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# A model investigation of recent ENSO impacts over southern Africa

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With 15 Figures

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**Summary**

This study investigates the impacts of five recent ENSO events on southern Africa, the associated circulation anomalies and the ability of an atmospheric general circulation model (UKMO HadAM3) to represent these impacts when forced by observed sea-surface temperature (SST). It is found that the model is most successful for the 1997/8 El Niño but does less well for the 1991/2 and 2002/3 El Niños and the 1995/6 and 1999/00 La Niña events. Diagnostics from the model and NCEP re-analyses suggest that modulations to the Angola low, an important centre of tropical convection over southern Africa during austral summer, are often important for influencing the rainfall impacts of ENSO over subtropical southern Africa. Since the model has difficulty in adequately representing this regional circulation feature and its variability, it has problems in capturing ENSO rainfall impacts over southern Africa. During 1997/8, modulations to the Angola low were weak and Indian Ocean SST forcing strong and the model is relatively successful. The implications of these results for dynamical model based seasonal forecasting of the region are discussed.

## 1. Introduction

The El Niño Southern Oscillation (ENSO) phenomenon is known to have significant impacts over southern Africa (e.g., Nicholson and Entekhabi, 1986; Ropelewski and Halpert, 1987; Lindesay, 1988; Jury et al, 1994; Rocha and Simmonds, 1997; Nicholson and Kim, 1997; Reason et al, 2000) although its influence shows marked regional and inter-event variations. There are also potential ocean influences originating, or at least most strongly manifest, in the Indian, Atlantic and Southern Oceans (e.g., Hirst and Hastenrath, 1983; White and Peterson, 1996; Goddard and Graham, 1999; Saji et al, 1999; Behera and Yamagata, 2001; Reason, 2001; Reason et al, 2002; Rouault et al, 2003) and some of these may also have a relationship with ENSO. As a result, assessing the mechanisms associated with interannual rainfall variability over southern Africa is difficult.

Good examples of the significant variations in the impacts of ENSO that can occur over southern Africa have happened in the last decade or so. For example, the relatively weak 1991/2 and 2002/3 El Niños were associated with widespread and severe summer drought across large areas of southern Africa whereas dry conditions were less intense during the 1997/8 El Niño episode, one of the strongest events on record in terms of the Southern Oscillation Index and SST anomalies in the tropical Pacific. For La Niñas, the relatively weak 1995/6 event led to significant wet anomalies across the southeastern and Congo basin

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regions of southern Africa but many tropical areas of the subcontinent had less than average rainfall. By comparison, the 1999/00 event had much more widespread positive rainfall anomalies.

In this study, we investigate the variations in rainfall impacts over southern Africa of the 1991/2, 1997/8 and 2002/3 El Niños and the 1995/6 and 1999/00 La Niñas. Although this set does not include all recent events, it contains a useful spread of impacts over southern Africa that is manageable to study. Given that the southern African impacts of ENSO can vary substantially, it makes more sense to investigate a range of events individually rather composite them together. An atmospheric general circulation model (AGCM) and National Center for Environmental Prediction (NCEP) re-analyses (Kalnay et al, 1996) are used in the investigation. Although there may be concerns with the quality of the re-analyses prior to the satellite period and over parts of Africa where there are less observations available for assimilation than other areas, they represent essentially the best freely available data over the region. During the 1990–2003 period of interest herein, the NCEP data quality is less problematic than prior to 1980. In addition, we compared the circulation anomalies for the various ENSO events derived from NCEP reanalyses with those derived from ECMWF to find that the results are very similar (and therefore only plots from NCEP are shown below).

The AGCM used in the study is the UKMO HadAM3 model forced in hindcast mode with observed SST for the January 1st 1990–June 30th 2003 period and implemented at UCT as part of a dynamical seasonal forecasting project. An important question in this regard is whether this model is able to realistically capture ENSO impacts over southern Africa when forced with observed SST. If the model is successful, then confidence in its ability to provide robust seasonal forecasts for the region will be increased. Attention in this study is focused on southern African anomalies for the austral early (OND) and late (JFM) summer season when the majority of the annual rainfall occurs.

## 2. Model description and methodology

The results discussed below used the UKMO 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 and the 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 parameterisation was used. A detailed evaluation of this model, its biases and the main parameterisations of the sub-grid scale physics can be found in Pope et al (2000).

As part of the seasonal forecasting project, HadAM3 has been integrated for the 1990–2003 period with the observed Reynolds monthly SST available as global data on a $1° \times 1°$ latitude-longitude grid (Reynolds and Smith, 1994). An ensemble of five integrations for this period has been performed and the results below present the ensemble mean differences (from the HadAM3 1990–2003 mean climatology). Statistically significant differences at the 95% confidence level, according to a student's *t*-test score, are indicated in each figure. The HadAM3 model results are compared with anomalies calculated in a similar manner using the NCEP re-analysis dataset.

## 3. HadAM3 moisture flux and divergence climatology

Figures 1–2 show the HadAM3 850 hPa rainfall, moisture flux climatology, and divergence for the early (OND) and late (JFM) summer together with the corresponding fields derived from NCEP re-analyses and CMAP rainfall (Xie and Arkin, 1996). Both plots indicate the seasonal southward shift of the easterlies over the subtropical Indian Ocean, the ITCZ and associated heavy rainfall, midlatitude westerlies and the intensification of the NE monsoon along the Tanzanian/Kenyan coast in JFM. Over the land, the Angolan low (part of the trough that develops over the continent during summer) is evident in both models during OND. The Angola low is of importance since it generally acts as the tropical source region for the tropical–extratropical cloudbands that extend NW–SE across southern Africa south of about 15–20° S and bring much of the region's summer rainfall (e.g., Harrison, 1984; Todd and Washington, 1998). In JFM, NCEP

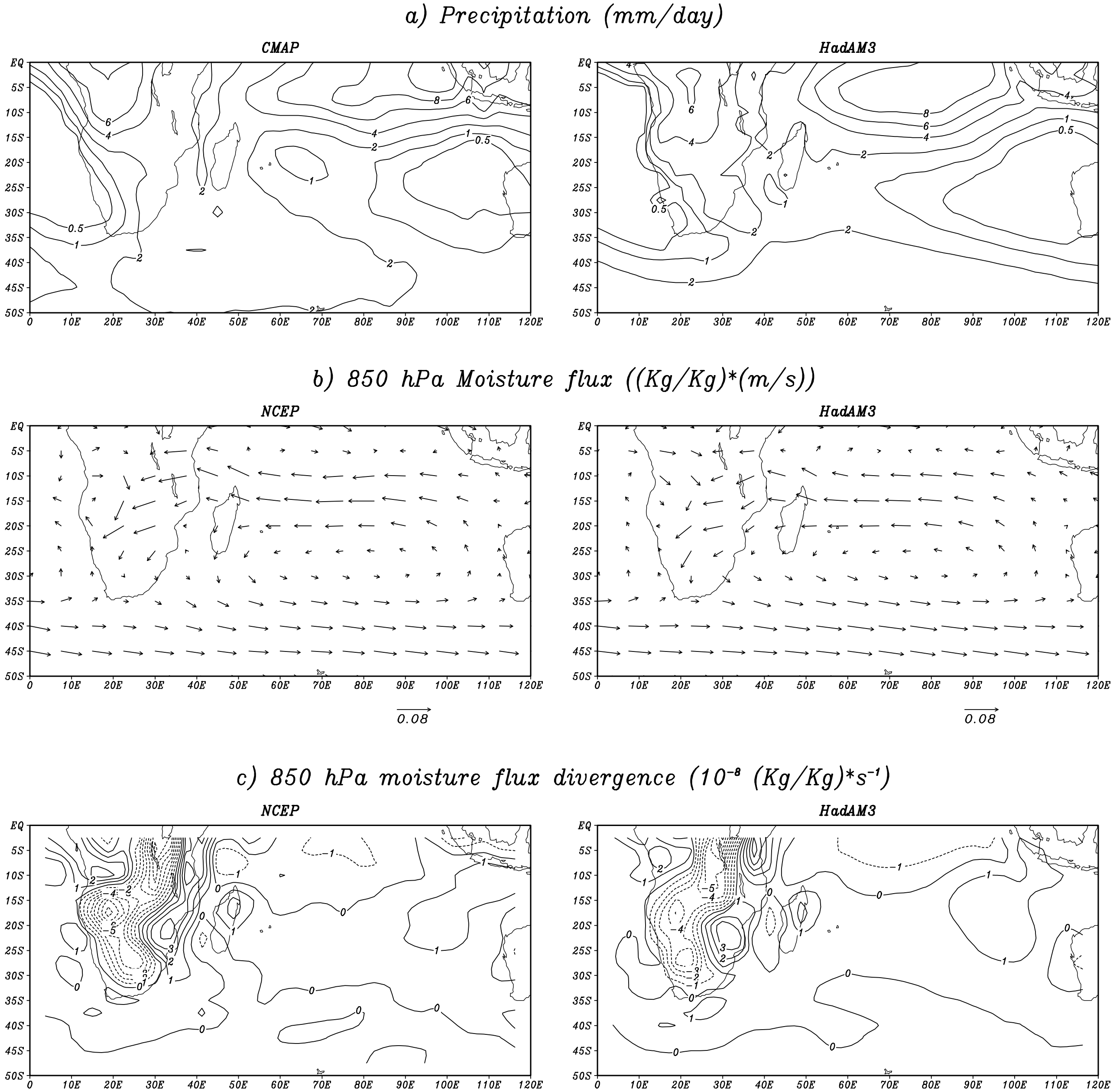


**Fig. 1a.** NCEP and HadAM3 climatological rainfall (mm/day), (**b**) 850 hPa moisture flux (a scale vector is shown), and (**c**) 850 hPa divergence for the OND season. Note that in panel (**a**) contour intervals are 0.5, 1, 2, 4, 6, 8 mm/day

shows the Angola low intensifying with an area of low-level convergence extending along the ITCZ across southern Africa. However, HadAM3 fails to capture this intensification in JFM and shows an area of low level divergence separating the Angola low region from the ITCZ over the Mozambique Channel. As seen later, HadAM3 deficiencies in capturing the Angola low have important implications for modelling the ENSO impacts over the region.

