Variations in intensity of the westerly monsoon-like flow from the tropical Atlantic and summer rainfall over equatorial and tropical southern Africa

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Abstract An empirical orthogonal function (EOF) of the onshore flow of moisture along the west coast of southern Africa using NCEP-DOE AMIP-2 re-analyses suggests two dominant modes of variability that are linked to: (a) variations within the circulation linked to the mid-latitude westerlies and the South Atlantic anticyclone, (b) the intensity of the westerly flow from the tropical Atlantic. The second mode, referred to as the Equatorial Westerly mode, contributes the most to moisture input from the Atlantic onto the subcontinent at tropical latitudes. This mode appears to be associated with large-scale rainfall anomalies over the upper lands surrounding the Congo basin in January–February, with potential impacts on land hydrology persisting until April–May to the east of the Great Rift valley. It is preceded in November–December by a strengthening/weakening of the South Atlantic anticyclone. Enhanced (reduced) advection of moisture over the Congo basin is accompanied by increased (inhibited) convection processes. In the positive phase of this mode, the excess water vapour is channelled from the Congo basin to the east and southeast at surface, while the southern extension of the African Easterly Jet (AEJ) could play a role in transporting more moisture southwards at mid-tropospheric levels, leading to above-normal rainfall. During its negative phase, often related to ENSO, an eastward shift of the ascending branch of the Walker-type circulation is found to reduce convection and thus rainfall over the upper lands surrounding the Congo basin. Further research into water vapour transport is required to better understand southern African rainfall variability.

Key words Tropical Atlantic; Southern Africa summer rainfall; moisture transport; hydrology

INTRODUCTION

Within tropical areas of southern and central Africa, rainfall regimes are largely dependent on deep convection processes and water vapour convergence at different tropospheric levels. The main source of variability in tropical African climate is linked to the latitudinal position of the Intertropical Convergence Zone (ITCZ) (Preston-Whyte & Tyson, 1988; Schott *et al.*, 2003), a highly energetic feature of Earth climate, migrating to its southernmost position in May over Brazil and in February over southeast Africa. Except for the Congo basin and eastern Tanzania, most regions of tropical southern Africa have one dry and one rainy season. Maximum rainfall tends to occur from November to April. Different mechanisms are known to characterize early and late summer rainfall (D'Abreton & Tyson, 1995; Nicholson, 2000). D'Abreton & Lyndesay (1993) report changes in zonal and meridional transport of water vapour over southern Africa during wet and dry summers, with the neighbouring oceans contributing as moisture sources. The tropical Atlantic has been regarded for a long time as a secondary source of moisture for the subcontinent (Preston-Whyte & Tyson, 1988; D'Abreton & Lindesay, 1993) but recent studies have shown its substantial importance to southern African climate variability (Cook *et al.*, 2004; Reason & Jagadheesha, 2005). However, a positive correlation has been established between SST anomalies off Angola and rainfall at the coast (Hastenrath & Hirst, 1983; Nicholson & Entekhabi, 1987; Camberlin & Poccard, 2001; Rouault *et al.*, 2003). We present a multivariate analysis of zonal moisture fluxes along the west coast of southern Africa in order to investigate the role of the tropical Atlantic in moisture input over southern tropical Africa, the potential impacts on local rainfall regimes and hydrological cycle.

DATA AND METHODS

Despite the fact that tropical southern Africa is one of the most energetic places in the world in terms of convection processes, it is still one of the least studied areas regarding moisture exchanges. We computed moisture fluxes from the newly released 6-hourly NCEP-DOE AMIP-2 re-analyses (NCEP-R2) data set (Kanamitsu *et al.*, 2002) over the 1979–2003 period, at eight pressure levels between 1000 mb and 300 mb over an area ranging from 2.5°N to 37.5°S latitude and from 5°E to 50°E longitude. At a given level, the horizontal moisture flux can be defined by equation (1):

$$Q_v = q_v \cdot v_v \quad (1)$$

where, q_v,v_v are the specific humidity and horizontal velocities at the given tropospheric level.

