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Interannual winter rainfall variability in SW South Africa and large scale ocean–atmosphere interactions

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With 10 Figures

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Summary

The Southwestern Cape (SWC) region of South Africa is characterized by winter rainfall mainly via cold fronts and by substantial interannual variability. Evidence is presented that interannual variability in SWC winter rainfall is related to sea-surface temperature (SST) and sea-ice anomalies in the central South Atlantic and adjoining Southern Ocean and to large scale ocean–atmosphere interaction in this region. During wet winters, the jet is strengthened just upstream of the SWC and significant cyclonic anomalies extend from the SW Atlantic over the region. SST tends to be anomalously warm (cool) in the SW Atlantic and SE Atlantic (central South Atlantic) and sea-ice extent increased in the central South Atlantic sector of the Southern Ocean. These patterns favor increased cyclogenesis upstream, a more northward track of midlatitude depressions, local intensification near the SWC and enhanced rainfall. Roughly the reverse patterns occur during dry winters. Some preliminary results from atmospheric GCM experiments are presented which help support these findings.

1. Introduction

Ocean–atmosphere interaction and interannual climate variability in the mid- to high latitudes of the Southern Hemisphere differ from that in the Northern Hemisphere due to the dominance of oceanic regions in the southern midlatitudes and the presence of the large Antarctic continent. This land–sea distribution is fundamental for the occurrence of important Southern Hemisphere phenomena such as the Semi-annual Oscillation (van Loon and Jenne, 1972), the Antarctic Circumpolar Current and the Antarctic Circumpolar Wave (White and Peterson, 1996). The three Southern Hemisphere tropical-midlatitude continents are also characterized by significant geographical differences which help influence their rainfall and its interannual variability.

This study is concerned with the interannual rainfall variability of the winter rainfall region of the southwestern region of South Africa (the Southwestern Cape – SWC) and the ocean–atmosphere interaction mechanisms potentially associated with it. Relatively little work has been done in this area despite the importance of this region for agriculture, fisheries and other primary industry, tourism and shipping. Historically, most South African research into climate variability has tended to focus on the summer rainfall region that covers the eastern and northern parts of the country and where a greater proportion of the national population and agricultural activities are located. There are important similarities and differences in the meteorology and topography of the SWC compared to southwest Western Australia (SWWA) for which a greater body of research is available and contrasts are drawn below which help to illustrate some of the important atmosphere–ocean interactions involved. Both the SWC and SWWA terminate at relatively low latitudes (around 34–35 S), are bounded by large ocean areas to the west and south, and receive rainfall predominantly in the winter half of the year. SWWA is considerably wetter than the SWC, e.g. the Perth Regional Office site at 31.9 S has an annual rainfall of 869 mm whereas Clanwilliam and Vanrhynsdorp on the coastal side of the escarpment in the SWC at 32.2 S and 31.6 S have annual rainfalls of 209 mm and 148 mm, respectively. These rainfall differences exist despite the fact that there are no significant mountain ranges in SW WA unlike the SWC and likely result from the presence of the warm Leeuwin Current that runs along the WA coast (strongest in winter and which overwhelms the upwelling tendencies of the coastal winds) and considerably warmer sea surface temperatures (SST) in the eastern South Indian than in the eastern South Atlantic Ocean (Gentilli, 1991; Reason, 1996).

Both these regions show substantial interannual and interdecadal variability in winter rainfall (e.g., Allan and Haylock, 1993; Ansell et al., 2000ab; Reason and Rouault, 2002). They also both receive winter rainfall largely via cold fronts, although in the case of SWWA (SWC) these may quite frequently (occasionally) link up with a disturbance in the easterlies over the tropical ocean regions to the northwest to form a tropical–extratropical cloudband. Lesser but still significant falls may result from other systems such as cut-off lows. Clearly, the location and intensity of the midlatitude storm tracks in the South Atlantic and Indian Oceans are likely to strongly influence the winter rainfall in these regions. Here, we shall consider large scale ocean–atmosphere interactions that may influence these tracks and hence winter rainfall. As discussed in Trenberth (1991), the location of Southern Hemisphere storm tracks tends to be closely related to the meridional temperature gradient in the lower troposphere. Surface factors which affect this gradient include SST and Antarctic sea-ice extent and we consider the variability of these together with anomalies in the winter subtropical jet and regional circulation that are likely to influence the rainfall. Finally, we present some preliminary results from atmospheric general circulation model (AGCM) experiments that illustrate the potential significance of regional ocean–atmosphere interaction for SWC rainfall.

2. Data and methodology

Both South African Weather Service station data (available for 1921–2001) and the 0.5 degree gridded rainfall data set of New et al. (2000) (available for 1900–1998) were spatially averaged over the SWC region (17–21 E, 31–34 S) for the May–September period each year to form a SWC winter rainfall index for each data set. This was performed for the full period of each data set but focus is placed on the post 1950 period for which NCEP re-analysis data are also available. Years for which the normalised MJJAS rainfall exceeded or fell below about one standard deviation were then defined as wet and dry, respectively. It was found that the data sets were consistent as respects the selection of the wet and dry years via this method.

