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Modelling the atmospheric response to SST dipole patterns in the South Indian Ocean with a regional climate model

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With 10 Figures

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Summary

Previous observational work and experiments with global atmospheric circulation models have provided evidence that a dipole-like sea surface temperature (SST) pattern in the subtropical South Indian Ocean may influence austral summer rainfall over a southern African region stretching southeast from Zambia towards the south coast of South Africa. Increased rainfall tends to occur during positive events when the SW Indian Ocean anomaly is warm and the SE Indian Ocean anomaly is cool, and decreased rainfall during negative events when the SST anomalies are reversed.

In this study, the regional climate model MM5 is used to investigate the atmospheric response to two strong events of opposite sign (1981 and 1998). In general, the MM5 response is broadly consistent with NCEP re-analyses for these years but tends to advect more low level moisture over than NCEP. The model results indicate that more moisture is advected over the subcontinent from the South West Indian Ocean during the positive event than during the negative event. This is consistent with observed rainfall over the region during these events.

1. Introduction

A number of observational and general circulation model (GCM) modelling studies (e.g., Walker (1990), Jury et al. (1991), Rocha and Simmonds (1997), Landman and Mason (1999), and Reason and Mulenga (1999)) provide strong evidence of interannual variability in sea surface temperature (SST) in the South Indian Ocean and its link with observed rainfall variability over southern Africa. Behera and Yamagata (2001) and Reason (2001) have presented observational and modelling evidence that a dipole-like pattern in subtropical South Indian Ocean SST is important for southern African summer rainfall for a region stretching southeast from Zambia towards the southeast coast of South Africa.

This pattern of interannual variability contains SST anomalies of opposite sign in the southwest and southeast Indian Ocean, i.e., to the southeast of Madagascar and west of Western Australia respectively. The pattern evolves during the austral summer, reaching its maximum around February, and is correlated with southern African summer rainfall such that increased rains tend to occur when the warm pole is in the southwest and the cool pole in the southeast (a so-called positive event – Behera and Yamagata 2001). A negative event is the reverse, i.e., the cool pole is in the southwest and the warm pole in the southeast Indian Ocean. More recent modelling work (Reason 2002) suggests that the rainfall response over southern Africa is

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increased if the southwest pole is located nearer southern Africa, i.e., south and southwest of Madagascar rather than southeast of this island as originally proposed by Behera and Yamagata (2001).

A potential limitation of the previous modelling (Reason 2001, 2002) of the atmospheric response over southern Africa to this SST forcing is that it uses a global atmospheric general circulation model (GCM) whose resolution is too coarse to represent the tight SST, vegetation and topographic gradients in the region. Typical GCMs have at best a horizontal grid of order 100–200 km or more and therefore cannot represent the details of the Agulhas Current or important mountain ranges such as the Drakensberg. In this study, we apply a regional climate model (MM5) at a higher horizontal resolution (60 km) to assess the sensitivity of the atmospheric circulation over southern Africa and the neighbouring oceans to this SST forcing. To date, relatively little work has been done on applying regional climate models to simulating southern African climate variability, although there is increasing interest in their potential. Although the MM5 model has significantly higher spatial resolution than a global GCM, the drawback is that it can only be implemented over a smaller domain, given available computer resources. In this study, the MM5 domain contains only the western pole of the SST anomaly pattern. Around the lateral boundaries of the domain, the model is nudged towards the NCEP re-analyses (Kalnay et al. 1996) which are obtained by assimilating all available observations into a global model and therefore will contain the signature of the eastern pole within them.

2. Methodology

Using the UKMO global SST data set (GISST2.3b), the SST dipole index defined in Behera and Yamagata (2001) has been extended backward to 1955 (Fig. 1). It is obtained by subtracting the spatial average of the SST anomaly for JFM over the eastern pole (18–28° S, 90–100° E) from that over the western (37–27° S, 55–65° E) pole after removing the long term trend. Index values of more than $+1$ and less than -1 are used to define and identify positive and negative events respectively. From Fig. 1, and by assessing the monthly SST anomalies for each event to ensure that a coherent positive and negative anomaly is observed as well as the JFM rainfall anomaly pattern over southern Africa, we determine that JFM 1981 and JFM 1998 are the most appropriate examples of a positive and negative event respectively to model with MM5.

The MM5 model domain of 0–45° S, 5° W–75° E covers the southern African region and neighbouring western South Indian and South East Atlantic Oceans at a horizontal resolution of 60 km. NCEP re-analyses ($2.5° \times 2.5°$ resolution) were used as the initial and boundary conditions for this domain. Although 60 km resolution is relatively coarse over a region such as southern Africa with its tight topographic, vegetation and SST gradients, computational resources precluded a finer grid. An ensemble of five different runs, each initialised from a different time on November 30/December 1 of the preceding year, was performed for each of the 1981 and 1998 cases. In the following, we compare output from MM5 with the same fields from the NCEP re-analyses. Note that rainfall is typically not well simulated in either MM5 or NCEP

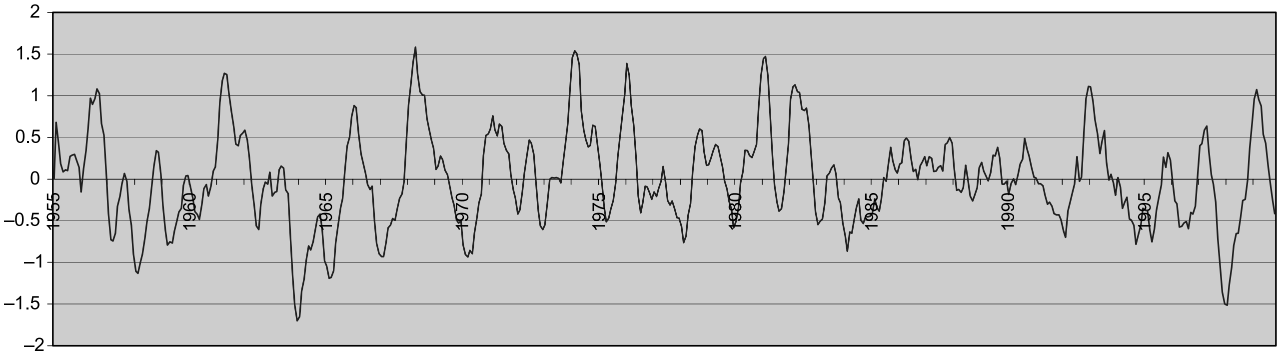


Fig. 1. Subtropical dipole index calculated from GISST2.3b SST data

and, thus, we focus on other related parameters such as moisture flux and outgoing long wave radiation (OLR).

In order to simplify the comparison between the two opposite strong events, and because a reasonable length climatology of MM5 over southern Africa was not available, the model difference between the 1981 and 1998 events are compared with the same fields derived from NCEP. The objective is to compare circulation differences in the two models with a view to assess the robustness of the MM5 simulation.