Consequently, for each level, moisture divergence (div Q) was computed from the divergence of zonal and meridional moisture fluxes. At monthly or seasonally time scales, the variations of precipitable water in a given volume can be approximated by equation (2) (Peixoto & Oort, 1992):

$$-\text{div } Q = P - E \quad (2)$$

where P is precipitation and E is evaporation. When integrated over the whole air column, moisture divergence finally appears as a direct estimate of the (P, E) budget: an excess in precipitation over evaporation locally corresponds to a convergence of moisture fluxes, while the reverse leads to moisture fluxes divergence. Furthermore, it is possible to decompose the humidity flux in its stationary and transient component as follows:

$$Q_{tot} = Q_{stat} + Q_{trans} \quad (3)$$

When averaging over a long enough time scale,

$$Q_{tot} = q^* \cdot v^* + q' \cdot v' \quad (4)$$

where ($q^* \cdot v^*$), ($q' \cdot v'$) represent stationary and transient specific humidity and wind, respectively. The first term characterizes the mean moisture flux through the mean circulation whereas the second term is the contribution of fluctuations from the mean. Considering the humidity input from the tropical Atlantic towards the subcontinent as mainly zonal, at least over tropical latitudes, moisture fluxes were averaged zonally for grid points along the west coast of southern Africa (ranging from 2.5°N to 37.5°S latitude and from 7.5°E to 15°E longitude). The simultaneous calculation of humidity convergence at each tropospheric level has the advantage of describing both lower and upper atmospheric dynamics. Simultaneously, we used rainfall estimates from the CRU TS 2.0 data set (Mitchell *et al.*, 2004) which features monthly values from 1901 to 2000 at a 0.5° × 0.5° spatial resolution. To characterise land hydrology, we used both NDVI version 3 (Myeni *et al.*, 2002) and NOAA NCEP CPC soil moisture (Fan & van den Dool, 2004) data sets (at 1° and 0.5° resolution, respectively). NCEP-R2 (Kanamitsu *et al.*, 2002) vertical velocities (Omega) and mean sea level pressures (SLPs) at a similar 2.5° spatial resolution were also processed for the 1979–2003 period. Finally we used the monthly 1° × 1° spatial resolution Hadley Centre sea surface temperatures (SSTs) data set (Rayner *et al.*, 2002) from 1950 to 2003. In order to homogenise the temporal window of study for all variables, we choose to concentrate on the following period, 1979–2000.

MOISTURE CONVERGENCE IN TROPICAL SOUTHERN AFRICA AND CONTRIBUTION FROM THE TROPICAL ATLANTIC

Climatological overview

Moisture from the oceanic basins appears to converge at tropical latitudes within the summer position of the ITCZ (Fig. 1), particularly to the east of the Congo basin, around 30°E where an area of pronounced convergence can be identified at 850 mb. Centred at about 17°S over the Bie plateau is a local feature known as the Angola low. Stronger divergence at 700 mb over south Angola suggests substantial convection mechanisms there, but less deep within the air column. A third low-level convergence zone is found to the south of Botswana at about 25°E corresponding with the subtropical heat-low location in summer (Preston-Whyte & Tyson, 1988).

Using a vertical domain along the west coast of southern Africa for zonal moisture fluxes is a way to quantify, at least zonally, the exchange in moisture at the land–ocean interface and thus the role of the tropical Atlantic in modulating southern African climate. The mean January–February climatological structure is presented in Fig. 2.

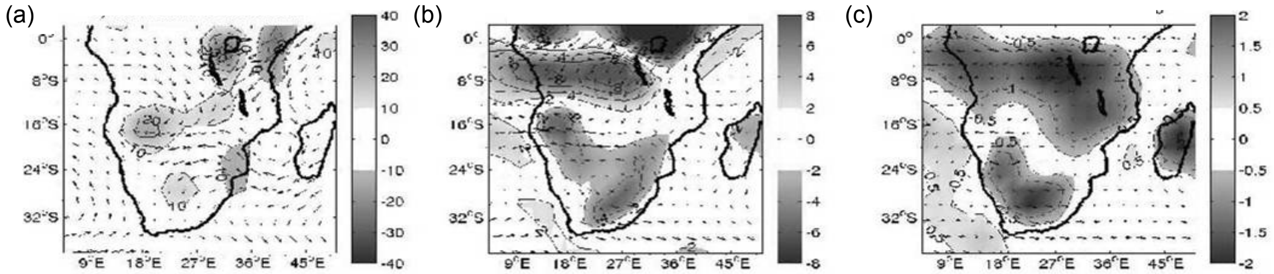

Fig. 1 Mean January–February moisture fluxes (streamlines in g·kg^{-1}·m·s^{-1} with arrows scaled at 1 unit/degree of latitude) together with contours of moisture divergence (in g·kg^{-1}·s^{-1}) at 850 mb (a), 700 mb (b) and 500 mb (c). Positive/negative values contour areas of moisture convergence/divergence at given levels.