Further south, the seasonal strengthening of the anticyclonic flux of moisture over eastern South Africa and southern Mozambique is evident in both NCEP and HadAM3 fields. This moisture inflow feeds into the tropical–extratropical cloudbands emanating from the Angola low and stretching southeastwards across South Africa into the SW Indian Ocean. Both NCEP and HadAM3 (Fig. 2) show a NW–SE band of low-level convergence stretching across the

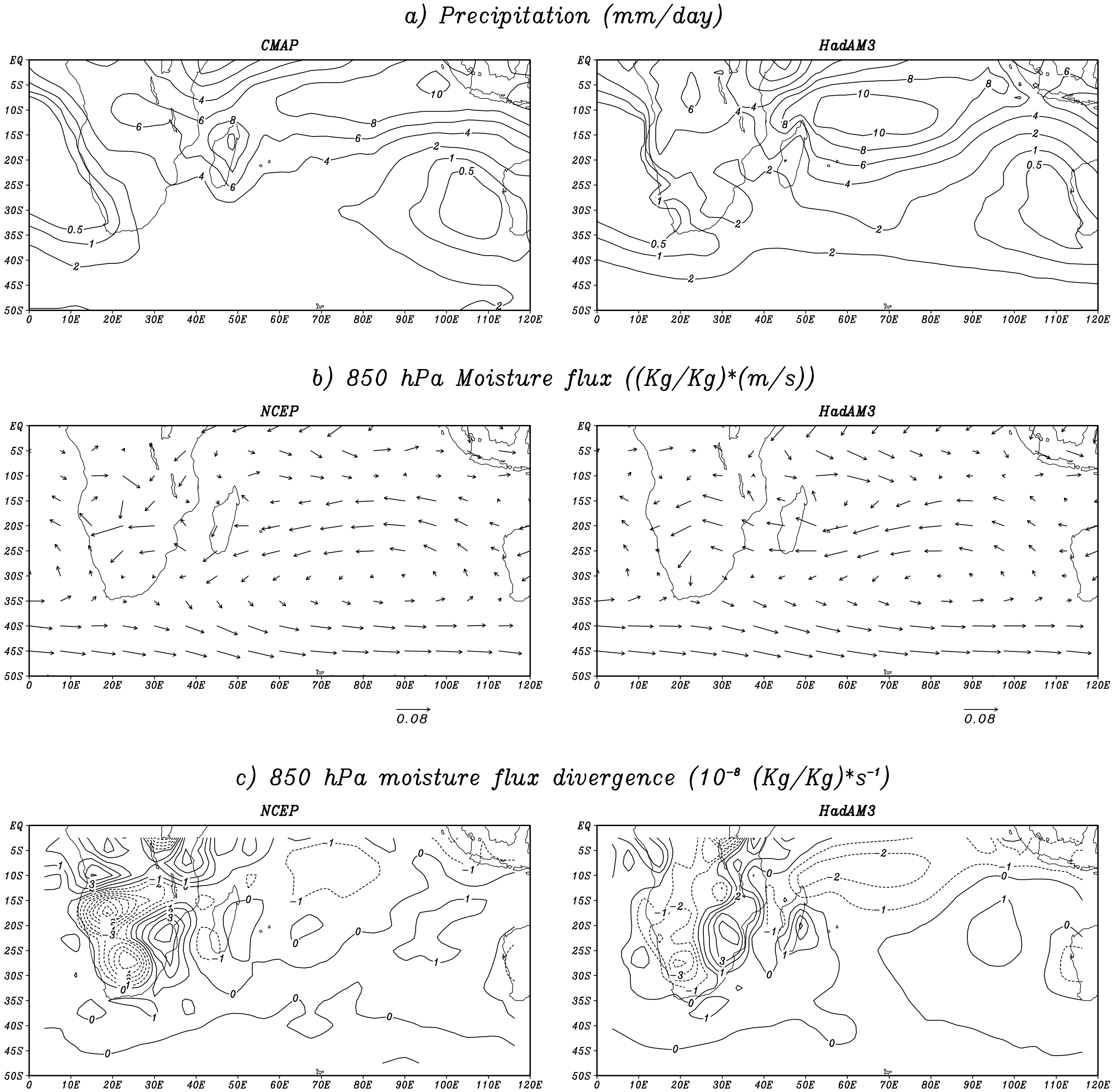


**Fig. 2.** As for Fig. 1, except JFM

tropics to subtropics of southern Africa with relative divergence over Mozambique and Zimbabwe, although the feature is less pronounced in HadAM3. The downstream adjustment of the easterlies to the Madagascan high topography and associated low-level convergence in the Mozambique Channel is less evident in HadAM3 than in NCEP, essentially as a result of the coarser resolution not capturing these mountains to the same degree. Also evident in JFM is a cyclonic circulation in NCEP and to greater extent in HadAM3, situated off the northeast coast of Madagascar. This partly results from the stronger equatorial westerlies to the north of this feature in HadAM3 (related to the NE monsoon which recurves over the Indian Ocean) and the stronger sub-tropical easterlies to be found to the south. In HadAM3, these easterlies flow straight over Madagascar instead of troughing as in NCEP because the model does not capture the orography sufficiently. Associated with this cyclonic anomaly, in JFM (and to some extent OND) the model precipitation climatology is positively biased over the tropical western Indian Ocean in the neighborhood of the ITCZ and negatively biased over neighboring Madagascar and eastern Africa.

## 4. Rainfall and circulation anomaly patterns

Figures 3–4 display the observed (CMAP – Xie and Arkin, 1996) and HadAM3 rainfall anomalies over southern Africa for three El Niño and two La Niña recent events for the austral early (OND) and late (JFM) summer seasons. These figures suggest firstly that there is a fair amount of spatial variation in ENSO rainfall impacts over southern Africa, and secondly, that 1997/8 is the ENSO event that shows the best agreement between the observed and HadAM3 precipitation anomalies. Dry conditions over southern Africa as a whole were also generally less severe for 1997/8 than for the 1991/2 or 2002/3 El Niños, despite the Pacific SST anomalies being substantially larger in 1997/8. JFM 1992 shows the most extensive and severe drought of the six El Niño seasons in both the observations and HadAM3. As is generally the case, HadAM3 underestimates both the magnitude and the distribution of the rainfall anomaly, though it is noteworthy that where the precipitation anomaly is statistically significant the sign of the anomaly is simulated correctly. This season was also one of the driest late summers over the last 80 years over much of central and northern South Africa. For the La Niña seasons, JFM 2000 was very wet over southeastern Africa and also Namibia. In an attempt to understand the differences in the severity of the rainfall impacts of these different ENSO events, various moisture-related and circulation diagnostics are discussed below.

### *4.1 1991/2 event*

Figures 5 and 6 portray anomalies for the OND 1991 and JFM 1992 seasons. The observed rainfall anomaly for OND 1991 (Fig. 3) indicates dry conditions over the western Congo, equatorial East Africa and over the southeast of the subcontinent with above average rainfall elsewhere, particularly in the central region and over southern South Africa. The model shows the same basic pattern except that the dry southeastern region is too far south; however, it tends to underestimate the magnitude of both the wet and dry anomalies. The reason for these discrepancies begins to emerge in Fig. 5a, the low-level moisture flux anomalies, in which NCEP re-analyses suggest strong cyclonic anomalies extending from east of Madagascar to Zimbabwe that oppose the mean flow, thereby leading to dry conditions over Mozambique and neighboring regions. On the other hand, HadAM3 has a weaker cyclonic feature east of Madagascar and an anticyclonic anomaly over this island and the Mozambique Channel with westerly anomalies further south, consistent with dry conditions over eastern South Africa. Furthermore, the NCEP re-analyses suggest that the Angola low and the ITCZ (near 10–15° S in OND) were weaker and less conducive to convective rainfall since there is reduced evaporation off the tropical western Indian Ocean (ITCZ region) and the tropical South East Atlantic (a moisture source for the Angola low) (Fig. 5b), and a band of relative low level divergence and anticyclonic vorticity across southern Tanzania/northern Mozambique/Zambia/Angola (Fig. 5c–d). The model also shows reduced evaporation and anticyclonic vorticity anomalies over parts of the South West Indian Ocean but does not capture the band of relative low level divergence across central and western southern Africa as clearly as in NCEP. Low- and upper-level velocity potential plots (not shown) indicate a marked shift in the Pacific and Indian Ocean Walker cells in both NCEP and HadAM3 during OND 1991. Consistent with dry conditions over equatorial East Africa, the ascending branch of the local Walker cell is weakened with relative ascent evident over the western Indian Ocean.

JFM 1992 stands out as one of the worst droughts in recent decades in southern Africa despite El Niño indicators such as the Southern Oscillation Index or Niño 3.4 SST anomaly index not being particularly extreme. Almost all of Africa south of the equator experienced negative rainfall anomalies during this season with particularly dry conditions over southeastern Africa (Fig. 4). The model shows dry conditions over most of the region but with decreased magnitude relative to observations. Fig. 6a suggests strong convergence of moisture in the NCEP fields over the tropical South Indian Ocean since the

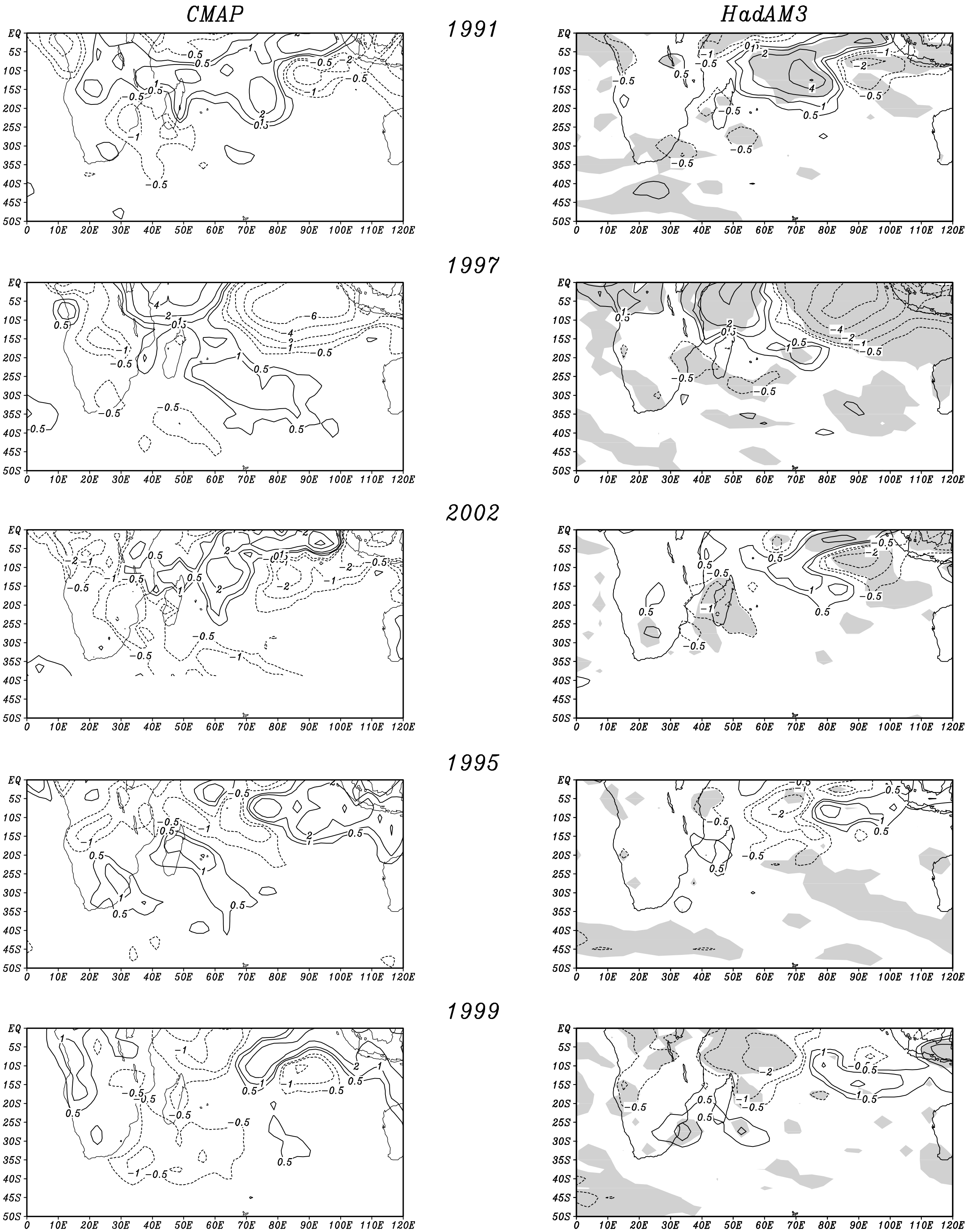


**Fig. 3.** Observed (CMAP) and HadAM3 seasonal (OND or JFM) rainfall anomalies in mm/day for the various El Niño (1991; 1997; 2002) and La Niña (1995; 1999) OND seasons indicated. Note that data for 2002/3 comes from GPCP Satellite-Derived (IR) monthly rainfall estimates (Janowiak and Arkin, 1991) since CMAP data were not available for 2002/3. Note contour levels are 0.5, 1, 2, 4 mm/day. Shading on the HadAM3 plots represents statistical significance at the 95% level

