# HEAVY PRECIPITATION AND FLOODING ON 12-14 FEBRUARY 1996 OVER THE SUMMER RAINFALL REGIONS OF SOUTH AFRICA: SYNOPTIC AND ISENTROPIC ANALYSES

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### *Abstract*

*Heavy precipitation and deadly flooding occurred on 12-14 February 1996 over the northeastern parts of South Africa. A persistent tropical moist conveyor belt supplied ample moisture and a deep layer of conditional instability favorable for heavy precipitation. The three-day heavy precipitation event occurred in several episodes. Rainfall on the 12th was due to deep convection triggered by a minor short-wave trough in the mid-latitude westerlies passing east-southeastward across the country. On the 13th, deep convection again occurred within the moist conveyor belt, triggered by enhanced moist, northerly flow resulting from an approaching mesoscale convective vortex (MCV). Much of the precipitation fell on upwind slopes, suggesting that orographic lift helped initiate the convection. Heavy precipitation on the 14th, in contrast, was not the result of deep convection within the moist tropical plume, but rather from lifting of the west edge of the moist plume over a cold front. Isentropic charts, derived from the output of the South African Eta numerical weather prediction model, depicted these key synoptic features very well. This case illustrates the advantages of using several tools such as observations, numerical model guidance on pressure and isentropic surfaces and satellite imagery — to identify the crucial factors in forecasting heavy rain events in South Africa. Because South Africa is located in a data-sparse region of complex terrain, the use of all available tools, including conceptual models of mesoscale weather systems, is the key to improved weather forecasting.*

## 1. Introduction

The summer rainfall regions of South Africa, generally encompassing the northeastern parts of the country (see Fig. 1 for orientation), receive approximately thirty percent of their annual rainfall during January and February. However, northeastern South Africa experienced one of its all-time wettest summers during the time period of December 1995 to February 1996. Most of the eastern parts of the country received 200% of the normal rainfall for the month of February. These widespread heavy rainfalls led to major flooding, exacerbated by localized flash flooding from intense convection. For the first time since 1988 the Vaal Dam, one of the largest dams in the country (point C in Fig. 1c), overflowed in February 1996. This is an even more remarkable event considering that its reservoir was only at 16% of capacity in September 1995.

One of the significant rainfall and flooding events occurred between 8 - 16 February 1996. The most intense rains fell during the period 12 - 14 February. Figure 1c shows locations of heaviest rainfall (provided by the South African Weather Bureau) and flooding, as referred in the text below.

On 12 February 1996, 119 mm of rain fell at Dendron in the Northern Province (point 1, Fig. 1c). Kleinwater (Mpumalanga) reported 138 mm (point 2, Fig. 1c), and the highest 24-hour total for the day was 149 mm at Vonda (Northern Province; point 3, Fig. 1c). On 13 February 1996, 160 mm was reported at Spelonken (Northern Province; point 4, Fig. 1c). Wilgeboom (Mpumalanga; point 5, Fig. 1c) reported 166 mm and the highest 24-hour total was 275 mm at Zwartrandjes in the Northern Province (point 6, Fig. 1c). Flash floods occurred in Marapyane (point A, Fig. 1c), where 3,000 people were left homeless. Flash floods were also reported at KwaNyamazane (Mpumalanga; point B, Fig. 1c) where the only two access bridges were washed away, leaving 200 houses completely cut off. On 14 February 1996, Johannesburg (Gauteng; point 7, Fig. 1c) reported 93 mm of rain, while 94 mm of rain fell at Umzinto in KwaZulu/Natal (point 8, Fig. 1c). The highest 24-hour total was 183 mm reported at Newark in KwaZulu/Natal (point 9, Fig. 1c). Nineteen people were reported missing as rivers burst their banks, dams overflowed and bridges were swept away in many areas of the latter province.

Rainfall totals for the three days exceeded 150 mm at several locations in the Northern Province, Mpumalanga, Gauteng and KwaZulu/Natal. These are listed in Table 1. The highest three-day total was 394 mm at Zwartrandjes in the Northern Province.

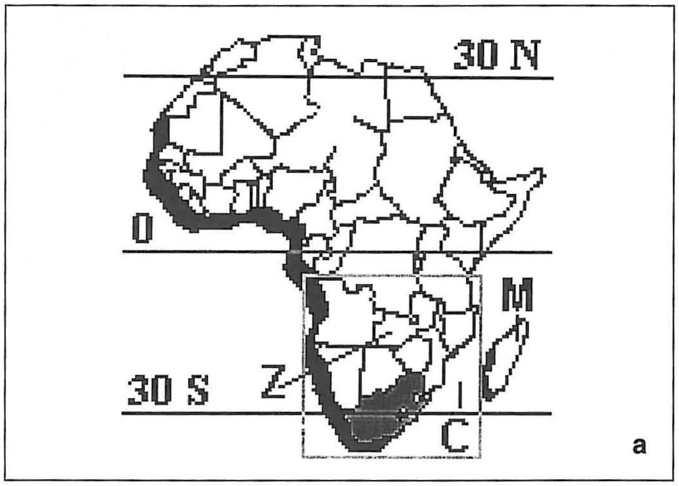


**Fig. 1a.** Geography of southern Africa. South Africa (shaded) is the southern most country on the continent. Other locations referred to in the text are Zambia (Z), Madagascar (M) and the Mozambique Channel (C).

