1.3: Dry-wet composites of the conversion rate (W.m^2) of eddy potential energy to eddy kinetic energy for central South Africa (DJF) and the southwestern Cape (JJA) over the period 1979 to 2002.

2. Interannual and interdecadal variability

ENSO is the dominant mode of interannual variability over the tropical Southern Hemisphere whereas the Antarctic Oscillation or Southern Annular Mode (SAM) is the leading mode in the mid- to high latitude atmospheric circulation. Trends towards high-index polarity in the SAM have been noted (Thompson et al. 2000), but the effects of such trends on southern African climate are unclear. It is worth noting however that Fyfe (2003) and Simmonds and Keay (2003) show that such trends are likely accompanied by a decrease in mid-latitude cyclones over the hemisphere as a whole.

ENSO is known to project strongly over southern Africa and the South Atlantic (e.g., Lindesay *et al.*, 1988; Venegas *et al.*, 1996; Reason *et al.,* 2000) and has significant rainfall impacts, particularly during the mature phase. Anomalously wet winters in the SWC region of South Africa have been linked to the SAM (Reason *et al.*, 2002). In addition, the tropical Atlantic develops both its own zonal SST variability on interannual timescales, the so-called Atlantic ENSO (Houghton, 1991; Zebiak, 1993). On longer time scales, a meridional SST gradient mode exists in the tropical Atlantic that appears to be related to changes in the tradewinds either side of the ITCZ.

In terms of climate impacts on southern Africa, in addition to ENSO, various South Indian Ocean SST patterns (Walker, 1990; Mason, 1995; Reason and Mulenga, 1999; Behera and Yamagata, 2001; Reason, 2002), the so-called Benguela warm and cold events (Hirst and Hastenrath, 1983; Shannon *et al.*, 1986; Rouault *et al.*, 2002) and modulations of SST in the subtropics and midlatitudes of the South Atlantic (Reason *et al.*, 2002) are thought to be significant for various regions in the subcontinent. It should be emphasized that SST variability in the South Indian Ocean is generally believed to exert more influence over southern Africa than that over the South Atlantic (e.g., Nicholson and Entekhabi, 1986; Walker, 1990; Mason, 1995; Mason and Jury, 1997) since the airmasses originating over the former tend to be relatively warm and moist whereas those from the eastern Atlantic are relatively cool and dry. However, it is also true to say that the climate impacts of the Atlantic on southern Africa are less well understood.

Most of southern Africa experiences substantial climate variability on interannual and interdecadal scales. One of the strongest interdecadal signals in the Southern Hemisphere concerns the roughly 18 year cycle in summer rainfall over South Africa and neighbouring countries (Tyson *et al.*¸ 1975). Various mechanisms have been proposed including regional SST forcing and modulations of the Southern Hemisphere circulation (Mason and Jury, 1997), and the projection of ENSO-like decadal modes onto the region (Fig.2.1) which could also explain interdecadal variability observed in SWC winter rainfall (Reason and Rouault, 2002). These modes have a significant expression in SST over the South Atlantic (Allan, 2000); however, their rainfall impact over southern Africa arises via changes to the atmospheric circulation (Fig. 2.2) rather than from South Atlantic SST. For the summer rainfall region, there are changes in the local Indian Ocean Walker cell and the easterly advection of moist marine air over the land whereas for the winter rainfall region, large scale shifts in the jet and westerly storm tracks over the midlatitude South Atlantic are important (Reason and Rouault, 2002). Another significant interdecadal scale signal concerns the hemispheric modulation of the subtropical high pressure belt (Jones and Allan, 1998; Reason, 2000) including the South Atlantic. Given the importance of the South Indian and South Atlantic anticyclones for southern African climate, one might expect significant impacts on southern African rainfall variability; however, this is unclear.

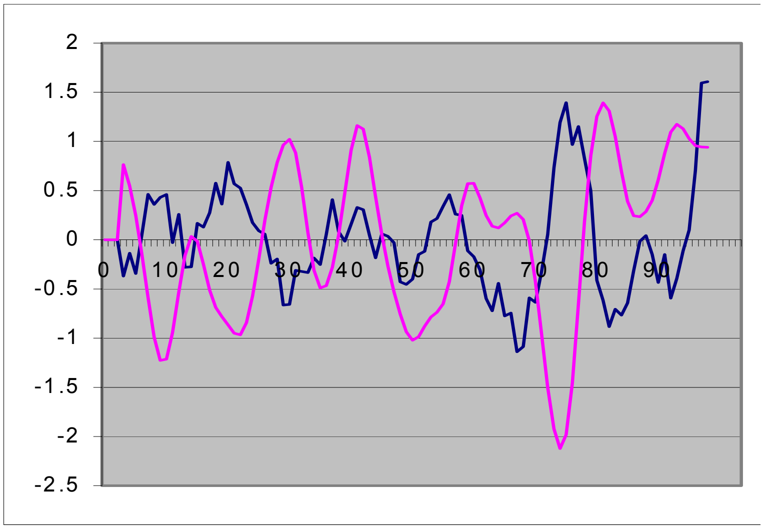


Fig. 2.1 South African smoothed summer rainfall (blue) for 1903-98 and average of ENSO-like EOFs on 9-13 year and 18-39 year filtered bands(pink). After Reason and Rouault (2002)

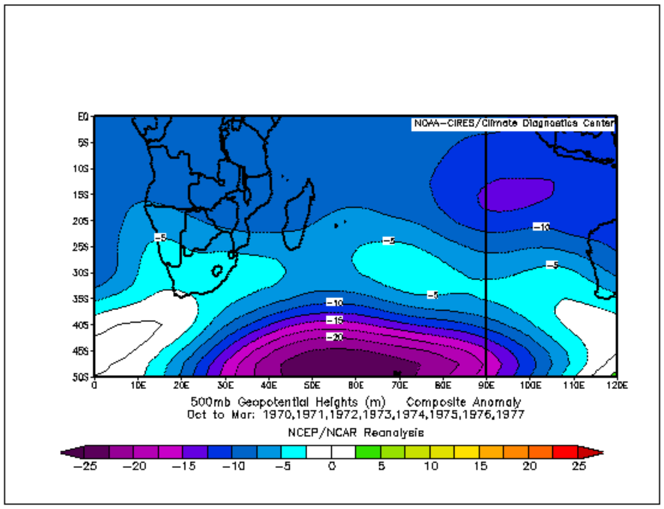


Fig. 2.2a. 500hPa height anomalies (m) for the wet 1970-1977 period. After Reason and Rouault (2002).

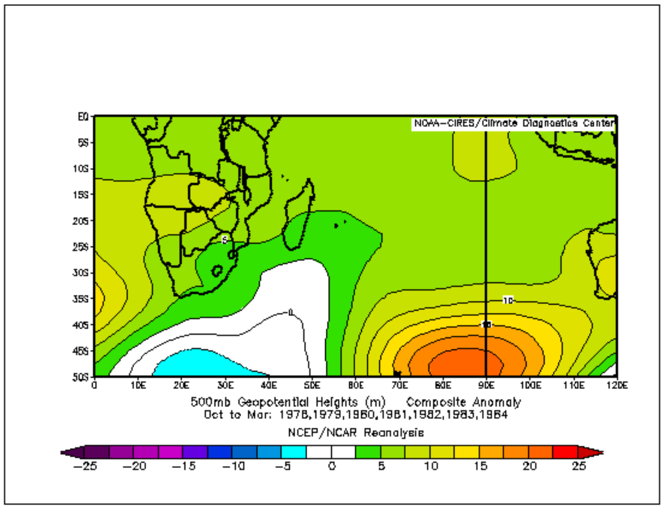


Fig. 2.2b. 500hPa height anomalies (m) for the dry 1978-1984 period. After Reason and Rouault (2002).

On interannual scales, variability around 2-3 years and 5-6 years is prominent (Nicholson and Entekhabi, 1986; Tyson, 1986). ENSO is a major contributor to interannual variability over southern Africa but by no means the only forcing. In addition to modulating the SST of the neighbouring Indian and South Atlantic Oceans, ENSO leads to changes in the regional atmospheric circulation, primarily via the local Walker circulation (e.g., Lindesay, 1988; Reason *et al.*, 2000) and the South Indian Convergence Zone (Cook, 2000, 2001) which tend to suppress (enhance) rainfall during the mature phase of El Niño (La Niña) events. Over the South Atlantic, Colberg *et al.* (2004) used a global ocean model forced by 50 years of NCEP fluxes to find that the SST and upper ocean circulation of the basin mainly responds passively to ENSO-induced changes in surface fluxes, the latter largely wind-driven via circulation anomalies associated with the Pacific South America (PSA) pattern (Mo and White, 1985; Karoly, 1989). In addition, to its influence on mid- and high latitude atmospheric circulation over the South Atlantic via the PSA pattern, ENSO also influences the South American Convergence Zone (SACZ), a feature that is most prominent in the austral summer. Local South Atlantic SST anomalies also influence the strength and location of this feature (Robertson *et al.*, 2003). Since the SACZ acts to export moisture and energy to higher latitudes, it influences the jet stream and generation of mid-latitude cyclones upstream of southern Africa which may then impact on the development of tropical-extratropical cloudbands over the subcontinent.

From the foregoing, it should be evident that southern African climate variability is sensitive to a range of factors and this poses great challenges for predictability. One simple way to try and isolate factors is to separate those clearly associated with ENSO events. Such a separation was attempted by Walker (1990) in an assessment of the influence of South Atlantic and South Indian SST anomalies on South African summer rainfall. More recently, Mulenga *et al.* (2003) separated interannual JFM droughts over northeastern South Africa into ENSO and non-ENSO droughts. The latter all appeared to show an atypically strong influence of relatively cool, dry South Atlantic air being advected over South Africa as a result of a cyclonic anomaly being located over the southeast Atlantic, either west of South Africa or just to the southwest. These droughts were classified by Mulenga *et al.* (2003) as ones where the atmospheric circulation over the subtropical to midlatitude South Atlantic had an anomalously strong role to play whereas most other droughts where tropical in origin, via ENSO. In addition to the very recent 2003/4 severe summer drought, previous strong examples include 1981/2, 1967/8 and 1951/2. The importance of the midlatitude circulation for these droughts suggests that their predictability is not high; however, some success in forecasting the current 2003/4 drought has been achieved using GCMs forced with forecast global SSTs from a coupled model. For example, the November-January seasonal forecast using HadAM3 forced with CSIRO COCA coupled model forecast SSTs suggested that the summer rainfall region would receive 80-100 % of average rainfall during this period whereas the COLA GCM run at the SA Weather Service indicated that northern South Africa would receive 50-75 % of average rainfall. Observed rainfall was considerably less than this in parts of South Africa but this model forecast was at least consistent in sign with the general drought conditions over most of South Africa.