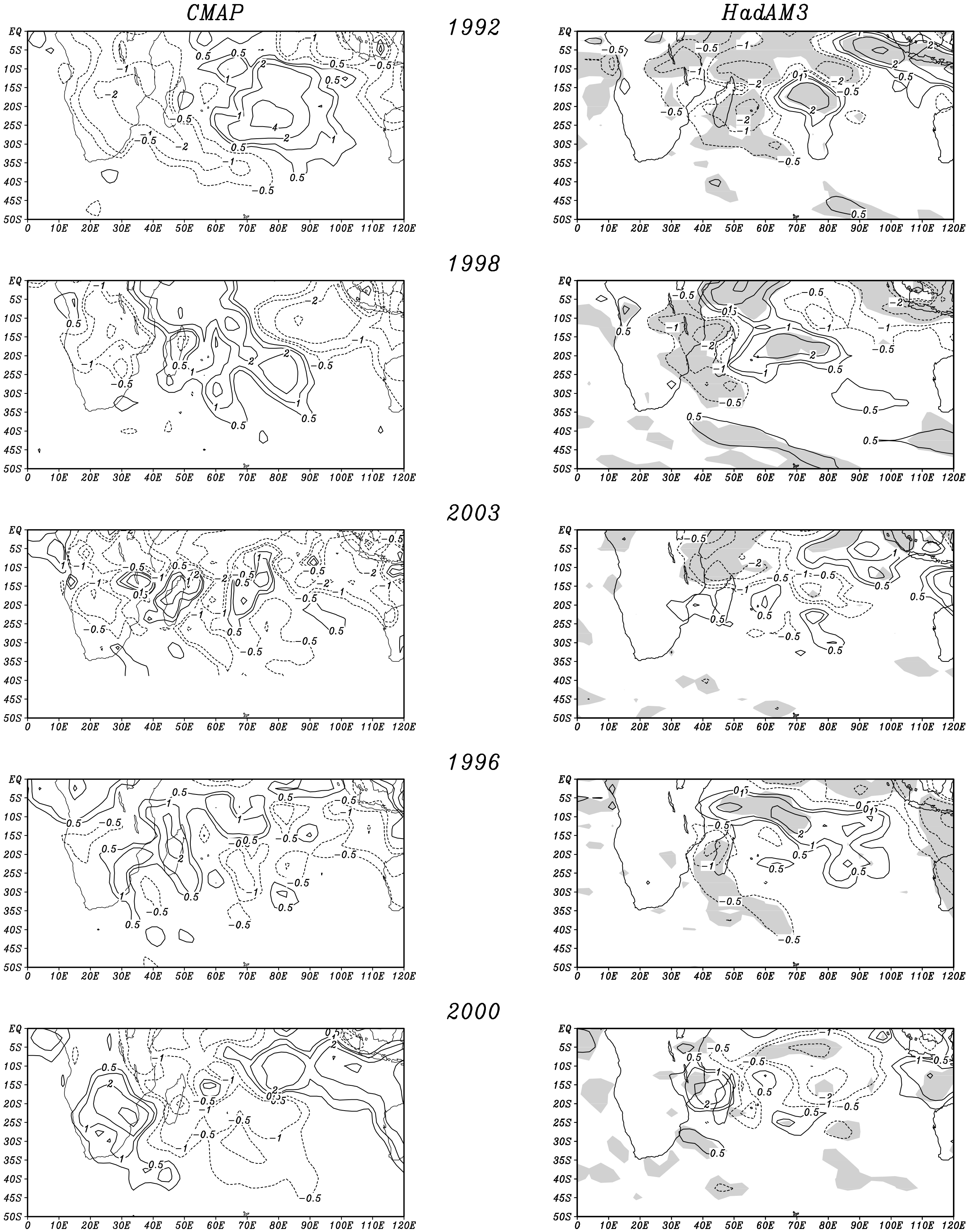


**Fig. 4.** Observed (CMAP) and HadAM3 seasonal (OND or JFM) rainfall anomalies in mm/day for the various El Niño (1992; 1998; 2003) and La Niña (1996; 2000) JFM seasons indicated. Note that data for 2002/3 comes from GPCP Satellite-Derived (IR) monthly rainfall estimates (Janowiak and Arkin, 1991) since CMAP data were not available for 2002/3. Note contour levels are 0.5, 1, 2, 4 mm/day. Shading on the HadAM3 plots represents statistical significance at the 95% level

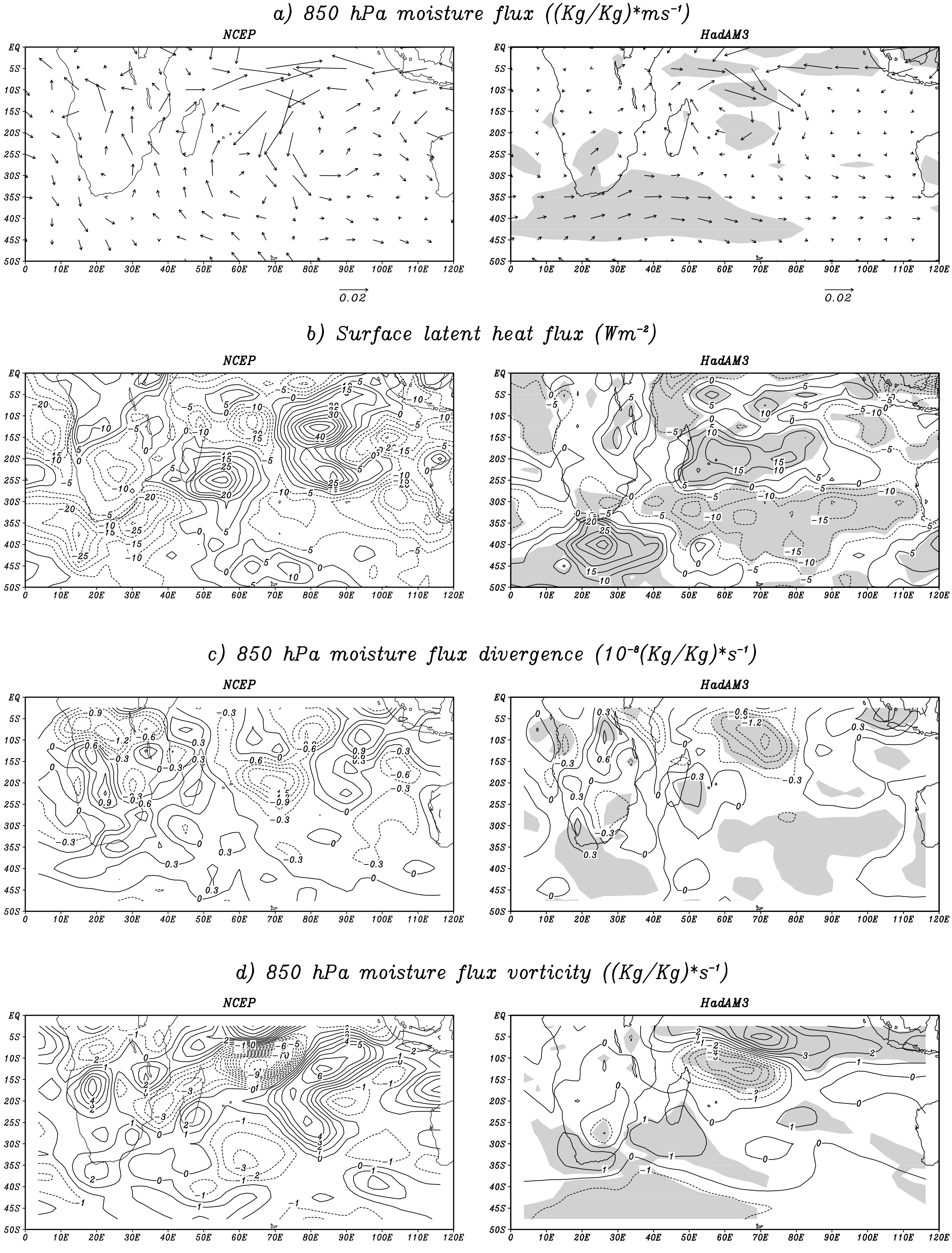


**Fig. 5.** NCEP re-analysis and HadAM3 anomalies of (**a**) 850 hPa moisture flux (a scale vector is shown); (**b**) surface latent heat flux; (**c**) 850 hPa divergence; (**d**) 850 hPa vorticity for OND 1991. Shading on the HadAM3 plots represents statistical significance at the 95% level

