Sensitivity of a tropical-temperate trough to sea-surface temperature anomalies in the Agulhas retroflection region

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Abstract

The Colorado State University Regional Atmospheric Modelling System's (RAMS) sensitivity to positive variations in sea-surface temperature is tested by adding positive anomalous temperatures to the ocean surface in the region of the Agulhas Current retroflection for a simulated period of four days from 21 to 24 January 1981. The simulated circulation and precipitation values of the sensitivity test are compared with a control simulation. The results of the experiment, although limited in response did result in noticeable increases in convective precipitation and are consistent with the expected climate responses to anomalously high sea-surface temperatures in this area. These simulated circulation changes are consistent with previously hypothesised features of ocean-atmosphere interaction for the Agulhas Current region. The development of the ocean anomaly served to intensify the sea-surface temperature front, leading to a poleward shift in the near-surface westerlies. The strengthened heat flux resulting from the higher ocean temperatures enhanced low-level instability initially over the modified sea-surface temperature field and then eastwards along the coast by the passage of the westerly troughs.

Introduction

A significant proportion of rainfall over Southern Africa is associated with tropical-temperate trough development, involving the linkage of a tropical low, a subtropical trough and a westerly wave (Harangozo and Harrison, 1983). Heaviest rainfall associated with tropical-temperate troughs occurs when the propagation speed of the mid-latitude disturbance is slower, along with a greater wavelength and amplitude of the westerly wave (Barclay et al., 1993). The large-scale atmospheric circulation that controls tropical-temperate trough development, shows an eastward shift in the preferred location of surface convergence in the tropics during dry summer conditions (Harangozo and Harrison, 1983; Harrison, 1986; Tyson, 1986; Jury, 1993, 1996). Hence, convection decreases over the subcontinent but increases over the tropical Indian Ocean east of Madagascar (Jury and Pathack, 1991; Jury et al., 1993). This longitudinal shift in convection is in part a response to changes in sea-surface temperatures in the equatorial Pacific, Indian and Atlantic oceans (Mason and Jury, 1997).

The influence of mid-latitude sea-surface temperature anomalies on tropical-temperate trough formation in the southern African sector is less well understood. On the east coast of South Africa higher sea-surface temperatures have been found to precede and accompany higher rainfall conditions (Walker 1990; Mason, 1995). The proximity of the warm Agulhas Current has been shown to enhance coastal rainfall (Jury et al., 1993) and to generate extensive cumulus cloud formation directly above it (Lutjeharms et al., 1986). The warmer atmospheric boundary layer and heightened instability are thought to be translated inland by the tropical easterly flow producing higher moisture convergence over the immediate interior (Walker, 1990; Mason, 1995). Similarly, positive sea-surface temperature anomalies developing at the Agulhas retroflection influence the atmospheric boundary layer by generating strong surface heat fluxes, thus enhancing instability and moisture levels (Walker and Lindesay, 1989; Walker, 1990; Jury, 1993; Mason, 1995). Sea-surface temperature anomalies in the Agulhas Retroflection region also have a direct influence on the meridional sea-surface temperature gradient to the south of the subcontinent. The combination of both an increased sea-surface temperature gradient and enhanced heat fluxes, facilitate the reduction of low-level stability, which in turn increases surface convergence, convection and finally precipitation within the westerly wave disturbance (Walker, 1990; Mey et al., 1990). Therefore the presence of positive anomalies to the east and south of South Africa may influence tropical-temperate trough development by increasing moisture availability and by increasing the amplitude of the westerly wave (Fig. 1) (Walker, 1989).

The Agulhas Current retroflection region is particularly noted for its large temperature variability. This is the result of the highly dynamic ocean processes that take place here. The warm Agulhas Current overshoots the southern tip of Africa, retroflects and carries most of its waters eastwards as the Agulhas Return Current (Lutjeharms and Ansorge, 1997). This retroflection process is not stable and large Agulhas rings are formed by loop occlusion (Lutjeharms and Van Ballegooyen, 1988). As part of this process of ring spawning, widely varying amounts of warm Agulhas water and cold Sub-Antarctic surface water are drawn into the retroflection region (Shannon et al., 1988; Shannon et al., 1990a) causing extreme sea-surface temperature anomalies, that may persist for weeks. The region is therefore ideal for testing the sensitivity of the atmospheric system to oceanic temperature changes, in the mid-latitudes.

Earlier experiments using RAMS have provided accurate simulations of Southern African meteorology (Van den Heever, 1995) and have proved valuable in simulating the meteorological response to sea-surface temperature anomalies in the western tropical Indian Ocean (Crimp, 1997). In this paper, the simulated response of a tropical-temperate trough to sea-surface temperatures anomalies within the Agulhas retroflection region is considered. The results of this model sensitivity experiment will be

