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The Extreme Precipitation Event of 11 to 16 February 1996 over South Africa

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With 13 Figures

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Summary

The extreme precipitation event of 11 to 16 February 1996 was one of four significant events during the 1995/96 rainfall season over southern Africa. Extensive flooding and related damage was recorded at this time, with historical records showing one of the highest flood peaks of the past century. This extreme event is analysed using a combination of mesoscale numerical modelling and Lagrangian trajectory analysis, allowing a comprehensive three-dimensional reconstruction of the associated atmospheric structure and its evolution. The adjustments in the circulation patterns as well as the timing and contribution of different moisture source regions are clearly important in influencing the duration and intensity of this extreme rainfall event over southern Africa. The moisture that contributed to precipitation during the event, as well as to the south-western part of the country, was imported mainly from the Indian Ocean to the east and south-east, suggesting that the equatorial Indian Ocean may not be the predominant source of moisture as previously believed.

1. Introduction

In the summer rainfall region of South Africa, the month of February 1996 represented a period of exceptionally high precipitation. The total rainfall for the month was approximately 150 to 200 per cent of the long-term average (Fig. 1a), resulting in severe flooding in many areas of the country and in loss of life (Edwards, 1997). On the whole the summer season experienced extremely high precipitation values in agreement with the February pattern. This period did not comprise of consistently above average rainfall, but was rather the result of four extremely intense rainfall events (Edwards, 1997). The rainfall events, as identified by the South African Weather Bureau, were 20 to 29 December 1995, 16 to 27 January 1996, 13 to 17 February 1996, and 22 to 26 February 1996. Of particular interest is the event in mid-February 1996, for on this occasion widespread rains fell over almost the entire summer rainfall region. Extensive flooding and related damage was recorded, and some of the highest flood peaks of the past century were experienced (Kroese et al., 1997). The event was characterised by the interaction of a tropical low, a cold front and a ridging anticyclone. The tropical low moved into a position over the subcontinent from central Madagascar during the period 9 to 11 February 1996, and interacted with a relatively strong cold front to the south. The ridging anticyclone provided additional rainfall by directing an inflow of moisture from the east to the central reaches of South Africa.

Because the southern subcontinent is an arid to semi-arid region with a marked east to west decrease in precipitation (Tyson, 1986), the availability of moisture must play a key role in

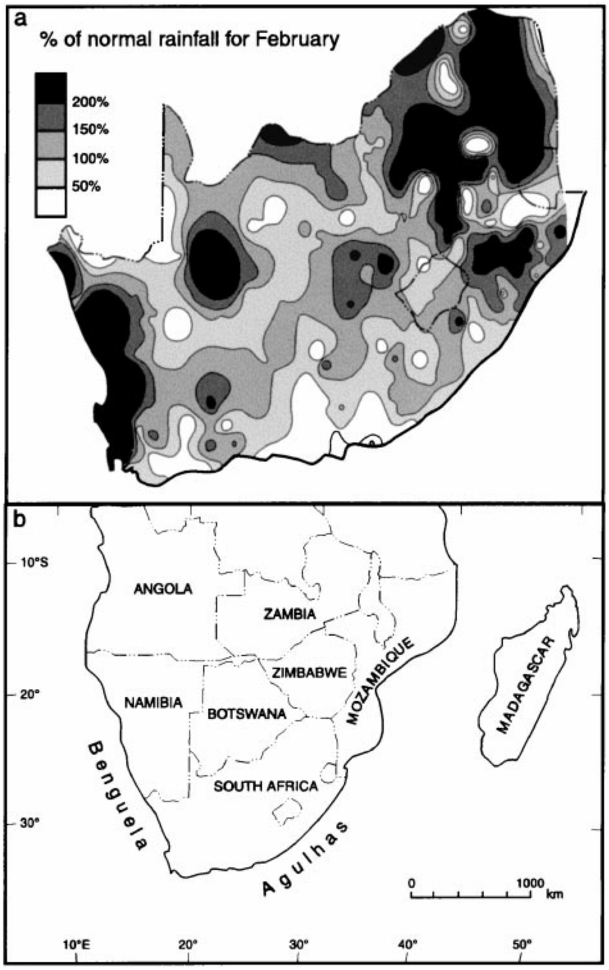

Fig. 1. (a) Map of South Africa showing the 1995/96 December–February rainfall totals as percentages of the 1961–1990 average. (b) Location map of southern Africa showing the political boundaries and places mentioned in the text

determining the nature and severity of precipitation events. The majority of moisture that contributes to southern African precipitation is imported from other source regions (D'Abreton and Lindesay, 1993; Mason and Jury, 1997) and so the identification of these regions is critical in determining the development and severity of such events. Macroscale vapour studies by James and Anderson (1984) have shown that the transfer of water vapour to tropical and mid-latitude regions serves to enhance the rate of growth and intensity of baroclinic systems. In southern Africa, research in this field has been limited to the investigation of mean vapour content and vapour fluxes over South Africa (McGee, 1971, 1972, 1975, 1978, 1986), the relationship between precipitable water and rainfall (Harrison, 1988) and the transport of atmospheric water vapour over the country (D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995; D'Abreton and Tyson, 1996). Because little is known about the sources of water vapour over South Africa during summer, continued debate exists over the possible source regions. Two areas are identified as possible sources for summer rainfall, the first of which is the tropical Indian Ocean, with water vapour being advected over the continent around the South Indian Anticyclone (Tyson, 1986; Taljaard, 1986, 1987, 1990). The second area identified as a moisture source for the summer rainfall region extends southward from the tropics along the Inter-Tropical Convergence Zone (ITCZ) and Zaire Air Boundary (ZAB) (Harrison, 1986). Air flow directly from the west, from over mid- and subtropical latitudes of the Atlantic Ocean, provides minimal moisture (D'Abreton, 1996).

In this paper, the general atmospheric conditions during the period 11 to 16 February 1996 are investigated using the Colorado State University Regional Atmospheric Modelling System (RAMS) (Tremback et al., 1985). The detailed evolution of the synoptic conditions responsible for the excessive rainfall that occurred over South Africa at this time can be determined from the model simulation. The model results suggest that there were important changes in the sources of moisture through the event, and so a Lagrangian trajectory model is used to infer the evolving nature of moisture inflow to regions that experienced the heaviest precipitation. The trajectory model used is a modified version of that developed by D'Abreton (1996).