NCEP/NCAR re-analysis data (Kalnay et al., 1996) were then used to investigate circulation anomalies associated with these wet and dry years and compositing used to highlight significant features in the regional circulation and SST. In the interests of brevity and isolation of the most important features, the results from the NCEP re-analyses are presented as composite difference fields between the set of wet and dry years defined previously. The SST data is from the re-constructed SST of Reynolds (obtained of the NOAA-CIRES web site at Boulder, Colorado *http://www.cdc.noaa.gov* and see Smith et al., 1996). The sea ice extent data were generated by a global ice-ocean model driven by the NCEP-NCAR reanalysis daily surface air temperature and winds (Fichefet et al., 2001). The simulation was carried out to document the variability of the Antarctic sea ice cover during 1958–1999. Both the mean state and variability of the ice extent over the satellite observing period are very well reproduced by the model, in particular from 1978 to 1998. Before 1979, the sea ice extent simulation may be considered less reliable due to the 1979 change in the satellite sea ice extent observing systems used in the NCEP-NCAR reanalysis. The data consist of monthly sea ice extent values from 1958 to 1998 at 1.5° resolution in longitude.

3. Results

Figure 1 shows the MJJAS rainfall anomalies for the 1950–2000 period spatially averaged over the

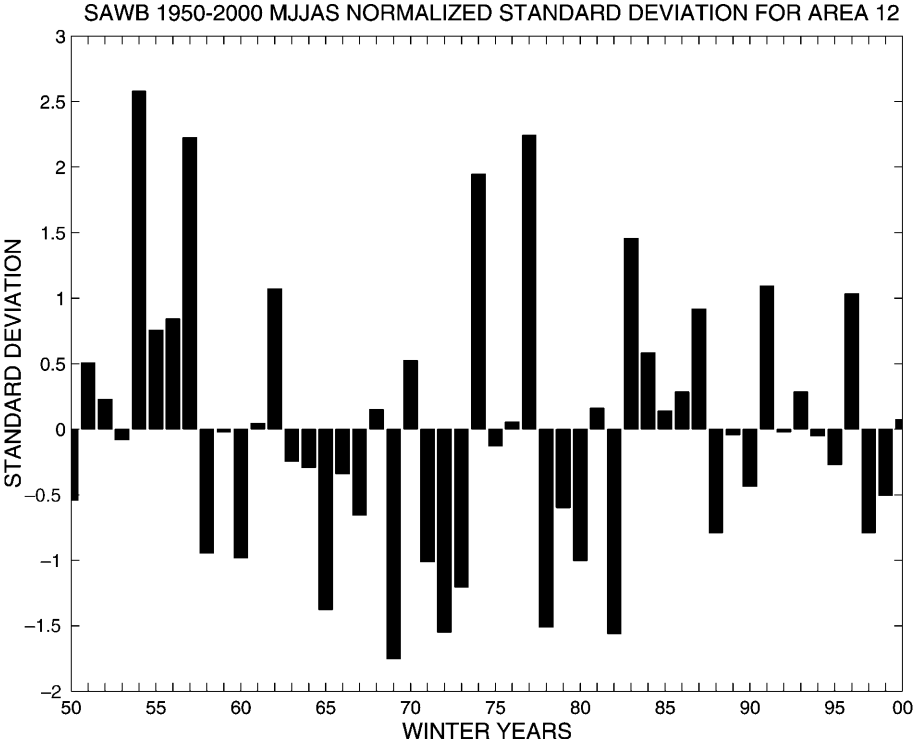


Fig. 1. Normalized time series of South African Weather Service winter rainfall anomalies for the SWC plotted from 1950–2000

SWC from South African Weather Service rainfall data and demonstrate that the SWC is characterized by substantial interannual variability. Investigation of the full dataset suggests that there is also substantial variability on decadal–multidecadal scales (Reason and Rouault, 2002). Based on Fig. 1, wet years are defined as 1954, 1957, 1962, 1974, 1977, 1983, 1991, 1996 and 2001 while dry years are defined as 1960, 1965, 1969, 1971, 1972, 1973, 1978, 1980 and 1982. Note that 2001 is not plotted in Fig. 1 as it has not yet been officially released by the SAWS; however, preliminary data indicates that this season was particularly wet (e.g., Cape Town received 2.5 times climatological rainfall in July 2001) and hence NCEP fields for 2001 are included. Examination of the SST anomalies for these years suggests that wet winters tend to be associated with warm anomalies in the SW Atlantic and immediately south of the SWC and cool anomalies in the central South Atlantic. Roughly the reverse SST distribution tends to occur during dry winters. Figure 2 shows the wet minus dry SST pattern. A similar pattern was obtained when UKMO GISST2.3b data were used (2001 data not yet available for SST).

Given that the rainfall is primarily frontal, SST patterns that affect cyclogenesis and the location and intensity of midlatitude storm tracks are of interest. The climatology of Southern Hemisphere extra-tropical cyclones derived by Jones and Simmonds (1993) indicates that the SW Atlantic is an important area of cyclogenesis. Warmer (cooler) SST in this area is therefore favourable for increased (decreased) cyclogenesis upstream of the SWC. These systems are then advected in the midlatitude westerly flow across the South Atlantic. Cool (warm) SST anomalies act like positive (negative) orography so to conserve potential vorticity, the mean flow tends to shift equatorward (poleward) in the central South Atlantic for the wet (dry) winters. These cool (warm) SST anomalies during the wet (dry) winters also help to enhance (reduce) the near-surface meridional temperature gradient in the tropical/midlatitude central South Atlantic, thereby further strengthening (weakening) the transient weather systems tracking towards the SWC. Finally, warm (cool) anomalies near the SWC itself during the wet (dry) winters are favourable (unfavourable) for local intensification and hence lead to increased (decreased) rainfall. Previous observational and modelling work has shown that the Agulhas Current retroflection region that lies to the south and southwest of the SWC is an area of large heat transfer to the atmosphere which