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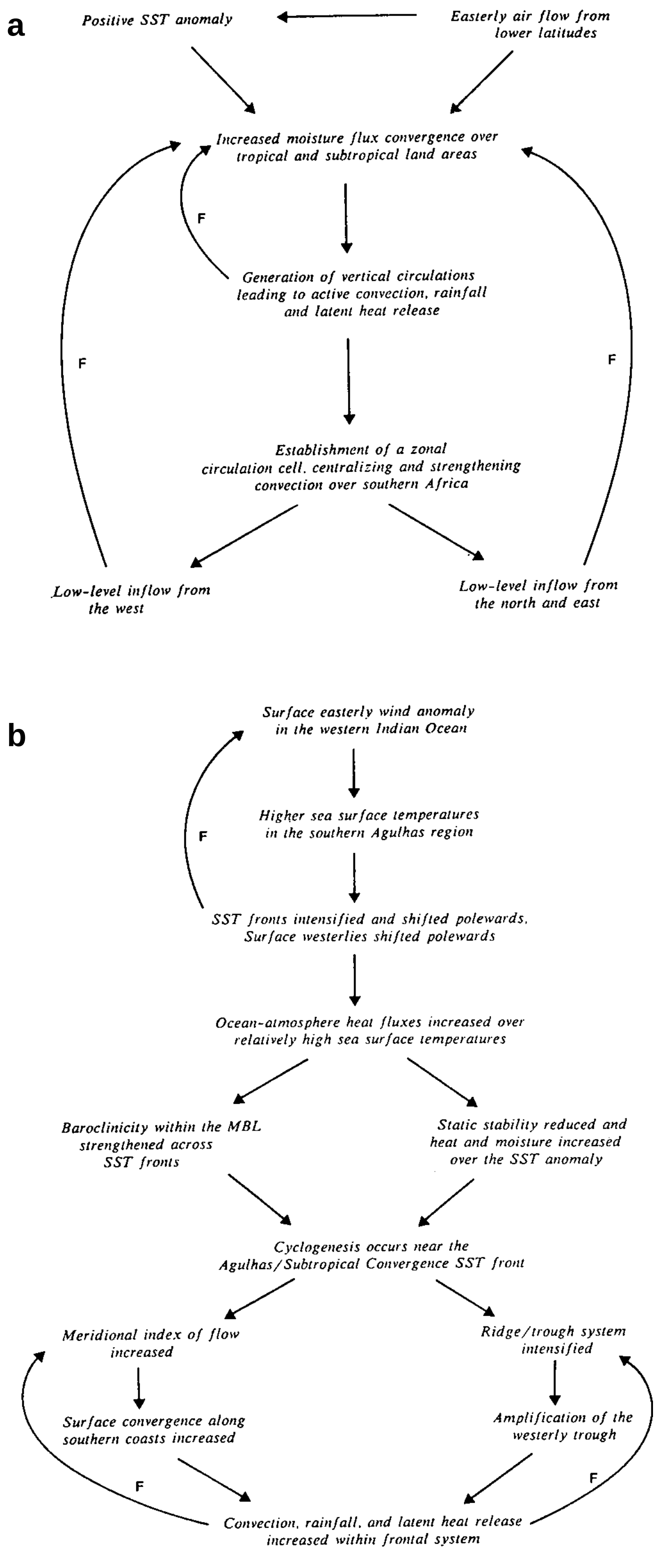

Figure 1

Possible ocean/atmosphere interactions along (a) the east coast and (b) the south coast of Southern Africa for wet case scenarios (after Walker, 1989)

compared with hypothesised circulation changes proposed by Walker (1989) resulting from sea-surface temperature anomalies in the Agulhas Current along the east and southeast coast of South Africa (Fig. 1).

The tropical-temperate trough of 21-24 January 1981

For this experiment RAMS has been used successfully to simulate the formation and dissipation of a tropical-temperate trough for the period 21 to 24 January 1981 (Van den Heever, 1995). The period 21 to 24 January 1981 forms an interesting case study for investigation as it marks the formation of a tropical-temperate trough during a particularly wet high phase of the Southern Oscillation. Cloud cover persisted for the entire four-day period, with highest precipitation values recorded on the day the tropical-temperate trough became fully coupled. The circumpolar westerly circulation was dominated by a wave-six structure (Fourie, 1981) that served to increase the overall amplitude of the westerlies.

On 21 January 1981, moist tropical air was in circulation around a low pressure centered over the Botswana/Namibian border, with thundershowers experienced over the northern and central parts of the country (Fourie, 1981). A westerly wave disturbance was situated to the south of the subcontinent, with little effect on the presiding weather conditions (Fig. 2a). By 22 January 1981, the cold front had moved to the south of Madagascar, and had been replaced by a second westerly wave perturbation (Fourie, 1981). The subtropical trough had intensified at its southern most extension. No interaction between the westerly wave and subtropical trough had taken place at this time (Fig. 2b).

The tropical-temperate trough had developed by 23 January through the linkage of the tropical low, a subtropical trough and the second westerly wave perturbation (Fig. 2c) (Fourie, 1981). Recorded rainfall values indicated widespread precipitation over the southern part of the subcontinent and along the fully developed cloud band. The tropical-temperate trough began to dissipate on the morning of 24 January, although cloud cover still persisted over the southern regions of South Africa and immediate interior (Fourie, 1981). Precipitation was reduced and more isolated as the temperate link between subtropical trough and westerly wave had broken (Fig. 2d).

Data and methods

The RAMS control simulation of the development and dissipation of the tropical-temperate trough of 21-24 January 1981 provides an accurate representation of the observed synoptic features. The model was initialised using European Centre for Medium Range Weather Forecasts (ECMWF) IIb Global Analysis data sets, global National Meteorological Center (NMC) surface data sets, and long-term mean sea-surface temperature data from the British Meteorology Office. Full details of the control simulation are given in Crimp (1997) and are not presented here. The simulated response of this tropical-temperate trough to positive sea-surface temperature anomalies in the western tropical Indian Ocean indicated a modification of the atmosphere in the marine boundary layer that would be consistent with the expected climatic response to the anomaly (Crimp, 1997). In this paper, a similar sensitivity experiment is conducted with a positive 2°C sea-surface temperature anomaly imposed in the region of the Agulhas Retroflection and bounded by an anomaly of 1°C anomaly (Fig. 3). The magnitude of the anomaly,