As previously mentioned, warm and cool events in the tropical South East Atlantic (the so-called Benguela Niños and Niñas) have significant impacts on late summer rainfall, particularly over Angola and northern Namibia (Hirst and Hastenrath, 1983; Rouault *et al.*, 2002). These events involve modulations of the tradewinds over the South Atlantic which then generate equatorial Kelvin waves in the western Atlantic that propagate across and lead to coastal wave signals along the Angolan and northern Namibian coast (Florenchie *et al.*, 2004). Where the thermocline shoals towards the surface, typically off southern Angola, a large SST anomaly expresses itself. Given the approximately two month lag between the wind stress modulations and the manifestation of SST anomalies along the Angolan coast, some predictability of the SST anomalies may be achieved. Current statistical forecasting schemes (CCA, neural nets) in use in South Africa (Landman and Mason, 2001) do not capture these events, —or indeed perform satisfactorily over the South Atlantic as a whole; this may be because of the importance of coastal trapped waves and other dynamics for their evolution which are not well represented by statistical models of this type.

3. Tropical South East Atlantic variability - Benguela warm and cool events

Benguela Niños are intermittent, acute, extreme warm events near the border between the southward flowing Angola Current and the Benguela upwelling system off southwestern Africa (Shannon et al. 1986). These anomalously warm events have dramatic effects on the fisheries and the climate of the region. They tend to induce significant rainfall anomalies (Rouault et al. 2003) and can drastically modify fish distribution and abundance (Boyer et al. 2001). Benguela Niños occurred in 1934, 1949, 1963, 1984 (Shannon et al. 1986) and more recently in 1995 (Gammelsrød et al. 1998). Such episodes are less frequent and less intense than their Pacific counterparts, and they tend to develop south of equator.

In essence, Benguela Niños express themselves as abnormally and persistent high sea surface temperatures (SST) along the coast of Angola and Namibia. Conversely, Benguela Niñas may be regarded as similar, except that the SST anomalies along the coast are cool (Florenchie *et al.*, 2004). Smaller warm and cool events along the Angola / Namibian coast occur frequently and may be generated in a similar way to Benguela Niños and Niñas; however, their surface expression is weak due to other factors.

A combination of various observational and model analyses at different depths suggests that, despite their limited surface expression, warm and cold episodes along the coast of Angola and Namibia are in fact large-scale events spreading from the equator at different depths with a duration of several months. Analysis of altimeter, SST and OPA OGCM output (Florenchie *et al.*, 2003, 2004) indicates that all warm (cold) episodes in the tropical SE Atlantic over the 1992-2000 period tend to be associated with positive (negative) sea level anomalies spreading along the African coast from the equator to as far south as about 20°S **(Fig. 3.1).**

The 1995 and 1996 warm events show positive anomalies with respective local maxima of 12 cm and 10 cm while the 1997 cold event shows strong negative anomalies with a local minimum of -11 cm. Calculations from the slope of Hovmoeller plots of sea level anomalies suggest a poleward propagation rate of between 0.5 and 1 m/s **(Fig. 3.1)**. Such an estimate agrees with the poleward propagations observed in the eastern Pacific by Enfield and Allen (1980) or simulated (Clarke and Van Gorder, 1994). A coastal trapped wave propagation process is consistent with the spreading of anomalies from the equator southward. However, discrepancies between theoretical phase speeds and the slower observed ones may occur because the theory does not take into account coastal shelf and slope bottom topography or bottom friction (Clarke and Van Gorder, 1994; Pizarro et al., 2001).

Analysis of ERS wind stress and Reynolds SST in the equatorial Atlantic (Florenchie *et al.*, 2003, 2004) indicates that, about 3 months prior to the appearance of SST anomalies along the Angola coast, the eastern equatorial Atlantic is directly influenced by remote zonal wind stress anomalies **(Fig. 3.2).** through equatorial wave dynamics (there is less than a one-month lag between the two signals). As noted by Picaut (1985), equatorial oceans tend to respond clearly and coherently to wind fluctuations as seems to be the case here. Anomalies in the trades in the western to central equatorial Atlantic basin excite eastward propagating Kelvin waves that depress or lift the thermocline all the way to the African coast and create subsurface temperature anomalies. On reaching the African coast, coastal trapped waves are generated which propagate southward and induce SSTA in the Angola Benguela frontal area (ABA), where the thermocline reaches the surface **(Fig. 3.3)**.

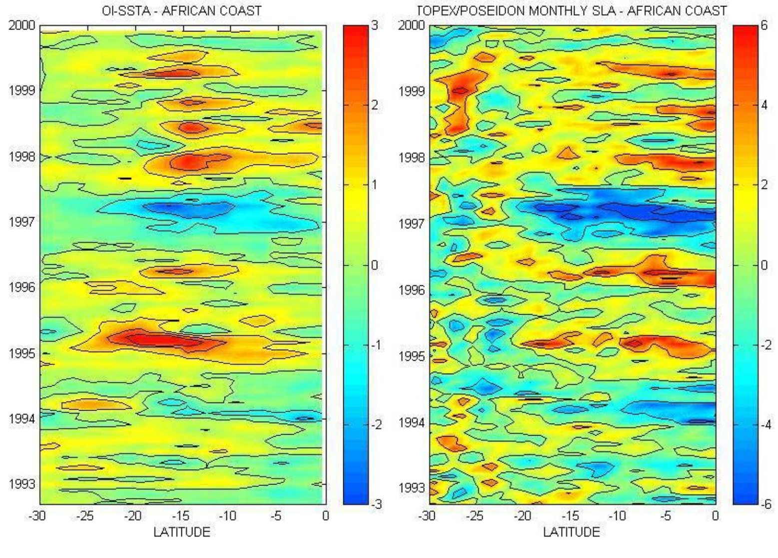


Fig. 3.1 Sea surface temperature (right) and sea level (left) anomalies along the African coast from the equator to 30°S versus time (after Florenchie *et al.,* 2003).

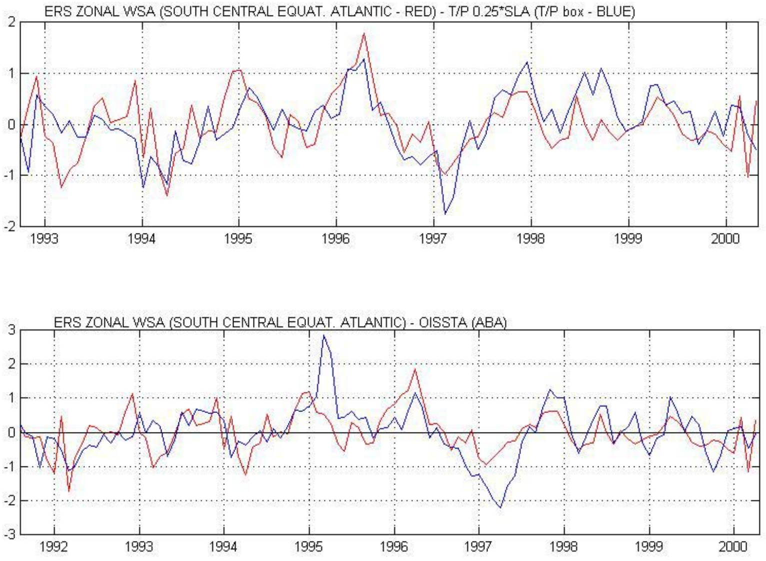


Fig 3.2: Time series of zonal WSA averaged south of the equator (between 5.5S and 0.5S) in the central basin from 29.5W to 9.5W and (a) SLA averaged over the Topex box and (b) OISSTA averaged over the ABA. After Florenchie *et al.,* 2004.

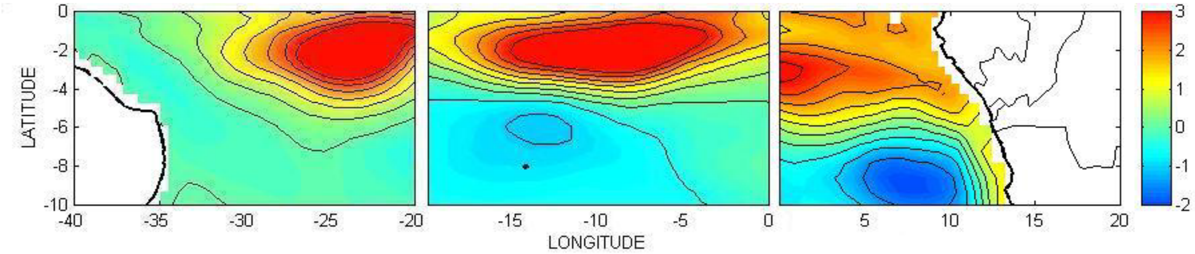


Fig. 3.3: Time – depth evolution 1984 over 1 month, shoaling from 100 to 45 m across tropical Atlantic. After Florenchie *et al.* (2003).

The strong correlation (Fig. 3.4) between SST anomalies in the ABA and interannual zonal wind anomalies just south of the equator over the western and central Atlantic basin suggests a mechanism based on equatorial and coastal trapped waves to explain the equatorial origin of most episodes. SST anomalies become visible at the surface one to two months after the appearance of subsurface temperature anomalies at the thermocline depth. Such anomalies can be attributed to vertical shifts of the thermocline under the action of propagating Kelvin waves initially triggered by zonal wind variations. These waves are deviated poleward on approaching the African continent and temperature anomalies become more or less visible at the surface as a function of various factors like the strength of the event, the depth of the thermocline or the upwelling or downwelling-favourable winds. Temperature anomalies start interacting with the atmosphere when and where the thermocline outcrops along the coast. Seasonal variations of the thermocline depth and shape also modulate the surface expression of the anomaly pool.

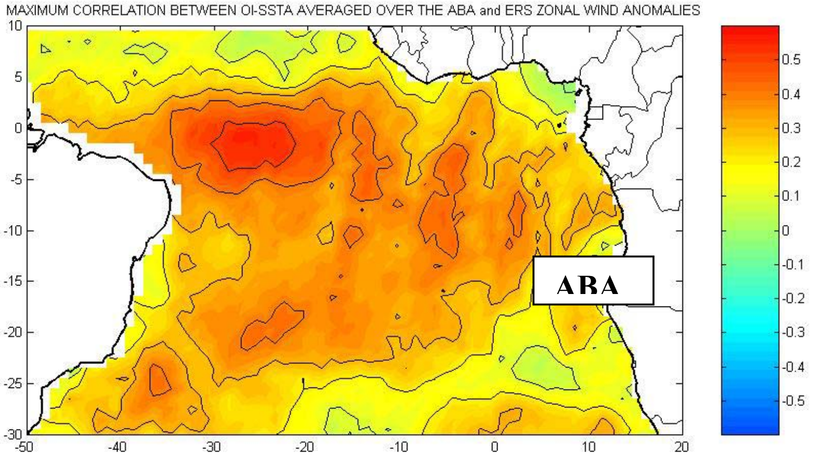


Fig. 3.4 Correlation between SST and ERS zonal wind anomalies. After Florenchie *et al.* (2004)

Analysis of local heat fluxes (Florenchie *et al.*, 2004) suggests that the latent heat flux seems to have a rather passive role on the evolution of events in the ABA and mainly acts as a thermostat to regulate cold and warm events at the surface. Local variations in latent heat flux definitively did not create the higher than normal SSTs in the large Benguela Niños of 1984 and 1995. Furthermore, since the local rain anomalies tend to be positive (negative), and cloud cover increased (decreased) during warm (cool) events, changes in solar radiation tend to weaken the events, i.e., they act in concert with the latent and sensible heat fluxes to moderate the surface expression of the events. Local wind-induced upwelling and offshore Ekman transports may have contributed towards producing lower SSTs during the 1992 and 1997 cool events, but, in general, the local wind regime does not seem to play the major role in the expression of Benguela Niños and Niñas.