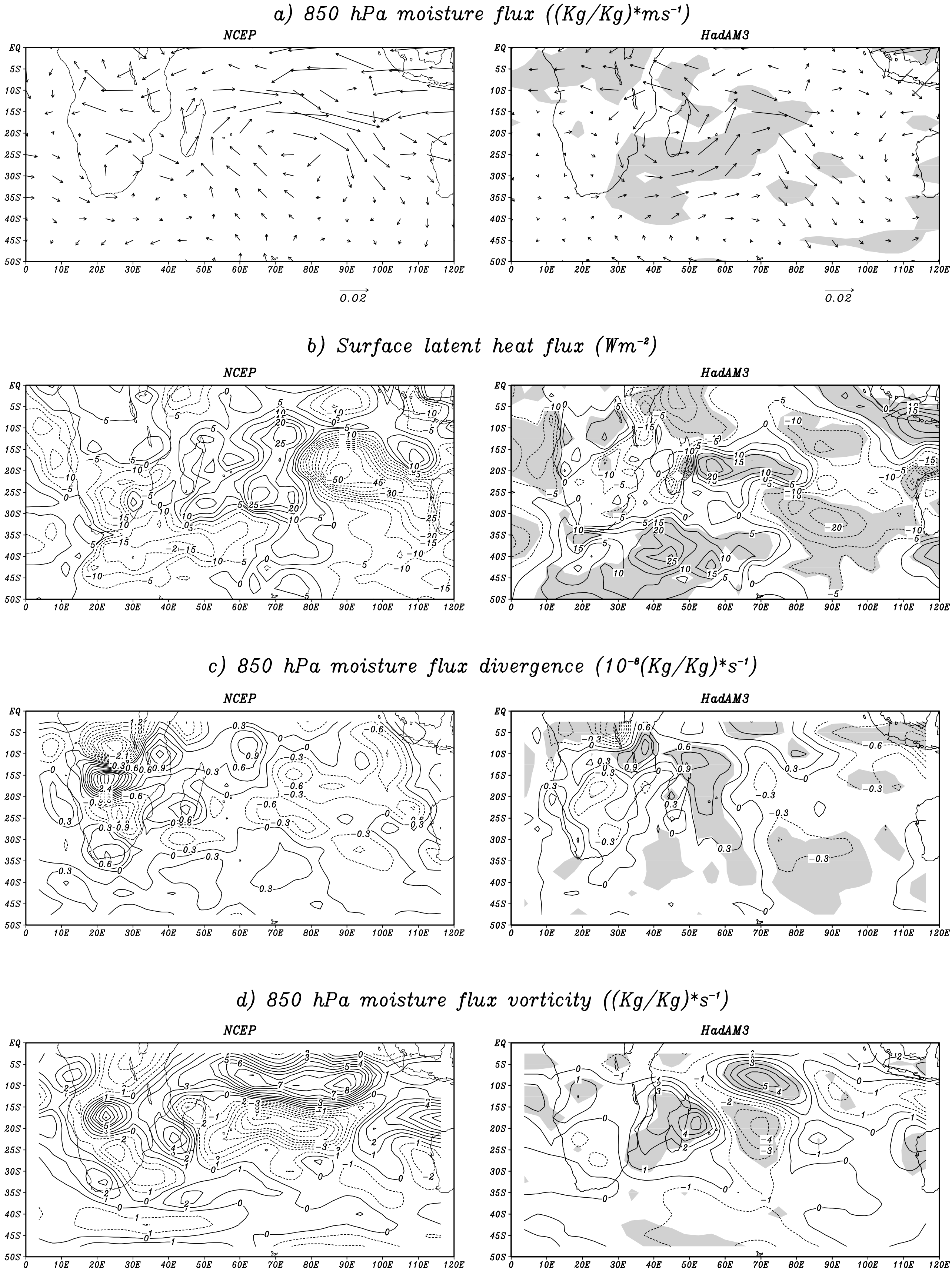


**Fig. 6.** As for Fig. 5, except JFM 1992

westerly anomalies there reflect a strengthening of the mean westerlies north of Madagascar and a weakening of the trades further south with a cyclonic anomaly over the subtropical ocean. This is further reflected by low level convergence and cyclonic conditions (Fig. 6c–d) near 60–80° E, 10–30° S. A large increase in evaporation here is also apparent (Fig. 6b). It is this attraction of the low-level moisture over the tropical South Indian Ocean together with a stronger ITCZ there and weaker terrestrial ITCZ and Angola low that appears to be important for the drought. This weaker Angola low (associated with reduced evaporation over the tropical eastern Atlantic – Fig. 6b) and ITCZ in the NCEP re-analyses is reflected in the band of strong relative divergence and anticyclonic vorticity across tropical southern Africa (Fig. 6c–d).

In HadAM3, dry conditions are mainly confined to the east of the landmass (Fig. 4) where low-level relative divergence and anticyclonic vorticity anomalies (Fig. 6c–d) are stronger and there is reduced evaporation off the neighboring Indian Ocean (Fig. 6b). There is a less obvious enhancement of moisture convergence over the central Indian Ocean (Fig. 6a, c) than in the NCEP re-analyses. These differences leads to HadAM3 underestimating the rainfall deficit for the JFM 1992 season compared to observations.

### *4.2 1997/8 event*

OND 1997 not only coincided with a very strong El Niño but also fell during an Indian Ocean Zonal Mode event; thus, the very wet conditions seen over East Africa in Fig. 3 are expected (Saji et al, 1999; Webster et al, 1999). Further south, dry conditions are apparent over central southern Africa in the observations and to lesser extent in HadAM3. Both NCEP and HadAM3 indicate easterly (westerly) moisture flux anomalies over the Indian Ocean near 0–10° S (15–25° S) (Fig. 7a), implying a weakening of both the equatorial westerlies and the trades. The former suggests that less moisture will be transported away from East Africa by the re-curving of the NE monsoon into the westerlies north of Madagascar whereas the latter implies less moisture evaporated off the tropical South West Indian Ocean and reduced flux into southern Africa (Fig. 7a–b). The observed wet (dry) conditions over East (central southern) Africa are consistent with these moisture flux anomalies.

Both NCEP and HadAM3 show low level convergent and cyclonic (divergent and anticyclonic) anomalies over East (central southern) Africa (Fig. 7c) and strong relative ascent over East Africa (not shown), again consistent with the rainfall anomalies. The low level divergence in HadAM3 over tropical southern Africa is weaker and further north than in NCEP, which helps explain why HadAM3 does not show as marked a rainfall deficit over this region in contrast to the observed (Fig. 3).

During JFM 1998, wet anomalies persisted over East Africa and the dry conditions intensified over tropical southern Africa (Fig. 4). HadAM3 shows a similar basic pattern but the anomalies do not extend far enough over the continent. Moisture flux anomalies over the tropical Indian Ocean are similar to the previous OND but are a bit weaker (Fig. 8a); hence they remain favorable (unfavorable) for good rains over East (southern) Africa. Increased evaporation over the equatorial western Indian Ocean (Fig. 8b) feeds the increased Kenyan/northern Tanzanian rainfall. Both NCEP and HadAM3 show areas of low level relative convergence (divergence) over East (southern Africa) (Fig. 8c); however, in HadAM3 these features are less spatially extensive consistent with the differences in rainfall anomaly pattern between HadAM3 and the observations. Anticyclonic vorticity anomalies (Fig. 8d) over southeastern Africa in both models further discourage rainfall there. Figure 8b–d together with velocity potential plots (not shown) also imply that the local Walker circulation will tend to have its ascending limb east of Madagascar, reinforcing the dry conditions over southern Africa.

### *4.3 2002/3 event*

Figure 3 indicates widespread rainfall deficits during OND 2002 with weak positive anomalies evident over East Africa. The NCEP moisture flux anomalies suggest a weaker NE monsoon over East Africa and anticyclonic conditions both north and south of Madagascar (Fig. 9a) as well as over the southern Angolan/northern Namibian region. These features are further confirmed in the low level divergence and vorticity anomaly