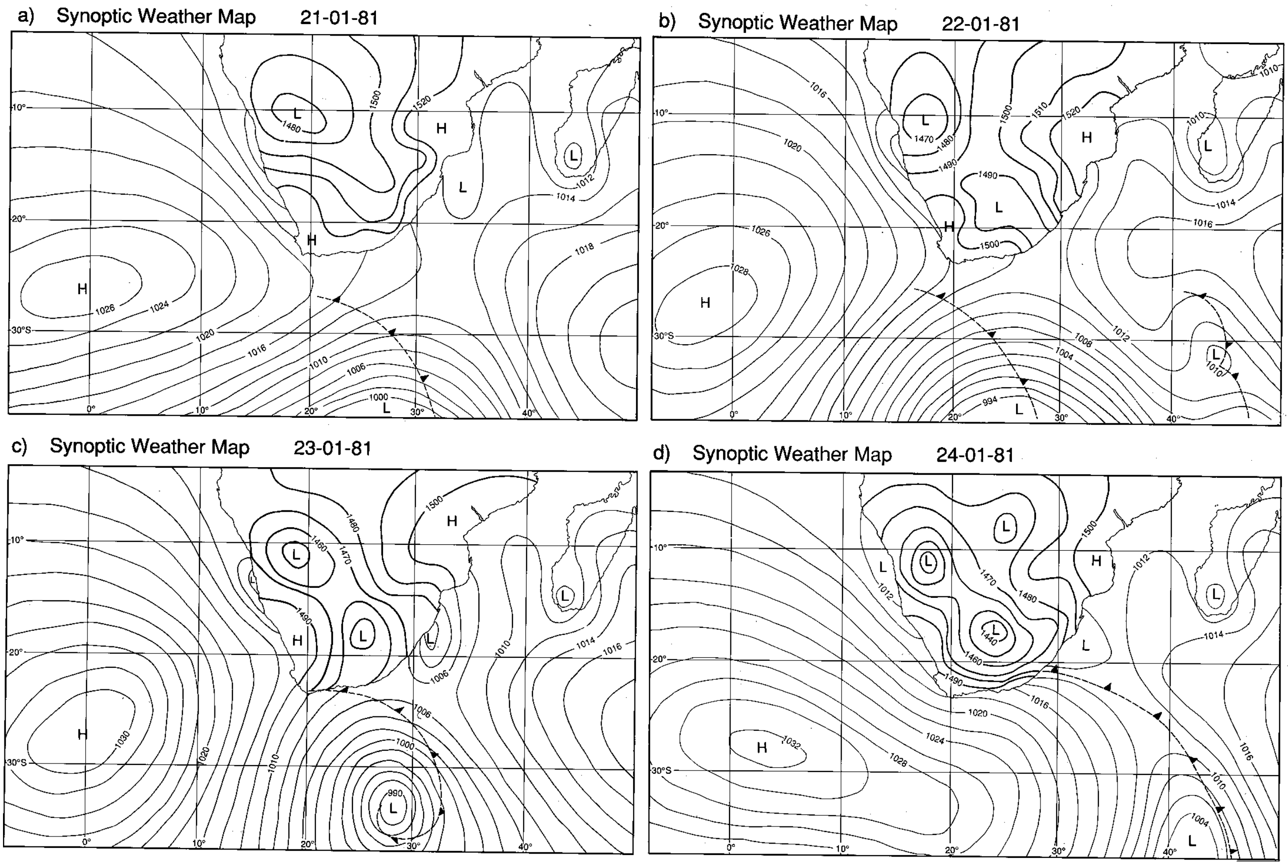

Figure 2
A schematic representation of synoptic conditions for (a) 21, (b) 22, (c) 23 and (d) 24 January 1981 (after Fourie, 1981). Contour values in hectopascals.

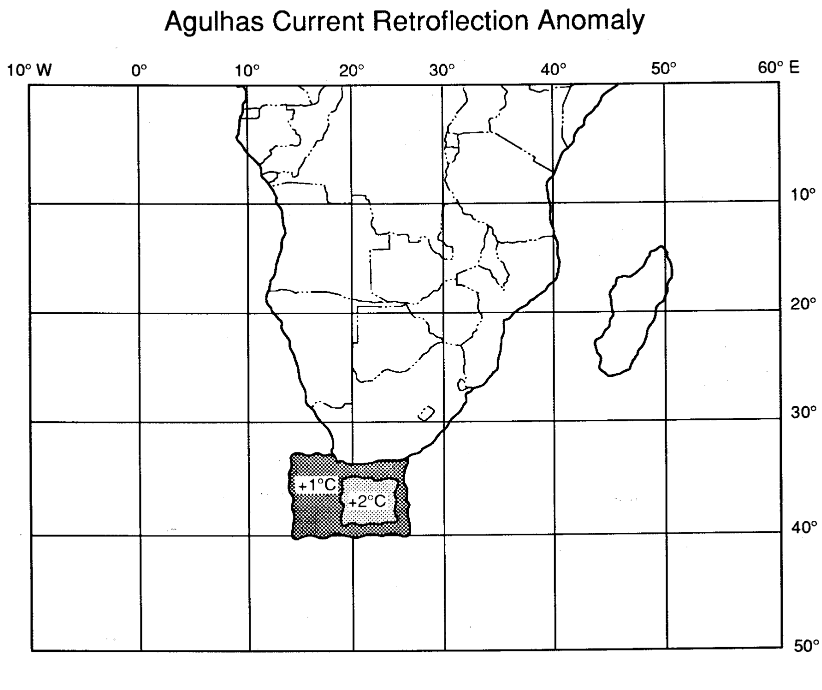

Figure 3
Representation of the sensitivity test, whereby a positive 2°C anomaly and positive 1°C anomaly were added to the Agulhas Current retroflection region.