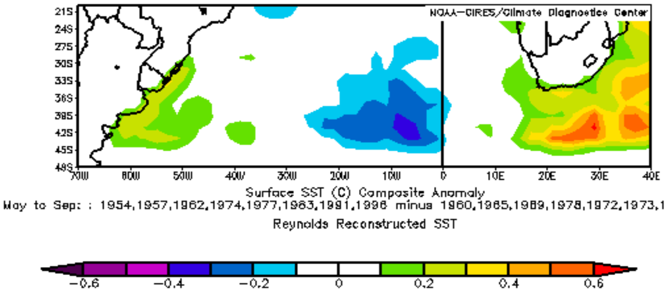
Despite the relatively rare occurrence of Benguela Niños and Niñas, warm and cold SST anomalies tend to develop regularly off Angola and Namibia. Monthly standard deviations reveal seasonality with a maximum of surface temperature variability in March/April and a minimum in September/October. Major warm events in phase with late summer are likely to give rise to Benguela Niños since they induce extremely high sea temperatures that affect the ecosystem. By interacting with the atmosphere via moisture fluxes, high SSTs may reinforce the rainfall season of southwestern Africa with sudden flooding and devastating consequences.

Sea level anomalies in the eastern equatorial basin show a strong correlation with the southern SSTA signal. The remote forcing of the SST anomalies highlights the possibility of being able to forecast future extreme events via real-time sea level and wind observations or predictive models. The development of equatorial subsurface anomalies could also be detected in advance using local measurements such as the ones performed by the PIRATA array (Servain et al. 1998). However, the non-linear response of SST anomalies in the ABA to the remote wind forcing emphasizes the need for further work to understand the way different mechanisms seem to control the development of each individual event in the tropical Atlantic basin.

There are also likely to be important links between these events and the West African monsoon. Analysis of NCEP OLR, wind and geopotential height data indicates that the winter intensification of wind-stress off the Angolan coast is linked with convective activity over equatorial West Africa (Risien *et al.*, 2004). Given that some of the moisture feeding into the West African monsoon emanates from the tropical SE Atlantic, better understanding of the teleconnections between monsoonal activity and variability in the heat budget of the eastern South Atlantic is needed. The role of modulations to the South Atlantic anticyclone, which is known to vary substantially on interannual to interdecadal scales (e.g., Venegas *et al.*, 1997; Reason, 2000) as well as respond to ENSO forcing (e.g., Venegas *et al.,* 1999; Reason *et al.,* 2000), in influencing both the SST and upper ocean heat content in the SE Atlantic as well as the moisture flux towards West Africa remains poorly understood.

4. South Atlantic subtropical / midlatitude SST variability and SWC rainfall

The SWC region of South Africa experiences significant interannual and interdecadal variability in its rainfall, which is predominantly during winter via cold fronts. Previous work (Reason *et al.*, 2002) has found evidence of relationships between interannual winter rainfall variability and anomalies in sea-ice extent near Drake Passage and the eastern Weddell Sea and in SST over the subtropical / midlatitude South Atlantic (Figs. 4.1, 4.2). Wet winters tended to be associated with warm anomalies in the Brazil / Falklands confluence region, climatologically an important cyclogenesis area, and also just to the south and upstream of the SWC near the Agulhas Retroflection region suggesting that frontal systems would be enhanced via increased moisture uptake just prior to landfall. Cool SST anomalies tended to be found over the central South Atlantic favouring a strengthening of the baroclinic gradient here as well as a northward shift of storm tracks via potential vorticity conservation. The large scale atmospheric circulation showed a negative SAM pattern with low pressure anomalies stretching northeast towards the SWC from the SW Atlantic (Fig. 4.3). Dry winters showed roughly the reverse atmospheric anomalies but with a more obvious shift in the wavenumber 3 pattern to produce anticyclonic anomalies over southern South Africa.



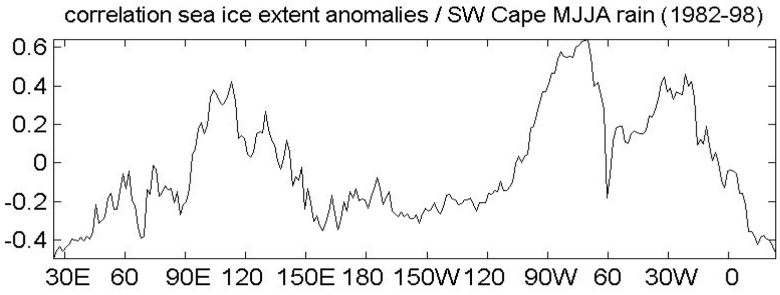


Fig. 4.1 SST anomalies (0.1 oC contour interval) derived for wet – dry southwest South African winters 1950-2001 (Reason *et al.,* 2002)

Fig. 4.2. Correlation between sea-ice extent and SW SA winter rainfall – maximum near Drake Passage and Weddell Sea (Reason *et al.,* 2002)

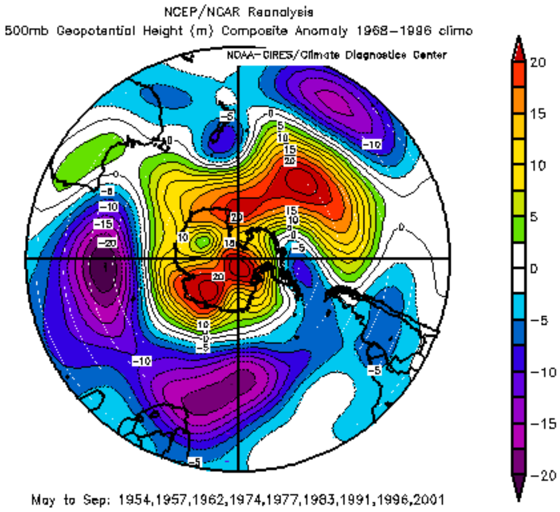


Fig. 4.3. 500hPa height anomalies for wet winter composite (Reason *et al.*, 2002)

Recent modeling work (Reason and Jagadheesha, 2004) with an AGCM (HadAM3) has shown that the regional atmosphere is sensitive to idealized representations of the SST anomalies observed over the subtropical and midlatitude South Atlantic during wet and dry SWC winters. Earlier, Robertson *et al.* (2003) showed that the atmosphere is sensitive to tropical and subtropical South Atlantic SST forcing during summer using a different AGCM; however, the impacts were mainly expressed over South America, the ITCZ and the South Atlantic Convergence Zone with those over Africa being restricted to West Africa.

Although there do appear to be some robust linkages between South Atlantic SST and SWC winter rainfall, much work remains to be done to elucidate these further. The question of what forces these SST anomalies and how they are related to large scale modes such as ENSO and the SAM remains to be investigated. If predictability is to be realised, then a better understanding of the projection of ENSO and the SAM onto the South Atlantic and the regional atmospheric circulation is needed. In addition, possible relationships between these two modes needs to be investigated as well as that with the Antarctic Circumpolar Wave. As yet, no clear evidence of the influence on the latter on southern African climate has been presented, although it has been claimed (White *et al.*, 2003; Cherry and White, 2002) that it impacts on southern Australian, New Zealand and southern South American rainfall.

5: Regional forecasting efforts using GCMs and statistical methods

The scientific basis for doing seasonal forecasting originates from the observation that slowly evolving sea-surface temperature (SST) anomalies influence seasonal-mean weather conditions (Palmer and Anderson 1994). Therefore, estimation of the evolution of SST anomalies, which may be relatively predictable, and subsequently employing them in atmospheric GCMs, potentially provides means of generating forecasts of seasonal-average weather (Graham et al. 2000). Although GCMs, commonly configured with an effective resolution of 200-300 km, have demonstrated skill at global or even continental scale, they are unable to represent local sub-grid features, subsequently producing rainfall over southern Africa that is typically overestimated (Joubert and Hewitson 1997; Mason and Joubert 1997). Also, the model representation of rainfall is complex and often not well estimated (Graham et al. 2000; Goddard and Mason 2002). Such systematic biases have created the need to downscale or recalibrate GCM simulations to regional level over South Africa. Semi-empirical relationships exist between observed large-scale circulation and rainfall, and assuming that these relationships are valid under future climate conditions and also that the large-scale structure and variability is well characterized by GCMs, equations can be constructed to predict local precipitation from simulated large-scale patterns (Wilby and Wigley 1997). Recently, empirical remapping of GCM fields to regional rainfall has been demonstrated successfully over southern Africa (Landman and Goddard 2002; Landman and Tennant 2000; Landman et al. 2001).

Predictability studies and forecast model development efforts in southern Africa have extensively sought links between large-scale phenomena, such as El Nino/Southern Oscillation (ENSO), and seasonal total rainfall anomalies in various regions (e.g., Lindesay *et al.*, 1986; Jury *et al.*, 1994; Mason, 1995; Mason, 1998; Jury *et al.*, 1999; Landman *et al.*, 2001). The focus to date has been on using SSTs as the primary source of seasonal predictability. Certainly, there are good associations between rainfall over southern Africa and SSTs in the South Atlantic, Indian and Pacific Oceans (Walker, 1990; Mason, 1995; Reason and Mulenga, 1999). Pioneering forecast efforts used statistical methods such as canonical correlation analysis (Landman and Mason, 1999) and a non-linear discriminant analysis model (Mason, 1998). Other predictors, such as cloud depth and upper zonal winds have also been explored (e.g. Jury, 1999; Jury, 2002).

Local forcing of climate, typically through positive feedback mechanisms with soil moisture (Douville et al., 2001; Zhang and Frederiksen, 2003) and vegetation (Zheng and Eltahir, 1998) is also recognized as an important contributor to seasonal predictability. With this in mind and the various non-linear feedbacks existing in the ocean-atmosphere system, the implementation of general circulation models has become a priority in South Africa. There are three major centres in South Africa that run global atmospheric models that they have acquired from international centres.

The first AGCM used locally is the T30 resolution spectral model, developed at the Center for Ocean-Land-Atmosphere Studies (COLA). The model has been used operationally since 1995 at the South African Weather Service to produce monthly and seasonal forecast guidance. It is applied in a multi-tiered seasonal forecast system (Landman et al, 2001) and in a monthly downscaling system (Landman and Tennant, 2000). The model is described by Kirtman et al. (1997) and its application at the South African Weather Service by Tennant (1999). The model has 18 unevenly spaced sigma layers in the vertical. Prognostic variables include surface pressure, divergence, vorticity, virtual temperature and specific humidity on all 18 levels. The physics include a Simple Biosphere model (SiB) (Sellers et al., 1986).

Secondly, the Hadley Centre Atmospheric Model (HADAM3), a hydrostatic grid-point model with a resolution of 3.75° longitude by 2.5° latitude, is used at the University of Cape Town for research purposes and to produce prototype seasonal forecasts every month. The vertical scheme uses hybrid eta coordinates on 19 levels and the prognostic variables include zonal and meridional wind components, geopotential height, specific humidity and liquid-water potential temperature. A comprehensive description of this model, an evaluation in terms of mean climate and the impacts of the physical parameterizations can be found in Pope et al. (2000). For forecasts over southern Africa it has been found that the original configuration produces little interannual rainfall variability over the continent. Hence the mixed phase precipitation scheme (Wilson,1999) is used which improves the rainfall response of the model. Biases in the asymmetric component of the zonal wind to the south of the continent are also reduced, this relates to the simulation of tropical-temperate troughs which are important for rainfall over the region.