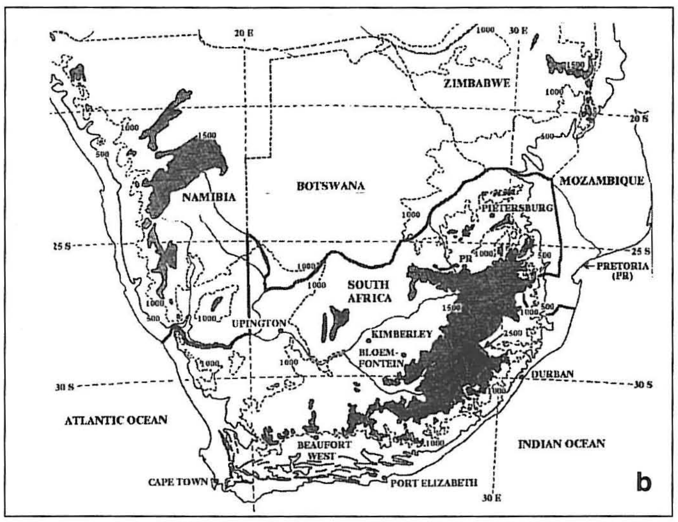


**Fig. 1b.** Relief map of southern Africa. Height contours are at 500, 1000, 1500 (lightly shaded) and 2500 m (heavily shaded).

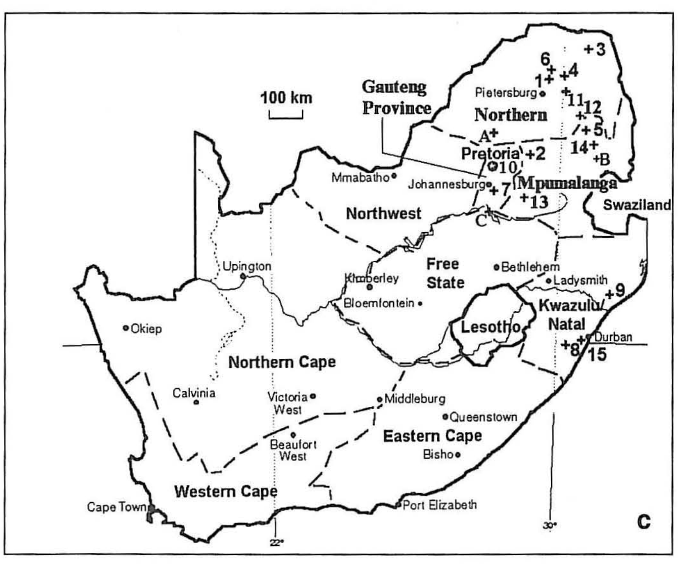


**Fig. 1c.** South Africa provinces, selected cities (dots), and locations in the northeast with heavy rain or flooding referenced in the text are indicated by + symbol and number or letter.

**Table 1. Three-day rainfall totals exceeding 150 mm, 12-14 February 1996.**

| Province (location) | 3-day rainfall total | points in Fig. 1c |
|---|---|---|
| Gauteng (Pretoria Zoological Gardens) | 266 mm | 10 |
| Northern Province (Tzaneen) | 171 mm | 11 |
| Northern Province (Zwartrandjes) | 394 mm | 6 |
| Northern Province (Spelonken) | 193 mm | 4 |
| Northern Province (Vonda) | 247 mm | 3 |
| Northern Province (Metz) | 178 mm | 12 |
| Mpumalanga (Delmas) | 155 mm | 13 |
| Mpumalanga (Pilgrimsrest) | 267 mm | 14 |
| Kwazulu/Natal (Newark) | 183 mm | 9 |
| Kwazulu/Natal (Durban) | 150 mm | 15 |

Several earlier studies (Triegaardt et al. 1991; Taljaard 1985) have revealed that extreme rainfall events in South Africa develop when weather systems originating in the tropical easterlies migrate south and interact with systems from the mid-latitude westerlies during the summer months. These tropical weather systems occur every summer between January and February although their intensities and durations vary. The interaction can lead to the development of a characteristic cloud pattern (such as that in Fig. 2a), described by Harrison (1986) as a tropical-temperate-trough. This type of interaction took place from 12-14 February 1996.

Tropical low-pressure systems or troughs are characteristic of the zone along 15°S extending across southern Africa between November and March (Torrance 1979; Taljaard 1972). They indicate the location of a branch of the Intertropical Convergence Zone (ITCZ). In the Southern Hemisphere summer, the ITCZ for Africa is located over northern Madagascar (M in Fig. 1a), the northern Mozambique channel (C in Fig. 1a) and then inland into Zambia (Z in Fig. 1a), where it turns northward (Taljaard 1981).