2. Data and Methodology

The European Centre for Medium Range Weather Forecasts (ECMWF) IIb Global Analysis data set was used in the initialisation of the atmospheric conditions for the RAMS simulation. Further initialisation is needed in the mesoscale numerical model in the form of surface data obtained from the US National Meteorological Centre (NMC), and monthly mean sea-surface temperature data from the United

Kingdom Meteorological Office. RAMS is comprised of three individually developed models, two of which are hydrostatic mesoscale models (Tremback et al., 1985; Mahrer and Pielke, 1977) and the third a non-hydrostatic cloud model developed by Tripoli and Cotton (1982). As RAMS is both flexible and versatile its number of applications is varied. For this reason the modelling system contains many options for both physical and numerical processes. The model itself can be broken down into three distinct modules. The first represents the isentropic analysis stage (ISAN), where a three-dimensional atmospheric grid is created in order to moderate the boundary conditions throughout the model simulation. The second module performs the actual model simulation (MODEL) by resolving a host of numerical parameters through prescribed equations. The final module represents the visualisation and analysis module (VAN). The actual simulation process begins once ISAN has created the global isentropic grid from the ECMWF analysis data set. The domain limits are then defined in order for specific coordinate extraction to take place. The atmospheric variables and topography are transferred to the model domain grid by polynomial overlapping interpolation. The numerical processing is then initialised and finally the graphic output is created. Further details of the model parameter settings used are provided by Crimp (1997).

A Lagrangian trajectory model was adapted to calculate backward trajectories. Because individual trajectories can diverge fairly rapidly (D'Abreton, 1996), clusters of nine trajectories were calculated to give an indication of the uncertainties in the trajectory pathways. The trajectory model considers topographic obstacles by using a prescribed terrain-following system, and will terminate when data boundaries are reached or until the prescribed time step has been completed (D'Abreton, 1996).

The output of both RAMS and the trajectory model was analysed in order to identity the major moisture sources, and to develop a more comprehensive understanding of the structure of the atmosphere over southern Africa during this extreme rainfall event. The methodology employed involves the simulation of the period 11 to 16 February 1996 using RAMS. Variables analysed from the RAMS simulation included: u-, v-, and w-wind vectors; mean sea level pressure; streamlines; total mixing ratio; and accumulated convective precipitation plotted at the 146.4 m (near-surface), 3744.6 m ($\approx$ 650 hPa), and 7406.2 m ($\approx$ 390 hPa) levels. The 650 hPa pressure surface was chosen because it is a significant level of water vapour transport in the region (D'Abreton and Lindesay, 1993; D'Abreton, 1996). Areas of greatest precipitation were identified, and the convergence of moisture into these areas was inferred from the atmospheric flow reconstructed using the lagrangian trajectory model. The trajectory model simulation produces graphical output of latitude and longitude position, with corresponding pressure values in hectopascals (hPa) at each point (D'Abreton, 1996).

3. Sequence of Events from Synoptic Record

Satellite and synoptic information were made available by the South African Weather Bureau for the period 11 to 16 February 1996 (Fig. 2a–f). The analysis of the data showed a sequence of events producing an extremely large quantity of precipitation.

3.1 11 February 1996

The presence of a large tropical low situated over Botswana (Fig. 2a; place names are indicated in Fig. 1b) with favourable upper level circulation produced widespread rains over the eastern half of southern Africa. The passage of a cold front and ridging anticyclone ensured heavy falls along the east coast, east of about 25° E. The predominant wind direction over the eastern half of South Africa was north-easterly, with strong onshore flow along the east coast due to the passage of the ridging high. Two other important features to note at this time were the low pressure over Madagascar, producing instability and convective activity over the northern limits of the Island, and a coastal low developing along the west coast of the subcontinent (Fig. 2a).

The precipitation over South Africa measured for the 24-hour period up to 12:00 UTC was widespread, with highest totals over the east coast, where falls of greater than 100 mm were experienced. Heavy rains ($>$ 90 mm) also were experienced inland in the north-eastern part of the country.

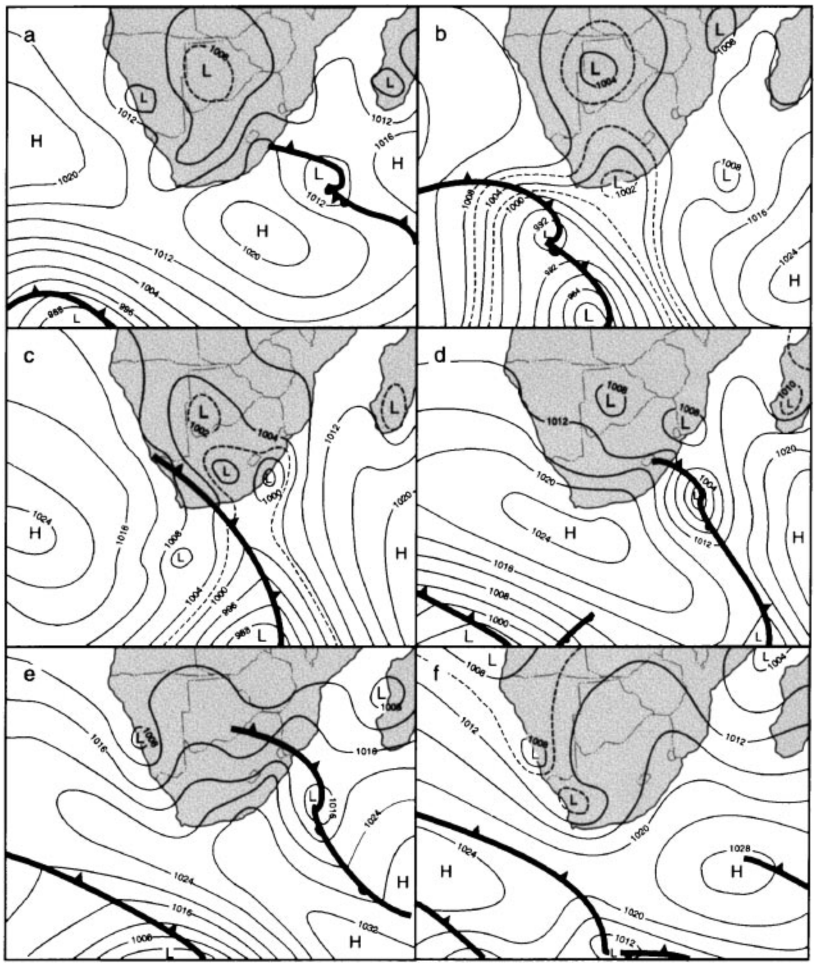

Fig. 2. Observed sea-level pressure (hPa) at 12:00 UTC for (a) 11th, (b) 12th, (c) 13th, (d) 14th, (e) 15th and (f) 16th February 1996