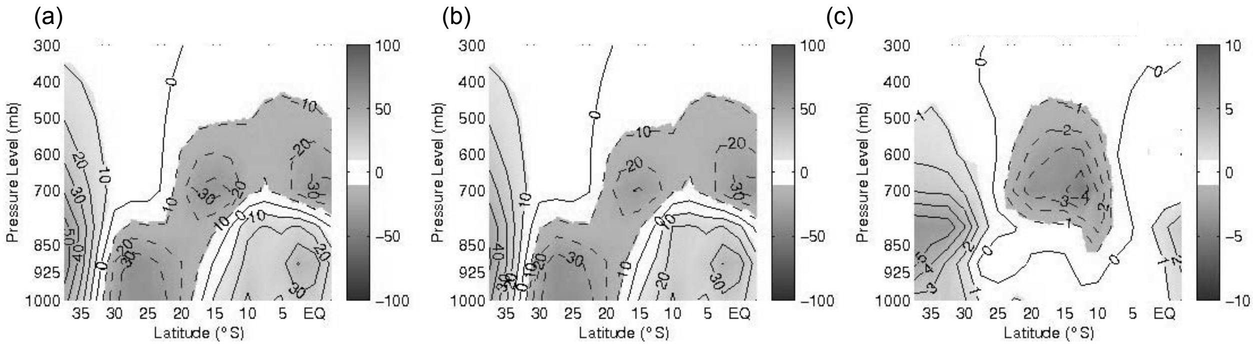

Fig. 2 Mean vertical structure: (a) of zonal moisture fluxes along the west southern African coast (in g·kg^{-1}·m·s^{-1}) for January–February together with its stationary (b) and transient (c) components. Positive values correspond to westerly fluxes while negative values refer to easterly fluxes.

In the tropics, the transient term represents less than 10% of the total zonal moisture transport. As with previous studies (Chen, 1985; Rocha & Simmonds, 1997; Fauchereau, 2004), the steady component in water vapour fluxes is well suited to represent moisture changes due to large-scale circulation in the tropics. Four key features are highlighted throughout the year:

(a) A westerly monsoon-like flux from the equator to 15°S at surface levels in summer. When particularly pronounced this flux appears to feed in deep convection to the east of the Congo basin.
(b) Overlying this westerly flux, the southern extension of the AEJ at mid-tropospheric levels as described in Hastenrath (1985), migrating in both latitudes and heights with the seasonal cycle. It is found just above 700 mbar in January–February, but is located at lower levels from March to August (not shown) when it is at about 4°S, consistent with the description given in Nicholson & Grist (2003).
(c) To the south (between 17°S and 32°S), an easterly flux is driven by the South Atlantic anticyclone. It connects to the southern AEJ during summer,
(d) South of 32°S, a westerly moisture flux occupies most of the air column and migrates during the year, reaching its northernmost position from May to July.

Moisture fluxes variability along the west coast of southern Africa

Due to abrupt shifts in zonal moisture fluxes (not shown), they were filtered at 8 years and empirical orthogonal functions (EOFs) were applied to their high-filtered (HF) component along the west coast of southern Africa using the covariance matrix. The first four leading EOF modes were retained and this truncated basis interestingly explains almost half of the total variance. Figure 3 shows the spatial patterns associated with the two primary modes. The first mode is typical of variations in the circulation linked to the mid-latitude westerlies and South Atlantic anticyclone. It explains about 25% of the total variance. Loadings are particularly strong from the surface up to 600 mbar and are balanced in the subtropics at upper tropospheric levels. The second mode characterizes the monsoon-like westerly moisture flux in the tropics, from the equator to about 15°S. It represents 11% of the total variance. It has a simultaneous loading at the surface between 20°S and 30°S. We subsequently refer to this component as the Equatorial Westerly mode.