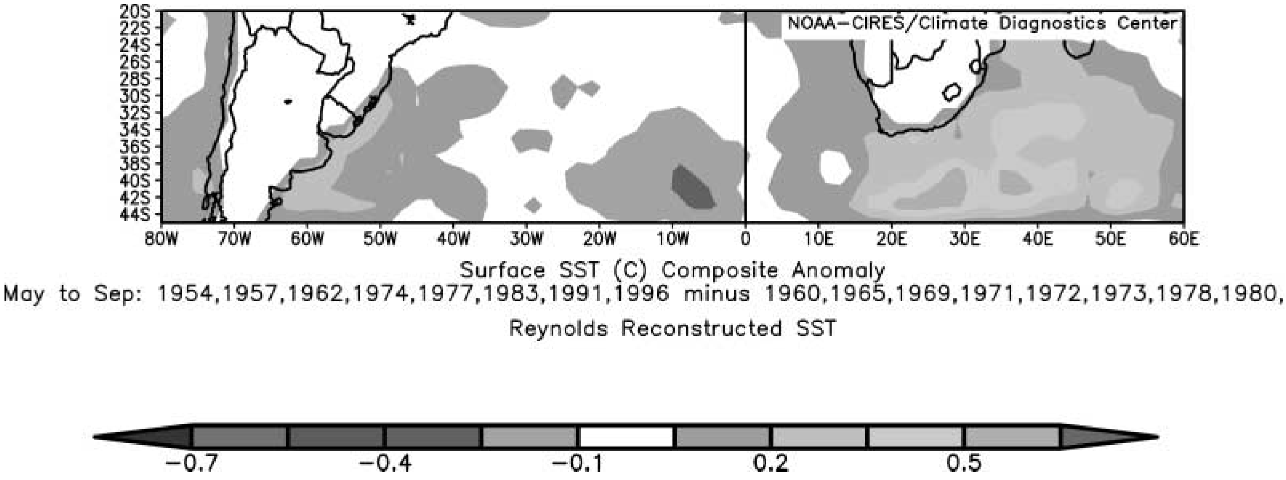


Fig. 2. Wet minus dry SST difference field. Note 2001 Reynolds data not yet available – however, NCEP SST skin temperature for which MJJAS 2001 data are available shows very similar difference pattern to Fig. 2

significantly influences both individual weather events and seasonal rainfall in southern South Africa (e.g., Walker and Mey, 1989; Walker, 1990; Reason, 2001; Rouault et al., 2000, 2002). Warm SST south of Africa helps to intensify the parent depressions tracking south of the landmass thereby strengthening the fronts crossing the SWC. The individual composite SST patterns for wet and dry winters (shown in Fig. 2 as wet-dry) are consistent with the foregoing argument.

It is of interest to note that the upstream SST pattern associated with SWC significantly wet and dry winters has some similarities with the South Indian Ocean patterns upstream of SW WA during wet and dry winters there. Thus, warm (cool) SST anomalies in the southwest (central) South Indian Ocean tend to be associated with wet SW WA winters (Ansell, 1998; Smith et al., 2000) and the reverse during dry winters. There are also significant SST anomalies in the waters north and northwest of Australia of opposite sign to those in the central South Indian Ocean during wet and dry SW WA winters (the so-called Nicholls dipole pattern; Nicholls, 1989) but the corresponding area in the African region is mainly land (although the anomalies in the tropical SE Atlantic are again consistent). Similar to the SWC situation, these SST patterns help strengthen the near-surface meridional temperature gradient and hence favour intensification of the fronts and NW cloudbands that bring most of the SW WA rainfall.

Figure 3 shows the correlation between SWC winter rain and Antarctic sea-ice extent during the 1982–1998 period. Relevant in the current context are the large positive correlations in the

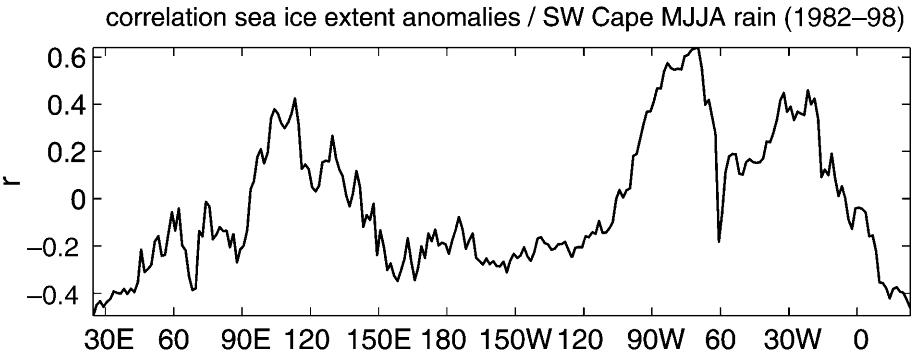


Fig. 3. Sea-ice extent/SWC winter rainfall correlation for the Southern Ocean. Sea-ice data are from Fichefet et al. (2001) and rainfall is as per Fig. 1. Note that the correlation is for the 1982–1998 period only as determined by the availability of the sea-ice data