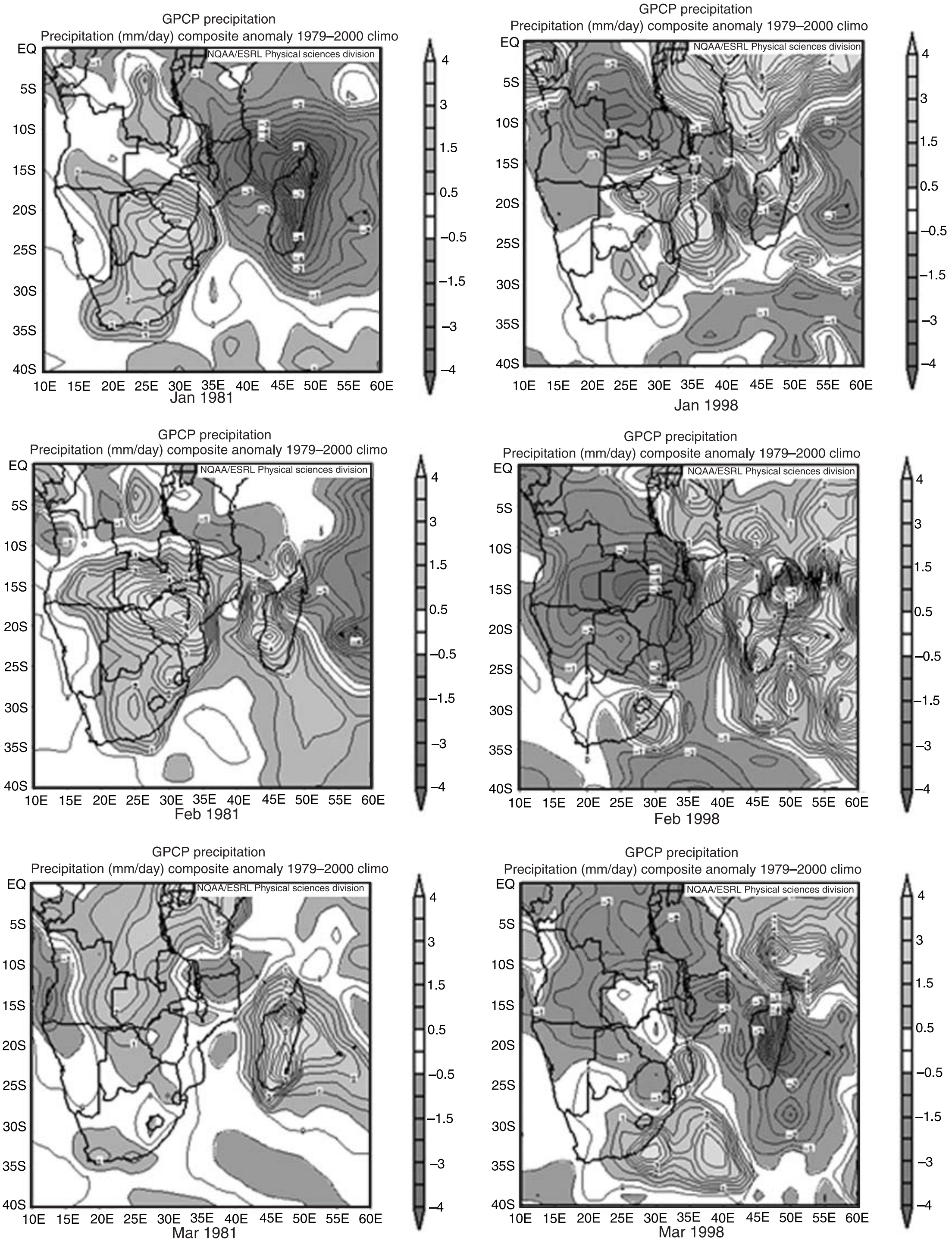


Fig. 2. GPCP rainfall anomalies for 1981 (left) and 1998 (right) for January, February, March expressed in mm/day. Plotted online at: http://www.cdc.noaa.gov/cgi-bin/composites/comp.pl

Rainfall observations (GPCP – Huffman et al. 1997) (Fig. 2) indicate that most of eastern and central Africa south of about 12–15° S was wetter than average during January and February 1981. In March 1981, the areas of increased precipitation shifted to Madagascar and the tropical interior of the subcontinent. By contrast, tropical southern Africa was drier than average during summer 1998 with February and March also showing extensive regions of drier conditions in both the equatorial and subtropical latitudes.

3. Model results

3.1 Outgoing long wave radiation (OLR)

Figure 3 shows monthly mean OLR differences between 1981 and 1998 for January, February and March for both models. Positive (negative) differences imply less (more) convective cloud in 1981 than 1998 and would be associated with less (more) convective summer rainfall. There is broad agreement in the patterns over the land between both models for January and February

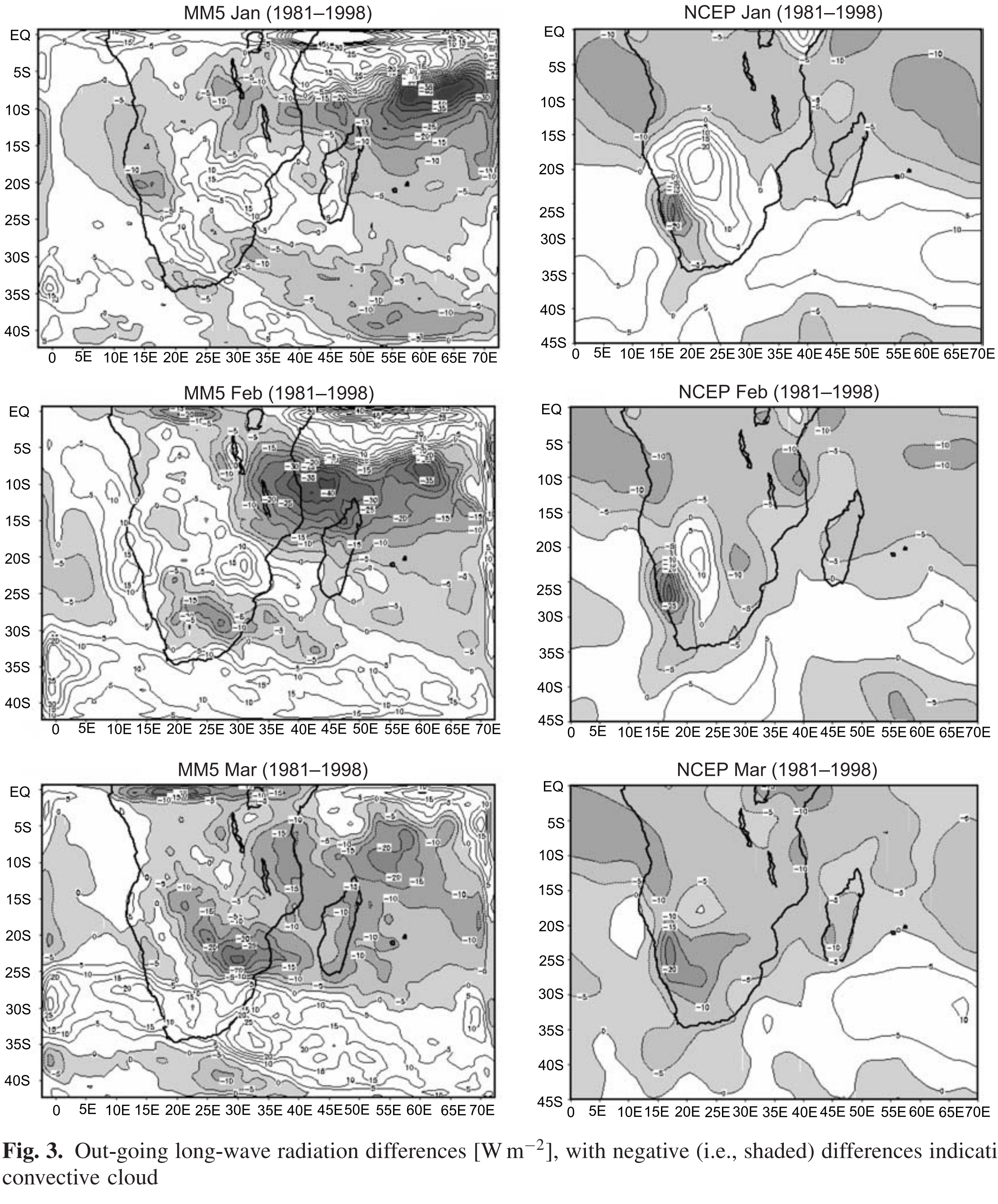


Fig. 3. Out-going long-wave radiation differences [W m^{-2}], with negative (i.e., shaded) differences indicating increased convective cloud

whereas March shows a large positive difference in MM5 over South Africa that is not evident in NCEP. Note that the MM5 differences are more detailed due to that model's higher resolution. Compared to Fig. 2, the MM5 OLR differences seem to be more consistent with the evolution of the rainfall anomalies over southern Africa than NCEP, although MM5 shows a positive anomaly over Mozambique/Zimbabwe for February which contradicts the much wetter conditions seen there in 1981 relative to 1998 in the observations for that month (Fig. 2).