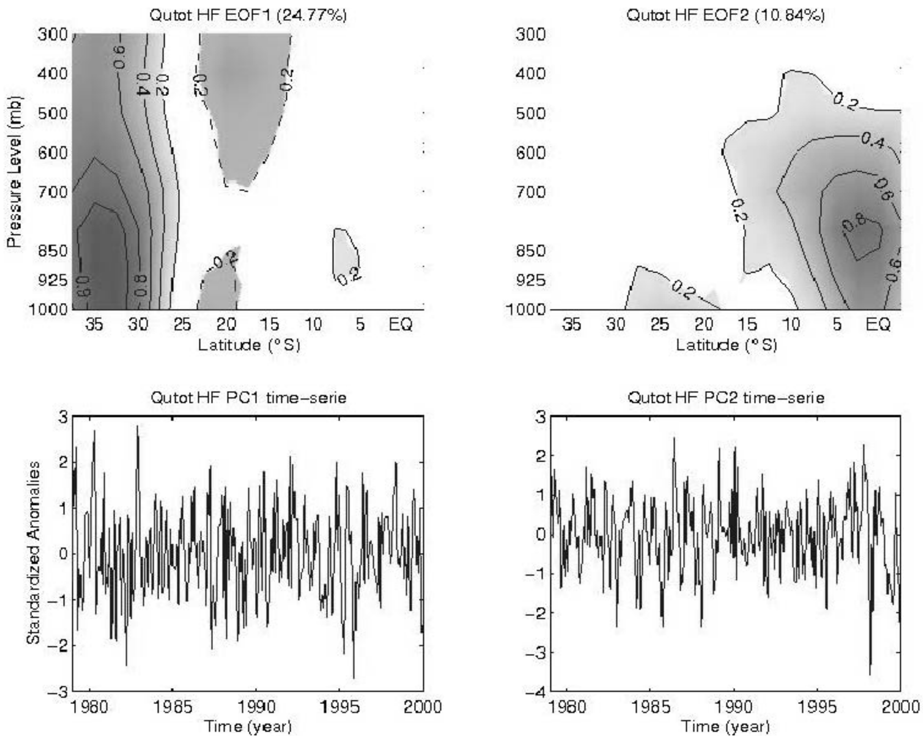

Fig. 3 Spatial patterns (top) and temporal variability (bottom) as represented by the firsts two EOF leading modes in HF zonal moisture fluxes along the west coast of southern Africa.

RESULTS AND DISCUSSION

Figure 4 presents the January–February time-series for the corresponding Equatorial Westerly mode expansion coefficient. A threshold at 0.6 of normalized anomalies deviation from the mean defines significant extreme years. We choose (1990, 1995 and 1998) and (1983, 1988, and 1992) as positive/negative events, respectively. Interestingly, all but one year corresponds to the mature phase of ENSO. This could explain the absence of correlation between ENSO and rainfall in central southern Africa (Camberlin & Poccard, 2001). Heterogeneous correlations between the January–February Equatorial Westerly mode expansion coefficient and CRU TS 2.0 rainfall are presented in Fig. 5.

The Equatorial Westerly mode appears to be well correlated in January–February with rainfall amounts over the uplands all around the Congo basin (i.e. from the east DRC and northwest Tanzania down to south Angola). This agrees with the findings of Mapande & Reason (2005) suggesting links between enhanced westerly moisture input from the Congo basin and above normal rainfall to the east. In addition, our results emphasize a potential decoupling between northern and southern hydrological regimes at basin scale, confirming the study from Laraque *et al.* (2001).