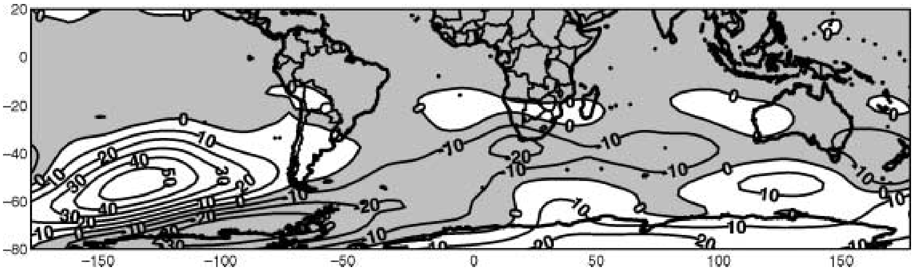


Fig. 4. Wet minus dry 500 hPa geopotential height difference field derived from NCEP re-analyses. Contour interval is 10 gpm and negative values are shaded in grey

central South Atlantic sector (around 15–35 W) and west of the Antarctic Peninsula (75–90 W). The latter is a noted region of high atmospheric variability (Kiladis and Mo, 1988) while the former appears consistent with the central South Atlantic region of SST anomalies noted earlier. That is, cool (warm) SST anomalies and increased (decreased) sea ice extent in the central South Atlantic sector tend to be associated with wet (dry) SWC winters. The sea-ice extent anomalies act in the same sense as the SST to reinforce the meridional near-surface temperature gradient and the shift in the mean flow to conserve potential vorticity. In other words, increased (decreased) sea-ice extent in the central South Atlantic sector of the Southern Ocean together with cool (warm) SST anomalies in the midlatitude central South Atlantic are favourable (unfavourable) for storm tracks being shifted equatorward of their mean path and lead to enhanced (reduced) SWC winter rainfall.

Given that there appears to be a plausible connection between South Atlantic SST/sea-ice anomalies and SWC rainfall, the next question concerns whether there are coherent signals in the regional circulation patterns that can account for the rainfall. Allan and Haylock (1993), Ansell et al. (2000), and Smith et al. (2000) found significant relationships between SW WA winter rainfall, the strength/location of the Australian winter and South Indian Ocean anticyclones, midlatitude cyclonic transient cyclonic activity and the long wave trough over the neighbouring Southern Ocean. Decadal variability in SW WA rainfall also appeared to be linked to the so-called Antarctic Oscillation with pressure signals of one sign over the Antarctic region and the opposite sign over the subtropics/midlatitudes of the Southern Hemisphere. Large scale circulation changes also appear to be responsible for the SWC rainfall variability. To address this question further, circulation fields and derived variables such as moisture flux, divergence and vorticity are considered below.

Figure 4 shows the 500 hPa geopotential difference field between the wet and dry SWC winter composites, respectively. The individual wet and dry composite anomaly fields both show consistent signals over the southern African sector with an Antarctic Oscillation type pattern (cyclonic anomalies through the subtropics-midlatitudes and anticyclonic at higher latitudes) seen for the wet composite while the dry composite is more suggestive of a wavenumber 3 shift and this is reflected in the mid- to high latitudes of Fig. 4. The substantial cyclonic feature extending from the SW Atlantic northeast across and over South Africa and the midlatitude South Indian Ocean is consistent with wet minus dry conditions. There are also consistent changes in the strength of the winter jet, for example, Fig. 5 showing a zonal wind section along 15 E (just upstream of the SWC) of the wet minus dry composite. Wet winters are characterized by a stronger jet over and just north of the SWC while during dry winters, the jet maximum shifts south and, as a result, is weaker above the SWC.

These circulation difference patterns imply changes to the amount of moisture advected into the region and Fig. 6 indicates increased northwesterly flux over the SWC at both surface and mid-levels during wet winters consistent with enhanced frontal activity. The latter is re-inforced by Figs. 7–8 which show enhanced low and mid-level cyclonic vorticity and low (mid-) level convergence (divergence) during the wet compared to the dry winters. Taken together, Figs. 4–8 suggest that interannual SWC rainfall variability is

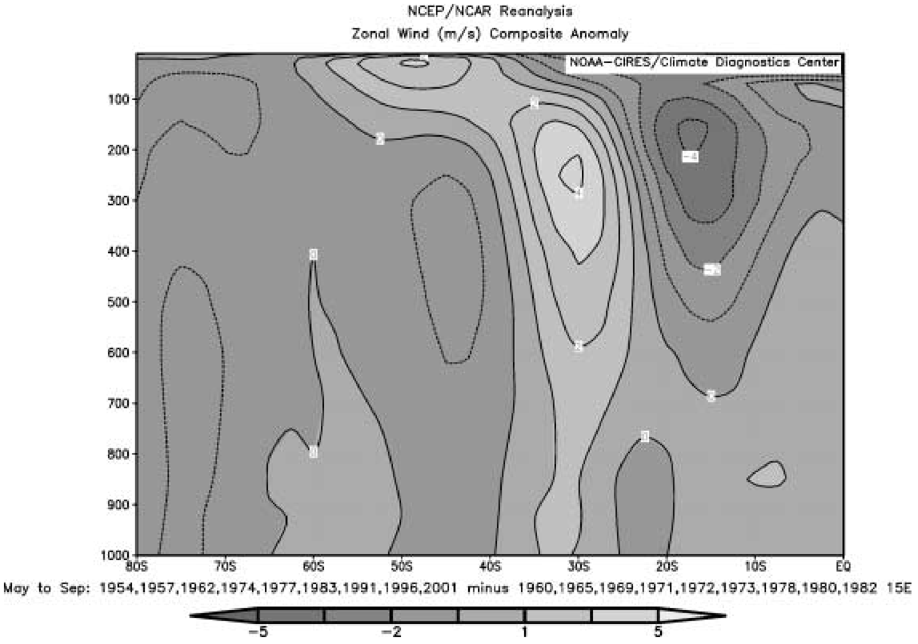


Fig. 5. As for Fig. 4 except zonal wind difference cross-section at 15 E or just upstream of the SWC. Contour interval is 1 m/s and shading bar at bottom

