A model investigation of inter-annual winter rainfall variability over southwestern South Africa and associated ocean–atmosphere interaction

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We have investigated the variability of inter-annual winter rainfall over the southwestern Cape region of South Africa and associated large-scale atmosphere–ocean interaction upstream over the South Atlantic using the HadAM3 atmospheric general circulation model. This model was run for the period from 1990 to 1999 using mean monthly global sea-surface temperature (SST) as surface boundary condition over the global ocean. Diagnostics of winter (May to September) model output averaged over 1990–99 suggest that the HadAM3 model represents the general circulation in the South Atlantic/African sector reasonably well for this season at least. In addition, model years with wet and dry winters over the study area tended also to be those that were observed to be anomalously wet or dry. Wet minus dry season composite fields were used to investigate the model's inter-annual variability. The composite difference fields for low- and mid-level winds, sea-level pressure, and moisture flux all indicated wet winters being associated with increased inflow from tropical South America (originating in the equatorial western Atlantic at low levels) contributing relatively moist air to the westerly flow heading towards the southwestern Cape. A stronger jet over the South Atlantic promoted the passage of storms towards the Cape. Large areas of cyclonic vorticity anomalies, enhanced eddy activity, increased thickness in the lower atmosphere and low-level convergence near and upstream of the southwestern Cape in the model composite differences all favoured increased storm systems as well as their local intensification, implying enhanced rainfall. The results presented here suggest that the model can represent the inter-annual variability of winter rainfall over the study region and shed light on the mechanisms potentially associated with anomalously wet winters there.

Introduction

With its large rural population, and widespread dependence on subsistence agriculture, southern Africa is vulnerable to variable rainfall. Improved prediction of rainfall is therefore a high priority, and a collaborative project involving dynamical modelling (using models such as the U.K. Meteorological Office's HadAM3) for seasonal forecasts has begun between the University of Cape Town, the South African Weather Service, and the University of Pretoria. As part of this project, the HadAM3 atmospheric general circulation model (AGCM) has been run with observed monthly sea-surface temperatures (SST) for the period 1990–99 and detailed model fields have been extracted for the southern African region. While the main focus of this project is on the summer rainfall region, which covers the northern and eastern parts of South Africa, recent work[1,2] recommends that the potential for predicting winter rainfall in the southwestern Cape region should be explored.

To date, relatively little work has been conducted on the mechanisms that may be associated with the substantial inter-annual variability in rainfall over the southwestern Cape (17–21°E, 31–34°S). Unlike the rest of the country, most rain in this area falls in winter, when the South Atlantic Anticyclone retreats northwestward and a col region forms between it and the winter anticyclone over eastern South Africa. Summers are mainly dry in the southwestern Cape as the South Atlantic Anticyclone approaches the region and there is a tendency for migratory anticyclones to ridge south of South Africa. Rainfall in the southwestern Cape arrives mainly via cold fronts and, to a lesser extent, cut-off lows and other perturbations of the westerly flow in winter. Previous work[1] indicates that some wet winters are associated with warm SST anomalies in the SW and SE Atlantic, cool SST anomalies in the central midlatitudes of this basin, a stronger jet, and enhanced mid-level moisture flux from the subtropical western Atlantic. It has been argued that these South Atlantic SST patterns are likely to induce atmospheric conditions favourable for rainfall in the study area in the following three ways. First, the SW Atlantic is a region of pronounced cyclogenesis[3] and, therefore, warm SST anomalies here are likely to promote the generation and intensification of the winter storms via enhanced evaporation and increased instability of the lower atmosphere. These storms then track in a generally eastward direction towards the southwestern Cape as influenced by the orientation of the mid- to upper-level mean flow (that is, the jet).

Second, since negative SST anomalies act like positive orography, in order to satisfy the conservation of potential vorticity, this airflow moves north over these anomalies in the central South Atlantic with the result that the storm track approaching the southwestern Cape is likely to lie farther north than usual. Third, the warm SST anomalies in the SE Atlantic (Agulhas retroflection region) lead to more evaporation and enhanced atmospheric instability and hence intensification of the storm systems in the neighbourhood of the southwestern Cape.

The influence of midlatitude SST anomalies on the atmosphere is less well-established than for the tropics.[4,5] The ocean and atmosphere are much more tightly coupled in the tropics, and tropical convection is sensitive to the underlying sea-surface temperature, particularly when this is greater than 26–27°C. These facts together with the importance of the El Niño-Southern Oscillation (ENSO) and other tropical modes of variability for global climate means that most SST-forced experiments with AGCMs have tended to focus on low-latitude anomalies. Nevertheless, mid- to higher latitude southern hemisphere modes such as the Antarctic Circumpolar Wave[6] and Antarctic Oscillation[7,8] are receiving increased attention as researchers realize that not all variability over the southern landmasses is driven from the tropics. With these considerations and observational evidence of midlatitude South Atlantic SST influences[1] in mind, our objective was to examine the HadAM3 AGCM over the southwestern Cape and South Atlantic, from 1990 to 1999, to obtain an idea of the model's ability to represent the regional winter climate and its variability.