3.2 12 February 1996

The tropical low pressure strengthened from the previous day to 1004 hPa (Fig. 2b). The coastal low along the west coast filled and a second coasted low developed along the south coast ahead of the approaching cold front. The ridging anticyclone to the east of the country became entrained into the South Indian Ocean high pressure system, thus reducing the input of moisture onto, and precipitation over, the east coast of South Africa. The general wind direction over the northern region of South Africa was north-easterly, with poleward transport of latent energy along the subtropical trough. The northern regions continued to receive heavy rains, and highest precipitation values for this period were found in the northern and eastern parts of the country (> 80 mm). Due to the development of a coastal low and strengthened tropical low, the south-western part of the country experienced precipitation values exceeding 45 mm, which is uncharacteristically high for a winter rainfall region.

3.3 13 February 1996

By 13 February the cold front had moved over the western part of South Africa (Fig. 2c), bringing with it widespread rains. Heavy rains and thundershowers were experienced over the eastern and central parts of the country, in association with a strengthening of the tropical low pressure. The coastal low moved along the south-east coast to about 30° E and strengthened from 1008 hPa on the previous day to 1002 hPa. Air flow at this time was predominantly meridional, having a strong southerly component on the west coast and a strong northerly component on the east coast.

Consistently high falls were a general feature over most of the country, except in the north-west and along the south coast ahead of the front. The east coastal precipitation values increased from the previous day due to the passage of the coastal low. Latent instability and thunderstorm activity were high in the northern regions of South Africa with high rainfall figures for the third day in succession. The highest recorded precipitation values were found over the central northern part of the country (> 80 mm).

3.4 14 February 1996

During the 24-hour period between 13 and 14 February 1996, the passage of the cold front brought it to a position over the eastern half of the country (Fig. 2d), maintaining heavy precipitation values over this region for the fourth day in succession. The South Atlantic Anticyclone began to ridge in behind the cold front enhancing onshore flow directly behind the front (Fig. 2d). At this time the coastal low was centred over southern Mozambique and had weakened. The tropical low over the continent had become less intense due to the intrusion of the ridging high. Heavy falls were recorded along the east coast and in the north-east (> 100 mm) due to the cold air mass brought in by the ridging anticyclone, undercutting warm tropical air in circulation from the north. Over most of the country recorded rainfall was less than the previous day.

3.5 15 February 1996

An easterly trough began to develop over the west coast as the ridging anticyclone moved away from the country to the south-east (Fig. 2e). The trough was focussed at about 25° S with a central pressure of approximately 1008 hPa. The cold front that had been prevalent for the last three days continued to move towards the north-east producing widespread instability by undercutting warm moist tropical air. The combination of moisture input from the South Indian Anticyclone and the undercutting action of the cold front together with the prevalence of upper-air divergence, served to produce widespread rains over the eastern half of the country at this time. However, recorded precipitation values exhibited a marked decrease along the east coast since the previous day. Further inland, over north-eastern South Africa, precipitation values remained fairly constant.

3.6 16 February 1996

A further southerly extension of the west coast easterly trough occurred over the following 24 hours (Fig. 2f). The cold front had moved away from the country although precipitation still persisted in its wake. Precipitation was limited for the most part to the north-eastern part of the country.

4. Model Simulation

4.1 11 February 1996

At the beginning of the simulation period, a tropical low (996 hPa) was centred at approximately 20° S and 20° E (Fig. 3a). The South Indian (1020 hPa) and South Atlantic (1017 hPa) quasi-stationary high pressures at about 30° S were positioned a little too far south, but the anticyclonic cell (1017 hPa) ridging away from the South Atlantic high pressure was identified (Fig. 3a). Westerly wave disturbances to the south-west and south-east of the country were also simulated. The model did not, however, represent the coastal low or the retreating westerly low well.

High moisture concentrations and strong uplift were evident along the Mozambique Coast ($0.021\,g \cdot kg^{-1}$) and eastern South Africa ($> 0.016\,g \cdot kg^{-1}$) throughout the day (Fig. 4). The heavy precipitation in this vicinity was apparently being fed by moisture supplied by the low level easterlies and north-easterlies around the ridging high and to the south-east of the inland tropical low. Further aloft at about the 650 hPa level, westerlies predominated over the entire country, probably supplying minimal moisture at mid-tropospheric levels (D'Abreton, 1996). However, strong uplift was facilitated by diffluent flow in the upper atmosphere.

4.2 12 February 1996

The simulated tropical low and subtropical trough strengthened slightly (Fig. 3b), as in the