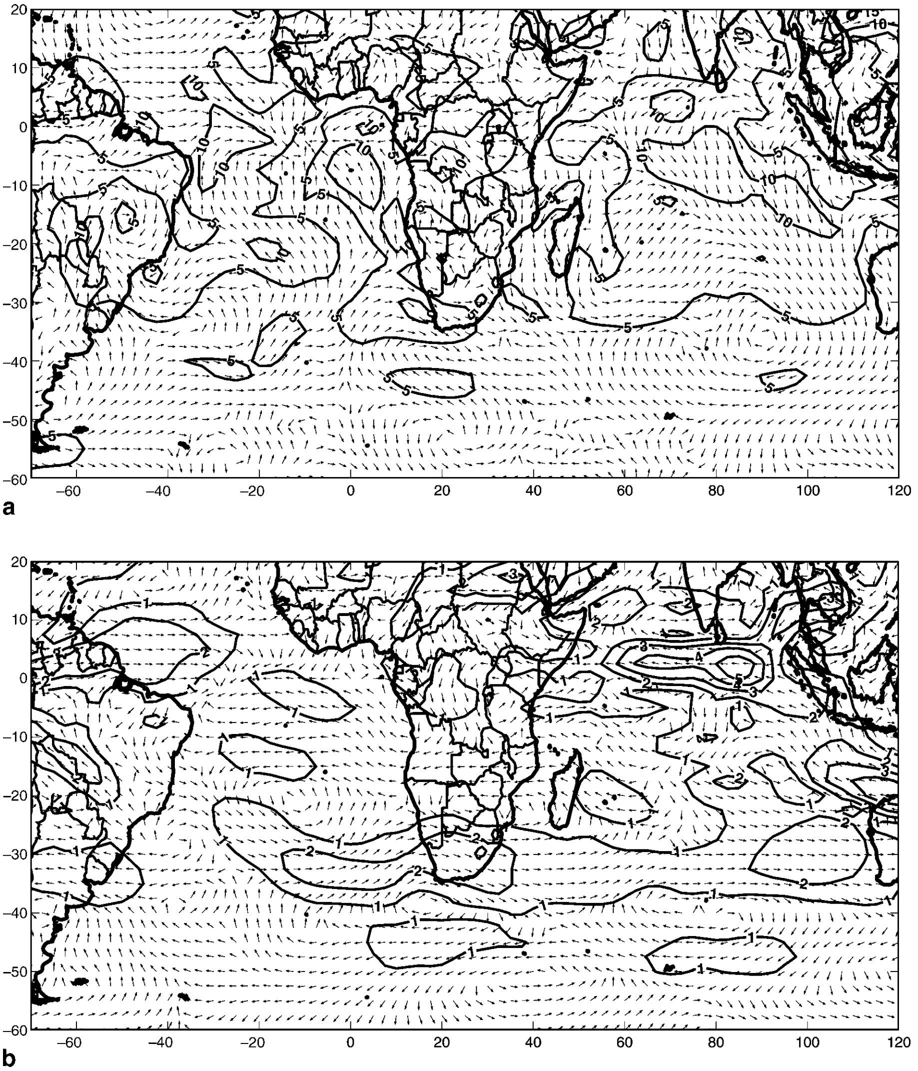


Fig. 6. As for Fig. 4 except moisture flux difference at **a** 1000 hPa, and **b** 500 hPa. Arrows show direction and the solid lines contour the difference magnitude at intervals of 5 g/kg m/s and 1 g/kg m/s, respectively