The Mark II version of the nine-level AGCM of the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) at a R21 horizontal resolution (approximately 5.6° by 3.2°) is used for research purposes and experimental seasonal forecasts at the University of Pretoria. In this AGCM, the spectral atmospheric equations in flux formulation (Gordon, 1981) are integrated over nine sigma model levels in the vertical. Details of the physics parameterizations are given in Rotstayn (1997), McGregor et al. (1993) and Watterson et al. (1995).

When used for seasonal forecasting purposes, these three models obtain their SST boundary conditions from CCA forecasts (Landman and Mason, 2001) or from the CSIRO coupled OAGCM COCA forecast model (Ian Smith, pers. Commun., 2003). The latter is a coupled model using the French "CERFACS" OASIS coupler to couple the CSIRO AGCM with the CSIRO OGCM and, after appropriate initialization and "coupled-nudging" produce global SST and atmospheric circulation forecasts up to twelve months ahead (see www.dar.csiro.au/climate/coca.html for more information). In addition to the seasonal forecasts produced for southern Africa in this way, there are also simulations using persisted SST anomalies or perturbation SST forcing for various sensitivity and process-oriented experiments by various workers at the three institutions.

Given that the sharp topographic, vegetation, soil and SST gradients characteristic of the southern African region are unlikely to be adequately represented by these AGCMs, it is important to consider downscaling of their output to the region of interest. Currently, two broad approaches to this are adopted locally; either downscaling using some statistical method or nesting a regional climate model (RCM) within the AGCM output. In terms of the latter, the three local institutions use three different overseas models; namely, MM5, RegCM3 and DARLAM. We briefly discuss some results using RegCM3 at the South African Weather Service (SAWS) and MM5 at UCT and then consider statistical downscaling activities in the region.

5.1.Regional climate modelling

The mesoscale atmospheric circulation systems and surface forcing have an important influence on southern African climate and therefore simulations using higher resolution regional climate models (RCMs) are important. At the SAWS, RegCM3 has been nested within NCEP reanalyses data using one way nesting (Giorgi, 1990).

The purpose of downscaling using RCMs is to obtain information in high-resolution detail as accurately as possible (Leung and Ghan, 1998). Currently, numerical models are still far from perfect, subject to internal error growth due to non-linearity and instability and external error growth due to model deficiencies (Qian et al, 2003). Therefore the question is, how do we obtain optimal results based on currently available tools? In order to address this question a series of experiments need to be done such as investigating the influence of the domain and also the influence of the spin-up period on the simulations. The experiments will help the regional modeller to identify the best parameters to use in order to get the best possible simulations. In a study at SAWS, the model was run using two different spin-up periods to identify the influence that soil moisture has on the simulations and also with different domains to identify the most appropriate domain.

In order to address the influence soil moisture has on the simulations over southern Africa, the RegCM3 was run for a large domain (extending to north of the equator and east of Madagascar) for a 14 month (January 1982 to February 1983) period and also for a 4 month (November 1982 to February 1983) period. The equilibration period is 11 months and 1 month respectively. The difference between the two simulations is great where the rainfall total is much higher e.g. north of Madagascar and the tropical regions. In South Africa the difference is ±100 mm generally. The patterns of the two simulations (Figures 5.1.1 and 5.1.2) are similar with region 4 having the highest rainfall total amount and region 1 having the least rainfall amount.

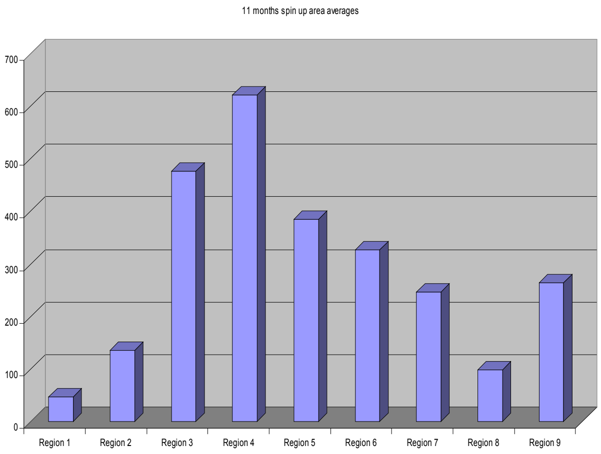


Figure 5.1.1: The area average of the 9 regions over South Africa, Namibia and Botswana using the big domain and a spin up period of 11 months

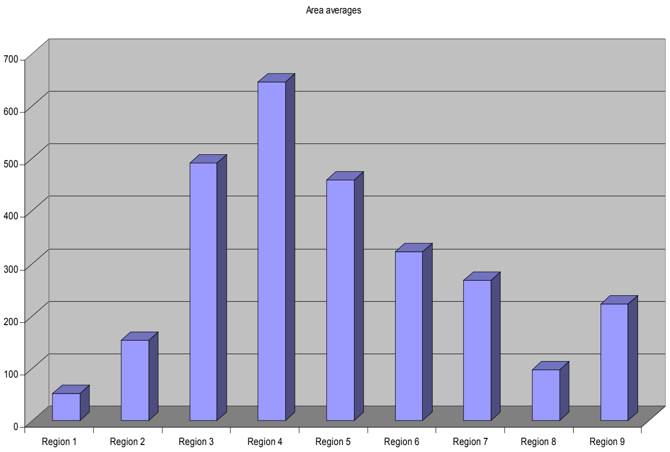


Figure 5.1.2: The area average of the 9 regions over South Africa, Namibia and Botswana using the big domain and a spin up period of 1 month.

Another set of simulations were made for the same four months as above in which case the equilibration period was one month as well, but with a smaller domain. This domain was smaller than the one used above in that the zonal extent was reduced by 7° on the Atlantic side. Since the Indian Ocean is an important moisture source for South African summer rainfall and is complicated by the presence of Madagascar, no adjustment to the eastern boundary was made. The pattern (Figure 5.1.3) of the rainfall was similar to the bigger domain case but the rainfall amounts were reduced. Comparison of the various simulations with observations indicates that the model overestimated rainfall especially over the eastern side of the country and it was concluded that the smaller domain was more appropriate.

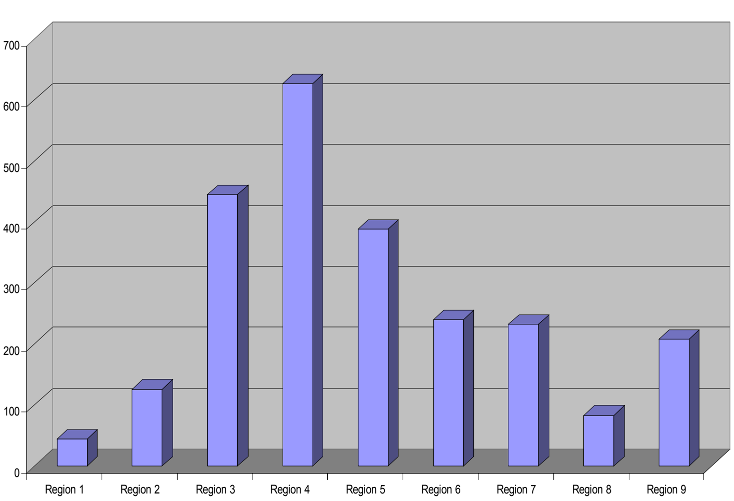


Figure 5.1.3: The area average of the 9 regions over South Africa, Namibia and Botswana using the small domain and a spin up period of 1 month.

Simulations with the smaller domain were run again for 4 months but this time for November 1995 to February 1996. This was a wet season and associated with a La Nina event. The aim of the experiment was to determine if RegCM3 is sensitive to large scale atmospheric forcings. In general, RegCM3 correctly simulated that the 95/96 season was wetter than the 82/83 season (Figure 5.1.5). However, the RegCM3 model, did not correctly simulate the wet anomaly over the east coast and adjacent interior and the Lowveld of South Africa (Figure 5.1.4).

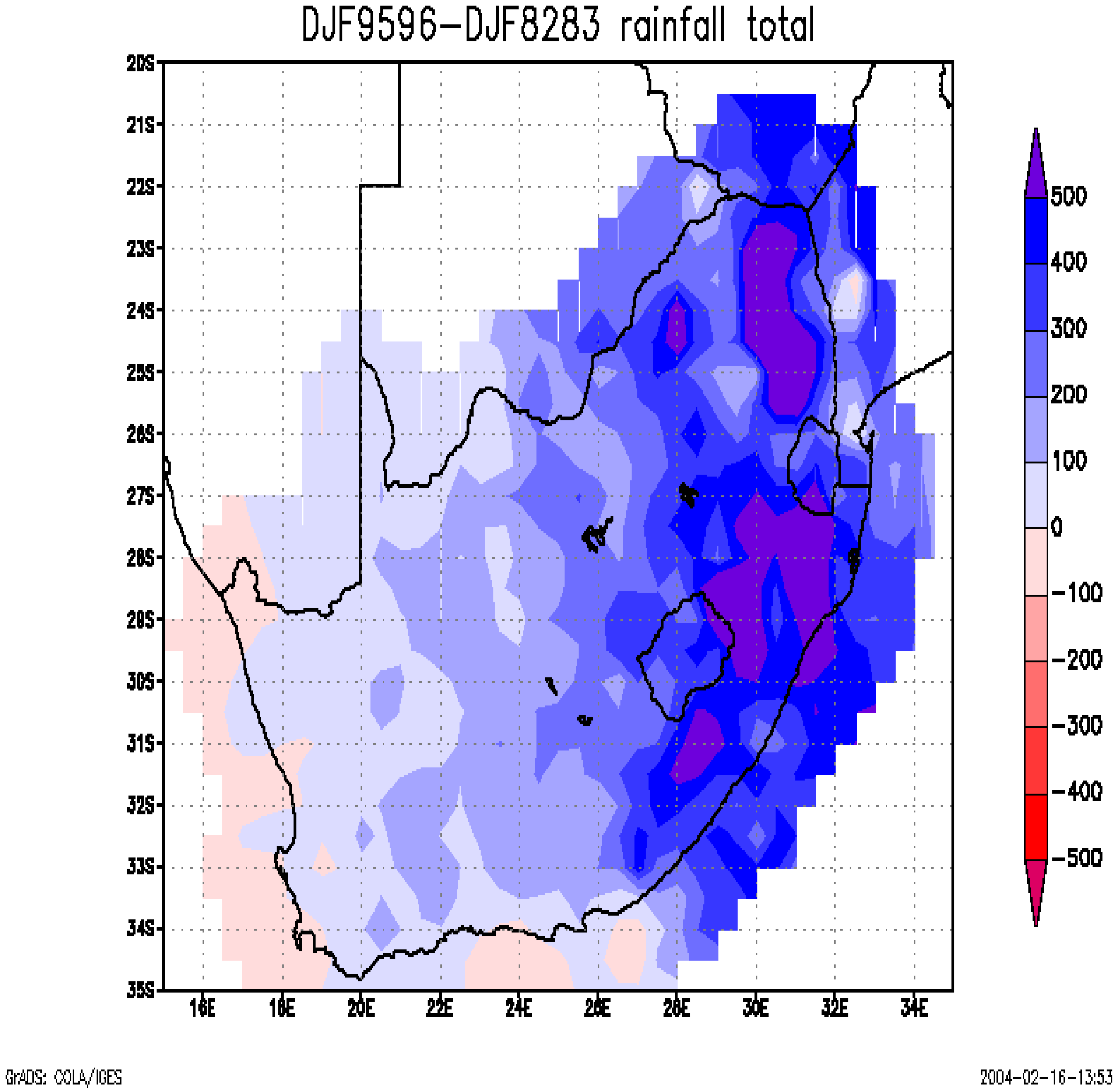


Figure 5.1.4: The observed difference between the rainfall total of December to February of 1995/96 and 198283.