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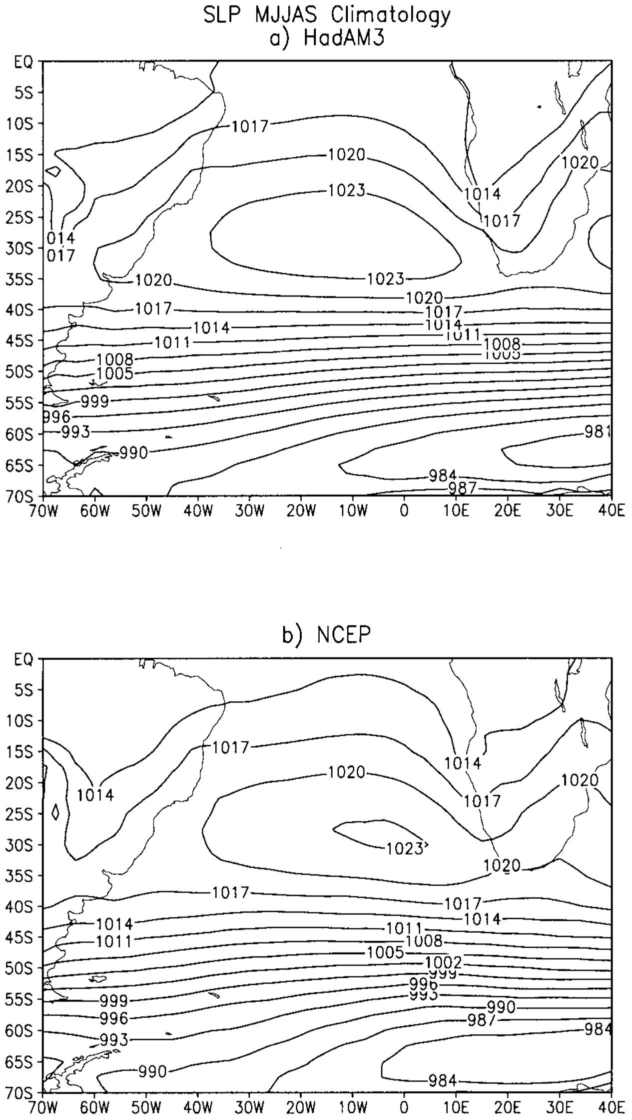


Fig. 1. May–September climatological sea-level pressure (contour interval 3 hPa) for (a) Hadley Centre climate model HadAM3, 1990–99 integration with observed sea-surface temperature and (b) NCEP re-analyses for same period.

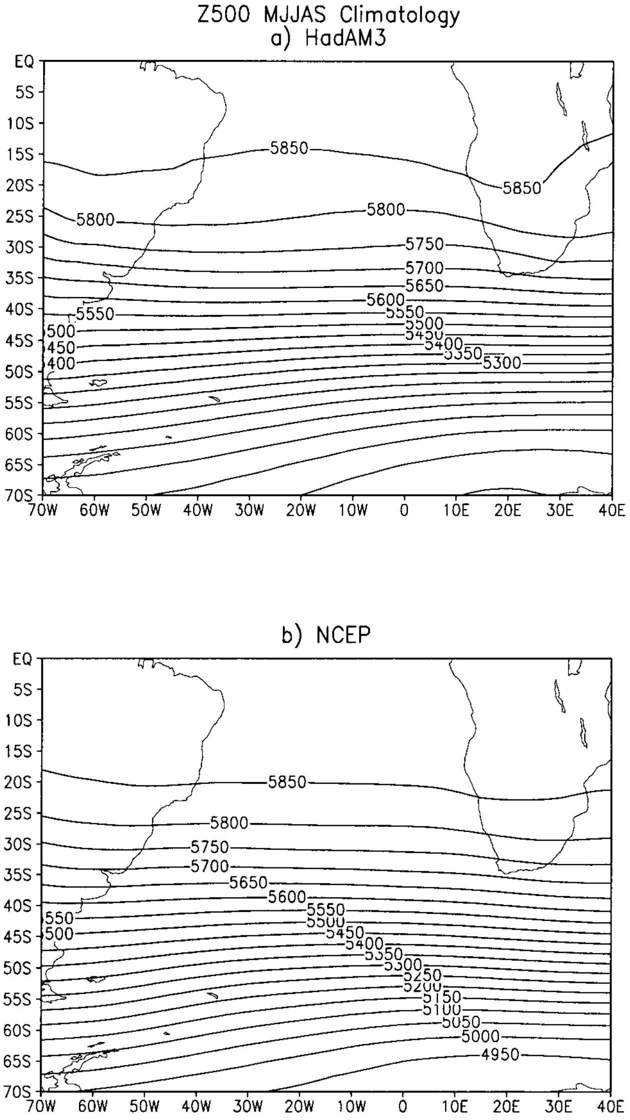


Fig. 2. As for Fig. 1 except for 500-hPa geopotential height (contour interval 50 gpm).