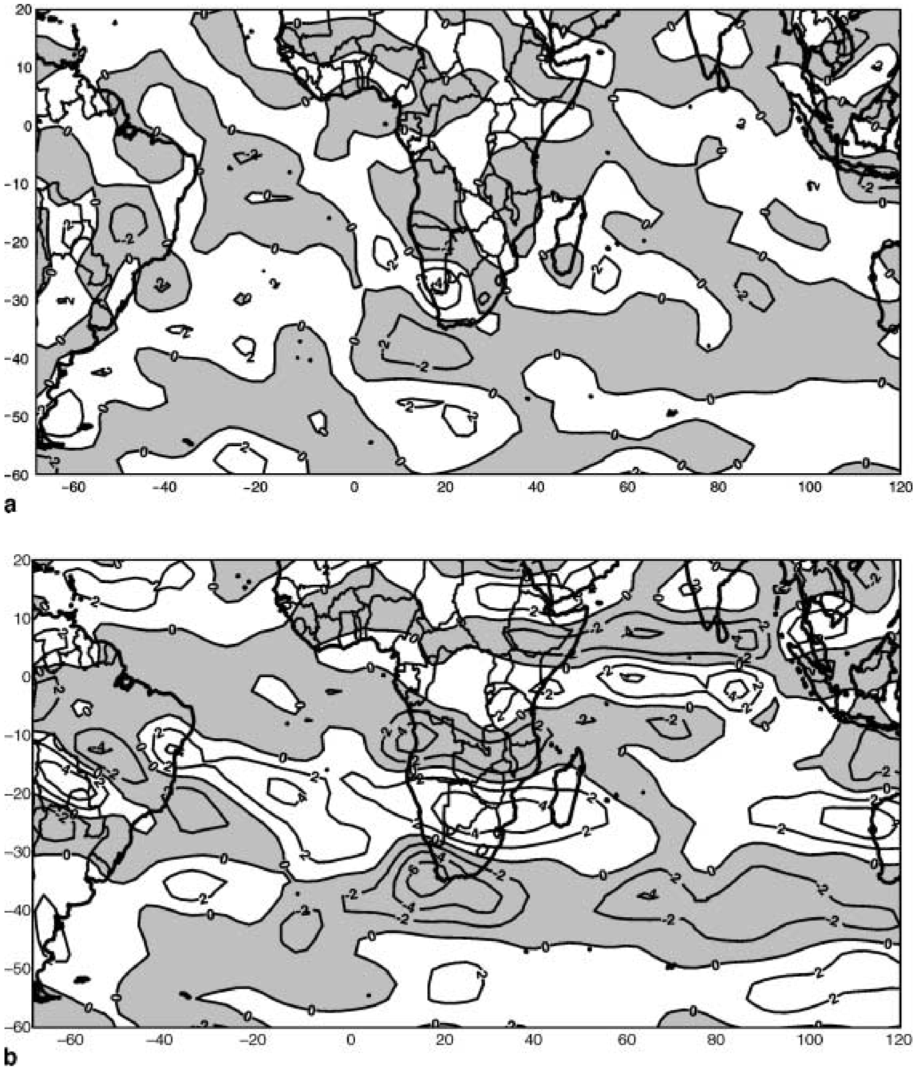


Fig. 7. As for Fig. 4 except relative vorticity difference at **a** 1000 hPa, and **b** 500 hPa contoured at $2 \times 10^{-6} s^{-1}$ and negative values are shaded in grey

strongly influenced by near-hemispheric midlatitude circulation patterns that affect the track and intensity of the cold fronts (and to lesser extent cut off lows) that bring almost all the SWC winter rainfall. The earlier discussion (Figs. 2–3) then suggests that these circulation shifts may be linked with SST and sea-ice gradients upstream in the South Atlantic and neighboring Southern Ocean through large scale atmosphere–ocean interactions in this oceanic region.

4. Model results

Dynamical models (UKMO HADAM3 and NCAR/PSU MM5) are starting to be applied at the University of Cape Town as part of a seasonal forecasting project. The emphasis of this is on the summer rainfall region of South Africa; however, some preliminary winter results are of interest. In very recent work, the HADAM3 GCM has been forced with the observed SSTs of Reynolds (1999) for the 1992–2000 period. In the current context, the model results (which are based on an ensemble of five runs each starting from a different initial condition) for the observed wet 1996 and relatively dry 1998 winters are of interest. It is recognized that substantially more comprehensive and sophisticated analyses of the model output need to be done in order have confidence in the robustness of the results; however, it was felt worthwhile to show some preliminary plots since they appear to support the preceding arguments developed from the NCEP re-analyses. The model 500 hPa height anomaly field for May–September 1996 is qualitatively similar to the NCEP re-analysis pattern for this particular

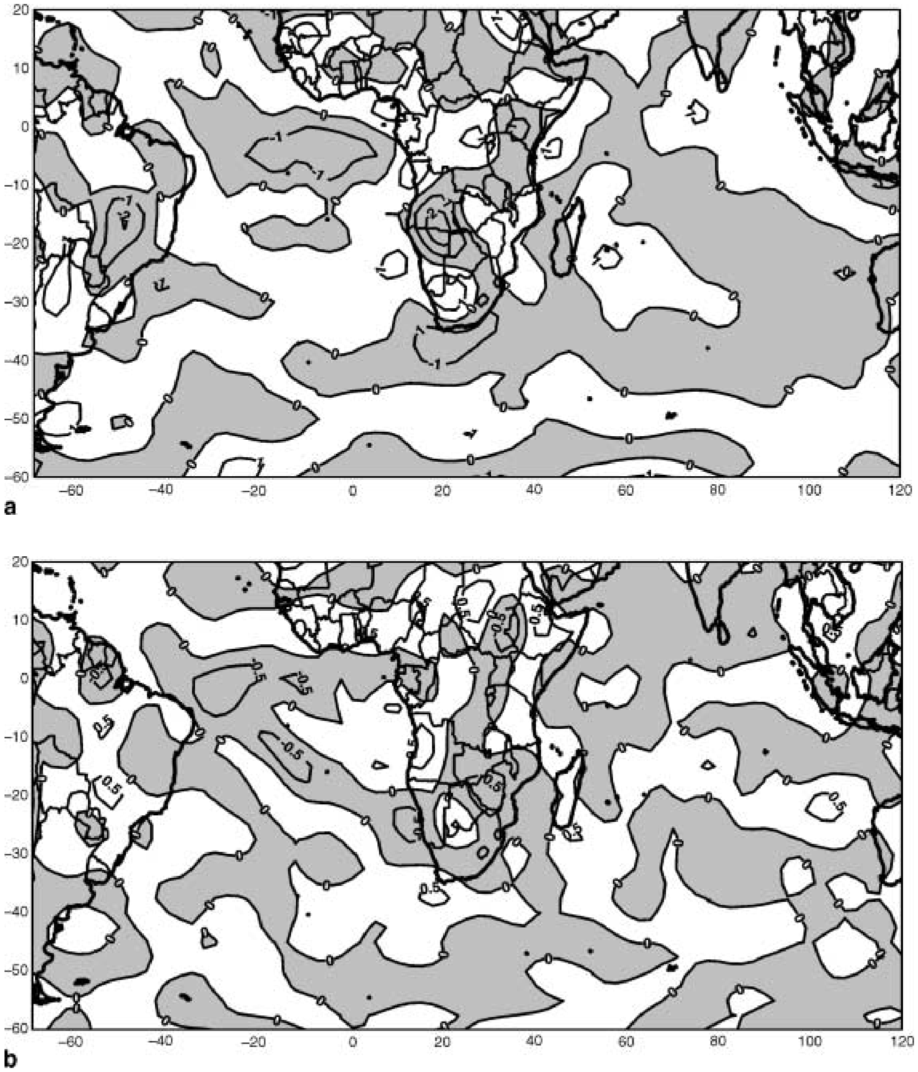


Fig. 8. As for Fig. 4 except divergence difference at **a** 1000 hPa, and **b** 500 hPa contoured at 1 and $0.5 \times 10^{-6}\,s^{-1}$, respectively, and negative values are shaded in grey