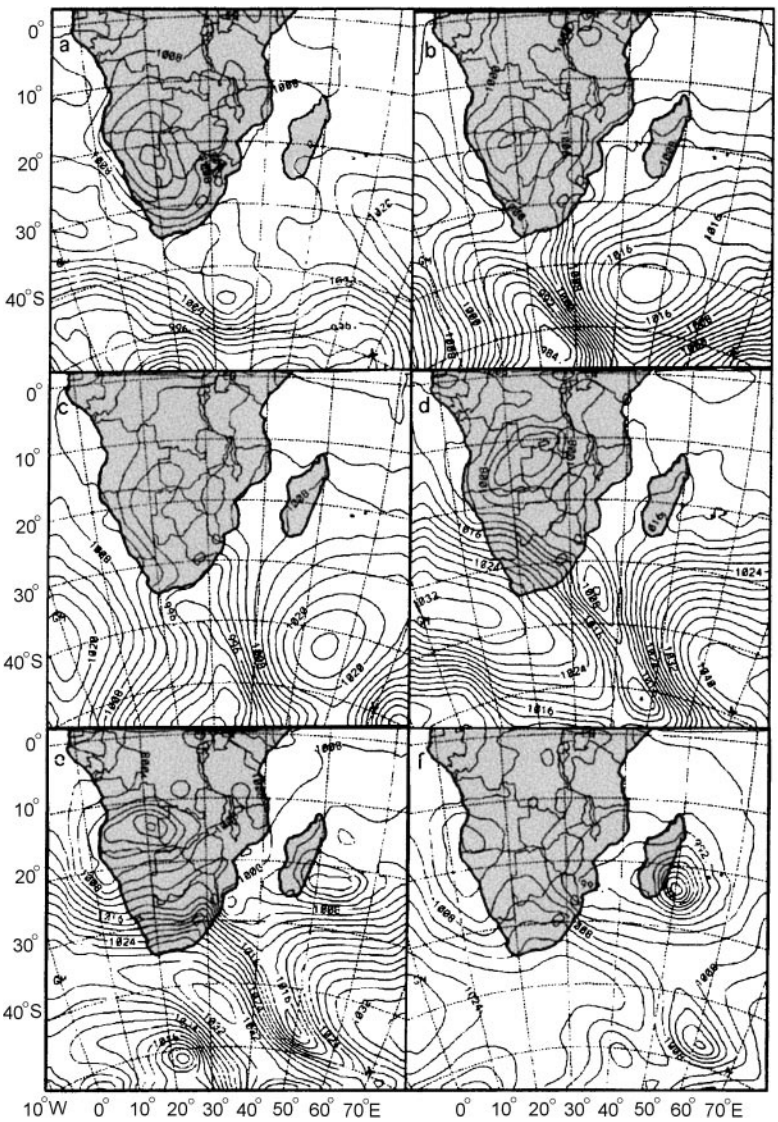

Fig. 3. Simulated sea-level pressure (hPa) at 12:00 UTC for (a) 11th, (b) 12th, (c) 13th, (d) 14th, (e) 15th and (f) 16th February 1996 by RAMS

synoptic analysis. As a result, by mid-day there was a strong near-surface poleward flow of air simulated over much of the subcontinent (with poleward components of $>16\,\mathrm{m \cdot s^{-1}}$) (Fig. 5), supplying tropical moisture to the eastern half of South Africa. Accordingly, uplift remained high along the east coast, with average near-surface values of $0.046\,\mathrm{cm \cdot s^{-1}}$ persisting since the previous day, and exceeding $0.25\,\mathrm{cm \cdot s^{-1}}$ at mid-tropospheric levels ($\sim$650 hPa). By about 21:00 UTC simulated vertical velocities at 650 hPa had increased rapidly to $0.48\,\mathrm{cm \cdot s^{-1}}$. Mixing ratios also increased in the region due to the heightened contribution from the tropics. Accumulated convective precipitation values showed continued heavy falls: maximum values of 10 mm in 9 hours simulated over the east coast of South Africa. The anticyclone to the south-east of the country appeared to remain in situ a little longer than observed, with the retreating cold front displaced to the south-east and forced further from South Africa by the sublimation of the ridging anticyclone into the South Indian Anticyclone.

The model only began to simulate the coastal low on the south coast late on the first day, but the approaching westerly disturbance was accurately simulated, with a central pressure as low as 982 hPa at 21:00 UTC. The approaching westerly disturbance produced increases in uplift through-

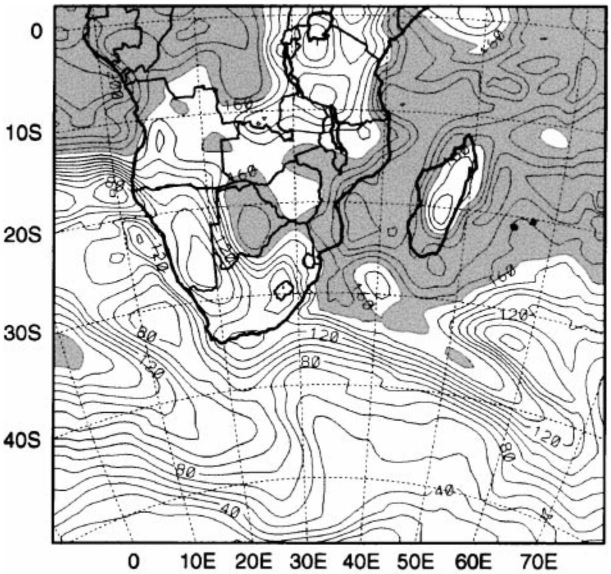

Fig. 4. Simulated near-surface (146.4 m) mixing ratios ($g \cdot kg^{-1} \times 10^3$) for 18:00 UTC, 11 February 1996 by RAMS. Areas with simulated mixing ratios of greater than 0.016 $g \cdot kg^{-1}$ are shaded

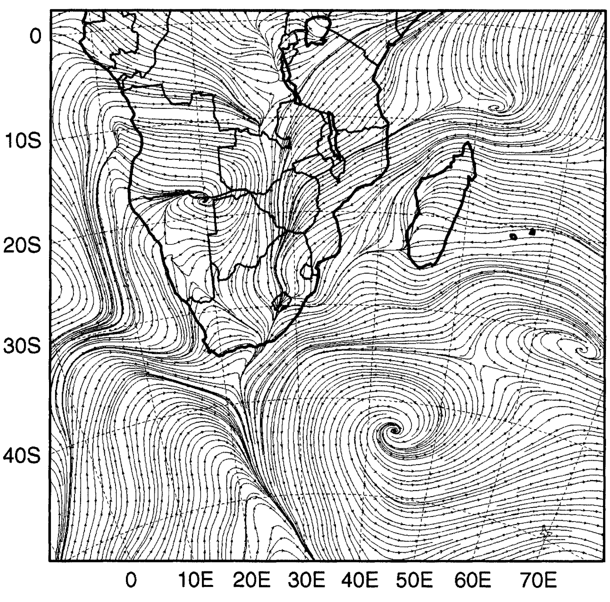

Fig. 5. Simulated near-surface (146.4 m) streamlines for 12:00 UTC, 12 February 1996

out the troposphere and in precipitation south of the country along the leading edge of the cold front.

4.3 13 February 1996

By 13 February the simulated trough of low pressure began to align itself in a north-west to south-east position (Fig. 3c), consistent with the observational data. The variations in the surface pressure field simulated by the mesoscale model indicated fluctuations in the strength of the trough of low pressure with the passage of the cold front. The simulated pressure increased from 994 hPa at 00:00 UTC to 1000 hPa at 06:00 UTC. Three hours later, the pressure began to decrease steadily to 996 hPa by 21:00 UTC. The simulated position of the coastal low over the east coast was comparable to the observational data. The South Indian Anticyclone, both simulated and observed, exhibited a strong blocking action on the departing cold front. The ridging anticyclone behind the cold front was thus forced to move at a slower rate over the near coastal regions of south-western South Africa.