Description of the model

We used the U.K. Meteorological Office's Hadley Centre atmospheric model HadAM3, a hydrostatic grid point model with a global resolution of 3.75° longitude and 2.5° latitude. The vertical scheme uses hybrid *eta* coordinates on 19 vertical levels; six prognostic variables are zonal wind, meridional wind, geopotential height, total specific humidity, ice content, and liquid-water potential temperature. The timestep is 30 minutes and the mixed phase precipitation parameterization was used. A detailed evaluation of this model, its biases and the main parameterizations of the sub-grid scale physics are described in ref. 9. As part of a seasonal forecasting project, HadAM3 was integrated for the period 1990–99 with the observed Reynolds monthly SST available as global data on a 1 × 1° latitude–longitude grid.[10] An ensemble of five integrations for this period was performed and the results below present the ensemble mean differences for wet minus dry winter seasons for the southwestern Cape during this decade.

Model winter climatology

In this section, we compare winter (May–September) fields from the model with National Center for Environmental Prediction (NCEP) re-analyses. The latter are available on a slightly different grid (2.5° × 2.5°) and were derived by the NCEP/NCAR after assimilating all available observations into the NCEP's global atmospheric model.[11] These re-analyses essentially represent the best available gridded 'observations' of the global 3-D atmosphere and have been widely used in numerous climate and model diagnostic studies.

Figures 1 and 2 show the model climatological sea-level pressure (SLP) and 500-hPa height fields over the southern African/Atlantic sector for May–September. The South Atlantic Anticyclone was broader than the NCEP re-analysis climatology but of similar magnitude and central location, whereas the pressure gradient across the circumpolar trough in the southern South Atlantic was more intense than in the NCEP re-analyses (particularly south of Africa) and was slightly more zonal (Fig. 1). Over the interior of southern Africa, the model displays a more distinct easterly trough over Namibia and less pronounced ridging over the eastern landmass than in the NCEP fields. With the exception of the model 500-hPa field (Fig. 2) being somewhat more zonal, there is reasonably good agreement between the model and NCEP fields over the midlatitude South Atlantic. Over southern Africa itself, the mid-level westerly flow exiting

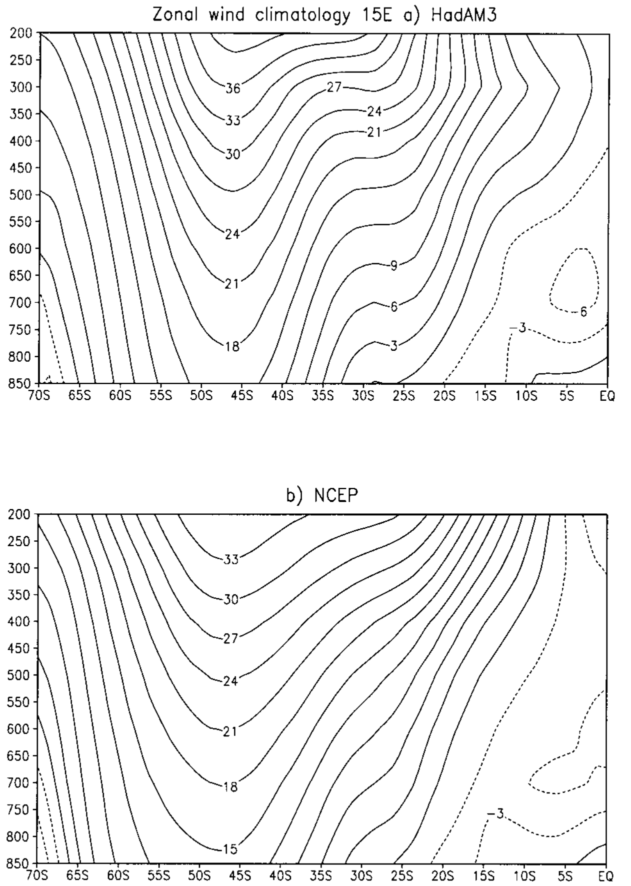


Fig. 3. As for Fig. 1 except for zonal wind transect (contour interval 3 m/s) through 15°E.