winter; both show significant negative departures over the subtropical-midlatitude South Atlantic and South Indian Oceans with positive anomalies at high latitudes. In the HADAM3 runs, the winter jet at 15 E (just upstream of the SWC) is stronger through 20–32 S (Fig. 9a) whereas in the NCEP re-analysis, positive anomalies in the jet occur further south through 20–40 S. The latter is consistent with the 1996 wetter winter observed – in the HADAM3 runs, the rainfall anomalies are weakly negative (positive) over western South Africa south (north) of 32 S.

The model 500 hPa height anomaly for MJJAS 1998 is also qualitatively similar to the NCEP re-analysis anomaly field for this period – both show positive departures over Africa with a cyclonic feature to the south and strong ridging over the SE Indian and SW Pacific sectors. The one significant difference of note between the two fields is that the model shows an anticyclonic anomaly in the SW Atlantic whereas in the NCEP re-analysis, the cyclonic feature south of Africa extends across the entire midlatitude South Atlantic. The anomalies in the winter jet at 15 E are similar in both the model and NCEP re-analysis (Fig. 9b) with stronger westerly flow evident for about 25–45 S. Rainfall observations (Fig. 1) indicate that 1998 was dry but not excessively so (about 0.5 standard deviations beneath the average) and the model run shows slightly below average rainfall over the SWC for 1998. GCM simulated rainfall is known to be problematic so the above mentioned discrepancies for this field are not surprising; however, what is encouraging is that the model and NCEP circulation fields show similar patterns and this suggests

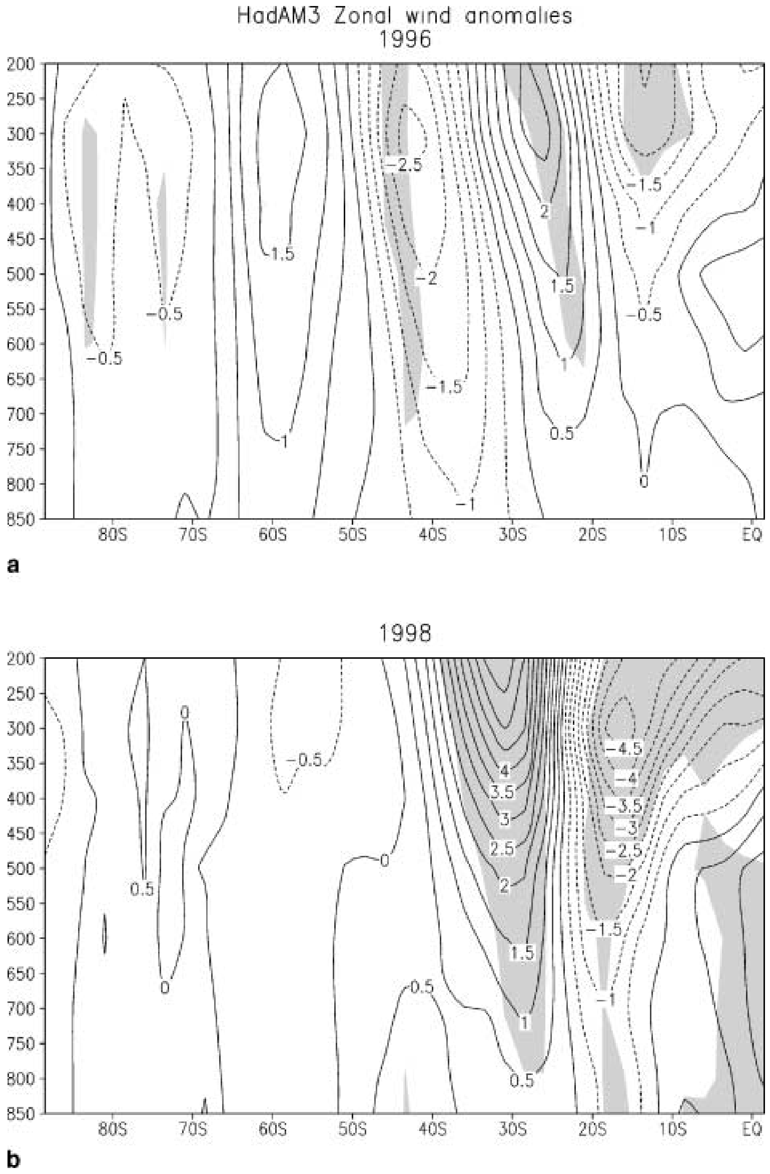
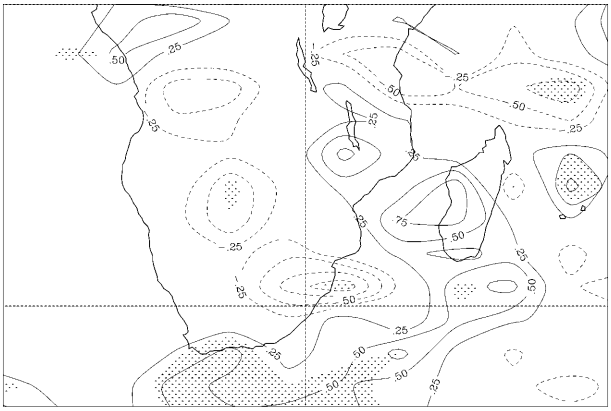