As the second cold front moved over the country the near-surface westerly zonal wind-components became predominant, reaching a maximum along the south coast ($18\,m \cdot s^{-1}$). A strong gradient between the westerly and easterly *u*-components developed as the progress of the cold front was reduced by the anticyclone to the east. Strong vertical ascent was simulated along the entire west coast of Namibia, and southward along the leading edge of the cold front (Fig. 6), where precipitation increased. Maximum near-

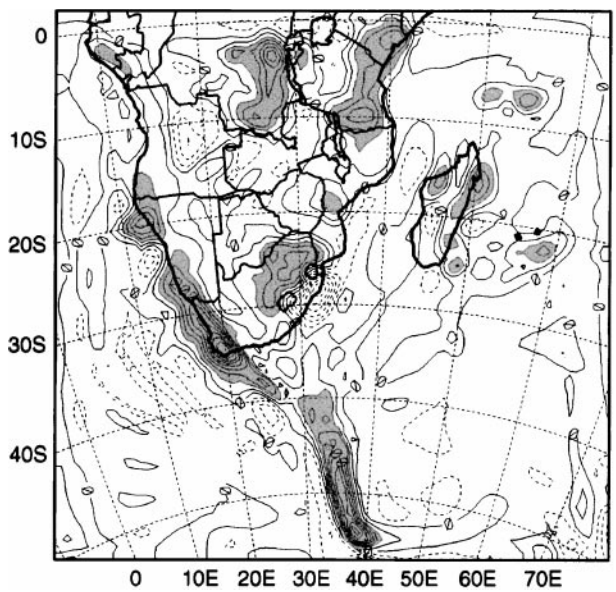

Fig. 6. Simulated near-surface (146.4 m) vertical velocities ($cm \cdot s^{-1} \times 10^2$) for 15:00 UTC, 13 February 1996. Areas with simulated vertical velocities of greater than $+0.1\,cm \cdot s^{-1}$ are shaded

surface vertical velocities of $0.045\,\mathrm{cm \cdot s^{-1}}$ were centred over the south-western part of South Africa and south of 50° S. Weaker uplift was simulated over the northern and central regions of the country ($0.020\,\mathrm{cm \cdot s^{-1}}$). The poleward flux of tropical air over the eastern part of the country remained strong, producing maximum total mixing ratio values ($0.022\,\mathrm{g \cdot kg^{-1}}$) just off the east coast. With vertical velocities in the mid-troposphere remaining high into the afternoon, simulated heavy convective precipitation persisted along the east coast, with as much as 8 mm falling in 9 hours. To the north, circulation around the tropical low appeared to strengthen with developing surface convergence.

4.4 14 February 1996

The simulated westerly low moved to a position of the east coast and began to weaken (Fig. 3d), with the central pressure increasing from 1000 hPa at 00:00 UTC to 1012 hPa by 21:00 UTC. The model simulated the position of the South Atlantic anticyclone too far over the western half of the country, but the South Indian Anticyclone remained correctly located in relation to the south-east of the country blocking the departure of the cold front. The simulated zonal pressure gradient between the departing cold front and the stationary high became pronounced during the course of the day with an approximately 32 hPa change in pressure over a longitudinal distance of 10 degrees (Fig. 3d). With the encroachment of the anticyclone from the south-west, the tropical low was displaced northward and began to weaken. The coastal low over southern Mozambique was not well-defined, but convergence into a weak tropical low began to occur over the island of Madagascar. The initiation of an easterly trough over the west coast was simulated, a little earlier than occurred in the observations.

The ridging anticyclone produced south-easterly flow over much of the country and undercut the warmer tropical air to the north. As a result, precipitation remained high over the north-eastern half of South Africa with simulated maximum values of 16 mm in 18 hours over the east coast. The pattern of vertical velocity changed quite substantially during the course of the day. Initially, vertical uplift remained pronounced along the west coast, but as the westerly disturbance advanced eastward, the region of strongest vertical uplift advanced to the southern and south-east coast ($0.099\,\mathrm{cm \cdot s^{-1}}$ and $0.077\,\mathrm{cm \cdot s^{-1}}$ respectively). As the cold front moved to the east of the country, the uncoupling of the tropical and extratropical systems became evident in the streamlines. The strength of the convergence over Angola and Zambia was enhanced as the system decoupled, with air flow becoming predominantly zonal between 10° S and 20° S.

4.5 15 February 1996

The model simulation continued to plot the slow movement of the westerly disturbance away from the country with a cell of anticyclonic circulation ridging in very close behind (Fig. 3e). The disturbance became isolated from the continent by the continued eastward extension of the ridging high. The weak low pressure simulated on 14 February over the island of Madagascar developed rapidly during the course of the day from 1008 hPa at 00:00 UTC to 990 hPa by 21:00 UTC. The developing convergence over Madagascar resulted in a westward and south-westward expansion of the westerly *u*-components from north of Madagascar, from the previous day. By 18:00 UTC the westerly component reached $12\,\mathrm{m \cdot s^{-1}}$ in the Mozambique Channel. However, the air flow over South Africa remained predominantly south-easterly due to the ridging action of the high pressure system.

Localised mixing ratio maxima were simulated in the southern Mozambique Channel ($0.021\,\mathrm{g \cdot kg^{-1}}$), and west of Namibia ($0.023\,\mathrm{g \cdot kg^{-1}}$) (Fig. 7). The moisture availability over the Indian Ocean, south of Madagascar, allowed the rapid growth of the tropical low in the region. The simulation of anomalously high mixing ratio values over the Atlantic Ocean took place due to the simulated westward movement of the tropical low. The circulation of the low facilitated the transport of moisture from a region near the equator to the Atlantic Ocean. Accumulated convective precipitation values for 15 February showed a concentration of heavy falls in the southern Mozambique Channel and south of Madagascar, where maximum falls of 24 mm in 18 hours were simulated.