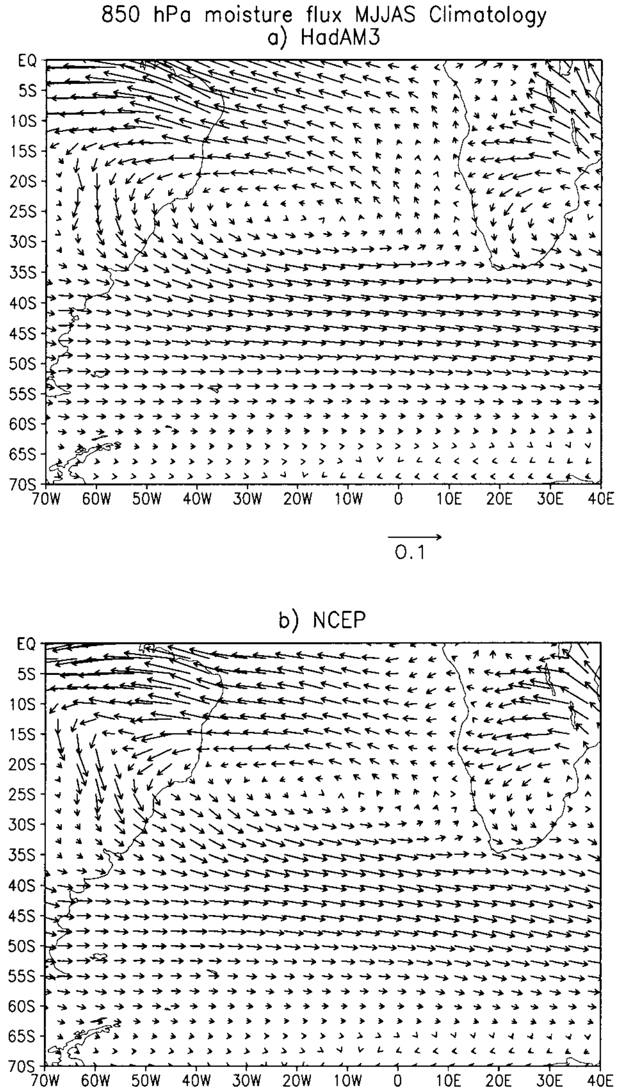


Fig. 4. As for Fig. 1 except for moisture flux (scale arrow represents 0.1 kg/kg m/s at bottom of upper panel) at 850 hPa. Note same scale for both panels.

over the east coast is perhaps more diffluent than that implied by the NCEP plot, whereas a transect of zonal wind through 15°E (just upstream of the southwestern Cape; Fig. 3) suggests that the model jet is slightly stronger than the NCEP result. In general, however, the model's winter climatology appears realistic enough for us to have confidence in the robustness of the results discussed below.

The model's moisture flux climatology for winter (Fig. 4) suggests that processes which modulate the westerly/northwesterly inflow from the western tropical South Atlantic/South American tropics and subtropics and associated South Atlantic Convergence Zone could influence rainfall over the southwestern Cape. Examples of such processes are SST anomalies in the Atlantic and modulations of tropical convection over the northern Amazon/central South American region with resulting propagation of Rossby waves to higher latitudes. Evidence for South Atlantic SST influencing southwestern Cape winter rainfall has been presented by Reason;[1] satellite-derived surface winds over the Benguela Current region show variability that appears linked to Rossby wave activity emanating from the tropics.[12] It is conceivable that both of these processes may influence the low-level moisture convergence seen in Fig. 4 in the southeastern South American/western South Atlantic region. Figures 2 and 3 suggest that this moisture will be efficiently advected downstream by the westerlies towards the southwestern Cape; additionally, this moisture convergence can also augment cyclonic systems generated in the SW Atlantic.

Rainfall variability

In general, the HadAM3 model's rainfall amounts over southern Africa for each rainfall season are different from observations (for example, for the southwestern Cape, the recorded spatially averaged mean for May–September from 1990 to 1999 was just over 1 mm/day whereas the HadAM3 model's mean is 0.3 mm/day; the inter-annual standard deviations are 0.15 and 0.06 mm/day, respectively). For this reason, direct comparisons of either the model rainfall with the observed climatology or of the absolute rainfall amounts for particular years are not particularly instructive. Instead, it is more helpful to examine whether the model inter-annual rainfall anomalies are of the right sense compared to those observed (that is, show similar patterns of wet and dry years) and whether the model is able to identify the extreme years or not.