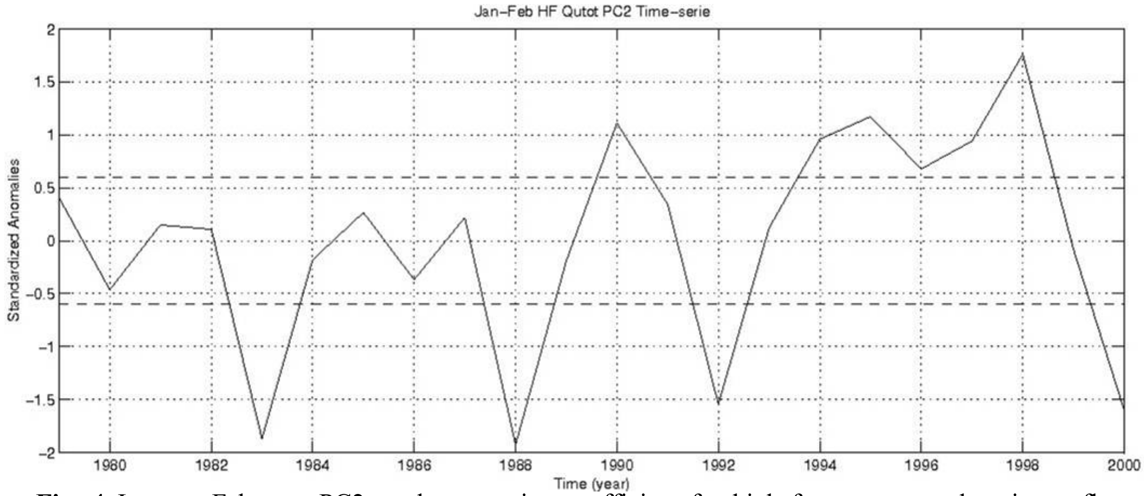

Fig. 4 January–February PC2 mode expansion coefficient for high frequency zonal moisture fluxes along the west southern African coast from 1979 to 2000. Dashed lines indicate ±0.6 levels.

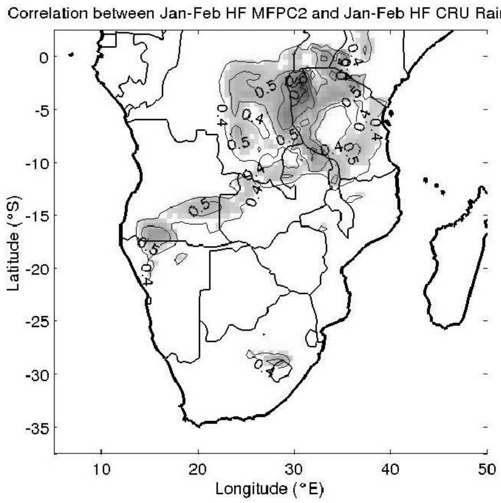

Fig. 5 Heterogeneous correlation between HF zonal moisture flux PC2 and CRU TS 2.0 rainfall in January–February over the period 1979 to 2000. The scores presented are significant at 95% level using Monte-Carlo simulation.

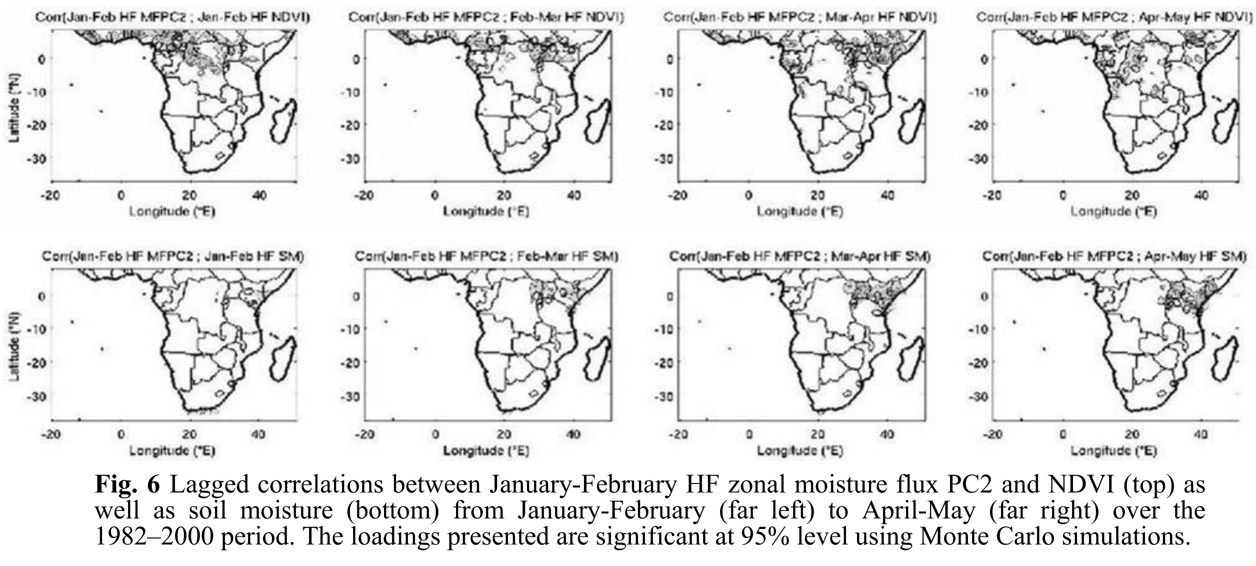

Fig. 6 Lagged correlations between January-February HF zonal moisture flux PC2 and NDVI (top) as well as soil moisture (bottom) from January-February (far left) to April-May (far right) over the 1982–2000 period. The loadings presented are significant at 95% level using Monte Carlo simulations.