3.2 Sea-level pressure and geopotential height

Figure 4 shows monthly mean sea-level pressure differences between 1981 and 1998 for January, February and March, derived for MM5 and NCEP. Over the subcontinent, both MM5 (left panel) and NCEP (right panel) show negative (positive) differences over the subtropics (tropics) during January, negative differences over most of the land in February and mainly positive differences over the land in March. In other words, both models suggest that 1981 had lower

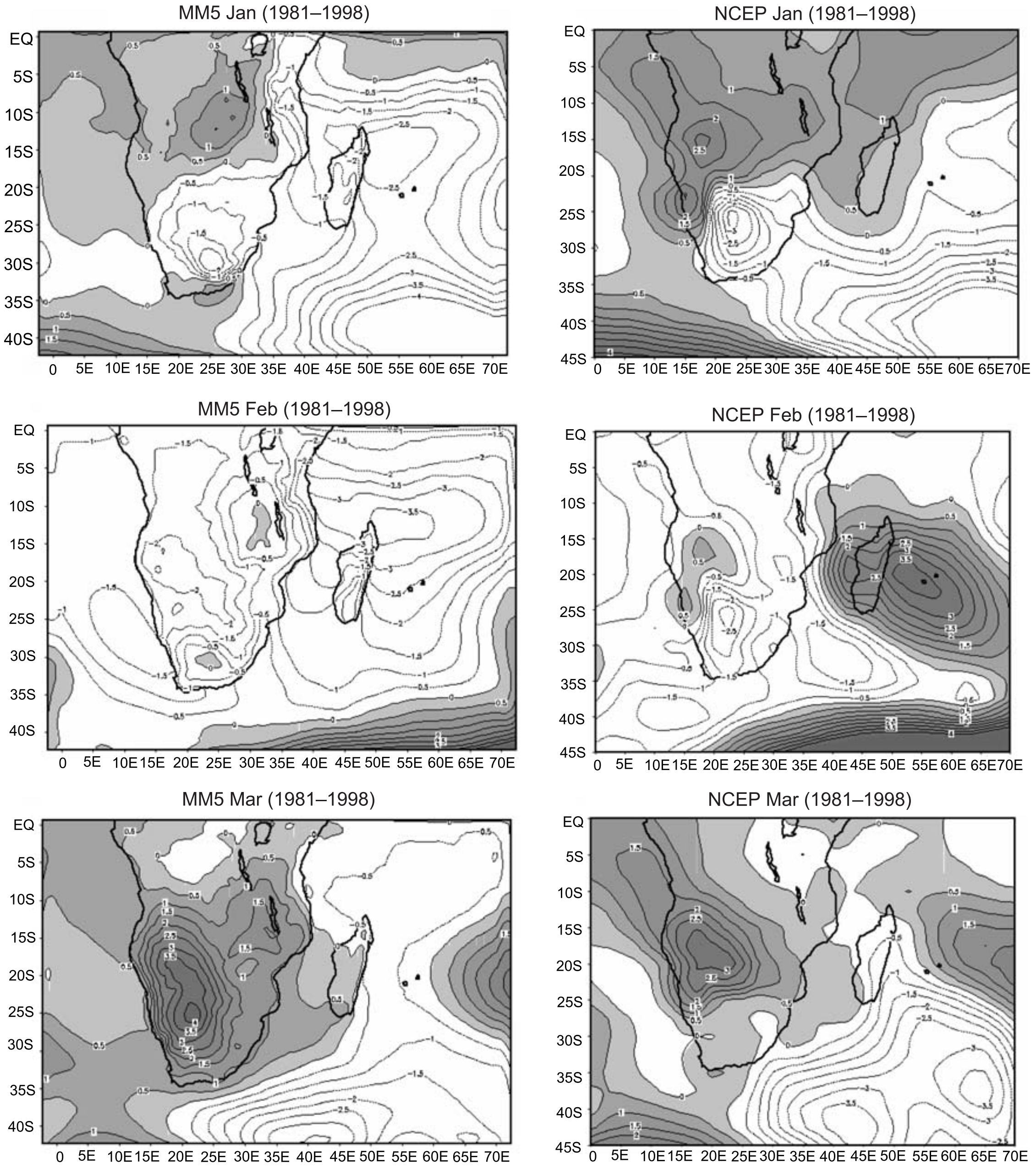


Fig. 4. Sea-level pressure differences [hPa] between 1981 and 1998, with positive differences shaded

pressure relative to 1998 over the subtropics in January, most of Africa south of the equator in February, and then higher pressure in March. This situation implies that the subtropical heat low over western South Africa/western Botswana was deeper in 1981 than in 1998 during January and February and the tropical heat low over southeastern Angola/northern Namibia shifted to the southeast. Cook et al. (2004) provides evidence that these conditions are conducive for above average summer rainfall over South Africa. Given that most of the summer rainfall over southern Africa south of about 15° S arises from tropical temperate troughs (Harrison 1984) associated with these heat lows, Fig. 4 is consistent with the observed wetter conditions during these months in 1981 (Fig. 2). These troughs, and their associated cloud bands, link a disturbance in the easterlies with a westerly disturbance passing south of the landmass.

The negative pressure anomalies southeast of Africa in January and February are also favourable for increased rainfall over subtropical southern Africa in 1981 relative to 1998 during these months since they imply increased westerly wave activity in this part of the midlatitude SW Indian Ocean that is needed for tropical temperate trough development (Tyson and Preston-Whyte 2000). During March, both models suggest higher sea-level pressure over the land in 1981 than in 1998, consistent with the weakening of the positive rainfall anomalies over subtropical southern Africa for that month.

One obvious difference in the SLP fields between the models concerns the region near and east of Madagascar during February. Since this difference occurs to lesser extent at 850 hPa (not shown) but is not apparent at 500 hPa (Fig. 6), it may be related to differences in the way the models represent the adjustment of the low level flow to the substantial Madagascan orography. In February, the ITCZ is furthest south and monsoonal westerlies impact on northwestern Madagascar, a pronounced cyclonic circulation exists in the Mozambique Channel and easterlies are incident on the central and south coast of eastern Madagascar. According to the NCEP re-analyses, these westerlies were weaker (stronger) than average in February 1981 (1998) with the easterlies shifted north (south) along the east coast of Madagascar in February 1981 (1998). In particular, the 1998 NCEP re-analyses show a strong cyclonic anomaly (relative to the 1968–1998 NCEP climatology) over Madagascar which strengthens the monsoonal westerlies to the north and weakens and shifts the easterly trades incident on the Madagascan orography. With a 60 km grid, MM5 is able to partially capture the