All AGCMs have limitations in simulating rainfall and preliminary experiments that we have performed with a regional climate model (MM5) over southern Africa do not seem to lead to appreciably better results than HadAM3 in terms of absolute rainfall. One difficulty that arises with these models is that they are unable to capture the details of the topography. The southwestern Cape possesses several mountain ranges with steep topographic and rainfall gradients, posing further difficulties for models. However, by spatially averaging both the model and observed data over the region, orographic effects on rainfall are smeared out and, as a result, more meaningful comparisons between the model and observed rainfall can be made. We

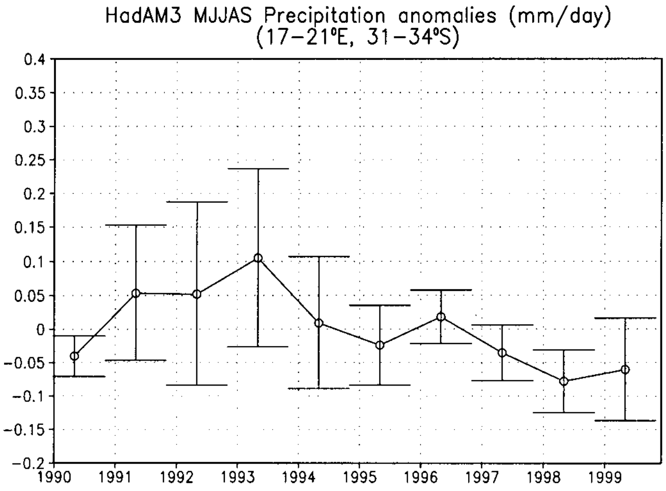


Fig. 5. HadAM3 model rainfall for May–September spatially averaged over the southwestern Cape (17–21°E, 31–34°S) for 1990–99. The bars around each data point represent the standard deviation of the ensemble members for that particular year.

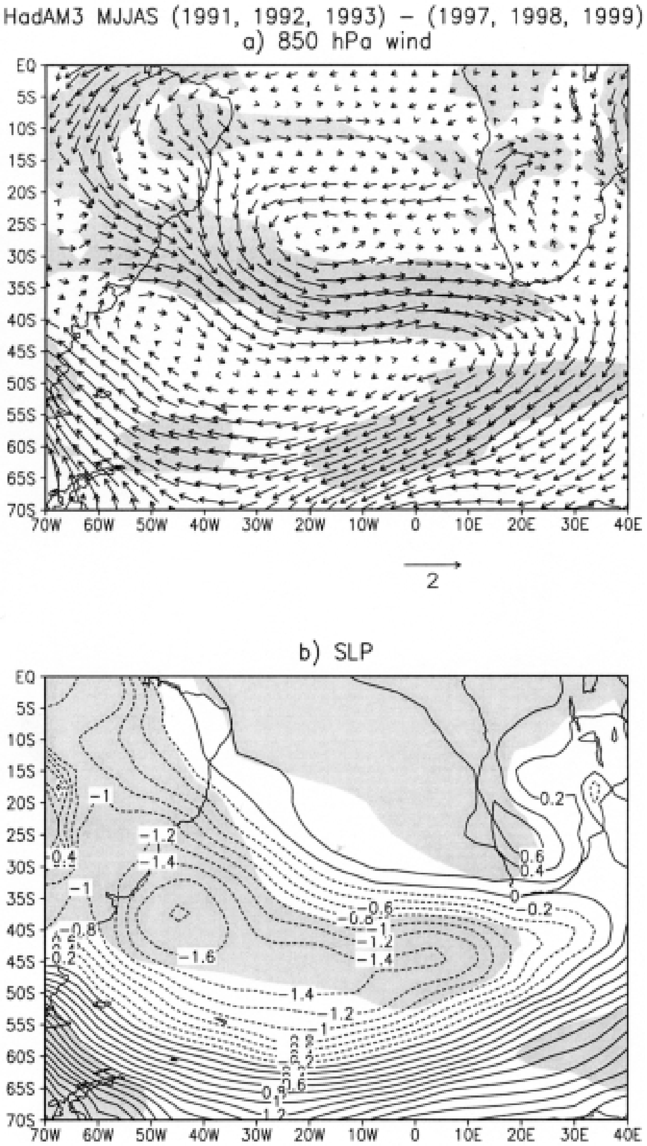


Fig. 6. Wet minus dry winter composite difference of HadAM3 model wind at 850 hPa [panel (**a**); scale represents 2 m/s] and sea-level pressure [panel (**b**), contour interval 0.2 hPa]. Shading represents *t*-test statistical significance at the 95% level.

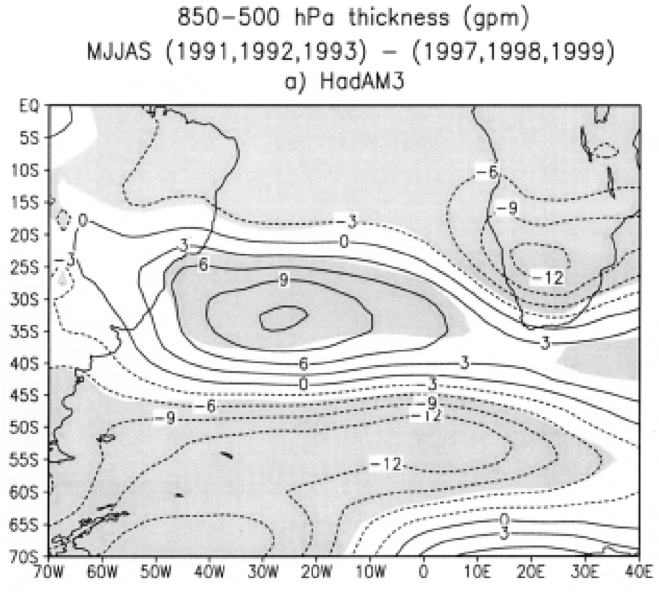
emphasize that we are considering the inter-annual variability of southwestern Cape regional rainfall and its relationships with large-scale SST and circulation anomalies and not the ability of the model to capture absolute rainfall totals for a particular season.