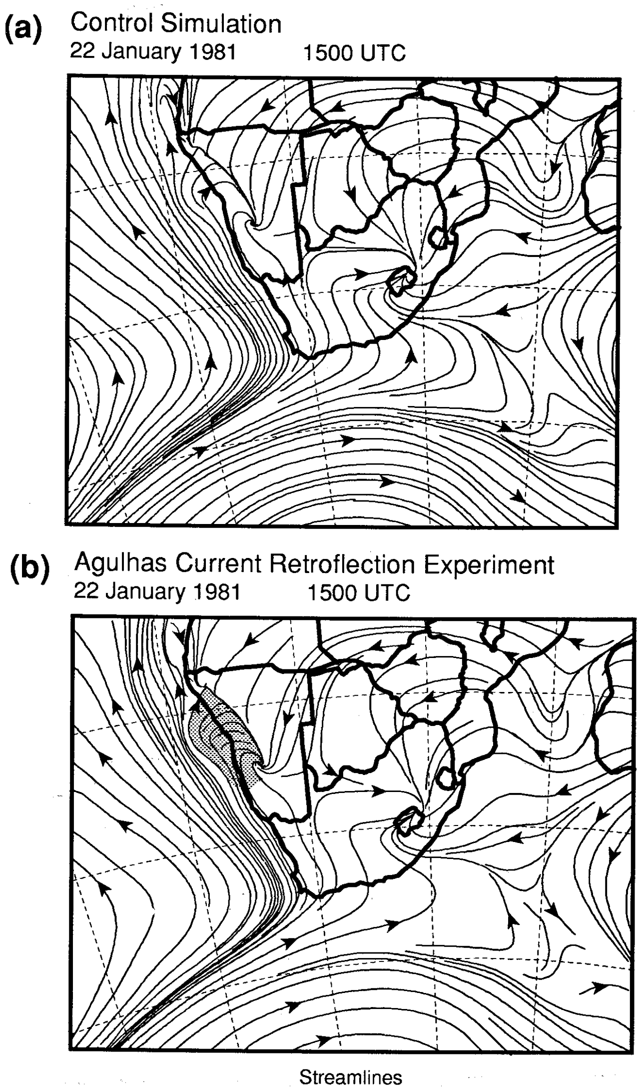

Figure 4

Streamline diagrams for (a) the control and (b) the sensitivity simulations at the 146.4 m level for 15:00 UTC on 22 January 1981

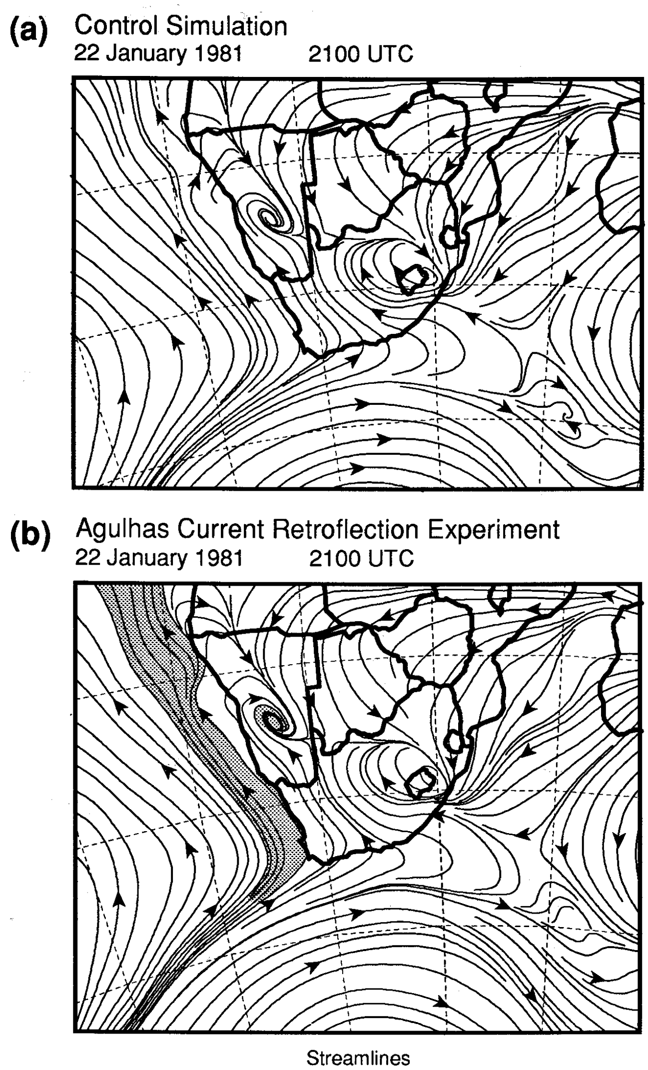

Figure 5

Streamline diagrams for (a) the control and (b) the sensitivity simulations at the 146.4 m level for 21:00 UTC on 22 January 1981

both in terms of temperature and geographic extent, is well within the range of observed values (Shannon et al., 1990b). All other details of the control simulation and the sensitivity experiment are identical to those of Crimp (1997). The sensitivity simulation was then compared with the control simulation by the analysis of wind components (*u*,*v*), streamlines, temperatures, vertical velocity (*w*), vapour and cloud mixing ratios, and accumulated convective precipitation at the 146.4 m level (Pielke et al.,1992; Cotton et al., 1994), representing the boundary layer.

Results

No circulation or atmospheric parameter differences between the Agulhas Current retroflection anomaly experiment and the control simulation at the initial time-step 12:00 UTC (universal time constant) 21 January 1981 were evident. As for the control experiment, the South Atlantic and South Indian Highs were positioned relatively far south at 35°S and 42°S respectively. Two prominent tropical lows were simulated over the continent, with significant moisture availability in these areas. High vapour and cloud mixing ratio values were also simulated over Madagascar and over the tropical Indian Ocean to the east. Easterly winds were predominant to the east of Madagascar along with westerly winds in the temperate latitudes.