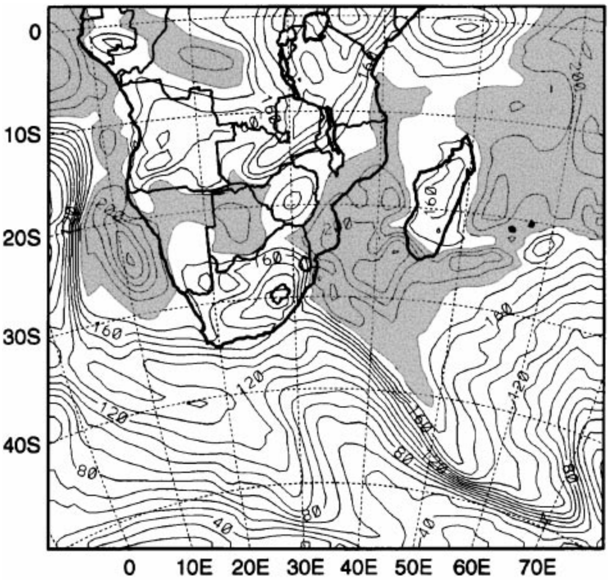

Fig. 7. Simulated near-surface (146.4 m) mixing ratios ($g \cdot kg^{-1} \times 10^3$) for 18:00 UTC, 15 February 1996 by RAMS. Areas with simulated mixing ratios of greater than $0.018\,g \cdot kg^{-1}$ are shaded

4.6 16 February 1996

The easterly trough over the west coast that had been simulated for the past two days became well-defined and showed signs of intensification (Fig. 3f), providing high vapour mixing ratio values to the region. The ridging anticyclone remained in circulation over most of the country, feeding moist air over the continent from the adjacent Indian Ocean. Simulated precipitation values therefore remained high along the east coast. Strongest precipitation occurred to the south of Madagascar, however, in association with the tropical low. This low intensified rapidly from 987 hPa at 00:00 UTC to 960 hPa at 12:00 UTC. Strong vertical ascent ($0.11\,cm \cdot s^{-1}$) was simulated and mixing ratio values intensified dramatically. The retreating westerly disturbance was positioned well to the south-east of the country (Fig. 3f).

4.7 Summary

On the whole the model simulation of the analysis period 11 to 16 February 1996 corresponded well with the synoptic and precipitation data supplied by the South African Weather Bureau. The model output showed some discrepancies in the strength and position of some of the synoptic features and an inability to simulate coastal features adequately, but the evolution of the main features was reproduced accurately.

From a simple analysis of the simulated synoptic conditions, it seems that there was a number of evolving moisture sources during the six-day period. Over the eastern part of the country, moisture was apparently supplied from tropical latitudes on the 12th and 13th, and by low-level easterlies and south-easterlies during the rest of the period. As the easterly disturbance to the north of South Africa became decoupled from the westerly disturbances to the south on the 14th, it moved slowly westward and may have diverted tropical moisture to the Atlantic coast. At the same time, the development of the tropical disturbance near Madagascar resulted in convergence of tropical moisture there from the 15th. It therefore seems unlikely that there was a large input of tropical moisture over South Africa some time after 14 February. Over the south coast and south-western part of the country, the cold fronts were responsible for some heavy rains. Details relating to the evolving moisture sources were inferred using backward trajectory analysis, as discussed in the following section.

5. Trajectory Analysis

Clusters of ten-day backward trajectories were calculated with initial points centred over the east coast (29° S, 32° E), the northern interior (23° S, 30° E), and the south-west Cape (34.5° S, 21° E). The backward trajectories were used to infer the evolution of moisture pathways over the period 11–16 February 1996. These sites were selected because significant volumes of rainfall occurred in their vicinity during the period.

5.1 East Coast

Over the east coast (29° S, 32° E), low-level flow (950–850 hPa) at first originated from the south-east. Most of the trajectory parcels had remained almost stationary near the surface over the warm Agulhas Current, although there was also some recirculation around the South Indian High onto the coast (Fig. 8). Approximately five days earlier, the air mass off the east coast formed part of the westerly flow, and was descending slowly from

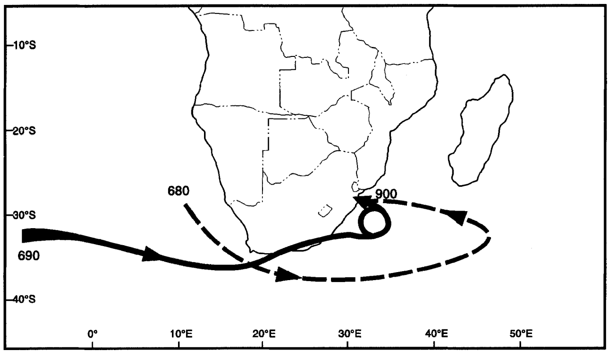

Fig. 8. Schematic diagram showing the main (solid) and secondary (dashed) pathways of ten-day backward trajectory clusters from a point centred over the east coast (29° S, 32° E). The trajectories were initiated at 12:00 UTC on 11 February 1996 at 900 hPa. The numbers indicate the approximate starting and ending altitudes in hPa

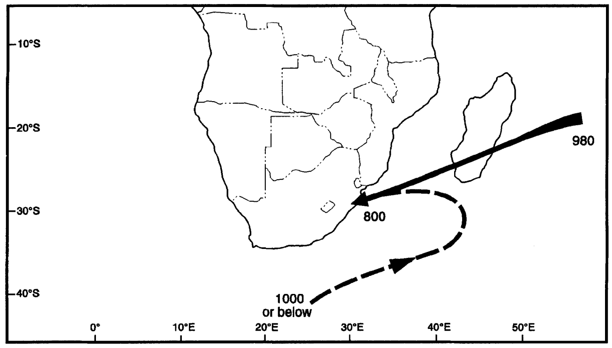

Fig. 9. Schematic diagram showing the main (solid) and secondary (dashed) pathways of ten-day backward trajectory clusters from a point centred over the east coast (29° S, 32° E). The trajectories were initiated at 12:00 UTC on 14 February 1996 at 800 hPa. The numbers indicate the approximate starting and ending altitudes in hPa

above 700 hPa. Above about 700 hPa, the backward trajectories exhibited a strong westerly pattern directly over the continent from the Atlantic Ocean. Presumably the low-level flow from over the south-west Indian Ocean had had time to evaporate sufficient moisture from the underlying ocean, which supplied the moisture for the east coast.