A time series of model winter rainfall for 1990–99 spatially averaged over the grid boxes most closely approximating the southwestern Cape indicates that 1991, 1992 and 1993 were relatively wet years and 1990, 1997, 1998 and 1999 relatively dry (Fig. 5). By comparison, spatially averaged observed rainfall from CMAP[13] (a combination of satellite and rain-gauge data) and the South African Weather Service both indicate that the southwestern Cape received well above average winter rainfall in 1991 (about 1 standard deviation), and that winter 1993 was a wetter (about 0.3 standard deviations) than average season. These data also show that 1997 and 1998 were rather dry (around –0.5 to –0.8 standard deviations), 1990 relatively dry (about –0.4 standard deviations) and the 1992 and 1999 winters received close to average rainfall. Thus, in terms of these spatial averages of seasonal rainfall, the model generally appears to represent the observed tendencies in winter rainfall variability over the study area, although it tends to underestimate the magnitudes of the seasonal anomalies.

It is instructive to compare composites of wet minus dry years. Plots of winter fields for the 1991, 1992, and 1993 composite minus the corresponding results for 1997, 1998 and 1999 are discussed in what follows. Note that 1990 and 1997 in the model display a dry anomaly of almost the same magnitude; however, we chose to include the 1997 result in the dry composite rather than 1990 because model and observed rainfall anomalies are much closer for this year than they are for 1990, when observed rainfall was somewhat less than in the model. On each composite difference plot (Figs 6–9), the shaded region refers to differences that are statistically significant at the 95% level using a *t*-test. Given that winter rainfall over the southwestern Cape results essentially from cold fronts and other westerly disturbances, we focus on circulation and moisture patterns upstream over the South Atlantic.

Wet minus dry composites of circulation patterns

Analysis of circulation patterns for wet and dry winters from 1950 to 2000 indicated that wetter seasons were associated with enhanced mid-level northwesterly flow from the subtropical South American/western South Atlantic region towards the southwestern Cape.[1] The composite wind difference between wet and dry years according to the model (Fig. 6a) shows a strong inflow at the 850-hPa level emanating from tropical South America and out along the South Atlantic Convergence Zone. Comparison with Fig. 4a indicates that this difference reflects a strengthening of mean wind across the South Atlantic at this level together with increased northerly inflow from the equatorial Atlantic/Amazon region into the westerlies tracking towards the southwestern Cape. The SLP (Fig. 6b) and 500-hPa height difference (not shown) reflects this inflow from the Amazon region and the extension of these negative anomalies out into the SW Atlantic (a region of strong cyclogenesis[3]) and along the midlatitude storm track across the South Atlantic is consistent with increased rainfall over the southwestern Cape. Both the model and NCEP re-analyses values for the thickness of the depth of the 850–500 hPa layer for the wet–dry composite indicate a belt of increased thickness in this part of the atmosphere across the subtropical to midlatitude South Atlantic that extends over and southeast of the study region (Fig. 7). The increased



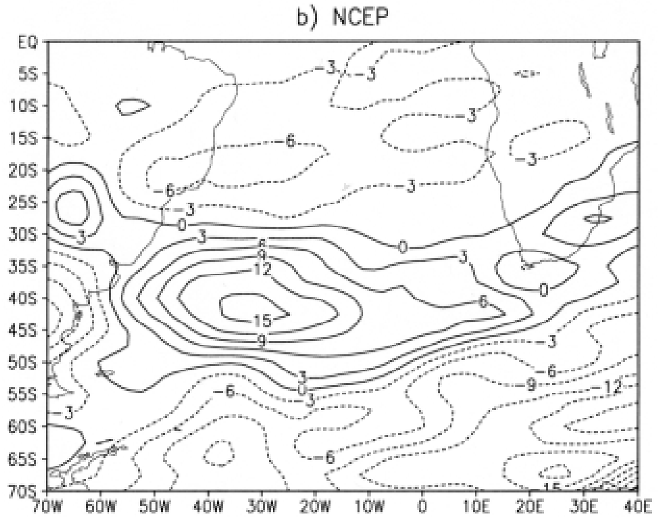
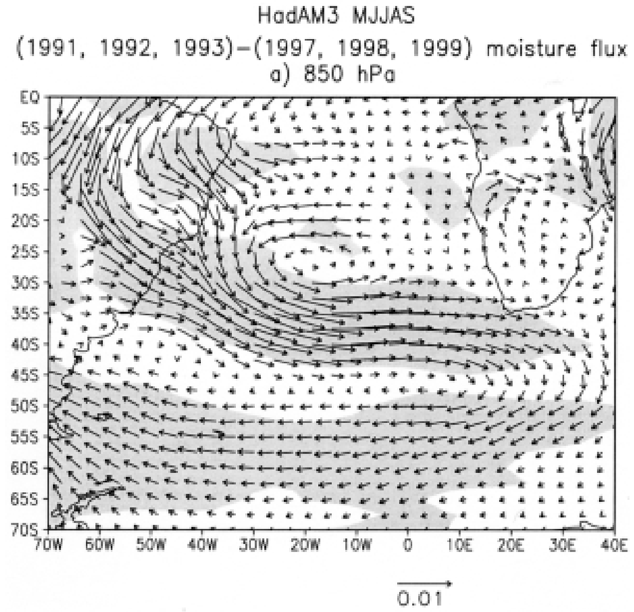