On the second day of the simulation (06:00 UTC) weakened south-westerly onshore flow along the south coast brought an increase in air temperature to the west coast of South Africa. The combination of weaker onshore flow and increased air temperatures served to perpetuate the acceleration of vertical velocities over the anomalous sea-surface temperature field. By 15:00 UTC south-easterly winds along the west coast strengthened, producing a marginal increase in surface convergence over Angola and Namibia, as well as a stronger cyclonic circulation over central Namibia (Fig. 4 a,b). The subtropical trough situated over the northern half of South Africa indicated the same pattern of change as the streamlines, with higher positive vertical velocities at the eastern limits, the west coast of southern Angola, and northern Namibia. Moisture availability increased over the eastern bound-

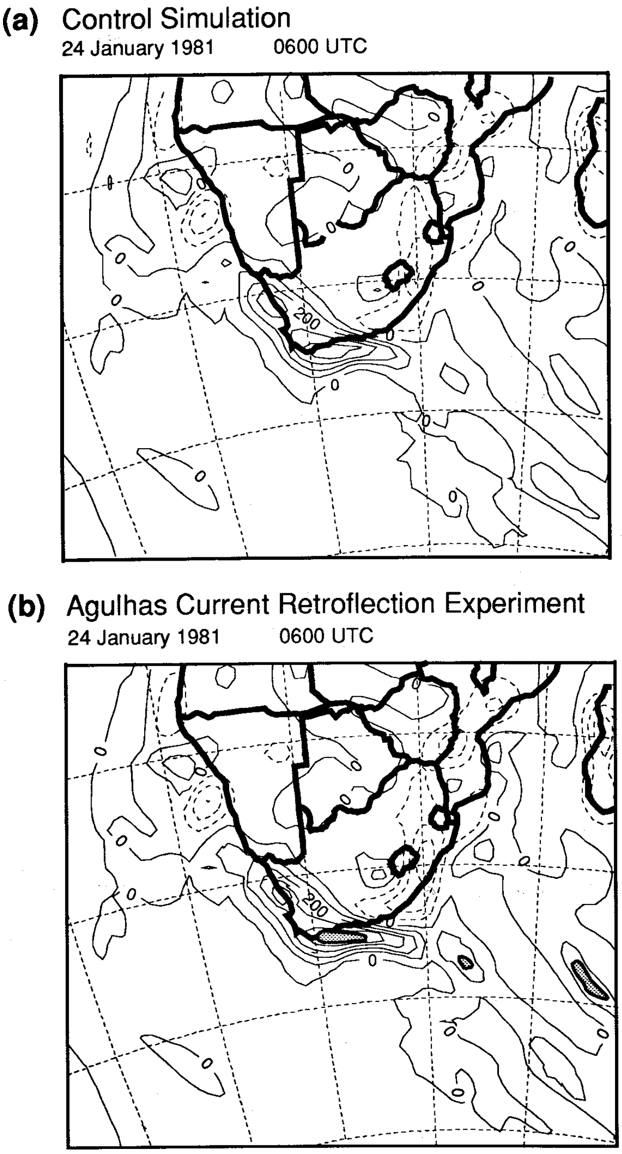

Figure 6
W component diagrams for (a) the control (contours from -0.3500E-01 cm·s⁻¹ to 0.4000E-01 cm·s⁻¹) and (b) the sensitivity simulations (contours from -0.3500E-01 cm·s⁻¹ to 0.4500E-01 cm·s⁻¹) at the 146.4 m level for 06:00 UTC on 24 January 1981. Labels 0.1000E+05 cm·s⁻¹.

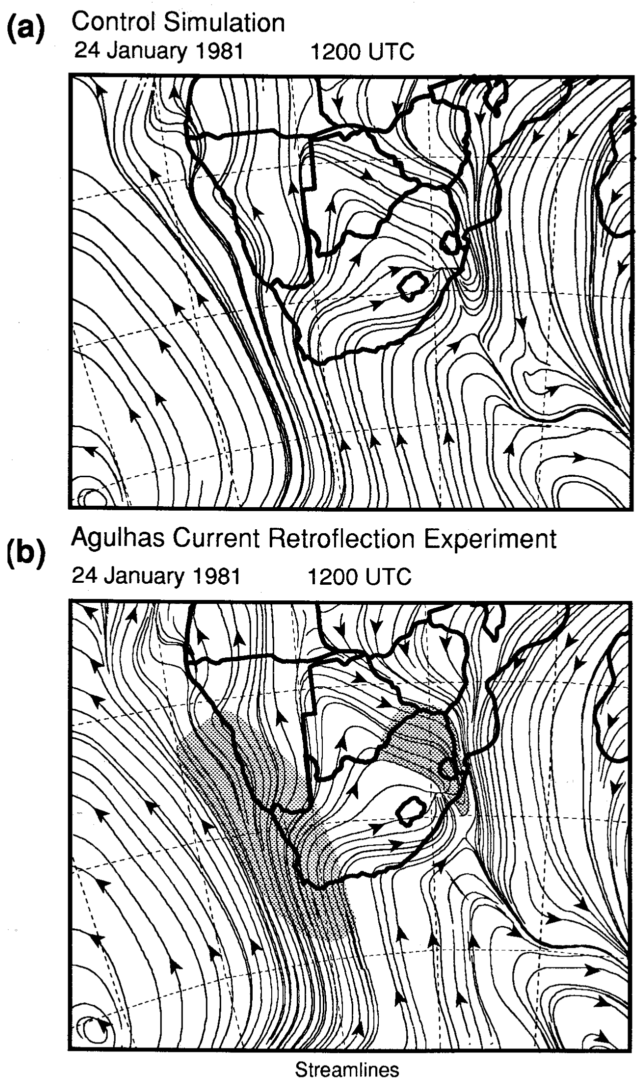

Figure 7
Streamline diagrams for (a) the control and (b) the sensitivity simulations at the 146,4 m level for 12:00 UTC on 24 January 1981.

ary of the modified sea-surface temperature field.