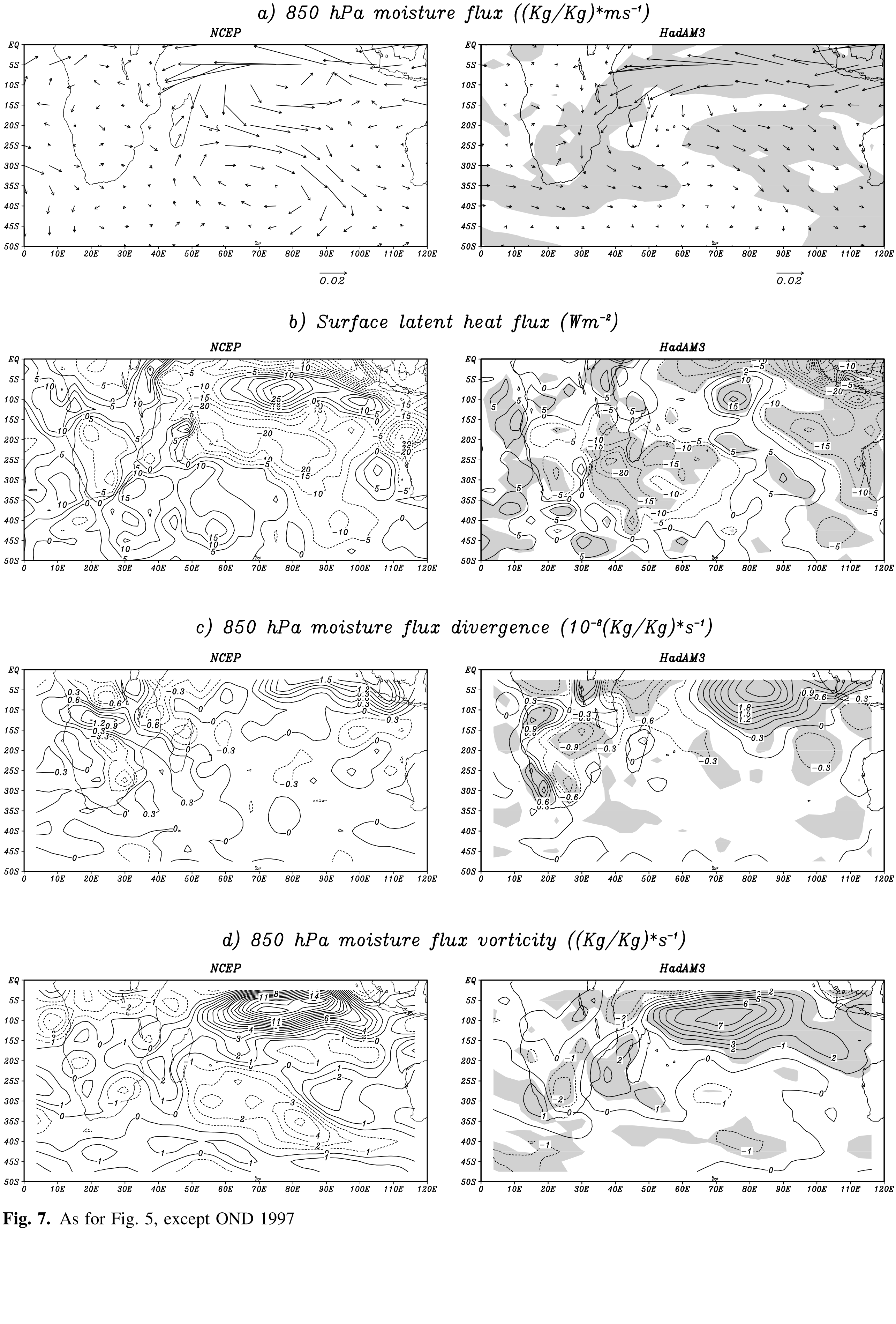


**Fig. 7.** As for Fig. 5, except OND 1997

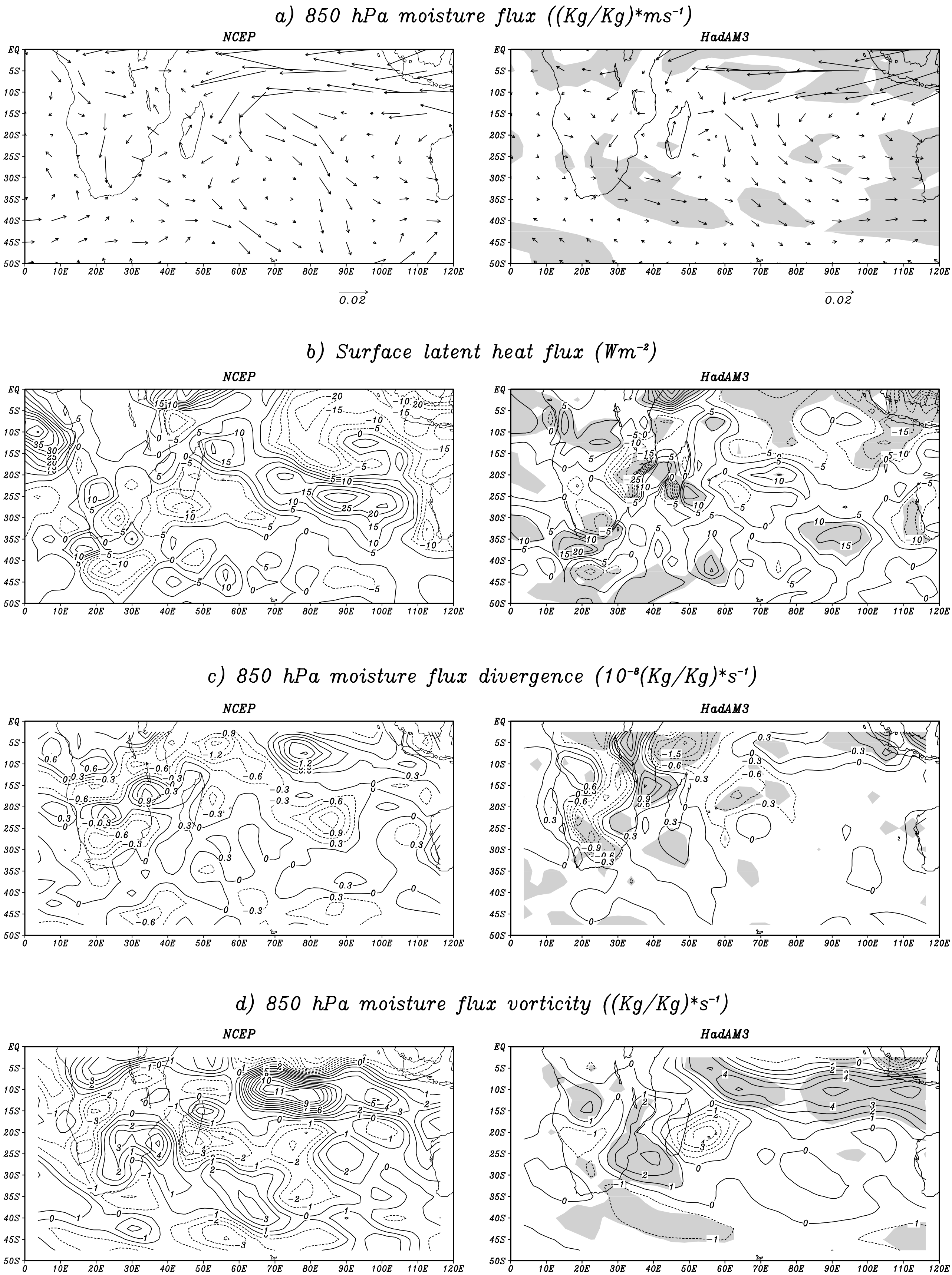


**Fig. 8.** As for Fig. 5, except JFM 1998

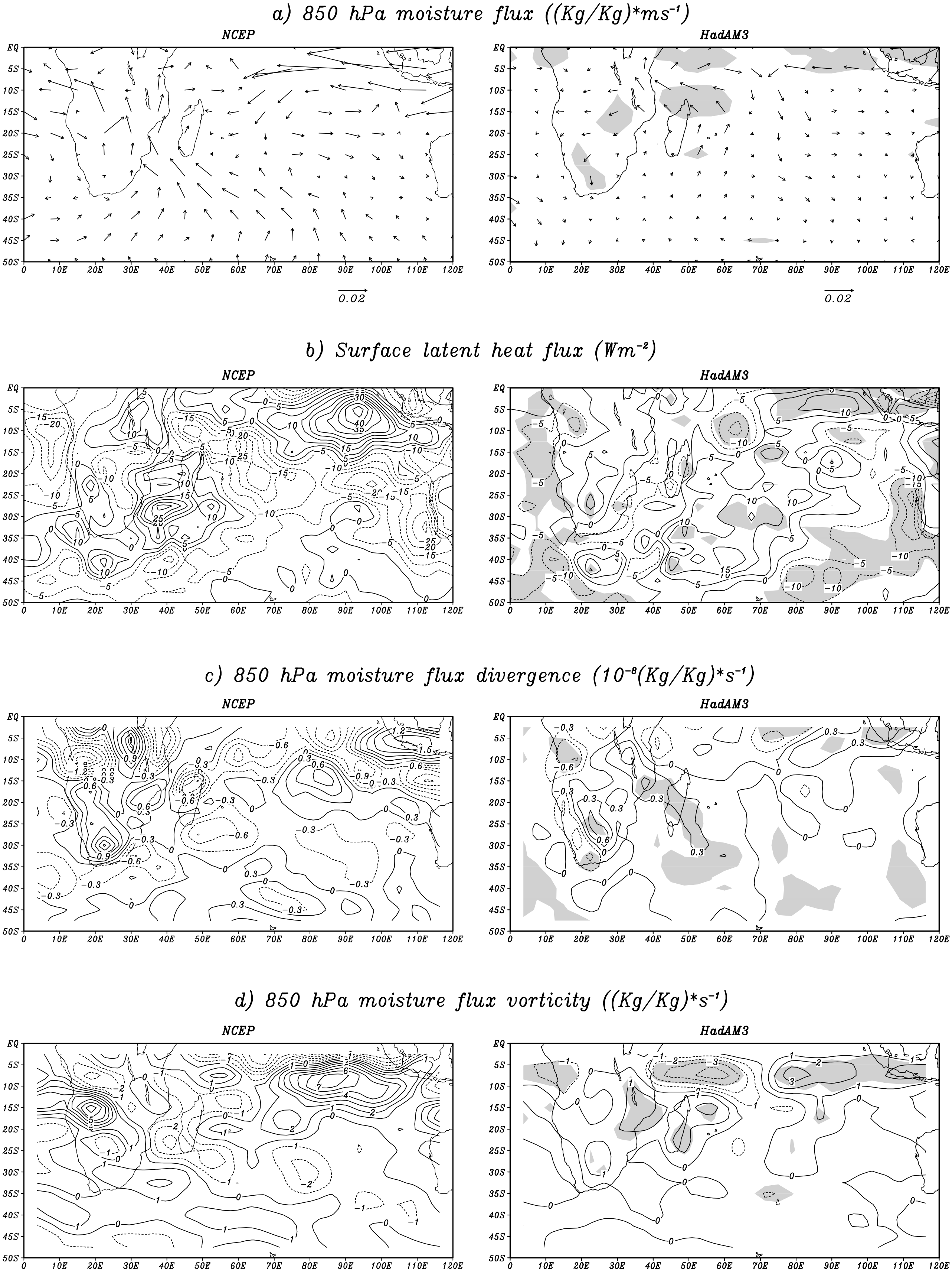


**Fig. 9.** As for Fig. 5, except OND 2002

plots (Fig. 9c–d) and imply a weaker Angola low, the source for tropical–extratropical cloudbands, and hence reduced rainfall over much of subtropical southern Africa. Reduced evaporation (Fig. 9b) is apparent over the tropical eastern Atlantic near the Angola low, weakening it further. A reduced inflow of moisture from the tropical South Indian Ocean is also implied in Fig. 9a together with reduced evaporation (Fig. 9b). HadAM3 displays anticyclonic conditions over Madagascar and Mozambique and thus, its rainfall deficits are mainly confined to those regions.

During JFM 2003, the dry anomalies are less widespread than in the previous season with large areas of southeastern Africa now showing positive anomalies (Fig. 4). The other notable feature is the reversal in sign of the rainfall anomaly over East Africa to dry, consistent with reduced evaporation off the neighboring equatorial western Indian Ocean (Fig. 10b). The model captures the sense of the anomaly over most of the tropical areas except the Congo basin but the anomalies are again too small. As for OND 2002, there are strongly divergent and anticyclonic conditions over Angola (Fig. 10c–d) weakening the Angola low and suggesting reduced rainfall over much of southern Africa poleward of about 15° S. Over tropical southeastern Africa, the NCEP moisture flux, divergence and vorticity anomalies (Fig. 10a, c, d) suggest that the ITCZ is shifted further south over Mozambique implying increased rainfall in this region as observed. Relative ascent is also found over Mozambique/Madagascar (not shown) consistent with the rainfall.

Although HadAM3 also shows an area of wetter conditions over southeastern Africa, they are further south (Fig. 4) and it appears that local changes in low level convergence and cyclonic vorticity lead to the wetter conditions rather than a shift in the ITCZ. There is little evidence of a weakening in the Angola low unlike NCEP; thus, the observed dry conditions over most of southern Africa are not captured by the model (Fig. 4).

### *4.4 Summary of El Niño cases*

The HadAM3 anomalies are in better agreement with NCEP re-analyses and CMAP precipitation for the 1997/8 event. For the other two El Niño cases, there are significant differences between HadAM3 and NCEP over southern Africa and the neighboring oceans for each season, with the possible exception of OND 1991. In these two cases (i.e., 1991/2 and 2002/3), the NCEP re-analyses indicate that strong relative divergence and anticyclonic vorticity anomalies in the Angolan region played an important part in the dry conditions over southern Africa since the resulting weakening of the Angola low reduces the tropical source region of the cloudbands. The model did not capture these anomalies properly and therefore showed much weaker dry anomalies than in the observations.

For the 1997/8 event, the Angola low did not appear to weaken significantly and we suggest that this is largely why the impact of this El Niño on southern African rainfall south of about 15–20° S was less than the other cases. Another difference between the events in this region is that during both 1991/2 and 2002/3 summers, there were cool SST anomalies and generally reduced latent heat flux off the tropical Atlantic near Angola whereas in 1997/8, positive SST and latent heat flux anomalies occurred here. This suggests that the northwesterlies around the northern margin of the Angola low would have advected less moist air off the tropical southeast Atlantic during the 1991/2 and 2002/3 seasons and the reverse during 1997/8, further weakening the Angola low and the cloudbands during 1991/2 and 2002/3 and strengthening these in 1997/8. As a result, summer rainfall over subtropical southern Africa was larger during 1997/8 than might have been expected from the magnitude of the Southern Oscillation Index and SST anomalies in the tropical Pacific.

All cases show warming in the tropical Indian Ocean but the magnitude and spatial extent is substantially greater in the west during 1997/8 since this is also an Indian Ocean Zonal Mode event (Saji et al, 1999; Webster et al, 1999). As a result, the positive rainfall anomalies over East Africa are much greater in 1997/8 than for the other cases. The other significant SST difference between the three cases is that not only is the warming in the tropical Pacific much larger in 1997/8 than in 1991/2 or 2002/3, but the largest anomalies occur in the east whereas for 1991/2 and 2002/3, they occur much closer to the dateline. This observation and the results presented