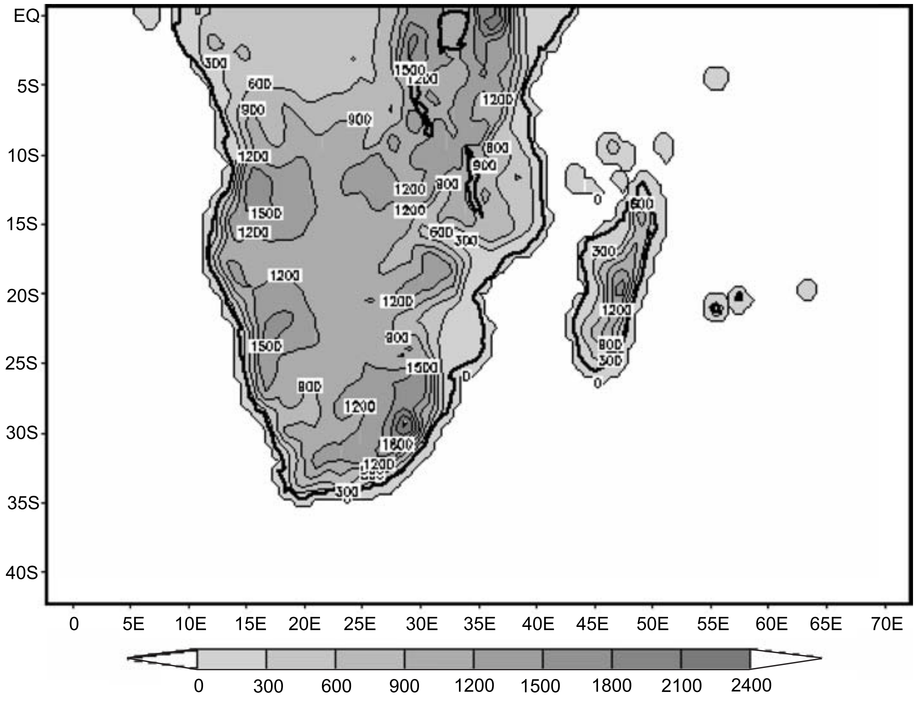
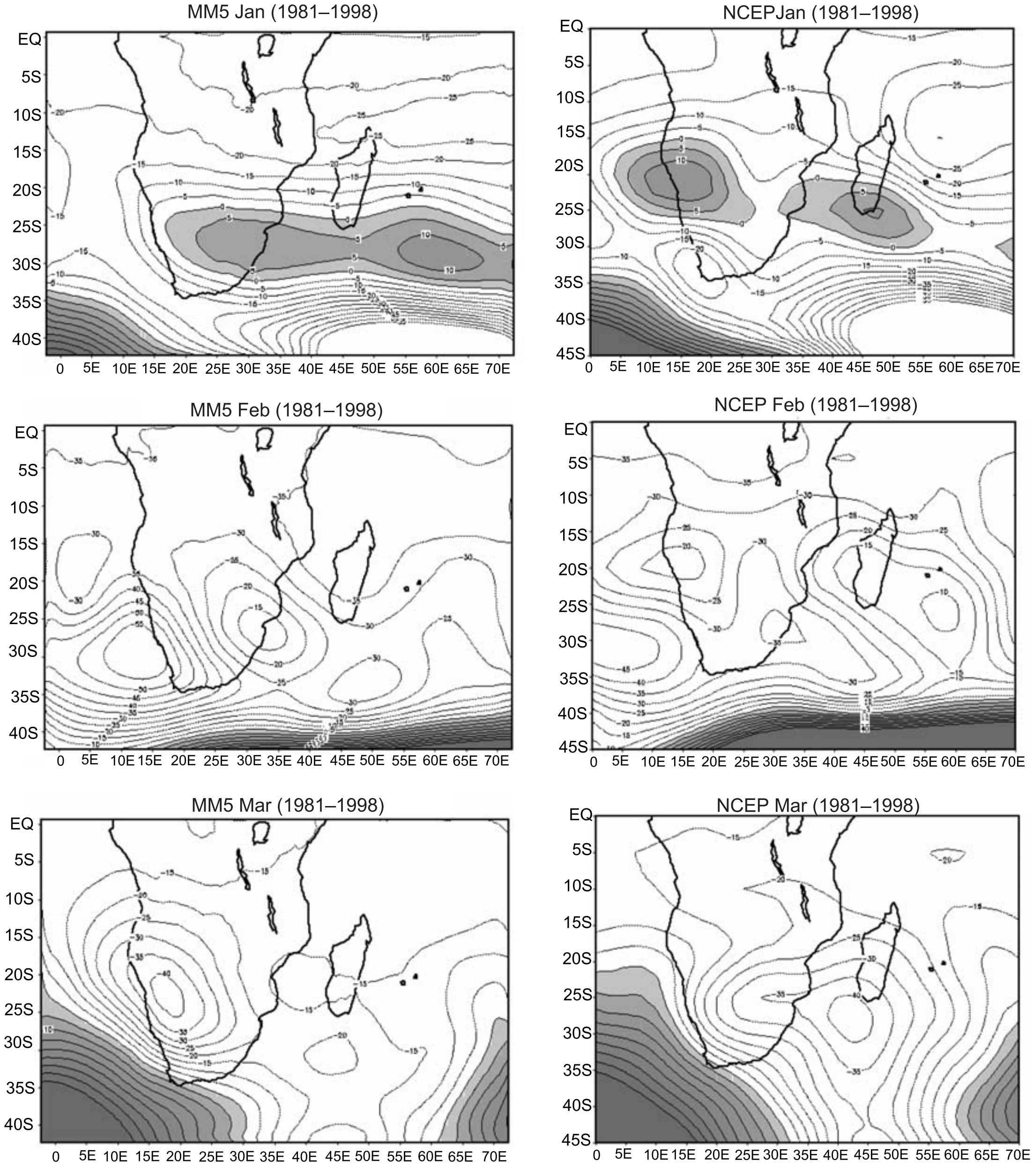


Fig. 5. Orography of southern Africa and Madagascar as represented in the MM5 model [m]

Madagascan mountains (Fig. 5) but the 250 km grid of NCEP is about the same distance as the width of these mountains at their broadest point. However, the observations assimilated into the NCEP model will contain some signature of the Madagascan orography and, if these observations are sufficiently dense, then the re-analyses should adequately represent the regional effects of these mountains. On the other hand, MM5 evolves freely over the domain and therefore is not influenced by any such observations in the Madagascan region. Furthermore, the 1998 NCEP anomaly over Madagascar is mainly over the interior of the MM5 domain; thus, the NCEP boundary conditions applied at the eastern boundary will contain no signature of it and so it does not appear in the MM5 field. Thus, it appears that it is this February 1998 NCEP field that leads to the discrepancy with the MM5 patterns for this month seen in Fig. 4.

No such difference is evident at the 500 hPa level and comparisons of geopotential heights (Fig. 6) indicate similarities in the patterns for the two models in all three months. This result


MM5 Jan (1981–1998)

NCEPJan (1981–1998)

MM5 Feb (1981–1998)

NCEP Feb (1981–1998)

MM5 Mar (1981–1998)

NCEP Mar (1981–1998)

Fig. 6. Geopotential height differences [m] between 1981 and 1998 at 500 hPa. Positive differences are shaded

is consistent with the reduced influence on the 500 hPa circulation of differences in orography and other surface forcing (such as vegetation) between the two models. Note that the SST forcing is the same in each case. For January, both models suggest slightly increased pressure over subtropical southern Africa in 1981 than in 1998, although in MM5 this feature is further to the southeast. This feature is absent in February and lower pressure occurs over the subcontinent and surrounding oceans in both models in 1981, consistent with the wetter conditions in this month than January (Fig. 2). Both models show an area of higher (lower) pressure in 1981 than 1998 over the southwest of the domain (southern Africa and neighbouring Indian Ocean) for March. This might imply increased rainfall in March 1981 relative to 1998; however, the SLP differences

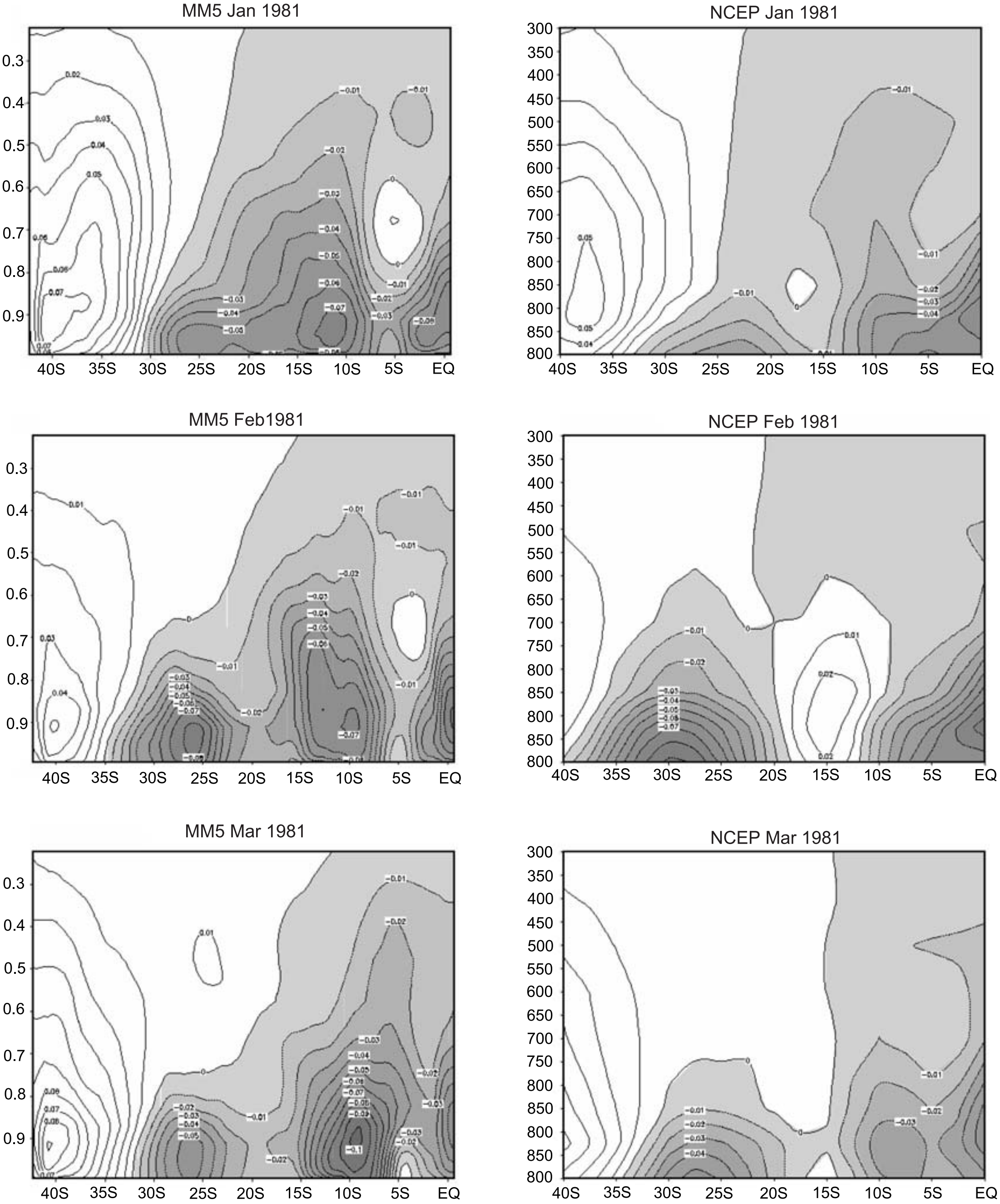


Fig. 7a. Zonal moisture flux anomaly from climatology transect along 40° E (increased easterly flux or negative differences are shaded) [g/kg m/s]