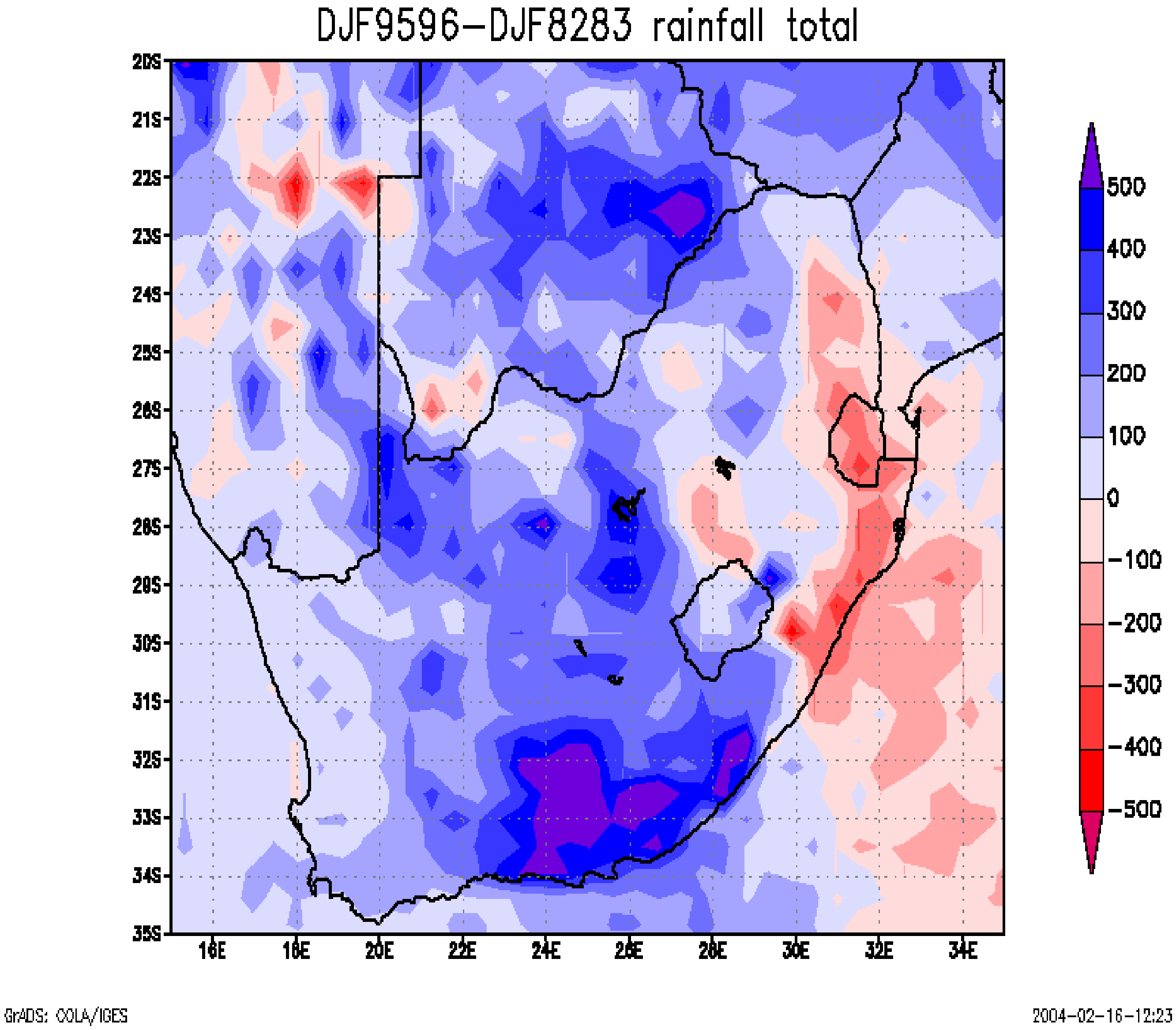


Figure 5.1.5: The simulated difference between the rainfall total of December to February of 1995/96 and 1982/83.

The MM5 regional model is being used at UCT in various research projects relating to extreme events, seasonal forecasting, and interannual climate variability. In addition, it is being used to produce downscaled climate change scenarios as part of an Assessment of Impacts and Adaptations to Climate Change (AIACC) project (http://www.csag.uct.ac.za/aiacc). Before using the model as a downscaling tool it is important to understand how uncertainties in the model configuration (convection scheme, planetary boundary layer etc) and lateral boundary conditions affect estimates of precipitation and temperature. Different combinations of model convection and boundary layer schemes have been tested for wet and dry seasons and reveal important differences in the simulated rainfall. A lack of observations over the region also leads to different representations of the observed atmospheric fields between the NCEP and ERA reanalyses. This is especially apparent in model derived parameters such as moisture but also in upper-level divergence over the continent. It is therefore important to understand the effect of these differences on the MM5 simulations and account for these uncertainties when testing MM5.

As part of AIACC, 10 year integrations of MM5 within NCEP reanalysis and the control and future climates of ECHAM4, CSIRO and HadCM3 GCMs are being simulated. This will enable high resolution climate change scenarios to be produced and the effect of GCM biases on the MM5 simulations to be evaluated. In particular and as mentioned in section 7, the effect of GCM biases in the westerly flow from the South Atlantic will be important to quantify.

This work is being carried out using computational Linux clusters and 'home-made' data storage facilities using PC hard disks and RAID technology. It demonstrates the possibilities with limited resources within Africa and the project is being carried out with researchers in Senegal, Ghana, Zambia, Nigeria and Zimbabwe as well as international partners. Elsewhere in Africa collaborators are able to run MM5 using desktop PCs. They perform simulations of their local area, generally at a higher resolution than those simulations in Cape Town, and are able to provide information based on detailed knowledge of their local environment. However, there are problems when local infrastructure is poor and a common problem, aside from African researchers having to fill a large number of roles, is the supply of power which is intermittent in most countries and restricts the length of simulations.

Additional work with MM5 at UCT involves assessing the sensitivity of both extreme events and seasonal rainfall to regional SST variability, and various modifications to the parameterizations in order to better represent local vegetation and soil moisture forcing. A long term goal is to produce high resolution surface winds and fluxes over the Benguela upwelling system which can then be used to drive ocean and biological models for marine ecosystem management and forecasting.

5.2. Statistical downscaling forecasting methods and progress

The inherent variability of the atmosphere requires seasonal climate simulations to be expressed probabilistically. Probabilistic forecasts are made possible through the proper use of GCM ensembles since ensemble forecasting is a feasible method to estimate the probability distribution of atmospheric states (Branković and Palmer 2000). In addition, errors in the initial conditions as well as deficiencies in the parameterizations and systematic or regime-dependent model errors can be to a large part accounted for through ensemble forecasting (Evans et al. 2000). Moreover, there is inevitable growth in errors of differences between forecasts started from very slightly different initial conditions suggesting that there is no single valid solution but rather a range of possible solutions (Tracton and Kalnay 1993). Information contained in the distribution of the ensemble members can subsequently be used to represent forecast probabilities by calculating the percentage of ensemble members that fall within a particular category (e.g. below-normal, near-normal and above-normal). Figure 5.2.1 shows the ranked probability skill scores obtained from a statistical remapping system using 10 ECHAM3.6 GCM (Deutches Klimarechenzentrum 1992) ensemble members for the DJF season over various southern African regions at a 1-month lead time.

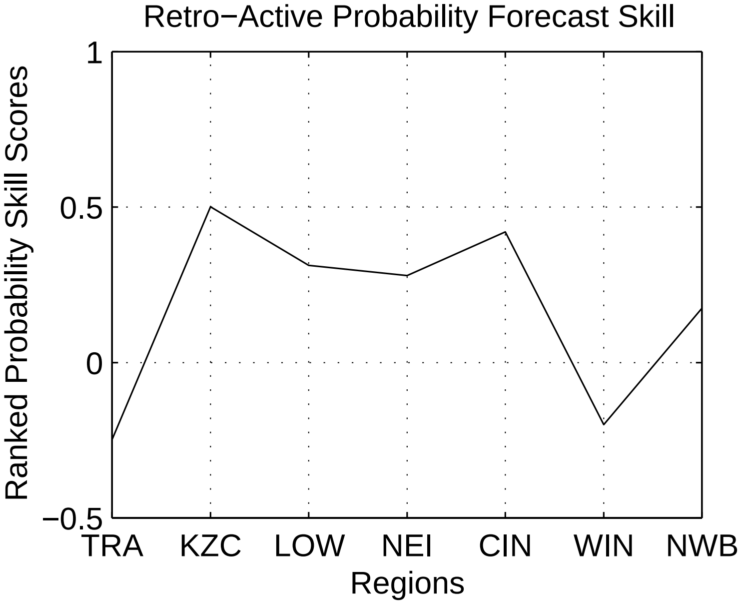


Fig. 5.2.1. RPSS of the 9-year retroactive forecast period from 1991/92 to 1999/2000. The target season is DJF. (TRA: Transkei; KZC: KwaZulu-Natal; LOW: Lowveld; NEI: northeastern interior; CIN: central interior; WIN: western interior; NWB: northern Namibia/western Botswana.

There are advantages in combining ensemble members of a number of GCMs into a multi-model ensemble since GCMs differ in their parameterizations and therefore differ in their performance under different conditions (Krishnamarti et al. 2000). Using a suite of several GCMs not only increases the effective ensemble size, it also leads to probabilistic simulations that are skilful over a greater portion of the region and a greater portion of the time series. Multi-model ensembles are nearly always better than any of the individual ensembles (Dirmeyer et al. 2003, Landman and Goddard 2003, Doblas-Reyes et al. 2000, Krishnamurti et al. 2000). The benefits from combining ensembles are a result of the inclusion of complimentary predictive information since the scheme is able to extract useful information from the results of individual models from local regions where their skill is higher (Krishnamurti et al. 2000). In fact, the most striking benefit obtained from multi-model ensembles is the skill-filtering property in regions or seasons when the performance of the individual models varies widely (Graham et al. 2000). Moreover, increased ensemble size leads to further benefits (Brown and Murphy 1996), but the multi-model approach is only beneficial if the individual systems produce independent skilful information (Graham et al. 2000).