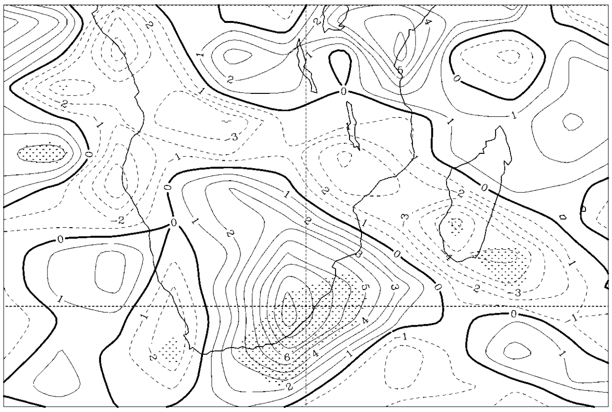
Fig. 9. UKMO HADAM3 winter zonal wind anomaly along 15E for **a** 1996, and **b** 1998 contoured at 0.5 m/s. Grey shading indicates statistical significance at the 95% level

that the planned approach of nesting MM5 seasonal runs within the GCM output in the later stages of the seasonal forecasting project over South Africa is appropriate.

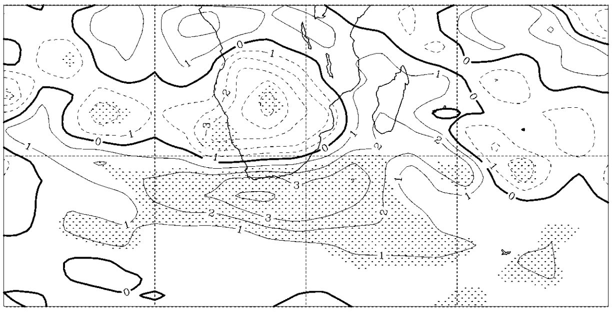
Some earlier perturbation experiments with the University of Melbourne AGCM (global R21 spectral resolution) reinforce the previous discussion about the potential significance of regional SST anomalies. In these experiments, a warm SST anomaly of 1–2 °C was imposed on the monthly climatology of Reynolds (1988) over the region immediately south of Africa and the model integrated for 9 months starting on April 1. Figure 10a–c shows the winter differences in precipitation and divergence and mixing ratio at the 850 hPa level between the ensemble mean of the 11 perturbation runs (i.e., each starting from a different April 1 initial state) and the mean of the control runs. Consistent with previous observational (e.g., Walker, 1990) and modelling work (Reason, 2001; Reason and Murray, 2001) there is increased evaporation off the warm anomaly, convergence of low level moist flow over and just upstream of the SWC, local intensification of cyclonic systems passing through the region and hence increased rainfall in the model SWC region (Fig. 10a–c). It is also worth noting that Reason and Murray (2001) found that extra-tropical cyclone tracks and intensity were rather sensitive in the model to



a Precipitation



b Divergence



c Mixing Ratio

Fig. 10. Winter difference between ensemble mean of 11 perturbation runs of the University of Melbourne AGCM with imposed warm SST anomaly (Gaussian shape and maximum amplitude of 2 °C) south of Africa and the control ensemble for **a** precipitation contoured at 0.25 mm/day, **b** divergence at the 850 hPa level (contour interval $1 \times 10^{-7}\,\mathrm{s}^{-1}$), and **c** mixing ratio at the 850 hPa level (contour interval 1×10^{-4} kg/kg). Stippling indicates statistical significance at the 95% level

SST anomalies of 1–2 °C magnitude in the region of the South Atlantic subtropical convergence and Agulhas Current retroflection region south of Africa, again supporting the arguments presented in Sect. 3. However, it should be emphasized that the AGCM grid used in all these experiments was relatively coarse and therefore these results need to be confirmed with higher resolution limited area modelling.

5. Conclusion

Evidence has been presented that interannual winter rainfall variability in SW Cape (SWC) region of South Africa may be influenced by SST upstream in the midlatitude South Atlantic and sea-ice extent in the South Atlantic sector of the Southern Ocean. These SST/sea-ice patterns then influence the lower tropospheric meridional temperature gradient in the central South Atlantic sector which is known to affect midlatitude storm tracks in the Southern Hemisphere (Trenberth, 1991). Associated with these patterns are large scale circulation anomalies in the Southern Hemisphere midlatitudes. Most notably, wet (dry) winters tend to be characterized by cyclonic (anticyclonic) anomalies across the midlatitude South Atlantic/South West Indian Ocean region, a stronger (weaker) winter jet just upstream of the SWC, and increased (decreased) cyclonic vorticity and low-level convergence (divergence) in the region.

There are similarities between these South Atlantic/southern African sector SST and circulation patterns for the SWC wet/dry winters with those previously derived over the South Indian/Australasian sector by Allan and Haylock (1993), Ansell et al. (2000), Smith et al. (2000) and others for SW WA winter rainfall variability. These similarities help increase confidence in the validity of the associated mechanisms suggested above. While these proposed mechanisms appear plausible, they need to be confirmed with more sophisticated analyses including regional modelling (e.g., MM5 or other limited area model). Such model analyses are planned as part of the South African seasonal forecasting project based at the University of Cape Town. Given the tight topographic, vegetation and SST gradients in southern Africa it is likely that relatively high resolution limited area model runs will be necessary in order to fully resolve all the complex regional forcings involved.

Acknowledgements

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