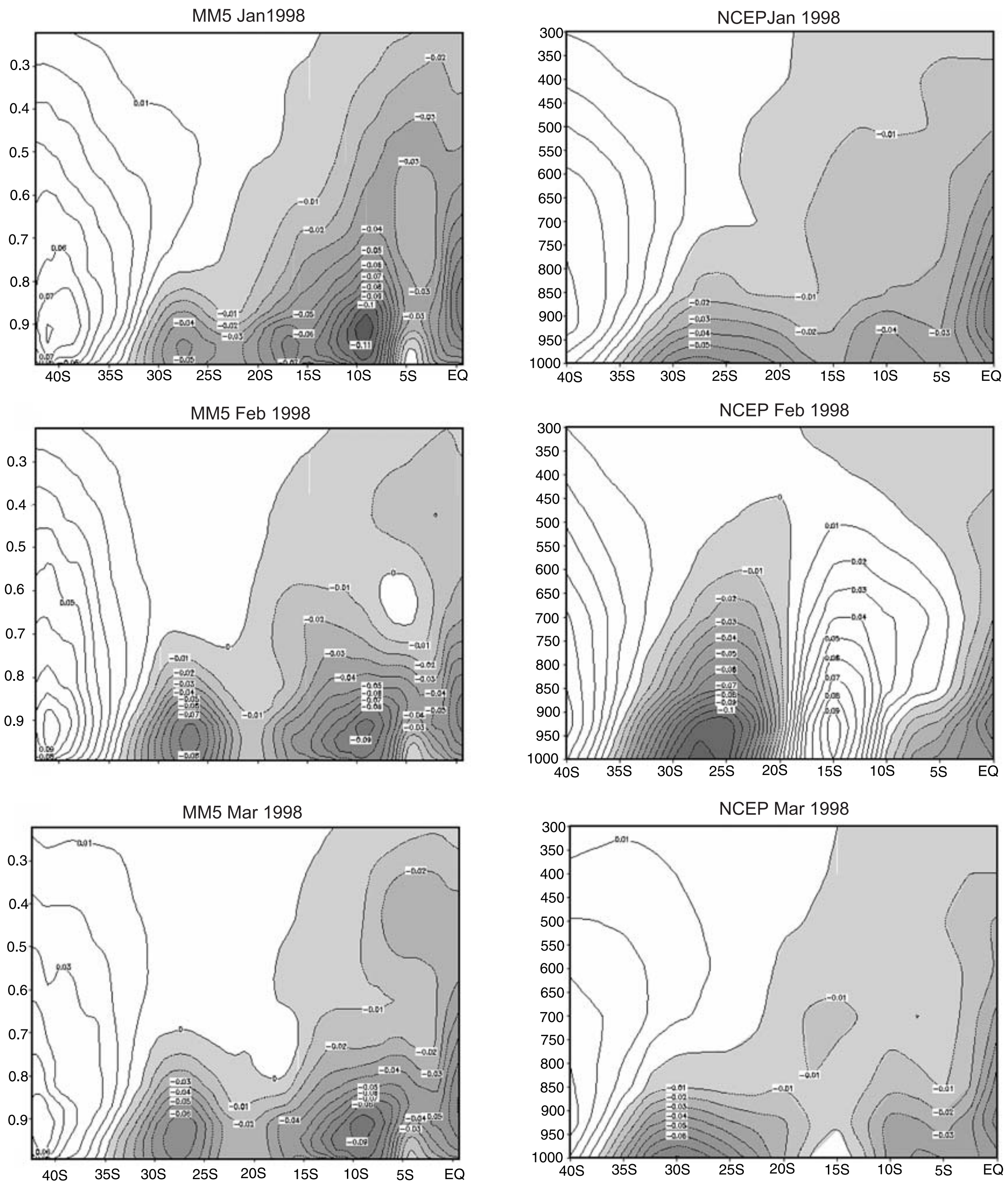


Fig. 7b. Zonal moisture flux anomaly from climatology transect along 40° E (increased easterly flux or negative differences are shaded) [g/kg m/s]

imply the reverse and the observed precipitation anomalies (Fig. 2) indicate that the rainfall in this month was only slightly higher in 1981 than in 1998 over most of subtropical southern Africa.

In summary, the MM5 and NCEP SLP and 500 hPa fields are broadly similar in pattern for all months except February 1998 for SLP. They are also generally consistent with the evolution of the monthly precipitation differences. In order to explore the latter in more detail, the next section considers the moisture fluxes.

3.3 Moisture flux

Transects of zonal moisture flux along 20 and 40° E are considered in order to investigate the relative influences of moisture originating from the South West Indian and tropical South East

Atlantic Oceans during JFM 1981 and 1998. Since moisture flux is a relatively less accurate field in NCEP than a primary variable such as geopotential height (Kalnay et al. 1996) and given that the fluxes need to be interpolated onto the same grid, it is considered preferable to display these fluxes for 1981 and 1998 separately. Interpolation is necessary since the MM5 output is on sigma levels whereas the NCEP data is available on pressure levels. The interpolation used here sets the bottom and top pressure levels for MM5 as 1000 hPa (corresponding to sigma level one) and 100 hPa (corresponding to sigma level zero) respectively. It should also be noted that there is minimal moisture above 300 hPa and that there are differences in the number of equiv-

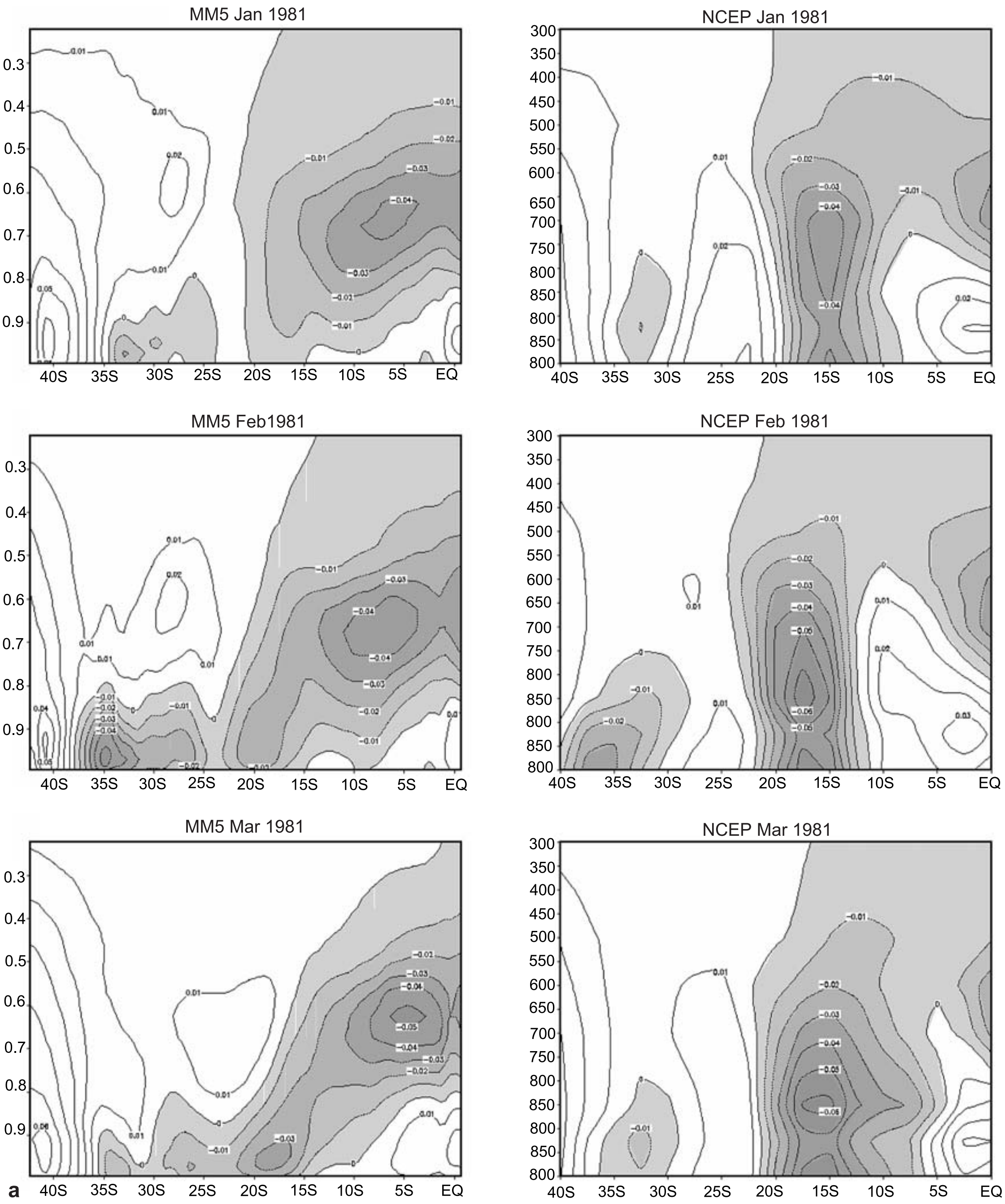


Fig. 8. Zonal moisture flux anomaly from climatology transect along 20° E (increased easterly flux or negative differences are shaded) [g/kg m/s]