To further emphasize the effects on the local hydrological cycle, heterogeneous correlations have been computed with both NDVI and soil moisture (Fig. 6). Maximum positive relationships are found from February–March to March–April in NDVI and from March–April to April–May in soil moisture from northeast Congo regions along the eastern slope of the Great Rift valley, extending until May across Uganda and Kenya. This suggests that impacts on rainfall regimes to the east of the Congo basin could be accompanied with 2–3 months lag by changes within the vegetation cover for regions to the northeast of the Great Rift valley.

In order to investigate potential links between the Equatorial Westerly mode and ocean–atmosphere variability within the South Atlantic basin, November–December composites of mean sea level pressures (SLPs), sea surface temperatures (SSTs) and 850 mb winds are shown in Fig. 7. Positive/negative events linked to the Equatorial Westerly mode appear to be preceded in November–December by a strengthening/weakening of the South Atlantic anticyclone. The warming/cooling found in the eastern tropical Atlantic, together with westerly anomalies in 850 mb zonal winds along the Angolan coast suggest the advection of warmer and moister/cooler and drier air over the subcontinent at these latitudes.

Finally, we intend to examine the potential atmospheric dynamics associated with extreme events of the Equatorial Westerly mode through a composite analysis of vertical velocity (Figs 8 and 9) and zonal moisture fluxes (Fig. 9). For years when the Equatorial Westerly mode was particularly enhanced (1990, 1995 and 1998), we show an increase in the meridional atmospheric energy flux over southern Africa (Fig. 9, middle panel). Anomalous advection of moisture over the Congo basin creates a situation where deep convection processes are enhanced (Fig. 8, top panel). Excess water vapour is channelled from these regions around the Congo basin to the east and southeast at the surface, while the southern extension of the AEJ appears to be the mechanism for transporting more moisture southwards at mid-tropospheric levels (Fig. 9, middle panel). Anomalies in vertical velocities further support an enhanced water vapour transfer to the south, resulting in more moisture available for local convection and enhanced rainfall over the uplands surrounding the Congo basin.