By 21:00 UTC on 22 January the stronger south-easterly winds along the west coast of South Africa expanded to cover the subcontinent. This increase in south-easterly wind flow served to heighten the circulation both around the tropical low over Namibia, and the subtropical trough over the northeast of the country (Fig. 5 a,b). Simulated vertical velocities followed the same pattern as indicated by the streamlines, with increases in magnitude on the eastern limits of the subtropical trough, as well as over the area of modified sea-surface temperatures. Precipitation values continued to be higher over the central plateau and south-eastern Namibia, the result of the stronger surface convergence over these areas, as indicated in the streamline output.

By the third day of the simulation (09:00 UTC), heightened vertical velocities at approximately 48°S, 70°E were evident with values of 0.020 $cm \cdot s^{-1}$ in the sensitivity simulation compared to control simulation values of 0.016 $cm \cdot s^{-1}$ and suggest an increase in atmospheric instability. Other areas experiencing increased vertical motion were found over the developing front and along the east coast. The origin of the heightened vertical impetus is found over the modified sea-surface temperature field and translated poleward by the predominant circulation. Vapour and cloud mixing ratios decreased over the southern Free State and northern parts of the Eastern Cape, but increased over southern Namibia and south-western Botswana. Moisture availability remained high over the south eastern coast of South Africa and adjacent Indian Ocean. After 33 h precipitation increases in the simulation experiment coincided with the areas of heightened vertical velocities. These regions are found over the east coast of South Africa at 30°S, over the sea-surface temperature anomaly: a marginal increase in accumulated convective precipitation since 21 January from 2 mm in the sensitivity experiment compared to

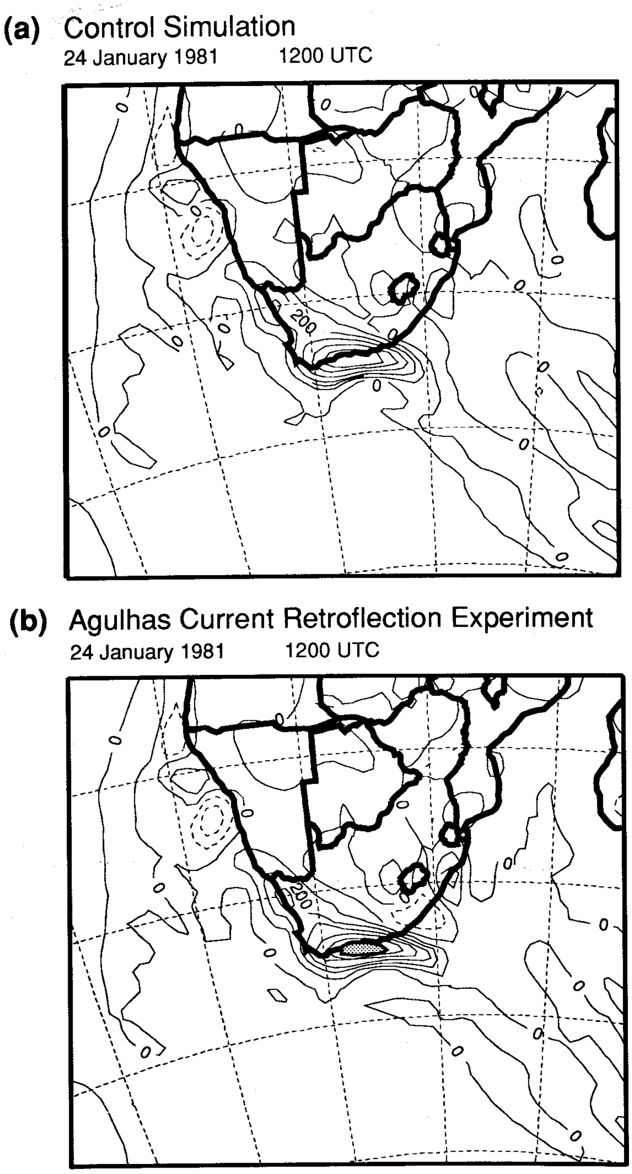

Figure 8
W component diagrams for (a) the control (contours from -0.2500E-01 cm·s^{-1} to 0.5500E-01 cm·s^{-1}) and (b) the sensitivity simulations (contours from -0.2500E-01 cm·s^{-1} to 0.6500E-01 cm·s^{-1}) at the 146.4 m level for 12:00 UTC on 24 January 1981. Labels 0.1000E+05 cm·s^{-1}

1 mm in the control simulation, over eastern Namibia (18 mm vs 16 mm), and over southern Botswana .

In the early morning (06:00 UTC) of the last simulation day, the westerly *u* component values continued to possess greater magnitudes than control values, along the cold front to approximately 37°S. The simulated lows over the eastern half of South Africa and over the Indian Ocean dissipated although vertical velocities remained higher over the south coast (0.045 cm·s^{-1} compared to 0.040 cm·s^{-1}) and along the receding cold front (0.015 cm·s^{-1} compared to 0.010 cm·s^{-1}), as a result of passage over the region of the sea-surface temperature anomalies (Fig. 6 a,b). At the end of the simulation period (12:00 UTC, 24 January) strong westerly *u* component values moved along the south coast in the same direction as the receding cold front, with streamlines