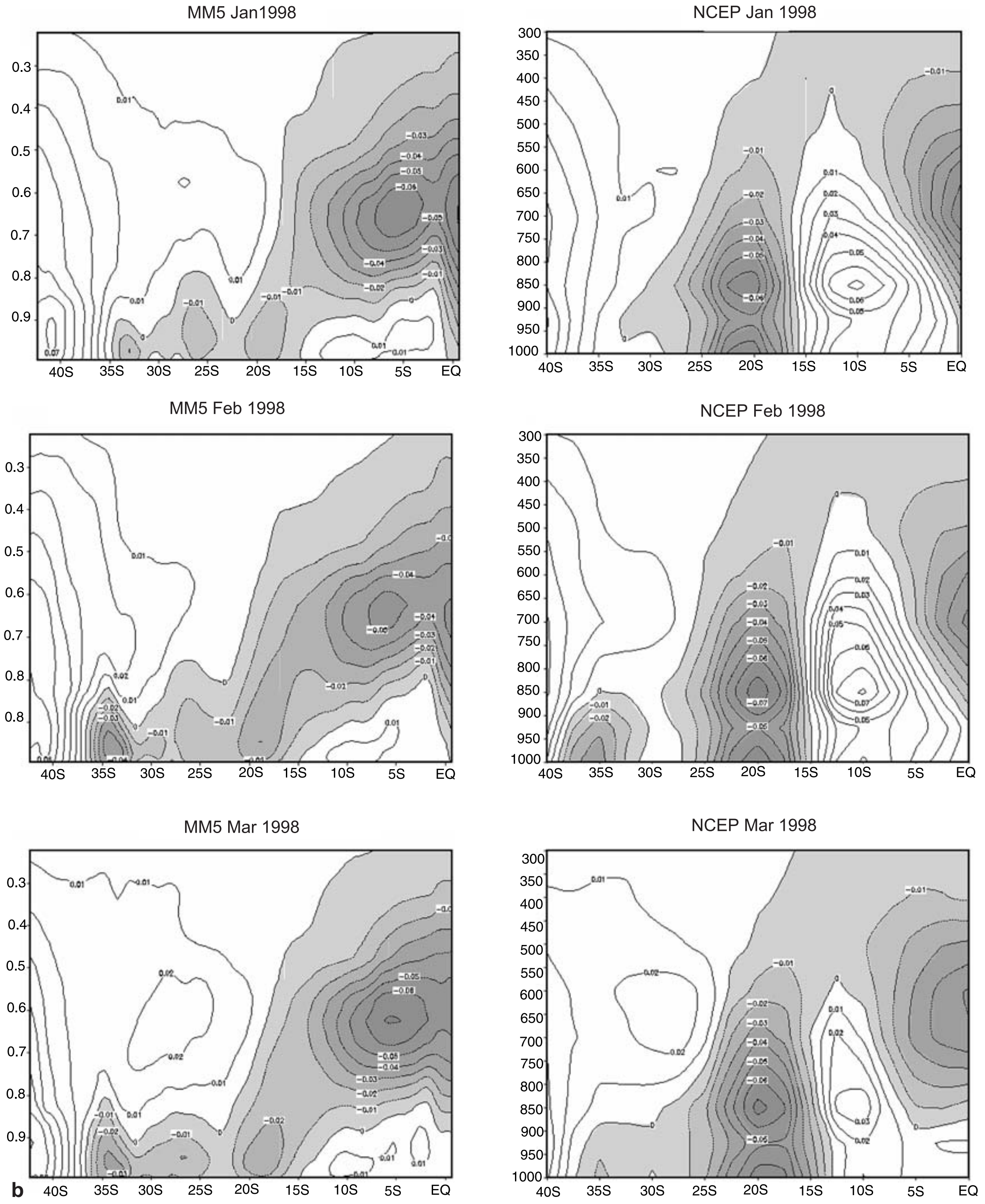


Fig. 8 (*continued*)

alent vertical levels between the two models (23 for MM5 and 17 for NCEP). With this in mind, we consider moisture transects from the surface up to about 300 hPa (Figs. 7 and 8).

Along 40° E, which runs through the Mozambique Channel and Tanzanian coast, Fig. 7a shows easterly flux from the equator to around 30–35° S in January and March 1981 in both models but somewhat stronger in MM5. This flux is consistent with 1981 being relatively wet (e.g., d'Abreton and Tyson 1995, 1996; Cook et al. 2004). February 1981 shows continued strong easterly fluxes in MM5 but a weak westerly flux near 12–18° S in NCEP, reflecting the SLP differences (Fig. 4) already discussed for this month. South of the ITCZ (i.e., about 15° S), MM5 shows stronger low level easterly fluxes along this transect in 1981 (Fig. 7a) relative to 1998 (Fig. 7b) for January, and to lesser extent February, with slightly weaker fluxes in March. This result is generally consistent with the evolution of the rainfall (Fig. 2) since increased subtropical easterly flux from the South West Indian Ocean is typically associated with wetter conditions over subtropical southern Africa (e.g., d'Abreton and Tyson 1995, 1996; Cook et al. 2004). Another notable feature in MM5 is a stronger vertical moisture flux gradient at low latitudes for January and February 1998 than for the same months in 1981. Strong vertical moisture flux gradients may have adverse implications for the formation of convective clouds, which are a major source of precipitation during this season. This may help explain the drier conditions experienced during the 1998 event. These differences in moisture flux gradients are also observed to some extent in NCEP.

Figure 8a, b shows the zonal moisture flux for 1981 and 1998 respectively for a transect that runs along 20° E (i.e., through Cape Agulhas and the western interior of southern Africa). Low level westerly fluxes are seen in both MM5 and NCEP for the low latitude region in both years and this reflects the flow off the tropical South East Atlantic around the northern part of the Angola low (e.g., Cook et al. 2004). Over the subtropics, there is easterly flux but of generally reduced magnitude for all months and both models than along 40° E since some of the moisture has been precipitated out over central and eastern southern Africa. In general, the boundary between the low latitude westerlies and the subtropical easterlies is sharper and deeper for both years in NCEP than in MM5 (Fig. 8). The latter tend to extend further south in MM5 in 1981 but are more comparable with NCEP in 1998. Stronger midlatitude westerly fluxes in 1998 than 1981 seen in Fig. 8 are consistent with the former summer being drier since they imply increased advection of relatively cool, dry South Atlantic air over South Africa which is unfavourable for tropical temperate trough formation and is often associated with summer droughts (e.g., Mulenga et al. 2003).

Meridional moisture flux transects were also constructed along 20° S (not shown) and, in MM5, show that more moisture is being advected south from the tropics into subtropical southern Africa during January, and to some extent, February 1981 than 1998. In March, the moisture flux is similar for 1981 and 1998 consistent with the rainfall anomalies (Fig. 2). For NCEP, the moisture flux differences are more apparent over the Mozambique Channel than over southern Africa itself.

In summary, the moisture flux results suggest that MM5 generally advects more low level moisture from the South West Indian Ocean over Africa south of the ITCZ than NCEP during the wetter 1981 summer. The reduced fluxes and strong vertical moisture gradients during 1998 for MM5 are consistent with 1998 being a drier summer over this region than 1981.