Fig. 7. As for Fig. 6 except for the thickness of the 850–500 hPa layer according to (**a**) the HadAM3 model and (**b**) NCEP re-analyses. Contour interval is 3 gpm.



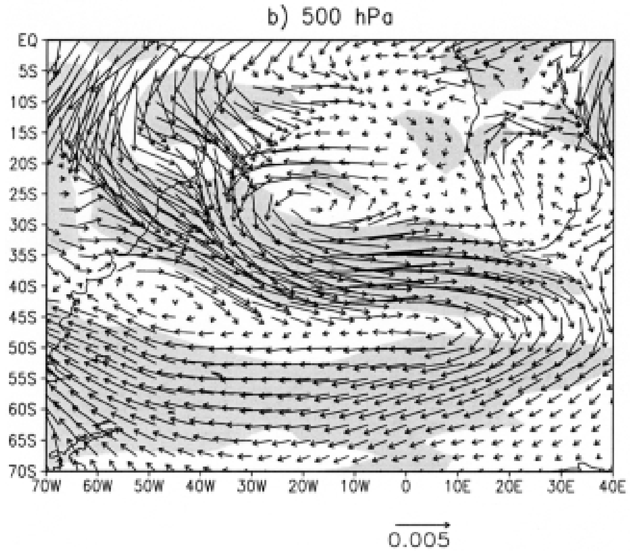


Fig. 9. As for Fig. 6a except for moisture flux at 850 and 500 hPa. Scale vectors in kg/kg m/s are given in each case.

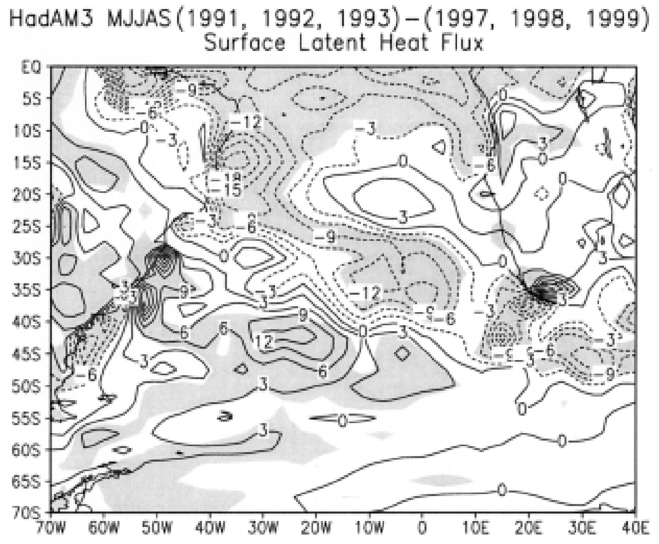


Fig. 8. As for Fig. 6a except for surface latent heat flux (contour interval is 3 W m^{-2}).

depth of this layer favours increased rainfall over the southwestern Cape, since it implies relatively warm and moist air over, and upstream of, the region.

Comparison of the 500-hPa composite difference of the model with that derived from NCEP re-analyses (not shown) indicates a broadly similar dipole anomaly pattern over the South Atlantic but suggests that the anticyclonic anomaly in the subtropics of the model is too weak and lies too far north. At 200 hPa (not shown), the corresponding model difference plot is very similar to the NCEP's; both plots show a strengthening of the jet over the midlatitude South Atlantic, thereby enhancing storm systems tracking towards the southwestern Cape.