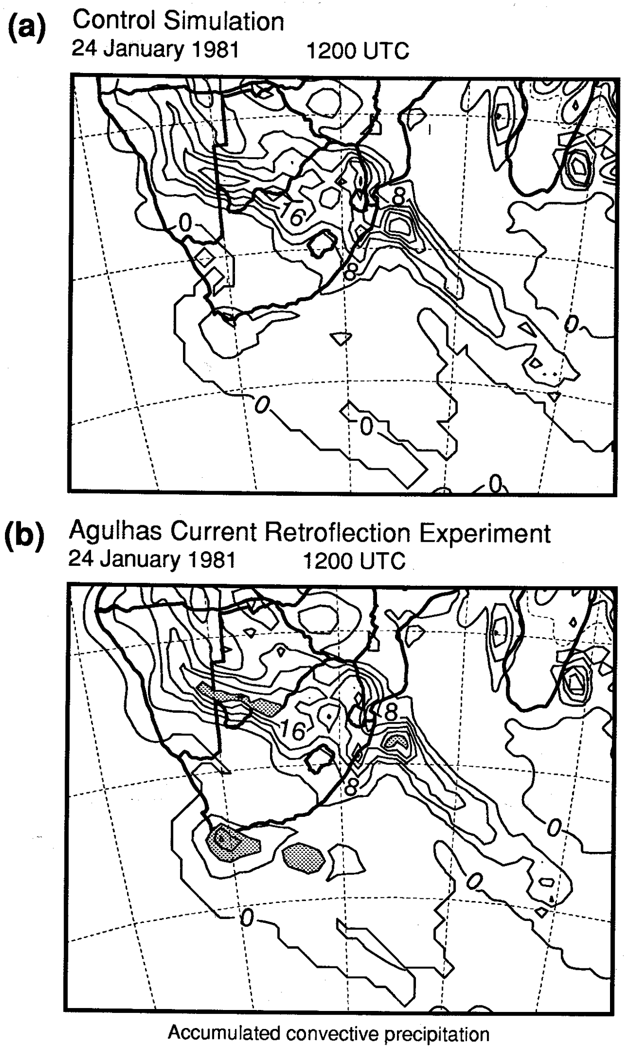

Figure 9
Accumulated convective precipitation (in mm) for (a) the control and (b) the sensitivity simulations at the 146.4 m level from the beginning of the simulation up to, and including 12:00 UTC on 24 January 1981

indicating localised stronger flow remaining *in situ* over the Northern Province adjacent to the Zimbabwe border. Streamlines indicate stronger south-easterly winds along the west coast of South Africa, with a concomitant increase in north-westerly winds over the Northern Province and Zimbabwe (Fig. 7 a,b). Vertical velocities remained higher along the west and south coasts, and northern parts of the east coast (Fig. 8 a,b), coinciding with zones of heightened westerly flow. Precipitation maintained the same pattern as from early on 23 January. Accumulated values were markedly higher over the area of modified sea-surface temperatures with sensitivity values of 16 mm compared to control values of 8 mm (Fig. 9 a,b). Similar differences were found over the eastern half of the country and adjacent Indian Ocean, as well as eastern Namibia and southern Botswana.

Discussion

Although the circulation changes found for the anomaly experiment over the Agulhas Current retroflection were small, the changes in the near-surface layers closely resemble the ocean-atmosphere feedback mechanisms proposed by Walker (1989) for the Agulhas Current to the south and east of South Africa (Fig. 1). The development of sea-temperature anomalies served to intensify the sea-surface temperature front, leading to a poleward shift in the surface westerlies. The strengthened heat fluxes, resulting from increased sea-surface temperatures, enhanced low-level vertical velocities and produced a marginal amplification of the cold fronts. The atmospheric differences that were found indicate that the origin of change lies over the modified sea-surface temperature field, and that the atmospheric circulation anomalies were translated both along the coast, from south-west to north-east by the passage of the cold fronts, and also by the enhanced recurved westerly flow over eastern Namibia, southern Botswana and the Northern Province of South Africa. Higher vertical velocity values began over the modified sea-surface temperature field and migrated eastward along the coast, and poleward along the cold front. The greatest precipitation differences were found over the summer rainfall areas of South Africa, eastern Namibia and southern Botswana, with highest magnitude differences over the area of positive sea-surface temperature increase.

The atmospheric circulation changes brought about by the modification of sea-surface temperatures in the region of the Agulhas retroflection took longer to translate into the atmosphere than for similar anomalies in the tropical Indian (Crimp, 1997). The explanation for this greater delay lies in a comparison of the background sea-surface temperatures and moisture values over the two oceanic regions. In the tropical Indian Ocean background sea-surface temperatures are higher, with stronger boundary layer heat fluxes and thus greater atmospheric heating. The enhanced atmospheric temperatures over the anomaly region, and neighboring ocean, allow for a greater moisture carrying capacity of the localised atmosphere. In the Agulhas Current retroflection region the lower background temperatures less readily affect moisture availability, instability and hence general circulation. A further explanation lies in the identification of the major moisture sources for Southern African precipitation. From research recent (D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995) the most important moisture source for South African summer rainfall lies in the tropical Indian Ocean region, with the eastern and southern Agulhas Current region having very limited direct input. Any temperature modification on the tropical Indian Ocean would thus have a far greater impact on southern African precipitation than the same modification in the eastern and southern Agulhas Current.

Conclusions

The sensitivity of the development of the tropical-temperate trough of 21-24 January 1981 to sea-surface temperature anomalies to the south of South Africa has been simulated using the Colorado State University Regional Atmospheric Modelling System. The addition of anomalous sea-surface temperatures in the Agulhas Current retroflection region had no effect on the general formation and dissipation of the tropical-temperate trough, but significant increases in convective precipitation were simulated. The precipitation increases can be linked to atmospheric modifications in the near-surface layers. A weakened onshore flow over the southern coast of South Africa, with heightened zonal or westerly flow to the south of the Agulhas Current anomaly was simulated. This type of atmospheric circulation change was proposed by Walker (1989) who stated that the development of sea-surface temperature anomalies in this region serves to intensify the sea-surface temperature front towards the poles and thus to shift the surface westerlies in a poleward direction. Strengthened ocean-atmosphere heat fluxes, in this case, reduced static stability over the anomaly, which in turn influenced both the structure of the westerly troughs and meridional flow along the west coast. The positive sea-surface temperature anomalies aided in the enhancement of surface and near-surface convergence along the Angolan and Namibian coast, by increasing moisture inflow to the area. The anticyclonic circulation around the semi-permanent South Atlantic High pressure passed over the anomaly and flowed equatorward along the west coast of the subcontinent. For this study the positive sea-surface temperatures would slowly have allowed moisture transfer from the anomaly source to the convergence zone along the west coast. The initial enhancement of convergence along the Southern African west coast produced higher convective precipitation values over the Namibia/Botswana border, with the westerly wave disturbances increasing precipitation values along the South African east coast.