3.4 Latent heat fluxes

Figure 9 shows monthly latent heat flux differences between 1981 and 1998 for both models. Consistent with 1981 being wetter than 1998, there is increased evaporation in 1981 over large areas of the subtropical South West Indian Ocean for all months. This increased evaporation is more extensive in MM5 than in NCEP, particularly near important moisture source regions such as the northern Mozambique Channel region and south of Madagascar (Cook et al. 2004). An important difference between the models is that over the tropical South East Atlantic, a secondary moisture source for subtropical southern Africa (Reason et al. 2006), MM5 shows increased evaporation for February 1981 compared to 1998 whereas NCEP shows the reverse. The MM5 field is consistent with the greater extent of the wetter conditions in February over southern Angola and northeastern Namibia seen in Fig. 2 and previous work (Hirst and Hastenrath 1983; Rouault et al. 2003) that shows the importance of this ocean region for late summer rainfall in Angola, Namibia and neighbouring areas.

3.5 Zonal wind shear

The wind shear fields (850–200 hPa zonal wind) are displayed separately for 1981 (Fig. 10a) and 1998 (Fig. 10b) rather than as a difference between the two summer seasons for the same reasons as that given earlier for the moisture fluxes. The wind shear is related to easterly (negative) and westerly (positive) disturbances over the tropical and midlatitude regions respectively. These disturbances are important for the formation of tropical temperate troughs and their

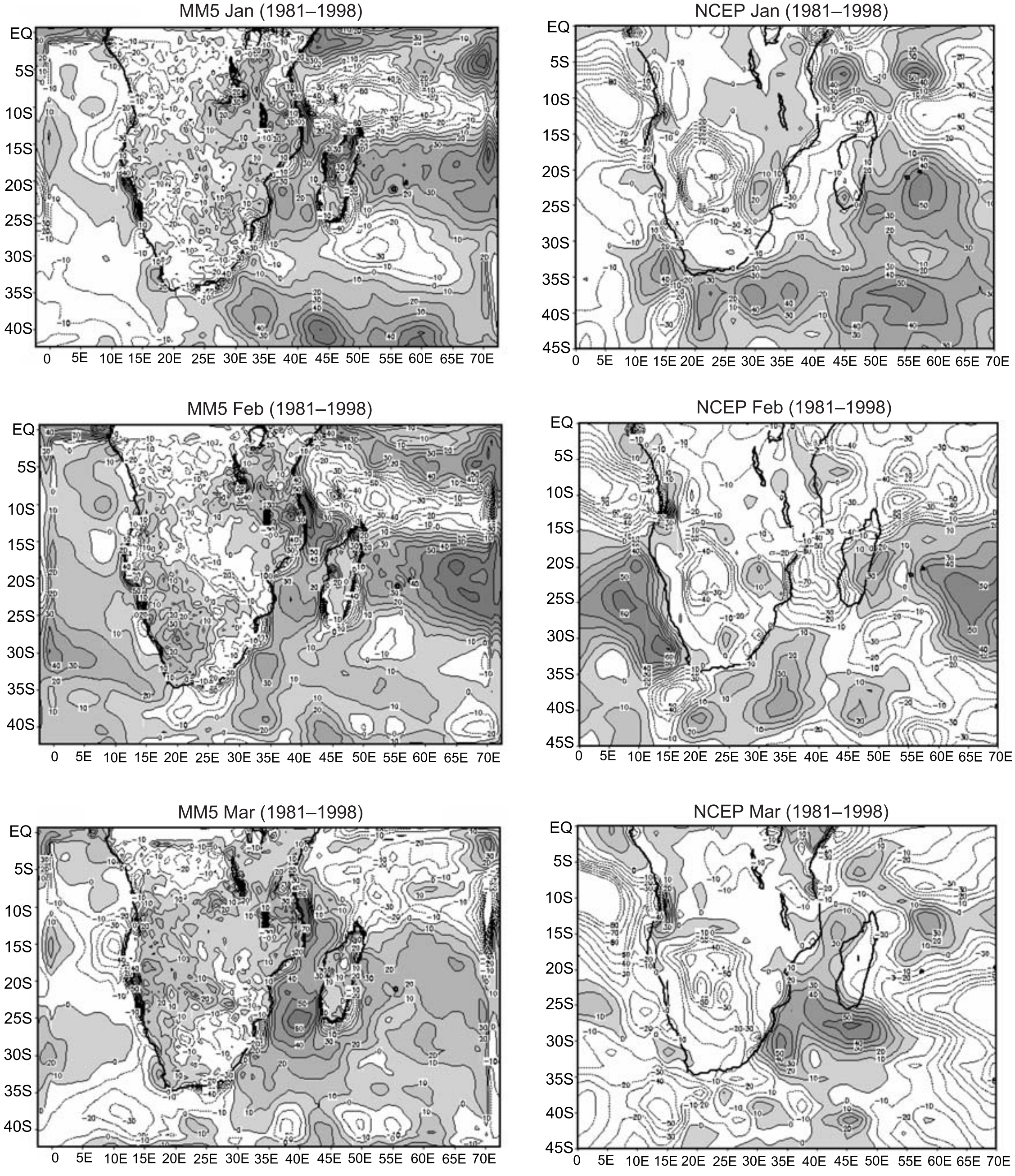

MM5 Jan (1981–1998)
NCEP Jan (1981–1998)
MM5 Feb (1981–1998)
NCEP Feb (1981–1998)
MM5 Mar (1981–1998)
NCEP Mar (1981–1998)

Fig. 9. Latent heat flux differences [W m^{-2}] between 1981 and 1998 (positive values are shaded)

associated cloud bands, the main summer rain-producing synoptic system over southern Africa (Tyson and Preston-Whyte 2000). Typically, good rains over the land are associated with a trough aligned NW–SE across subtropical southern Africa. A strong westerly shear located near the region southeast of South Africa, in January during 1981 in both models (Fig. 10a), is consistent with the orientation of the cloud band across central South Africa that is associated with wet conditions over much of the region during this summer. This feature is however stronger in NCEP than in MM5 and appears to weaken and split into two in February in NCEP and MM5 with the westerly shear maximum being further north in MM5 compared to NCEP. In MM5, the shear over the Atlantic appears like a cut-off low and that in the Indian Ocean is further east. The shear weakens further and shifts north in March. This weakening indicates reduced westerly disturbances and implies reduced rainfall over subtropical southern Africa, consistent with smaller positive anomalies in March 1981 than earlier in the season (Fig. 2).

During January 1998 (Fig. 10b), the westerly shear maximum is weaker than in January 1981 (Fig. 10a) and is less obviously aligned (particularly, in MM5) just to the southeast of South Africa as would be conducive to tropical temperate trough formation across the land. This suggests weaker cloud bands and drier conditions in January 1998. The area of maximum shear in the westerlies shifts northeastward to lie just south and southwest of Cape Town in February 1998 in NCEP. This implies that baroclinic disturbances intensify southwest of South Africa, which is unfavourable for cloud bands across southern Africa. Indeed, almost all of Southern Africa shows dry conditions in February 1998. In MM5, the westerly shear maximum is further west than NCEP (over the South Atlantic) and is weaker. A westerly shear maximum is located just off the south coast in March in NCEP whereas MM5 does not show any clear feature here. Consistent with this NCEP shear maximum, which is more favourable for cloudbands lying across the land, March 1998 shows positive precipitation anomalies over southeastern South Africa.