It is important to note that the wet–dry SST difference (not shown) constructed from the Reynolds SST used to run the model indicates a large warm anomaly over the SW Atlantic which favours increased cyclogenesis of storms in this region and their subsequent intensification. A warm SST anomaly in this area was also observed[1] to be linked with increased rainfall over the southwestern Cape. The plot of latent heat flux difference (Fig. 8) suggests that significant moisture evaporates in the area of the warm SST anomaly in the SW Atlantic and also from the western Amazon basin and adjoining southeastern subtropical South America. This moisture is then advected towards the southwestern Cape (Fig. 9). A secondary source of increased evaporation appears to be over the Agulhas Current offshore from Cape Agulhas to Port Elizabeth (Fig. 8), a region that is anomalously warm in the Reynolds SST wet minus dry composite. This enhanced local moisture may re-circulate over the southwestern Cape in the flow associated with passage of a given frontal system through the region. Further downstream, over the Agulhas retroflection region and further west, the SST composite difference is negative and consistent with this situation, the latent heat flux difference indicates reduced evaporation in this region (Fig. 8). While at first glance this might seem counterintuitive to wetter southwestern Cape winters, the enhanced contrast between the relatively drier local airmass over the waters immediately west of the study area and that being advected in from the central South Atlantic as well as that re-circulating in from the Agulhas/Southern Cape region via the pre-frontal flow could lead to enhanced instability and more intense frontal systems and rainfall. Investigating that aspect further requires significant experiments with a high-resolution regional atmospheric model and is beyond the scope of this study.

Differences in moisture flux at 850 hPa (Fig. 9a) further reinforce the suggested influence of low-level moisture inflow from the equatorial Atlantic/Amazon region into the westerlies approaching the southwestern Cape. At mid-levels (Fig. 9b), the difference plot reflects a strengthening of the near-zonal westerly to northwesterly flow emanating from subtropical South America. The anticyclonic anomaly over the subtropical western Atlantic serves to weaken the mid-level export of moisture from South America in this latitude zone and strengthen the midlatitude transport towards the southwestern Cape.

In the SE Atlantic, near the study area itself, the plots of moisture difference suggest an increase in flux towards the region, particularly at the 850-hPa level. Divergence plots were also constructed and indicated relative low-level convergence of airflow over and just upstream of the southwestern Cape. Differences in composite vorticity (not shown) indicated enhanced cyclonic vorticity (that favours cyclogenesis and storm development) in the SW Atlantic and also over a large area south and southwest of the southwestern Cape. Finally, differences in eddy geopotential height in the wet minus dry composite fields were constructed and showed increased eddy activity (consistent with more midlatitude depressions and frontal systems) upstream of and over the southwestern Cape in both the model and NCEP re-analysis fields (not shown).

In summary, the wet minus dry composite differences in low- and mid-level model winds, moisture fluxes, sea-level pressure, thickness of the lower atmosphere, eddy geopotential height, vorticity and divergence all appear to be consistent with wetter winter conditions over the southwestern Cape.

Summary and discussion

Comparatively little work has been conducted on the inter-annual rainfall variability of the southwestern Cape. While most climate research has focused on the summer rainfall region where most of South Africa's agricultural activity and rural population are located, the increasing importance to the national economy of tourism, the service sector and of other industries in the southwestern Cape requires that investigating the climate variability of this region and its associated mechanisms should be given attention. Previous work[1,2] suggests that there are identifiable mechanisms that may explain a significant portion of the substantial inter-annual and inter-decadal rainfall variability observed in this region.

Diagnostics from integrations of the Hadley Centre climate model HadAM3 forced by observed global sea-surface temperatures for the period from 1990 to 1999 suggest that this model displays substantial inter-annual winter rainfall variability over the southwestern Cape that is qualitatively similar to the observed. Furthermore, the circulation patterns derived from the model for the wet minus dry winters are consistent with what is expected from previous observational analyses for relatively wet conditions.[1] The model results therefore support earlier observational work suggesting that enhanced inflow of moisture from low-latitude South America and the neighbouring South Atlantic Convergence Zone may lead to above-average winter rainfall over the southwestern Cape and that this may be enhanced by warm SST anomalies in the SW Atlantic.

Comparison of basic atmospheric fields (sea-level pressure, 500-hPa geopotential height, winds, and moisture fluxes at various levels) derived for a winter climatology using the model with those obtained from NCEP re-analyses suggests that the HadAM3 model can represent the general winter circulation in the South Atlantic/southern African sector of the southern hemisphere reasonably well. A detailed analysis of the ability of this model to represent the statistics of the transient weather systems during winter (midlatitude depressions, fronts, cut-off lows, migratory anticyclones, etc.) has not been performed. However, the model's success with the larger-scale circulation patterns in the South Atlantic/African region and knowledge of its capabilities concerning transient weather statistics in other regions of the globe suggest that this tool can be profitably used to help understand the climate variability of the region. Such understanding is potentially useful for assessing the feasibility of forecasting winter climatology for the western and southern Cape and also for putting South African climate change scenarios into an appropriate context.

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