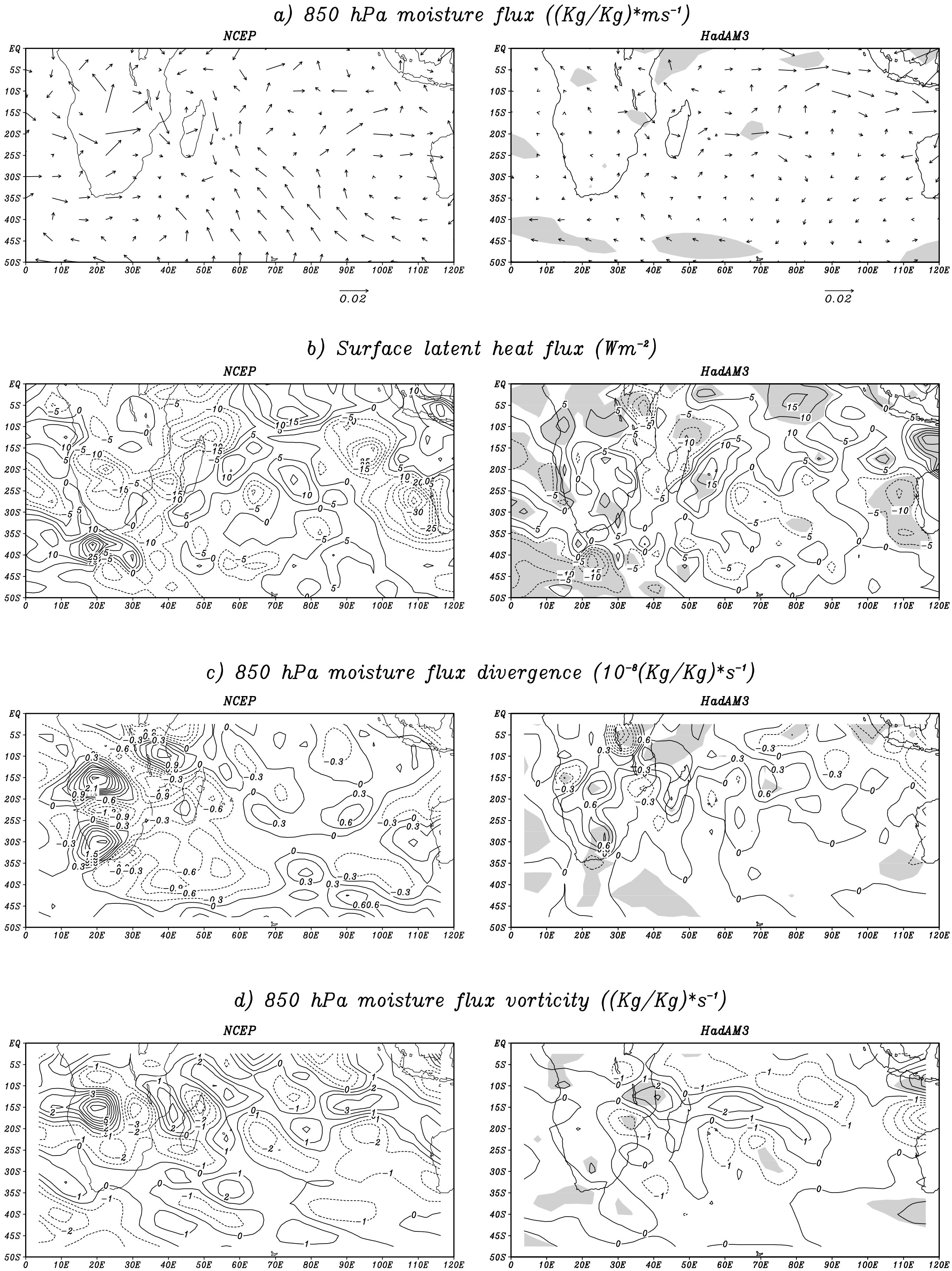


**Fig. 10.** As for Fig. 5, except JFM 2003

above suggest that HadAM3 is more likely to capture ENSO impacts over Africa when the Pacific and Indian SST anomalies are large and when the Pacific maximum occurs further east. Global velocity potential plots (not shown) indicate that HadAM3 generally captures the modulations to the Pacific Walker cell during the various ENSO events. This result supports the suggestion that it is the inability of HadAM3 to adequately represent regional features such as the Angola low that is an important source of error in the model, which unlike NCEP has no information about observed conditions other than the SST forcing.

## 5. La Niña cases

### *5.1 1995/6 event*

For OND 1995, Fig. 3 indicates dry conditions over East and central southern Africa with wet anomalies over much of subtropical southern Africa. The model only shows this pattern over the eastern margins of the subcontinent but not elsewhere. OND 1995 also corresponds to a negative Indian Ocean Zonal Mode event with stronger westerlies over the equatorial Indian Ocean that transport more moisture away from East Africa, thereby leading to dry conditions. This feature is evident in the NCEP re-analyses but not in HadAM3 (Fig. 11a). Westerly anomalies exist over tropical southern Africa in NCEP, and to lesser extent HadAM3 (Fig. 11a), and these act to strengthen the Angola low (Fig. 11c–d). Increased evaporation (Fig. 11b) occurs off the tropical Atlantic near the Angola low as well as over the South West Indian Ocean feeding into the cloudbands in the mean easterly flow over subtropical southern Africa. Favorable low-level convergent and cyclonic vorticity anomalies are strongly apparent over much of southern Africa in NCEP but less so in HadAM3. As a result, the cloudband source is strengthened, leading to increased rain over much of subtropical southern Africa.

During the following JFM, wet anomalies become established over tropical southern Africa north of about 12° S (Fig. 4) as well as remaining strongly evident over southeastern Africa. Over East Africa, the model captures the basic pattern, but at reduced magnitude, but in contrast to the observations, shows dry conditions over the southeast. This error arises because HadAM3 develops an anticyclonic anomaly in this southeastern region (Fig. 12a, c, d) that occurs further east over the South West Indian Ocean in NCEP. Over the land, the Angola low and ITCZ are again intensified in the NCEP fields (Fig. 12a, c, d) but not in HadAM3. As for the previous season, the intensified Angola low promotes cloudband activity and increased rainfall over the subtropical landmass as observed. Increased evaporation occurs over the Atlantic Ocean near the Angola low as well as over the South West Indian Ocean (Fig. 12b), favorable for stronger cloudbands.

### *5.2 1999/2000 event*

The observations for OND 1999 (Fig. 3) show a relatively dry eastern half and wetter than average western half. In contrast, HadAM3 shows wet anomalies over the subtropics and dry anomalies at lower latitudes. This error results because HadAM3 displays a cyclonic anomaly over southeastern Africa and the adjoining South West Indian Ocean (Fig. 13a, c, d) unlike NCEP which indicates an anticyclonic anomaly further south. NCEP shows both a northward shift in the Angola low to near 5–10° S and a band of relative divergence extending both towards southern Mozambique and further north across the ITCZ region (Fig. 13c) with relative subsidence (not shown). As a result, southeastern Africa is dry or near average rainfall whereas Angola and the western Congo experience wetter conditions. Reduced evaporation occurs over the western tropical and parts of the South West Indian Ocean (Fig. 13b) consistent with the relatively dry or weak anomalies over the east. In contrast, HadAM3 evolves a band of relative convergence and cyclonic vorticity stretching southeast from Angola to eastern South Africa; hence increased precipitation occurs in this season in HadAM3 over southeastern Africa. Over South Africa and southern Namibia, both NCEP and HadAM3 show easterly to northeasterly moisture flux anomalies which imply increased troughing here (Fig. 13a). This increase, together with cyclonic relative vorticity anomalies and strong relative convergence over the western half, lead to increased precipitation over western South Africa and Namibia.