The statistical approach used here to develop equations relating the GCM quantities to a forecast quantity is called Model Output Statistics (MOS) (Wilks, 1995). This approach is normally preferred because it can include directly in the regression equations any influence of specific characteristics, such as systematic errors. These errors can be included because MOS uses predictor values in both the development and forecast stages. Therefore, to develop MOS forecast equations, it is mandatory to have a developmental data set that consists of historical records, preferably more than several decades, of the predictand (regional or station rainfall data) as well as archived records of the forecasts produced by the GCM for the same season on which the predictand was observed. The time lag in MOS forecasts is therefore incorporated in the GCM forecasts. Figure 5.2.2 shows probabilistic forecast skill of a multi-model approach where each of five GCM's simulated DJF rainfall over South Africa and Namibia / western Botswana was first recalibrated statistically to regional level.

A number of ensemble combining algorithms exists. The most simple of these is the unweighted combination of ensembles from different models (Graham et al. 2000, Mason and Mimmack 2002), and is also the one used here. Combining forecasts this way improves on skill levels of individual model forecasts for southern African summer rainfall (Figure 5.2.2). The improvements over the individual ensemble systems are attributed to the collective information of all the models used in the mean of probabilities algorithm. Combining algorithms using Bayesian methods (Rajagopalan et al. 2002) may further improve the forecasts.

Such a multi-model system is in the process of being developed through a four member consortium consisting of the South African Weather Service, the International Research Institute for Climate Prediction, the University of Cape Town, and the University of Pretoria. Four GCM forecasts downscaled or recalibrated to station and regional level will be optimally combined to produce a probabilistic categorized (above-normal, near-normal and below-normal) seasonal forecast for South Africa. Some of the GCMs run at local centres will be forced with prescribed sea-surface temperature (SST) anomalies, each producing a minimum of 10 ensemble members. The prescribed SST anomaly fields consist of two sets of which the first set is global SSTs simultaneously observed with the target period. The skill levels associated with this type of simulation may be considered as an upper boundary of the skill of the GCM. The second SST forcing fields are sets of persisted SST anomalies. The skill assessment of the multi-model approach will only be conducted at lead-times not exceeding a few months. At these lead-times, persisted SST anomalies are a strong competitor for other more elaborate SST forecast models (e.g. Landman and Mason 2001). As a result of having these two distinct set of SST forcing fields, an upper skill limit as well as an operational forecast skill limit of the GCMs can be established. Ensemble members will be generated using established techniques such as the lagged average forecasting technique of Hoffman and Kalnay (1983).

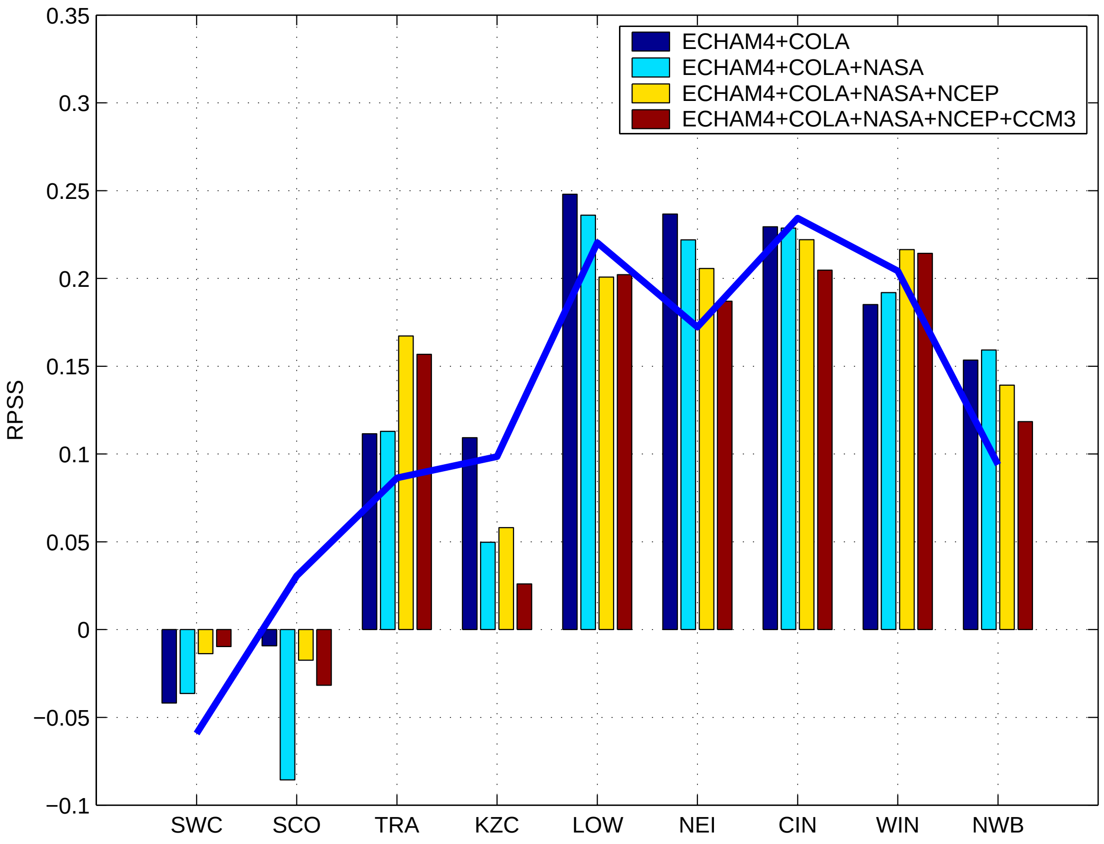


Fig. 5.2.2. RPSS of the 33-year cross-validated period from 1965/66 to 1997/98. The bars are RPSS values for different model combinations, and the solid blue line is the RPSS values of the best model (ECHAM4.5-MOS) The target season is DJF (for region definitions, see Fig.5.2.1).

An empirical downscaling method that is currently being used operationally by the South African Weather Service uses a combination of MOS and perfect prognosis (Wilks 1995). MOS equations are developed using 24-member ensemble ECHAM4.5 GCM simulation rainfall data (the ensemble was forced with simultaneous observed SSTs for each of the 3-month seasons considered) and then 24-member ensemble rainfall real-time forecast fields at different lead-times from the same GCM are subsequently used in these MOS equations to predict rainfall for a 1028 stations. It is therefore assumed that the skill with which the GCM can produce forecast at lead-times is as good as skill obtained from simulation data, reminiscent to the assumption of a perfect prognosis approach where "perfect" forecasts are assumed. For example, the ECHAM4.5 predictions are generated for DJF 2003/04, JFM 2004 and FMA 2004, by persisting observed November 2003 SST anomalies on top of the monthly varying annual cycle of climatological SSTs. At initialization, ensemble members differ from each other by one model day integration for both the simulation and forecast data. Figure 5.2.3 shows an example of a forecast generated by this MOS-perfect prognosis system issued in early December 2003 for the DJF 2003/04 season.

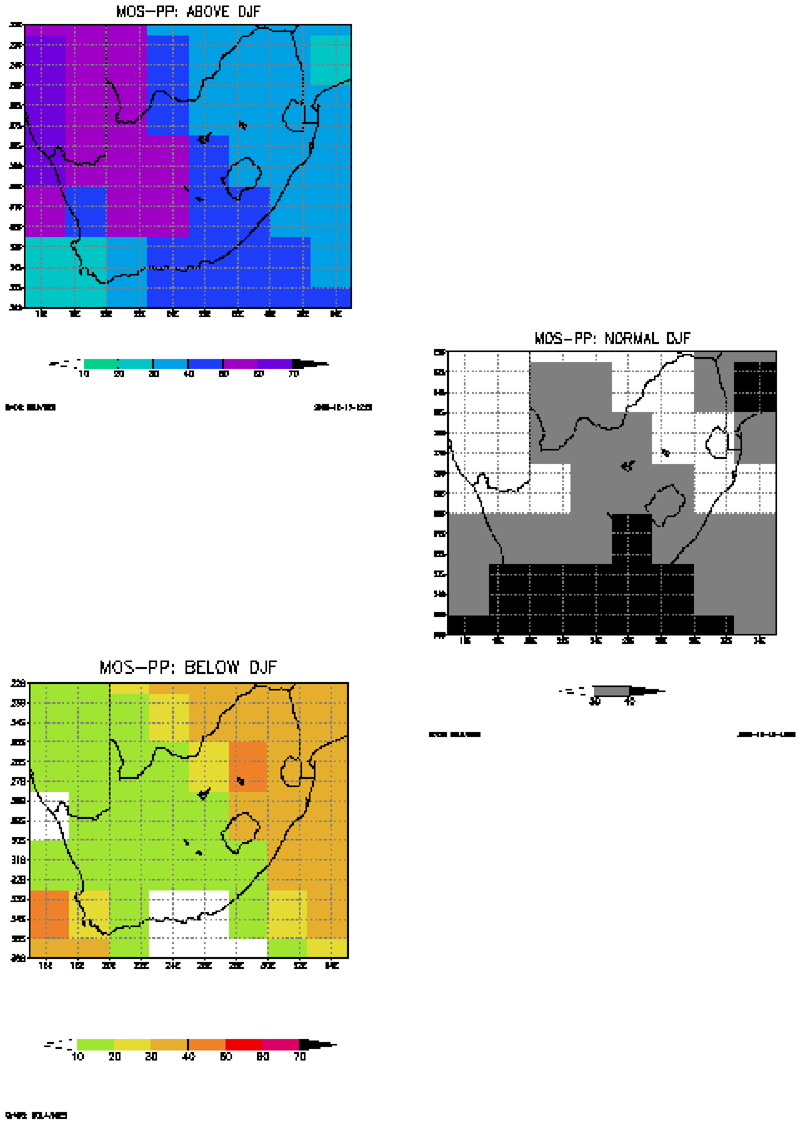


Fig. 5.2.3. MOS-perfect prognosis forecasts for DJF 2003/04. The forecast is for three categories and presented as probabilities.

The MOS-perfect prognosis issued in early December for the 2003/4 DJF season (Fig. 5.2.3) suggests that over the northeast of South Africa the probability of an above, near and below average rainfall season are about 20-30 %, 20-30 % and 40-50% respectively. By comparison, the observed rainfall for South Africa (Fig. 5.2.4) shows most of this part of the country received below or near average rainfall.