Trajectories run from 12 February highlight the strong influence of the ridging anticyclone on the lower atmospheric levels below 850 hPa. The trajectory parcels reaching the east coast had again originated in the westerlies, but at levels below 850 hPa. They followed a pathway directly northward over the three days up to 12 February, due to the proximity of the ridging anticyclone and the passage of a cold front. Above 850 hPa the westerly flow once again predominated, although at levels higher than about 600 hPa evidence of continental recirculation existed: the air had originated from over Botswana and Namibia (Tyson, 1997; Tyson and D'Abreton, 1998). A similar pattern persisted on 13 February, whereby low-level inflow was again originally from the westerlies, recurving over the warm south-west Indian Ocean and reaching the east coast from the south and south-east. Above 800 hPa, westerly flow remained dominant, and it was only above about 600 hPa that there was evidence of a tropical origin.

By 14 February the origin of low-level air converging over the east coast began to change. Although at near-surface pressure levels (below about 900 hPa) the predominant westerly flow into the Indian Ocean with characteristic south-easterly recurve onto the east coast still predominated, there was some evidence for input from the east of Madagascar. Between the 850 and 700 hPa levels, this easterly flow onto the east coast was the dominant trajectory pathway (Fig. 9). Above 700 hPa the continental recirculation was again evident up to about 550 hPa, above which ascending easterly flow would have provided a source of mid-tropospheric moisture. On 15 February the near-surface easterlies originating from east of Madagascar became the main source due to the passage and proximity of a cold front and because of the influence of the South Indian Anticyclone. The easterlies extended up to at least the 500 hPa level. Low-level easterly inflow around the large ridging anticyclone located to the south-east continued to occur on 16 February. Above the 800 hPa level, however, recurved westerly flow became evident, but the ascending easterly flow persisted above 550 hPa.

5.2 Northern Interior

For the northern interior (23° S, 30° E), the predominant influence on the trajectory pathways for 11 February was the proximity of the ridging high pressure system east of South Africa and its passage over the previous days. Low-level flow (below 800 hPa) reaching the northern interior on the 11th originated over the southern Indian

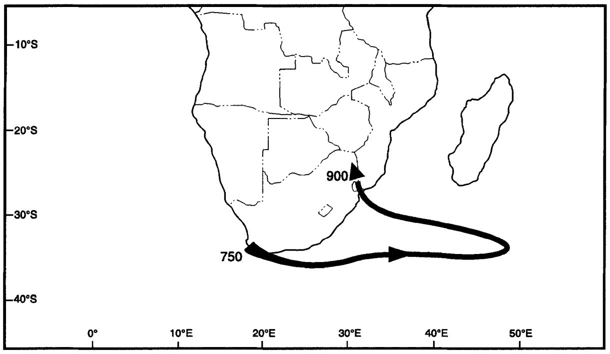

Fig. 10. Schematic diagram showing the main pathway of ten-day backward trajectory clusters from a point centred over the northern interior (23° S, 30° E). The trajectories were initiated at 12:00 UTC on 12 February 1996 at 900 hPa. The numbers indicate the approximate starting and ending altitudes in hPa

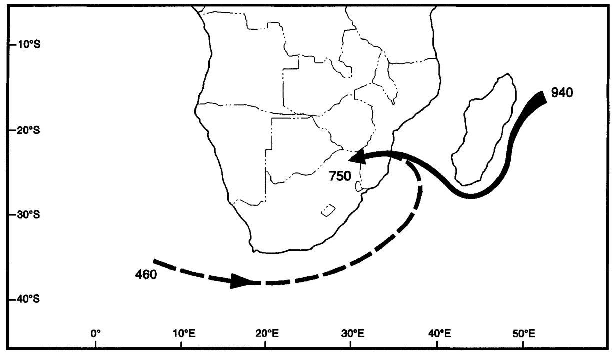

Fig. 11. Schematic diagram showing the main (solid) and secondary (dashed) pathways of ten-day backward trajectory clusters from a point centred over the northern interior (23° S, 30° E). The trajectories were initiated at 12:00 UTC on 14 February 1996 at 750 hPa. The numbers indicate the approximate starting and ending altitudes in hPa

Ocean and not over the Atlantic Ocean as for the east coast. Between the 800 and 700 hPa levels, continental recirculation predominated. Above 700 hPa localised recirculation occurred above the northern interior.

On 12 February the near-surface pattern remained relatively unchanged from the previous day with the main trajectory pathways showing recirculation of the westerlies over the Indian Ocean around the succession of ridging anticyclones (Fig. 10). This pattern was prevalent below the 750 hPa pressure level with a greater westerly component with increasing altitude. Between 750 and 650 hPa the trajectory pathways were almost entirely continental with strong localised recirculation over many parts of South Africa. Above the 650 hPa level the trajectories followed a westerly pathway directly over the continent. The inflow of air on the 13th was very similar to the previous day: low-level air originated from ocean areas to the south-east, while higher up, westerly flow became evident.

As over the east coast, by 14 February the origin of air converging over the northern interior became the area to the east of Madagascar. Below 850 hPa the inflow was mainly from the south-east, but between 850 and 700 hPa ascending air from the east was predominant (Fig. 11). Ascending tropical air also occurred above 600 hPa, originating from the continental interior. The ascending easterly and south-easterly flow persisted on 15 and 16 February below the 650 hPa level. Above 700 hPa, some descending westerly flow was apparent. This convergence of descending westerly and ascending easterly flows producing heavy rainfall over the country is consistent with the results of D'Abreton and Tyson (1996).

5.3 South-west Cape

Over the south-west Cape (34.5° S, 21° E), near-surface trajectory pathways for 11 February indicate localised recirculation over the western half of South Africa with limited westerly input (Fig. 12). Between the 850 and the 700 hPa pressure levels, easterlies dominated the overall

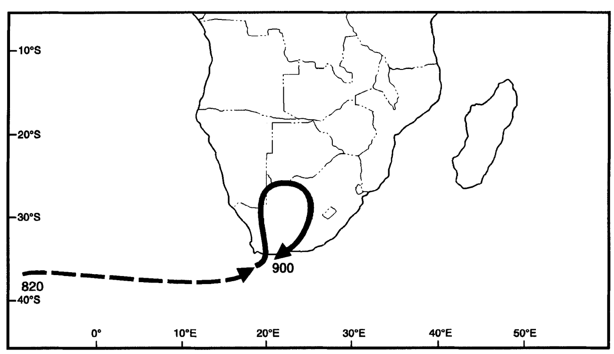

Fig. 12. Schematic diagram showing the main (solid) and secondary (dashed) pathways of ten-day backward trajectory clusters from a point centred over the south-west Cape (34.5° S, 21° E). The trajectories were initiated at 12:00 UTC on 11 February 1996 at 900 hPa. The numbers indicate the approximate starting and ending altitudes in hPa