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References

BARCLAY JJ, JURY MR and LANDMAN W (1993) Climatological and structural differences between wet and dry troughs over southern Africa in the early summer. *Meteorol. Atmos. Phys.* **51** 41-51.

CRIMP SJ (1997) A sea-surface temperature sensitivity test using the Colorado State University Regional Atmospheric Modelling System (RAMS). *S. Afr. J. Sci.* **93** 133-141.

COTTON WR, THOMPSON G and MIELKE PW (1994) Real-time mesoscale prediction on workstations. *Bull. Am. Meteorol.* **75** 349-362.

D'ABRETON PC and LINDESAY JA (1993) Water vapour transport over southern Africa during wet and dry early and late summer months. *Int. J. Climatol*. **13** 151-170.

D'ABRETON PC and TYSON PD (1995) Divergent and non-divergent water vapour transport over southern Africa during wet and dry conditions. *Meteorol. Atmos. Phys.* **55** 47-59.

FOURIE M (1981) Weer van die Maand. *SA Weather Bureau Newsletter* **382** 76-79.

HARANGOZO S and HARRISON MSJ (1983) On the use of synoptic data in indicating the presence of cloud bands over southern Africa. *S. Afr. J. Sci.* **79** 413-414.

HARRISON MSJ (1986) A Synoptic Climatology of South African Rainfall Variations. Unpublished Ph.D. Thesis, Univ. of the Witwatersrand.

JURY MR and PATHACK B (1991) A study of climate and weather variability over the tropical southwest Indian Ocean. *Meteorol. Atmos. Phys.* **47** 37- 48.

JURY MR (1993) A thermal front within the marine atmospheric boundary layer over the Agulhas Current south of Africa: Composite aircraft observations. *J. Geophys. Res.* **99 C2** 3297-3304.

JURY MR, VALENTINE HR and LUTJEHARMS JRE (1993) Influence of the Agulhas Current on summer rainfall on the southeast coast of South Africa. *J. Appl. Meteorol.* **32** 1282-1287.

JURY MR (1996) Regional teleconnection patterns associated with summer rainfall over South Africa, Namibia and Zimbabwe. *Int. J. Climatol.* **16** 135-153**.**

LUTJEHARMS JRE, MEY RD and HUNTER IT (1986) Cloud lines over the Agulhas Current. *S. Afr. J. Sci*. **82** 635-640.

LUTJEHARMS JRE and VAN BALLEGOOYEN RC (1988) The Agulhas Current retroflection. *J. Phys. Oceanogr*. **18** 1570-1583.

LUTJEHARMS JRE and ANSORGE I (1997) The Agulhas Return Current. *J. Phys. Oceanogr*.

MASON SJ (1995) Sea-surface temperature - South African rainfall associations, 1910-1989. *Int. J. Climatol.* **15** 119-135.

MASON SJ and JURY MR (1997) Climatic variability and change over southern Africa: A reflection on underlying processes. *Prog. Phys. Geogr.* **21** 23-50.

MEY RD, WALKER ND and JURY MR (1990) Surface heat fluxes and marine boundary layer modification in the Agulhas retroflection region. *J. Geophys. Res.* **95** 15 997-16 015.

PIELKE RA, COTTON WR, WALKO RL, TREMBACK CJ, LYONS WA, GRASSO LD, NICHOLLS ME, MORAN MD, WESELY DA, LEE TJ and COPELAND JH (1992) A comprehensive meteorological modelling system - RAMS. *Meteorol. Atmos. Phys*. **49** 69-91.

SHANNON LV, LUTJEHARMS JRE and AGENBAG JJ (1988) Episodic input of Subantarctic water into the Benguela region. *S. Afr. J. Sci.* **85** 317-322.

SHANNON LV, AGENBAG JJ, WALKER ND and LUTJEHARMS JRE (1990a) A major perturbation in the Agulhas retroflection area in 1986. *Deep-Sea Res*. **37** 493-512.

SHANNON LV, LUTJEHARMS JRE and NELSON G (1990b) Causative mechanisms for intra-annual and interannual variability in the marine environment around southern Africa. *S. Afr. J. Sci.* **86** 356-373.

TYSON PD (1986) *Climatic Change and Variability in Southern Africa.* Oxford University Press, Cape Town.

VAN DEN HEEVER SC (1995) Modelling Tropical-Temperate Troughs over Southern Africa. Unpublished M.Sc. Dissertation, Univ. of the Witwatersrand.

WALKER ND (1989) Sea-surface Temperature-Rainfall Relationships and Associated Ocean-Atmosphere Coupling Mechanisms in the Southern African Region. Unpublished Ph.D. Thesis, Univ. of Cape Town.

WALKER ND and LINDESAY JA (1989) Preliminary observations of oceanic influences on the February-March 1988 floods in central South Africa. *S. Afr. J. Sci.* **85** 164 -169.

WALKER ND (1990) Links between South African summer rainfall and temperature variability of the Agulhas and Benguela current systems. *J. Geophys. Res.* **95 C3** 3297-3319.