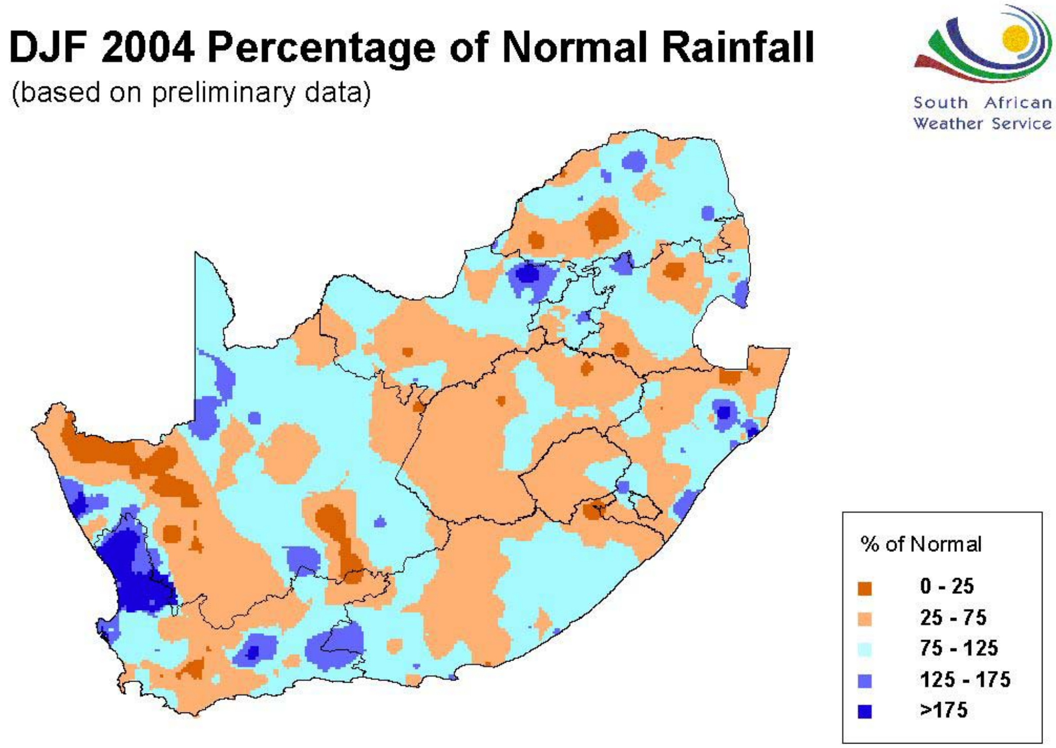


Fig. 5.2.4: Observed rainfall anomalies over South Africa during DJF 2003/4

6. Applications of seasonal forecasting to user groups, their needs and feedback etc

The SAWS compiles a consensus seasonal forecast for three rainfall and temperature categories every month using model output from the SAWS, the Universities of Cape Town and Pretoria, the IRI and ECMWF. Figure 6.1 is an example of such a forecast.

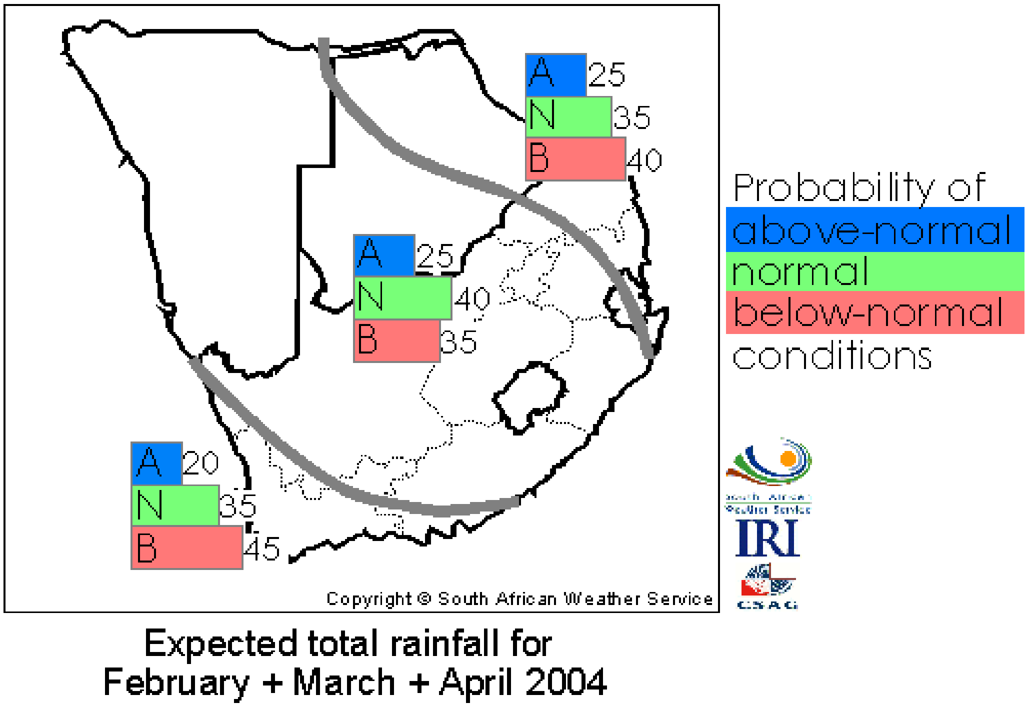


Fig. 6.1. An example of a forecast produced at the SAWS. Forecast maps like this one are also produced for seasonal surface temperatures.

These forecast maps are available at www.weathersa.co.za, but are also presented every month on an agricultural television programme AgriTV. The presented forecast maps are put on the AgriTV website (www.agritv.co.za) immediately following the programme on which they were presented. Forecasts and a short summary are also sent every month to the agricultural magazine Landbouweekblad for publication. Forecasts are also regularly presented to the National Department of Agriculture and included in their guidance to the agricultural sector via extension officers and various publications.

Elsewhere in southern Africa, seasonal forecasting tends to be done via statistical regression models that relate global SST anomalies (particularly, those in the tropical Pacific) to rainfall averaged over representative regions of individual countries. The latter are often defined using clustering or PCA techniques. A consensus seasonal forecast for large regions of southern Africa is produced at Southern African Climate Outlook Forum (SARCOF) meetings organised by the Drought Monitoring Centre – Harare. The most important meeting, attended by both operational meteorologists, researchers and representatives from various user groups (agriculture, health, water resources), tends to be scheduled in September, prior to the start of the main summer rainy season, and to be located in different southern African centres each year. Previously, almost all the information that was used to produce the consensus forecast was based on regression models; however, in recent times more attention has been paid to the output from AGCMs forced with forecast SSTs.

Given the highly variable rainfall over southern Africa and the need to carefully manage water resources, better forecasting of streamflow and dam levels is a high priority. Since atmospheric GCMs do not explicitly simulate streamflow, work at the South African Weather Service has investigated statistical linkages between GCM-simulated fields (ECHAM3.6) and South African streamflow. Note that the GCM has a much coarser resolution than the distances between the inlets of the dams. Thus recalibrating the GCM output to streamflow is truly a downscaling exercise. The recalibration procedure using hindcast data for forecasting rainfall is next applied to the streamflow at the inlets of six dams in the Vaal and upper Tugela river catchments, which lie within the north-eastern interior region of South Africa. Only the cross-validated forecasts are presented for the period 1971/72 to 1994/95. The naturalized streamflow data used in this paper are not available for the period after early 1995. The same predictor set, the hindcast mode 850 hPa geopotential height field that is used to recalibrate to seasonal rainfall anomalies is used by Landman and Goddard (2002), because streamflow is directly affected by precipitation and its variability should therefore similarly be affected by the variability of the 850 hPa geopotential heights.

Sensitivity runs using cross-validation are performed to obtain the optimal streamflow downscaling model. Using three predictand and five predictor modes in the model produced the highest averaged cross-validation correlation value, with each set of modes explaining more than 90% of the respective total variances. Additional factors affecting streamflow are evaporation and changes in soil moisture, as well as non-meteorological factors such as vegetation cover and the soil surface characteristics of catchments. The association between rainfall and streamflow is therefore complex, and also depends on factors that are not directly related to atmospheric variability. However, none of these factors are explicitly simulated by the atmospheric GCM and thus can not be incorporated into the downscaling process described in this paper. This downscaling model, however, can at least set a baseline against which other more complex downscaling processes can be compared.

The main purpose of this section is to assess if the proposed MOS can be of some value as an operational applications forecast procedure. Cross-validation is performed on each of the five hindcast (prescribed SSTs are obtained by persisting November SST anomalies through the forecast period of DJF) ensemble members and the average of the forecasts is obtained. The correlation values between the ensemble mean MOS and the observed streamflow vary between 0.54 for the Vaal Dam and 0.65 for the Johan Neser Dam (Figure 6.2). A high association is found between the observed streamflow and the observed rainfall of the region that contains the catchments of the dams. The high association is a manifestation of the effect rainfall has on the streamflow at the inlets of these dams, and indicates that the 850 hPa geopoetential height field that contributed to the rainfall prediction skill is a reasonable choice as predictor for streamflow also. Streamflow forecast skill should improve further if other non-atmospheric variables were allowed to participate in the recalibration process. As is the case in the rainfall recalibration, improved streamflow forecasts also occurred after the 1989/90 season. Based on these results, the South African Weather Service plans to start operational streamflow forecasts in time for the 2004/5 summer rainfall season.

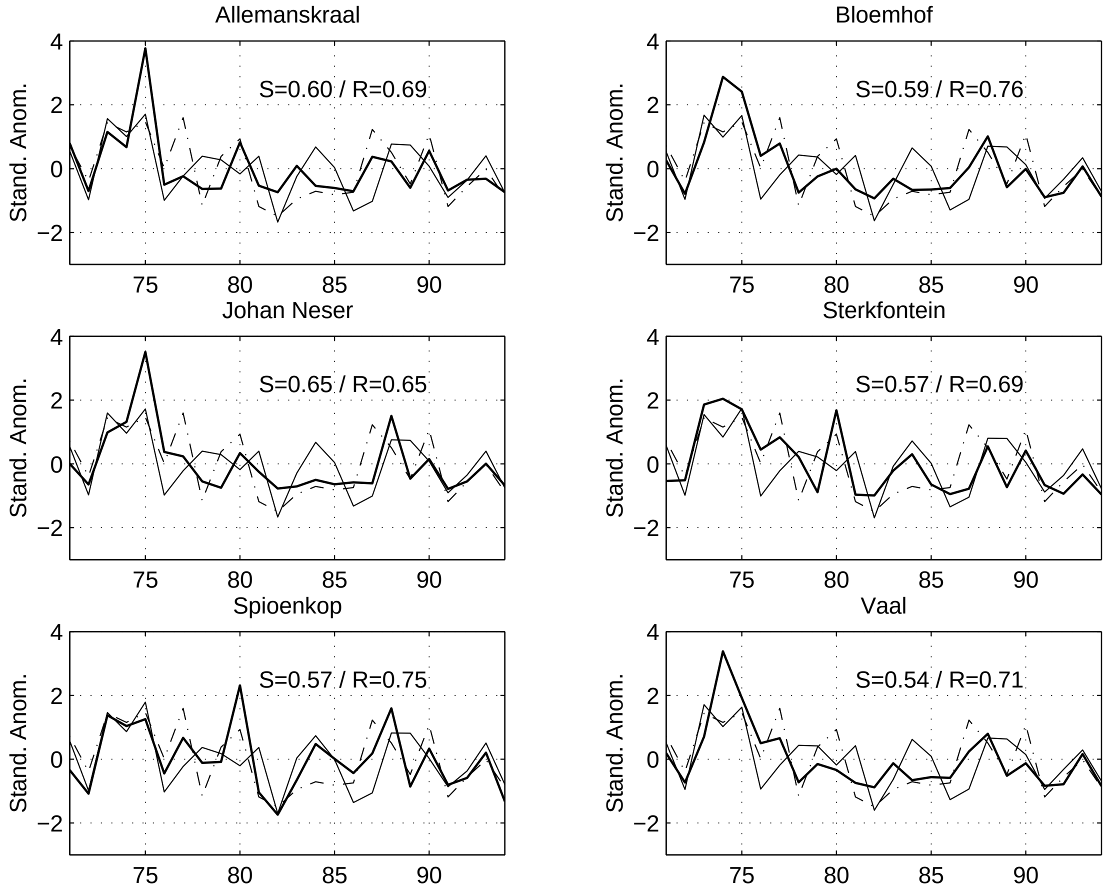
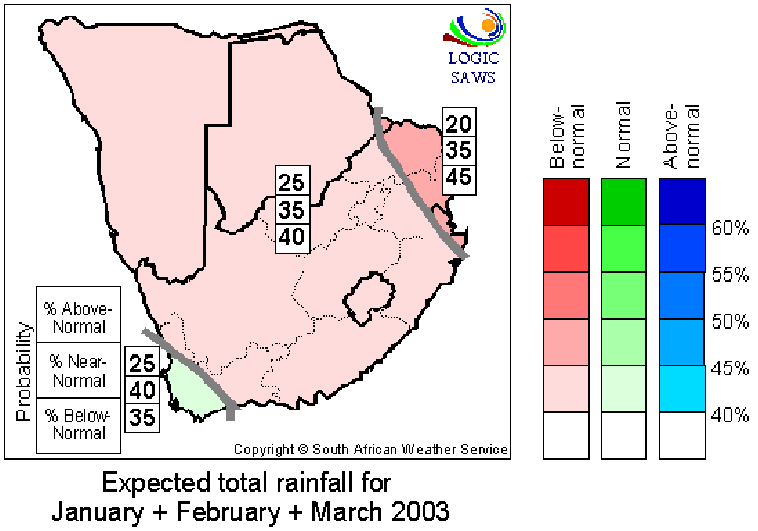