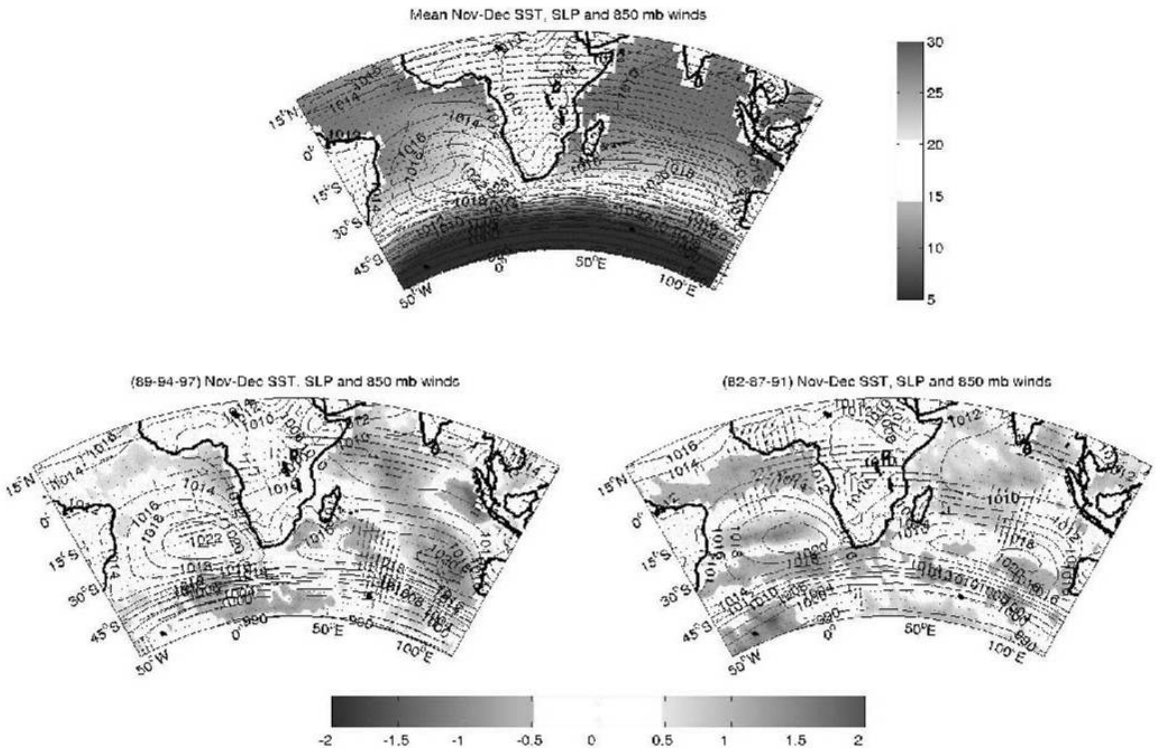

Fig. 7 Mean (top), and November–December composites prior to positive/negative January–February events (bottom left/right) linked to the Equatorial Westerly mode for SLPs (contours), SSTs (shaded with positive/negative values in dark/light grey, respectively) and 850 mb winds (streamlines) significant at 90% confidence level of Student t-test.

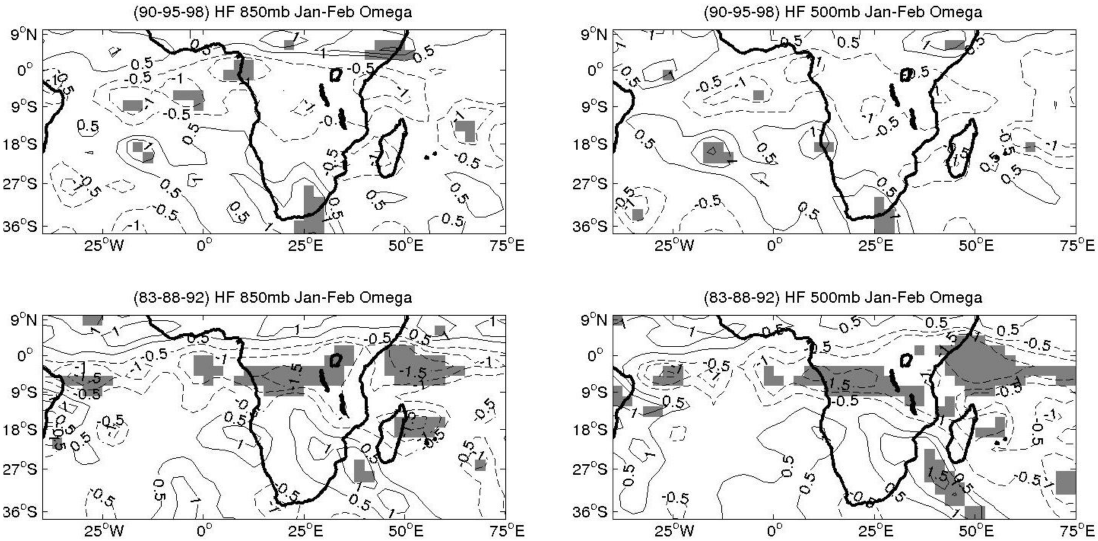

Fig. 8 (1990, 1995, and 1998) composite (top) and (1983, 1988, and 1992) composite (bottom) for HF omega at both 850 mb (left) and 500 mb levels (right) in January–February over the period (1979–2000) with shaded areas representing 90% (light grey) and 95% (dark grey) confidence level of Student t test. Negative (positive) values correspond to ascending (descending) motion.