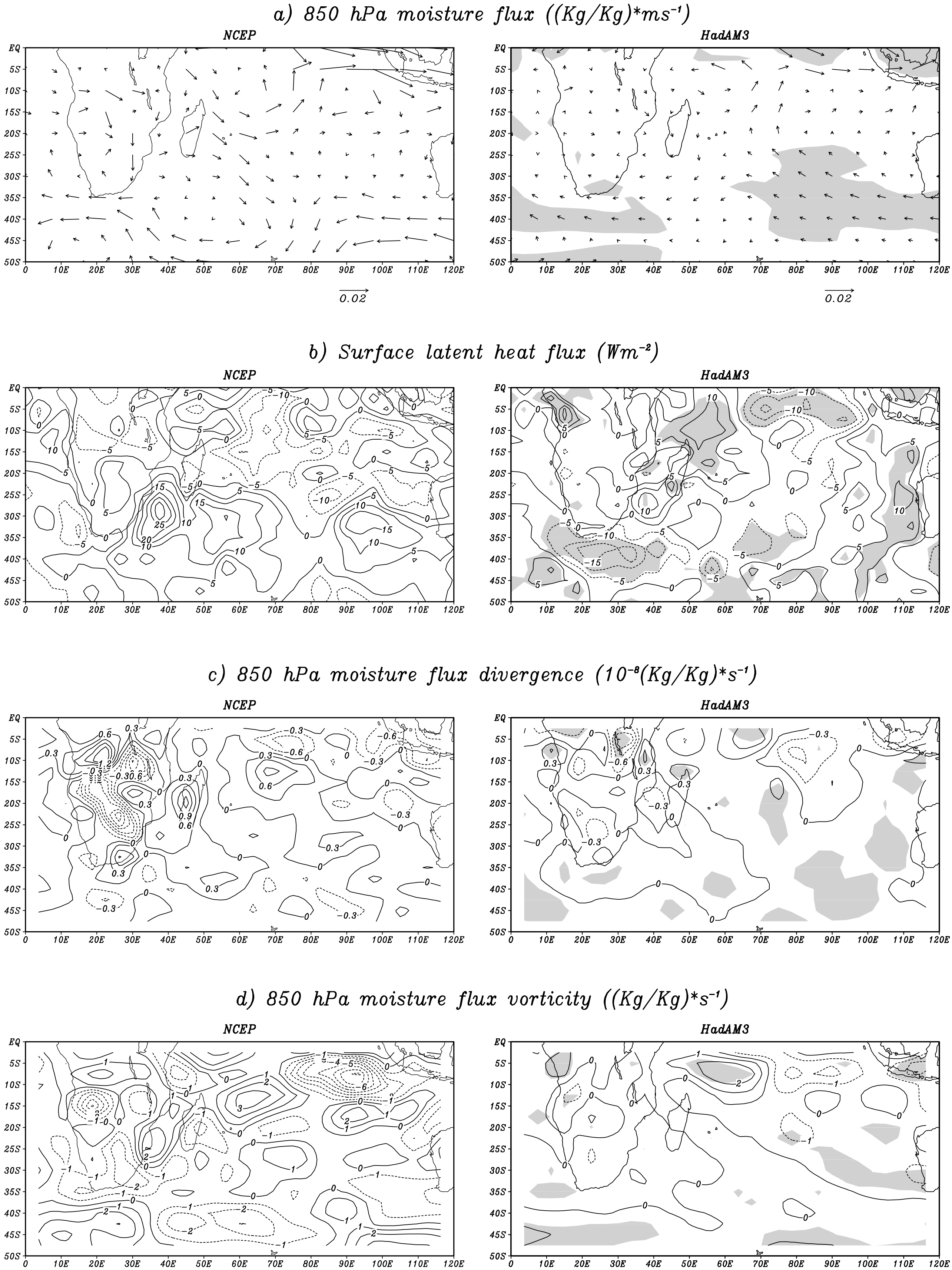


**Fig. 11.** As for Fig. 5, except OND 1995

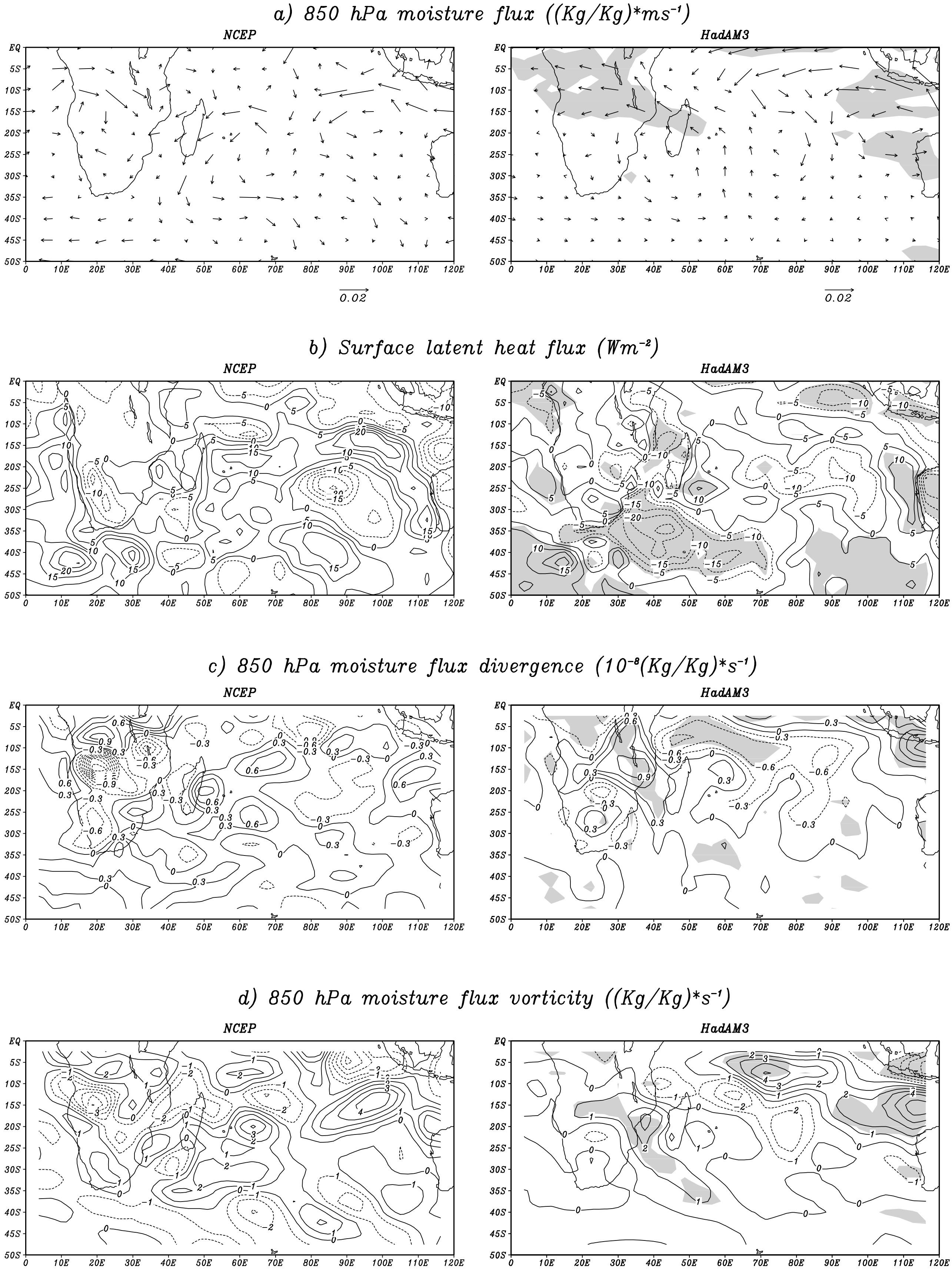


**Fig. 12.** As for Fig. 5, except JFM 1996

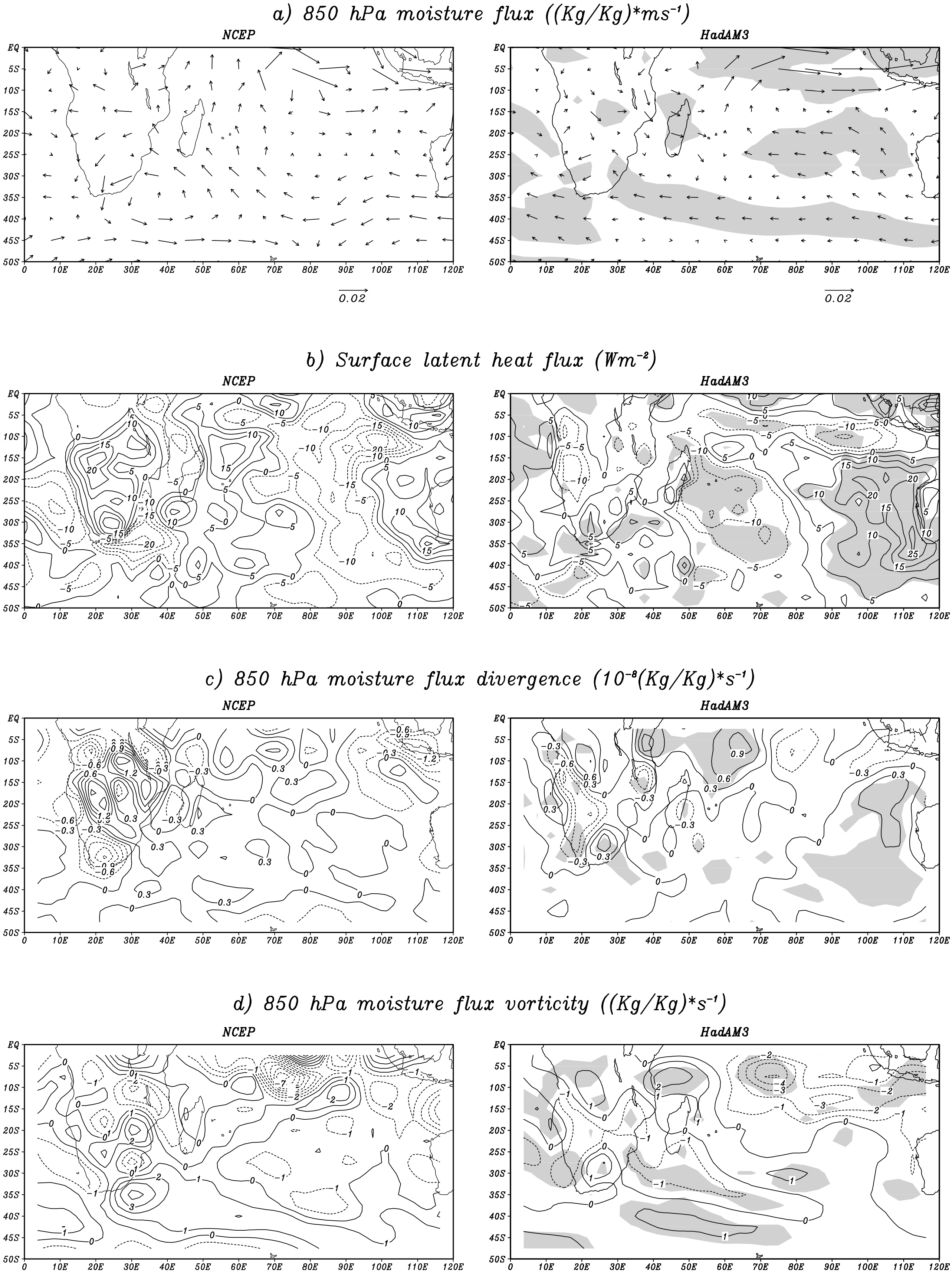


**Fig. 13.** As for Fig. 5, except OND 1999

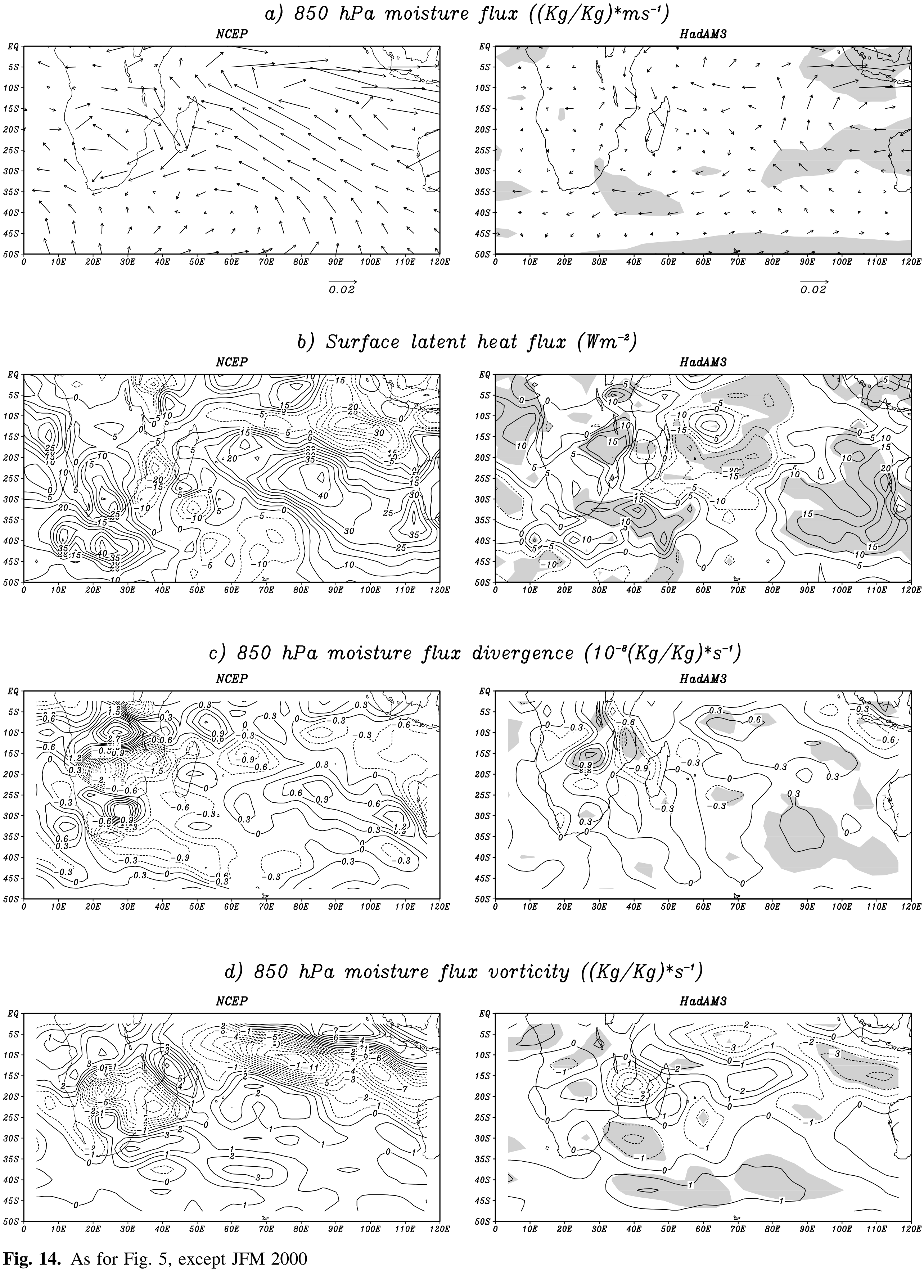


**Fig. 14.** As for Fig. 5, except JFM 2000

JFM 2000 was extremely wet over almost all of southern Africa south of around 15° S and dry over East Africa. HadAM3 shows significantly increased precipitation over northern Mozambique, Madagascar and the northeast coast of South Africa (Fig. 4). However, a considerable proportion of the JFM rainfall, at least over northern South Africa, Botswana, Namibia, southern Mozambique and Zimbabwe was due to the remnants of Tropical Cyclone Eline and other tropical depressions that penetrated unusually far into the landmass from the Indian Ocean (Dyson and van Heerden, 2001; Reason and Keibel, 2004). The NCEP moisture fluxes show a very strong anticyclonic anomaly over the western Indian Ocean with stronger westerlies over Angola and northern Namibia whereas in HadAM3, a weak cyclonic feature exists near Madagascar (Fig. 14a). The NCEP anticyclonic anomaly implies that a westward steering current existed to steer tropical depressions and cyclones towards Mozambique from the Indian Ocean; this did not exist in the HadAM3 fields. The unusually frequent occurrence of these tropical storms in the SW Indian Ocean in JFM 2000 is reflected in the NCEP cyclonic feature over the Mozambique Channel that extends right across to northern Namibia/southern Angola where it merges with an enhanced Angola low and associated strong relative convergence (Fig. 14a, c) and precipitation (Fig. 4). Associated with the intensified southeasterlies over the South Indian Ocean in the NCEP plots is increased evaporation (Fig. 14b) that leads to increased moisture flux and hence rain over much of southern Africa. An intensified Angola low (with associated large increase in evaporation off the neighboring tropical Atlantic – Fig. 14b) and ITCZ are reflected in the moisture flux, divergence and vorticity anomalies (Fig. 14a, c, d) in NCEP; hence increased rainfall occurs particularly to the south and southeast where the cloudbands tend to be located. The stronger ITCZ and Angola low near 15–20° S are not well captured in HadAM3 and hence increased rainfall only occurs near Mozambique, Madagascar and the northeast coast of South Africa. Velocity potential anomalies (not shown) imply relative ascent (descent) over southeastern Africa (Indian Ocean) in NCEP and to lesser extent in HadAM3, consistent with the rainfall anomalies.