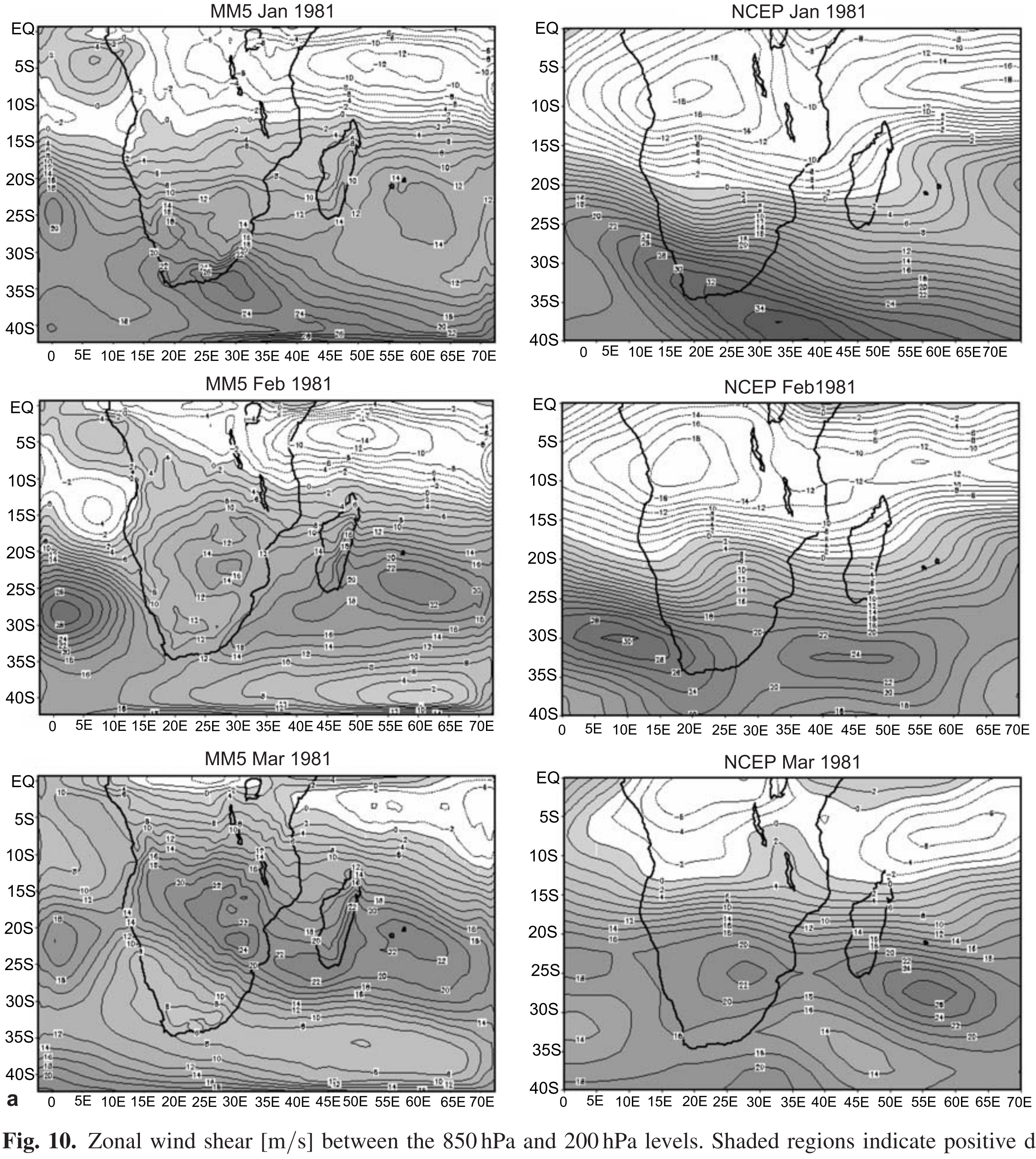
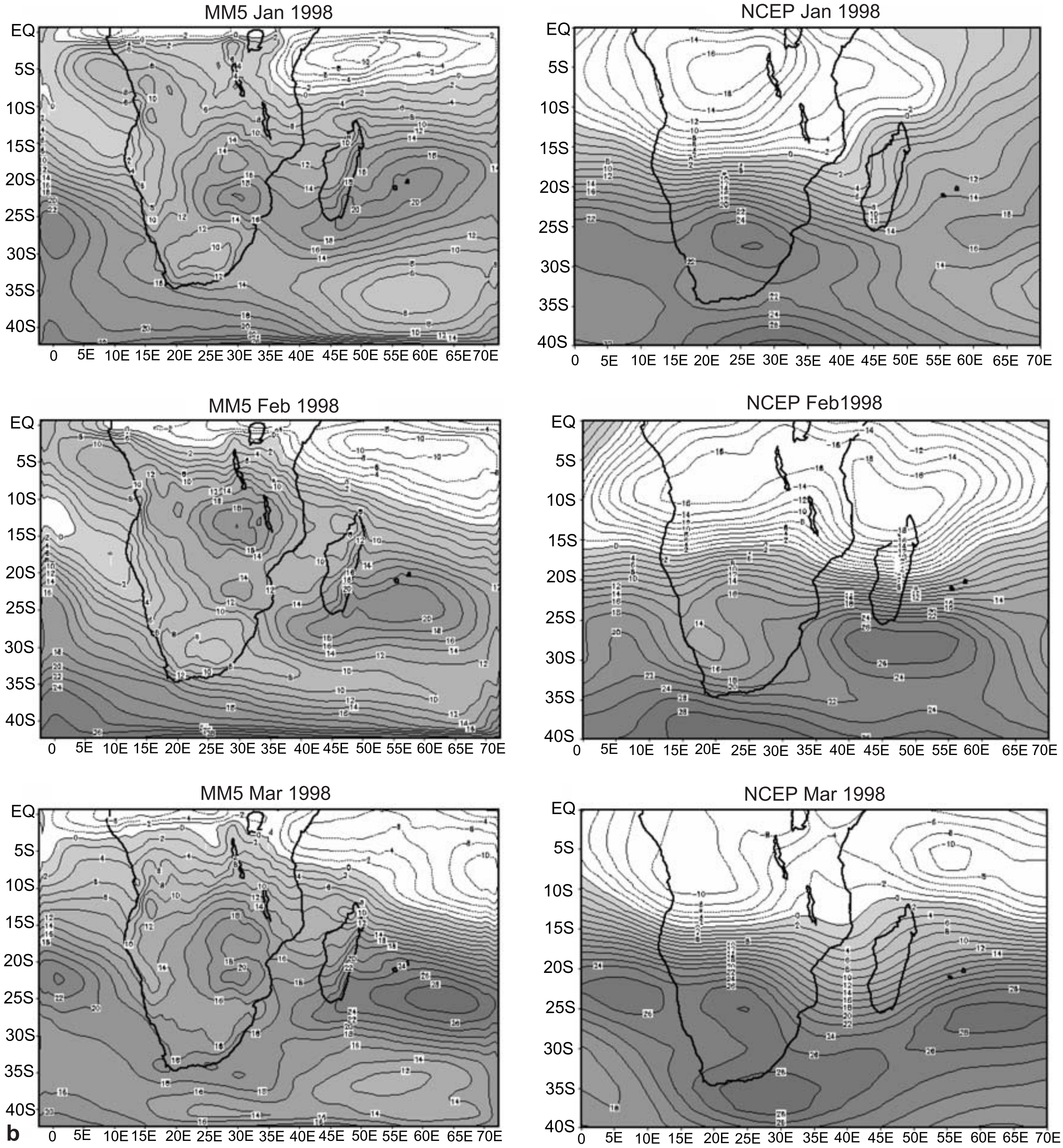


Fig. 10. Zonal wind shear [m/s] between the 850 hPa and 200 hPa levels. Shaded regions indicate positive differences



MM5 Jan 1998

NCEP Jan 1998

MM5 Feb 1998

NCEP Feb1998

MM5 Mar 1998

NCEP Mar 1998

Fig. 10 (*continued*)

4. Conclusions

Two sets of experiments have been performed with a regional climate model (MM5) to assess the sensitivity of the regional atmospheric circulation to two dipole-like SST anomaly events of opposite phase (1981 and 1998) in the subtropical South Indian Ocean. To date, relatively little work has been done on applying regional climate models like MM5 to simulating climate variability over southern Africa. Comparison of circulation differences for these events between MM5 and NCEP broadly shows similarities between these models, thus indicating that simulations from MM5 are representative of the regional atmospheric circulation during these two events. There are however, significant differences between MM5 and NCEP in the February 1998 mean sea-level pressure field near and east of Madagascar. These differences appear to be related to a significant cyclonic anomaly that is present in the NCEP fields in the Mozambique Channel region, well to the west of the MM5 boundary.

Another significant difference is that MM5 generally appears to advect more low-level moisture from the South West Indian Ocean over southern Africa than NCEP during the wetter 1981 summer, consistent with the observed increased rainfall for that season. The MM5 simulations also suggest that moisture evaporated off the tropical SE Atlantic and feeding into southern Africa via the Angola low may be relatively more significant than suggested in the NCEP re-analyses. This low acts as the source region for many of the tropical temperate troughs and their associated cloud bands that bring much of the region's summer rainfall. These troughs link the tropical low to a midlatitude westerly disturbance passing to the south of South Africa. Models need to be able to adequately represent both the low and midlatitude disturbances in order to have some success in capturing these troughs. The Angola low is a relatively small feature (perhaps 500 km or so in width) and therefore it is quite possible that the 60 km resolution MM5 model used in this study may represent it better than the approximately 250 km resolution NCEP re-analyses.

Acknowledgements

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