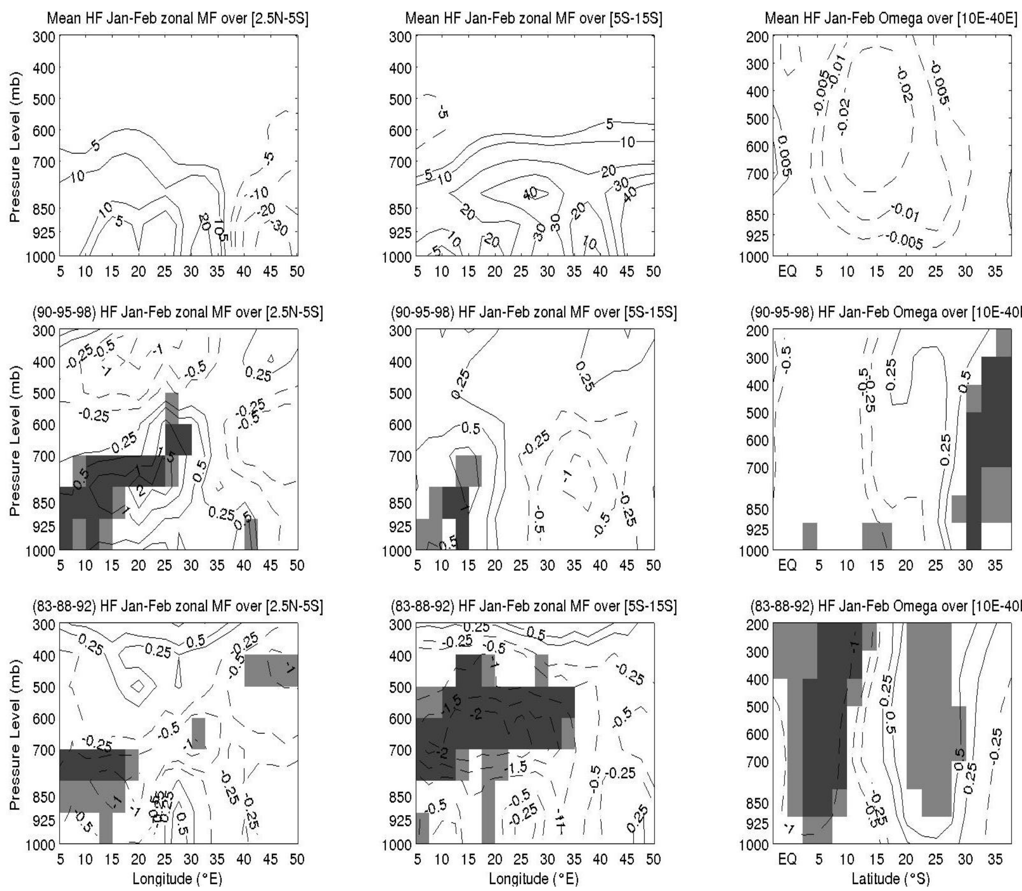

Fig. 9 Mean (top), (1990, 1995 and 1998) composite (middle) and (1983, 1988, and 1992) composite (bottom) for January–February HF zonal moisture flux (in $g{\cdot}kg^{-1}{\cdot}m{\cdot}s^{-1}$) averaged over (2.5°N–5°S) (left), and (5°S–15°S) (middle), with positive values corresponding to westerly fluxes while negative values refer to easterly orientated fluxes. On the right, mean (top) and similar composites for HF omega in January–February averaged over (10°E–40°E). Negative (positive) values for omega correspond to ascending (descending) motion. Data are averaged over the period (1979–2000) and shaded areas represent 90% (light grey) and 95% (dark grey) confidence level of Student t test.

During the years when the equatorial westerly monsoon-like moisture transport was reduced (1983, 1988 and 1992), a deficit in moisture advection over the Congo basin occurs (Fig. 9 bottom panel). These changes are accompanied by modifications in deep convection processes, suggesting a shift eastwards to the southwest Indian Ocean and southeastern parts of southern Africa (Fig. 8, bottom panel). This reduction in convection over the subcontinent led to below average rainfall. This finding agrees with D'Abreton & Tyson (1995) who showed that during dry summers, transport from the tropical Atlantic is replaced by an enhanced moisture source over the Indian Ocean.

CONCLUDING DISCUSSION

In this work, we describe the role of the tropical Atlantic exclusively through zonal moisture input. However, the meridional moisture transport across the south Atlantic onto southern Africa requires further research. Moreover this study did not consider controls exerted by Indian Ocean regions and these should be examined further. The modulation of other isolated atmospheric features needs deeper investigation, as for the migration of the south Atlantic anticyclonic cell. The variability in the southern dependence of the African Easterly Jet also requires to be better documented. It is important to notice that the results presented here are subject to the short period chosen for this study, and the small size sample used for compositing. Limitations linked with the sparse data network within the region have also to be taken into account as this can degrade the quality of the different data in use. However, our study shows that a better understanding of processes linked with moisture input from the tropical South Atlantic could help to assess issues such as summer rainfall predictability over tropical areas of southern Africa.

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