### *5.3 Summary of La Niña cases*

As for the El Niño cases, the 1995/6 and 1999/00 La Niña events again suggest the importance of modulations to the Angola low in influencing impacts over much of southern Africa. Again, the model has problems in adequately capturing these modulations; these lead to significant discrepancies between it and the NCEP reanalyses.

## 6. Discussion and conclusions

The previous discussion for the various El Niño and La Niña cases suggests that HadAM3 has difficulty in capturing the changes in the Angola low and associated low level convergence to the southeast. This deficiency seems to be worsened in El Niño seasons when there were cold anomalies off the Angola coast. By the same token, during the 1995/6 and 1999/00 La Niña seasons, there were warm SST anomalies off the Angola coast and a generally stronger Angola low. The significance of these modulations to the low is that, firstly, they strengthen (1995/6, 1999/00 La Niñas) or weaken (1991/2, 2002/3 El Niños) the westerly flow and associated evaporation off the southeastern Atlantic near 5–10° S, or north of the Angola-Benguela frontal zone, where the mean summer SST is of order 25–27° C, and secondly, increase (1995/6, 1999/00 La Niñas) or decrease (1991/2, 2002/3 El Niños) the convergence of low level moisture to the southeast across southern Africa.

The model performs best for the 1997/8 season which was characterised by a strong El Niño event and positive Indian Ocean zonal mode in late 1997. Also, unlike for the 1991/2 and 2002/3 El Niños, during the 1997/8 event there were warm SST anomalies off the Angola coast with increased evaporation here. The relative increase in moisture from this region in 1997/8 together with little weakening (OND) or even a strengthening (JFM) of the Angola low worked against the typical ENSO-induced drought over southeastern Africa. Note that ENSO-induced weakening of the Angola low is characteristic; e.g., composite OND and JFM MSLP anomaly plots for 14 strong El Niños in Reason et al, (2000). Thus, the 1997/8 ENSO impacts over much of southern Africa were weaker than might

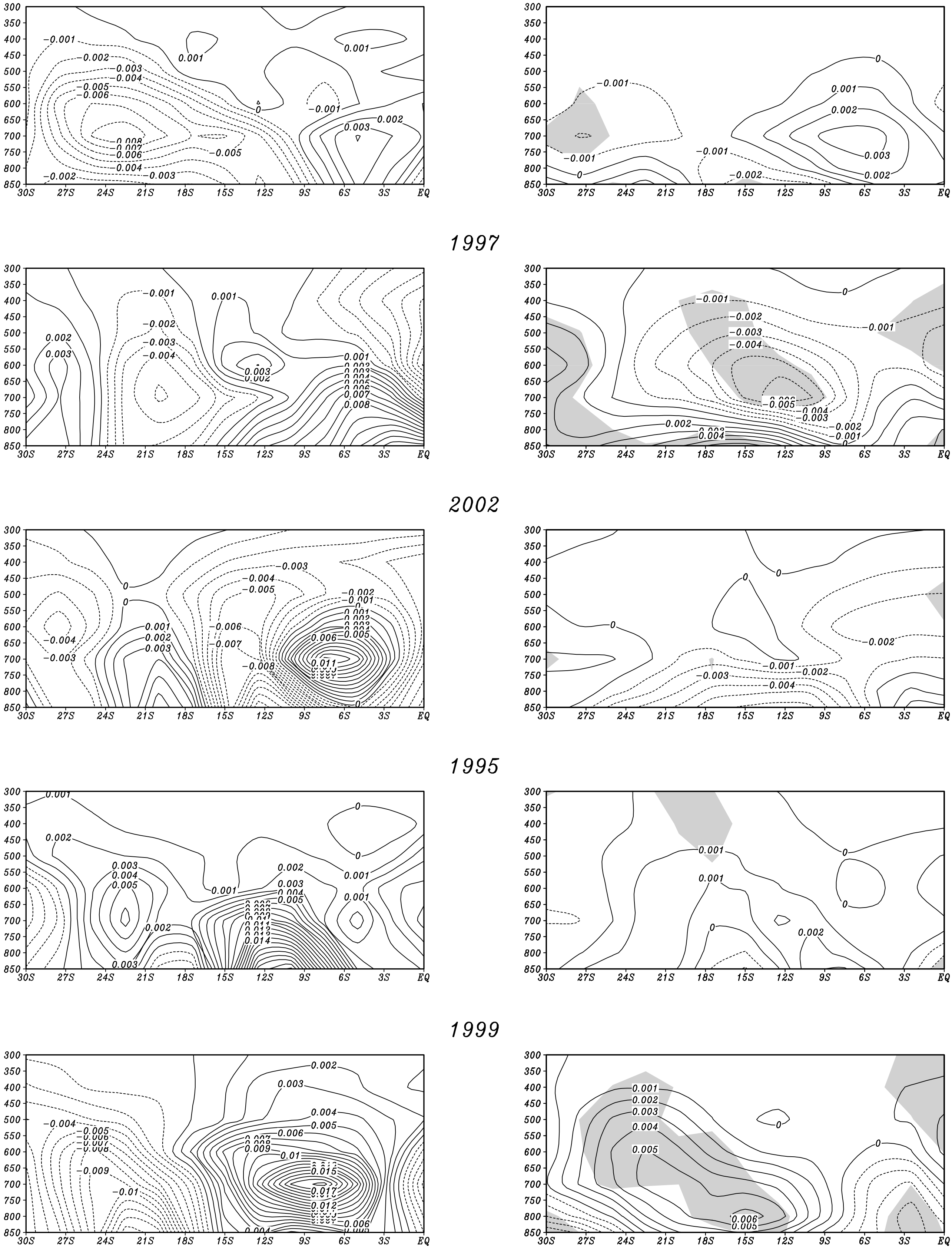


**Fig. 15.** Transect of seasonal moisture flux anomalies (contour interval 0.001 kg/kg m/s) along 20° E for the OND season of the various ENSO events shown. Shading on the HadAM3 plots represents statistical significance at the 95% level

have been expected given the magnitude of the SOI and Niño 3.4 SST anomalies.

To highlight the different 1997/8 event further, Fig. 15 shows a transect of moisture flux for each event along 20° E which, for latitudes 8–15° S, represents the westerly flow off the tropical South East Atlantic into the northern half of the Angola low. Looking at the NCEP values first, it is immediately clear that, for the northern Angola low region (8–15° S), the OND 1997 anomalies are more like the two La Niña cases than the 1991/2 and 2002/3 El Niños. In OND 1991 and 2002 (very dry), there were easterly anomalies over the northern Angola low region (8–15° S), consistent with a weaker low and less moisture import from the tropical Atlantic. In OND 1997, like for the two La Niña cases (1995 and 1999), there were westerly anomalies implying a stronger low and increased moisture import. Examination of the same transects for JFM (not shown) leads to the same conclusion that modulations of the Angola low during ENSO are important for the rainfall impacts over subtropical southern Africa. The right hand panels in Fig. 15 indicate that HadAM3 is unable to capture these patterns, highlighting its difficulties in representing the Angola low.

However, it should be emphasized that is not just during ENSO seasons that HadAM3 has difficulties in representing the Angola low; indeed this appears to be a general problem relating to HadAM3 deficiencies in capturing orographic effects across southern Africa. Comparing the HadAM3 climatological moisture flux, precipitation and divergence with the CMAP/NCEP fields reveals that during both OND and JFM seasons, HadAM3 is too dry in regions near significant orography such as eastern Madagascar, southeastern Africa and southern Angola. This results, at least in part, because HadAM3 does not develop significant troughing downstream of the Madagascan mountains, the Drakensberg and Chimanimani mountains in southeastern Africa or the Bie plateau in Angola (Figs. 1–2). In addition, the HadAM3 climatological ITCZ is significantly weaker (stronger) across tropical southern Africa (the western Indian Ocean) than the NCEP re-analyses.

These HadAM3 deficiencies in representing orography and associated circulation features across southern Africa suggest that HadAM3 will be least successful in capturing regional ENSO impacts when modulations of these features (such as the Angola low) is a relatively important component of a particular event as in 1991/2, 2002/3, 1995/6 and 1999/00. The latter season was also characterised by an anomalously large number of tropical depressions and cyclones that made landfall over Mozambique and penetrated inland, resulting in enhanced rainfall over much of subtropical southern Africa (Dyson and van Heerden, 2001; Reason and Keibel, 2004). Given its deficiencies in representing regional orographic effects, HadAM3 was unable to capture this characteristic of the 1999/00 summer.

However, when Indian Ocean forcing is relatively more prominent such as during the El Niño and positive Indian Ocean Zonal Mode event of 1997/8, HadAM3 is considerably more successful. Several other studies (Rocha and Simmonds, 1997; Goddard and Graham, 1999; Reason and Mulenga, 1999) using different GCMs have presented evidence for the importance of Indian Ocean SSTs for southern African rainfall. Another example of Indian Ocean forcing coinciding with ENSO when HadAM3 was rather successful at representing regional anomalies in precipitation and circulation anomalies occurred during the JFM 1999 La Niña season. This season also corresponded with a positive dipole pattern in the South Indian Ocean (i.e., warm anomalies south of Madagascar and cool anomalies in the central South Indian Ocean (Behera and Yamagata, 2001; Reason, 2001) which typically leads to above average JFM rainfall in southeastern Africa. Indeed, increased precipitation occurred across this region, both in the observations and in HadAM3 and the model captured the low level cyclonic and convergent conditions over southeastern Africa apparent in the NCEP re-analyses that led to this rainfall increase.

Consistent with the view that it is the model deficiencies in capturing regional circulation features over the landmass that are the main problem for its representation of ENSO impacts over southern Africa, comparison of global 850 and 200 hPa velocity potential anomaly fields for the various ENSO events (not shown) indicates that the model modulations of the Walker circulation over the tropical Pacific region are rather similar to the NCEP fields. Thus, it appears that the model can do a good job on the large scale reorganisation of the atmospheric circulation over the tropical Pacific and eastern Indian Oceans that occurs during ENSO but is less successful at capturing the impacts on important southern African region circulation features such as the Angola low.

From the viewpoint of developing dynamical model based seasonal forecasting for the region, these results suggest that attention needs to be paid towards improving the HadAM3 representation of southern African orography and land surface conditions. One possible solution is to nest a limited area model within the global HadAM3 since these models not only offer the opportunity of higher resolution (and potentially better representation of orography) but may also provide more sophisticated parameterizations of vegetation and soil physics. This is indeed an approach being adopted in South Africa using MM5 at 50 km resolution but preliminary results suggest that it will be necessary to increase the resolution significantly beyond this as well as adapt the parameterisations to local conditions in order to significantly improve the simulation of regional circulation and precipitation fields. An added challenge in the region is that the availability and density of observations over southern Africa, which are necessary for climate analysis and for model validation, are being reduced in many areas due to financial and human resource constraints. For example, many southern African countries are reducing their rain gauge networks and, in those countries that release radiosondes, the number is often declining. Given these constraints, instead of trying to improve coverage everywhere, it may make more sense to devote observational and model resources towards addressing specific deficiencies in models such as the representation of orographic effects in the Angolan and southeastern African regions discussed here, particularly when such activities could potentially tie in with other funded research programs in these regions such as the BCLME efforts off the Angolan coast.

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