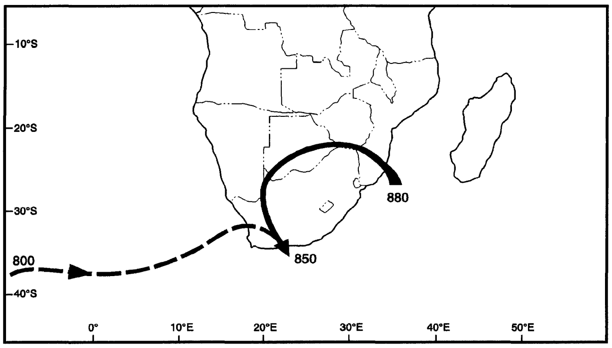

Fig. 13. Schematic diagram showing the main (solid) and secondary (dashed) pathways of ten-day backward trajectory clusters from a point centred over the south-west Cape (34.5° S, 21° E). The trajectories were initiated at 12:00 UTC on 13 February 1996 at 850 hPa. The numbers indicate the approximate starting and ending altitudes in hPa

pattern of air flow into the region. The trajectories between these pressure surfaces travelled at a constant level, with limited vertical ascent or descent. Above 700 hPa, air flow was exclusively from the west, again with limited vertical motion. This pattern of air flow was broadly similar on 12 February, although the near-surface flow was more distinctly westerly than on the previous day, and the easterly inflow below 700 hPa was less dominant. The easterly mid-level inflow (between 850 and 700 hPa) was re-established on 13 February, this time recirculating from the north and east (Fig. 13). Vertical motion in this flow was weak, but undercutting by the near-surface flow from the west resulted in frontal rain. Above 700 hPa, westerly inflow predominated. On 14 February, the easterly mid-level flow that had provided much of the moisture for the rainfall over the south-west Cape started to become less dominant. By the 15th, the westerlies were prevalent throughout the atmospheric column, and this pattern persisted into the following day.

5.4 Discussion

On 11 February 1996, the departing cold front and ridging anticyclone produced an import of warm, moist air over the eastern part of the country from the south-west Indian Ocean. On penetrating the interior the onshore flow became entrained in the flow pattern of the developing tropical low pressure system over Botswana. Above the near-surface, however, strong westerly *u*-components predominated over the country. This relatively cold, dry air aloft together with the warm, moist near-surface inflow would have been responsible for the strong instability along the east coast. Uplift of the near-surface layer, and the release of instability, was initiated by the topographic effects of the air moving inland, and was propagated by diffluent flow in the upper atmosphere.

The tropical low situated over Botswana strengthened on 12 February and a subtropical trough linked the system with a westerly disturbance to the south of the country. Despite the resulting poleward flow, the source of low-level moisture was ultimately from the south-east. The inland low provided the pressure gradient to maintain the convergence of air and moisture over the land, resulting in persisted heavy rainfall over the eastern part of South Africa. Westerlies in the mid-troposphere and diffluent flow aloft continued to provide sources of instability, although some evidence of mid-tropospheric tropical air was identified and would have provided additional moisture.

On 13 February 1996 the synoptic circulation pattern showed the landfall of the cold front approaching from the south-west. The front provided heavy rainfall to the south-western part of the country, which usually receives rainfall only in winter. The cold descending westerly air in the rear of the front undercut easterlies in the mid-troposphere that had imported moisture from the Indian Ocean. Convergence of moisture into coastal low on the 13th and 14th provided the continued heavy rains over the eastern part of the country. Moisture was now being supplied from areas directly to the east, rather than the south-east.

By 14 February 1996 the cold front had moved over the eastern half of the country with a ridging high developing behind. The tropical low pressure and cold front decoupled, resulting in a reduction in vertical ascent along the cloud band. Heavy precipitation was now limited to the eastern coastal regions. Over the eastern part of the country, mid- to low-level moisture was supplied from east of Madagascar by the South Indian Anticyclone. This moisture source persisted over the next two days, providing heavy rains to the eastern half of the country.

6. Conclusions

The combination of mesoscale numerical modelling and trajectory analysis of the extreme rainfall period from 11 to 16 February 1996 over South Africa has proved a useful tool in the analysis of both mesoscale atmospheric circulation and the identification of important moisture pathways. The general circulation for the period 11 to 16 February is well modelled with the RAMS regional scale numerical model and creates a three-dimensional perspective not available before. The trajectory model provides a useful depiction of parcel transport, giving an indication of possible moisture sources throughout the analysis period.

Initially, the moisture source for the event was the south-west Indian Ocean. Recurved westerlies to the south of the country were forced over the warm Agulhas Current inland by a ridging anticyclone and a tropical low over Botswana. Uplift was forced by topography and was facilitated by strong instability caused by cold westerlies in the mid-troposphere and diffluent flow in the upper-troposphere. The easterly supply of moisture became increasingly dominant after 14th February when most moisture originated from north of 30° S. The streamlines calculated by the RAMS model suggested that tropical moisture was an important source on 12th and 13th February when the tropical low over Botswana was coupled with a westerly disturbance to the south. The trajectory analysis, however, suggests that the snapshot image provided by the streamlines is misleading; there is a lag of one or two days before the tropical moisture reaches South Africa. Of particular interest is the absence of a significant moisture supply from tropical areas to the north, or from the equatorial Indian Ocean. Presumably the development of the west coast trough and the tropical low over Madagascar diverted the tropical moisture away from the country. Apparently, given favourable synoptic conditions, significant rainfall events can occur over South Africa with moisture supplied from the subtropical latitudes of the Indian Ocean. The commonly held premise that atmospheric moisture is predominantly derived from the equatorial Indian Ocean during extreme rainfall events over South Africa appears to be inaccurate. For the duration of the event of 11–16 February 1996, the subtropical Indian Ocean to the south and east of Madagascar provided moisture for the continued genesis of precipitation. Research of this nature must continue in order to determine if moisture sources for rainfall over South Africa are event-specific or indeed are derived predominantly from the equatorial Indian Ocean.

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