Figure 6.2. Cross-validated MOS normalized DJF streamflow anomalies (thin line) versus the observed DJF normalized streamflow anomalies (thick line) for each of six dams of the Vaal and upper Tugela river catchments of South Africa. Normalized DJF rainfall anomalies (dashed-dotted line) of the northeastern interior are also shown. The correlations between the predicted and observed streamflow anomalies (S) and the observed streamflow and rainfall anomalies (R) are shown in the top right of each dam.

Maize is the staple food for much of southern Africa's population and the onset of sufficient rains for planting has been identified as a seasonal characteristic about which most subsistence farmers would like forecast information. Recent work on the onset of the maize growing season (Tadross et al., *submitted Journal of Climate*) has demonstrated that early onset occurs over South Africa and Zimbabwe when positive daily 500 hPa eddy geopotenial heights are present to the south and east of South Africa. These positive anomalies are associated with increased tendency of synoptic ridging along the south and east coasts of South Africa or the formation of blocking highs in this region which help to increase the low level transport of moist maritime tropical air over eastern South Africa, southern Mozambique and Zimbabwe. The presence of similar high pressure systems during August is also linked to increased rainfall over Madagascar, likely a consequence of a strengthening of the South Indian anticyclone. This difference in pre-season rainfall could prove useful for prediction and may indicate an influx of moisture to the continent before onset. It remains to be seen whether it is this influx of pre-season moisture or the circulation at the time that creates the conditions for early onset.

Since 1979, onset over South Africa and Zimbabwe has been occurring later in the season (Tadross et al., 2003) and this is confirmed in interviews with farmers in southern Zambia (P. Mushove, pers comm.) and Limpopo province, South Africa Over South Africa there is evidence of decadal variability, with onset on average being earlier during the late 1950's and late 1970's. Although not a test of predictability, by relating onset to synoptic features it raises the possibility of prediction, though as discussed below GCMs may have difficulties simulating some of these synoptic features.

Tourism is a major contributor to the economies of many southern African countries and national park authorities are aware of the need to better understand the impacts of extreme weather and climate events and to make use of available forecasts. For example, the southern part of the Kruger National Park (KNP) for example suffered significant flooding in February 2000 along with other parts of northeastern South Africa and southern Mozambique. Consultations between the South African Weather Service and parks authorities suggests that early warnings of extreme seasons are likely to be more beneficial to smaller parks which have less flexibility and may be more sensitive; KNP has a basic policy of minimum interference. The type of rainfall season determines the severity of the fire season during the following winter and whether veld burning is likely to be needed. KNP may want a tailored forecast system in place in anticipation of a big natural die-off of wildlife caused by flooding or severe drought. Fig. 6.3 shows the drought conditions over the KNP and other parts of southern Africa during the most recent El Niño for the JFM 2003 season and the forecast issued in November 2002. Dry conditions were experienced over much of South Africa, Namibia and Botswana and were particularly marked over the KNP and neighbouring areas in northeastern South Africa. The forecast was skillful in predicting the more intensely dry conditions in this part of South Africa and that the central part of the country was less severely impacted by this El Niño.



Expected total rainfall for
January + February + March 2003

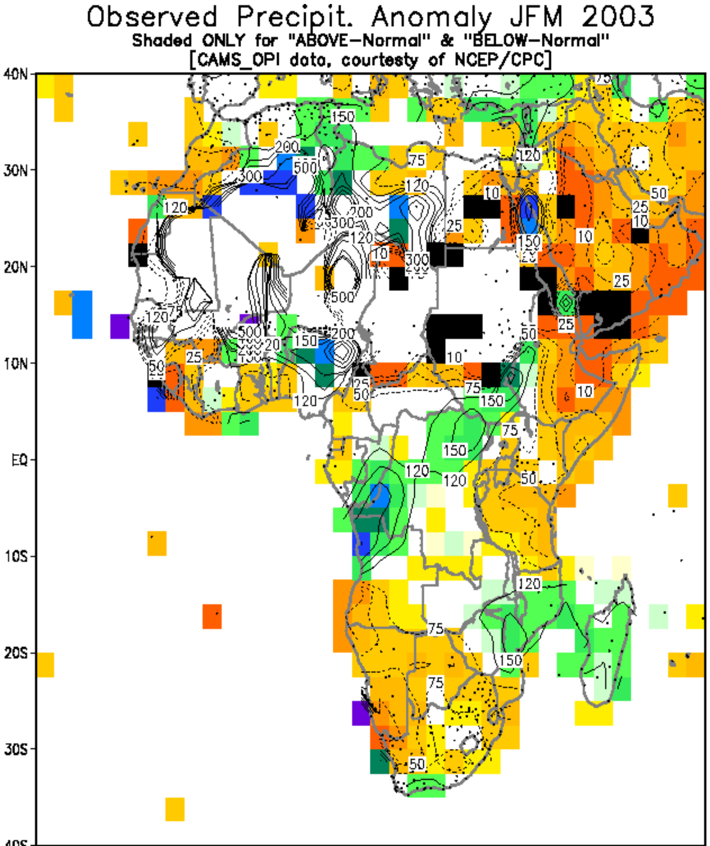


Fig. 6.3 Observed rainfall anomalies for JFM 2003 and SAWS forecast issued in November 2002.

7. Challenges of improving seasonal forecasting, observing system needs etc

One of the major challenges within southern Africa, which is a region characterised by low incomes and high rainfall variability and whose populations rely on rain-fed subsistence farming, is to provide forecasts that are useful for agriculture. This is a challenging prospect as it will involve predicting intra-seasonal rainfall characteristics such as onset, cessation and dry spell frequency. Further research is required but by relating these features to synoptic conditions, the possibility of increasing forecasting skill may be increased.

Given the importance of both the zonal (a possible control of onset) and meridional changes in the westerly circulation for rainfall over southern Africa, it is logical to enquire how predictable these variations are. As part of the aforementioned AIACC project (http://www.csag.uct.ac.za/aiacc), work at UCT is currently underway to assess how well GCMs represent the climate and westerly circulation in the southern African region. This is important to quantify as they are one of the primary tools used for seasonal forecasting and climate prediction. Simulation of the westerly flow also impacts on any RCMs or statistical downscaling that uses their data to provide downscaled climate change scenarios or seasonal forecasts. Initial results suggest that individual GCMs vary widely in their representation of the westerly flow e.g. it is known that HadAM3 has a bias for stronger than observed westerlies the core of which is placed too far south (Pope et al., 2000). However, compared to ECHAM and CSIRO, HadaM3 appears to better represent the position of troughs and ridges embedded in the mean flow. The CSIRO model suffers because of its low resolution, simulating weaker anomalies and ECHAM is biased towards simulating a higher frequency of low pressure anomalies to the east of the subcontinent.

In terms of its ability to represent the interannual variability of winter rainfall and circulation over southern South Africa, when forced with Reynolds SST, HadAM3 was found to get the sign and tendency correct during the 1990-1999 period studied by Reason *et al.* (2003) but to significantly underestimate the size of the anomaly. This finding suggests that there may be some skill in HadAM3 forecasting whether a winter season might expect above or below average rainfall, given adequate SST forcing, but not in the magnitude of the anomalies. It therefore raises the question as to which is more important for prediction, the zonal or the asymmetric component of the westerly flow and should forecasters be selective about which GCM to use depending on what seasonal characteristic they are trying to forecast ? As an example, it has already been mentioned that HadAM3 better simulates the asymmetric component of the zonal flow which may be important for onset. However during the JFM season HadAM3 has a notable cyclonic bias in the tropical Indian Ocean which disrupts the flow of moisture over the continent. ECHAM appears to better simulate the regional climate at this time and may prove a more useful tool for forecasting rainfall during this season.

Of major concern within the region is the severe decline in atmospheric observations, both of surface parameters such as rainfall, and soundings. This problem is apparent in the rainfall records for most of the continent and can be seen in the recent decline in the number of reporting stations communicating over the General

Telecommunications System (GTS). Funding for African NMHs is low and even in South Africa where an extremely valuable rainfall dataset was compiled until 1997 by the Computing Centre for Water Research (CCWR), the last few years has seen a dramatic decline in the records available to researchers. Similar trends can be seen in the atmospheric soundings over the continent and this results in the earlier remarked discrepancies between the ERA and NCEP reanalyses. In particular these discrepancies are apparent over Angola, Mozambique and the DRC where civil war and an almost non-existent funding base has severely restricted data collection. The majority of the work presented in this paper relies on access to observations of a sufficient quality. Climate models can only provide one realisation of the climate if there are no data to check them against and statistical downscaling relies on sufficient training data. Hence, future efforts at realising the potential of forecasting in the region ultimately rely on improvement in the current observing system over both Africa itself and the neighbouring oceans. In terms of the latter, the South Atlantic is not well monitored compared to the North Atlantic. Plans to extend the PIRATA moored array in the tropical Atlantic into the tropical South East and South West Atlantic have not come to fruition as yet. Present Argo float coverage is relatively good near 30°S, the AX8 line between South Africa and the US, and the SR2 line between Cape Town and Neumayer base (Antarctica). Large gaps exist in the tropical South West and South East and midlatitude South Atlantic. Surface drifters are released mainly in the subtropical and midlatitude South Atlantic with again large gaps in the tropics and some midlatitude areas. The recent South Atlantic Climate Observing System (SACOS) workshop concluded that better monitoring air/sea fluxes, SST and upper ocean variability in the subtropics and midlatitudes are needed in order to progress towards better understanding of South Atlantic modes and assessing their predictability.

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