South Africa came under the influence of intense and extensive tropical troughs and lows during the summer of 1995-96. Where mid-latitude, upper-level baroclinic systems interacted with moist plumes extending southward from these tropical systems, heavy rains and flooding developed.

In this study the synoptic-scale setting for the heavy rainfall events will be discussed using satellite imagery, surface and upper-air analyses, and output fields from the South African Weather Bureau Eta model (Mesinger et al. 1988). In addition to traditional displays on pressure levels, analyses of Eta model output on isentropic surfaces (section 4) are introduced. This forecasting tool has recently been implemented at the South African Weather Bureau. Several isentropic fields will be presented to show how they can be valuable tools for forecasting the synoptic-scale setting for South African heavy rainfall events. The purpose of this paper is to show that, for a relatively data-sparse location such as South Africa, extracting clues from a variety of observations and numerical model output fields is critical to improving the understanding and forecasting of heavy rain events.

## 2. Procedures

Isentropic analyses are generated from the South African Weather Bureau Eta model output. The current version of the model has a 80 km horizontal resolution and 38 levels in the vertical. Model output is interpolated from the Eta-coordinate vertical levels to constant potential temperature surfaces. Output data from the 0000 UTC run are used to calculate a variety of variables on isentropic surfaces, including: pressure, condensation pressure difference (or saturation deficit, defined as the number of hPa of lift needed to saturate the air), adiabatic vertical velocity, and moisture flux convergence.

Since much of the analysis in this study is based upon output from the South African Eta model, a brief assessment of the Eta model's performance during the period 12 - 14 February is given here. The Eta model's mean sea level pressure and 500 hPa height fields were compared with the observed data. In general, the Eta model simulated the heavy rainfall event well. The 12-hour accumulated rainfall compared favorably with the observed rainfall distribution and timing. Not surprisingly, however, predicted rainfall amounts generally were less than the reported figures. The aerial distribution of rainfall was forecasted well, but areas of light rainfall (less than 10 mm) were not always predicted by the model.

The areas of high model relative humidities at 850, 700 and 500 hPa relate well to the locations of cloud bands in satellite imagery and to the areas experiencing precipitation. On the other hand, Showalter indices computed from the Eta output indicated more stable atmospheric conditions than those from the upper-air soundings. An upper-level, tropical low-pressure system, present on 12 February, was not very well described by the Eta model upper-air forecasts, but the westerly system which dominated the period thereafter was analyzed and forecasted very well.

## 3. Synoptic-Scale Sequence of Events

Figure 2 is a sequence of satellite images showing the overall evolution of the cloud patterns during the period of the 12-14 February flood-producing rains. Quite evident in this sequence of images are two cloud bands. The northernmost band is a subtropical moist conveyor belt (Carlson 1991) — a moist plume associated with air of tropical origin. This moist conveyor belt is similar to those in the United States described by McGuirk and Ulsh (1990). In this case, the moist plume is embedded in northerly flow at most levels, and its southern edge lies near the confluence of the subtropical northerlies with the base (north edge) of the mid-latitude westerly airstream. The southern cloud band evident in Fig. 2 is affiliated with a mid-latitude trough and frontal system, as seen in the time lapse sequence of satellite pho-

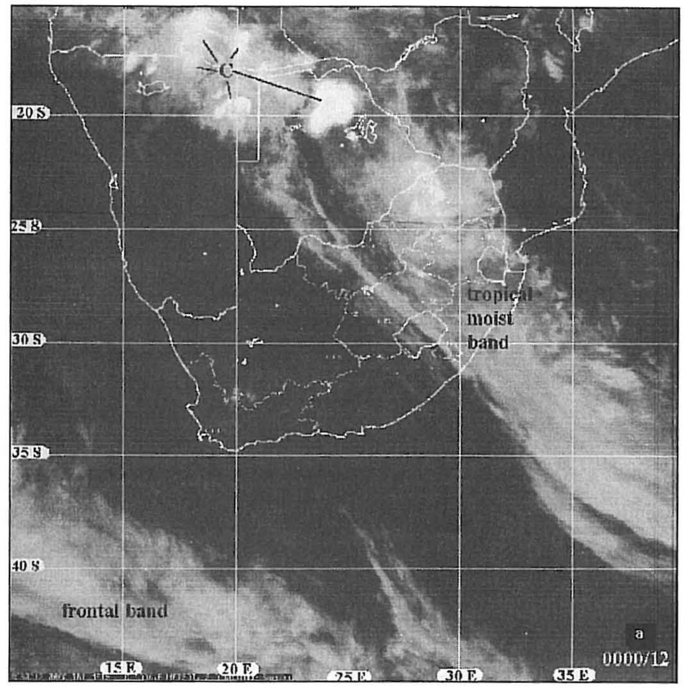


**Fig. 2a.** Infrared (IR) imagery from the geostationary European Meteorological Satellite (EUMETSAT) at 0000 UTC 12 February 1996.

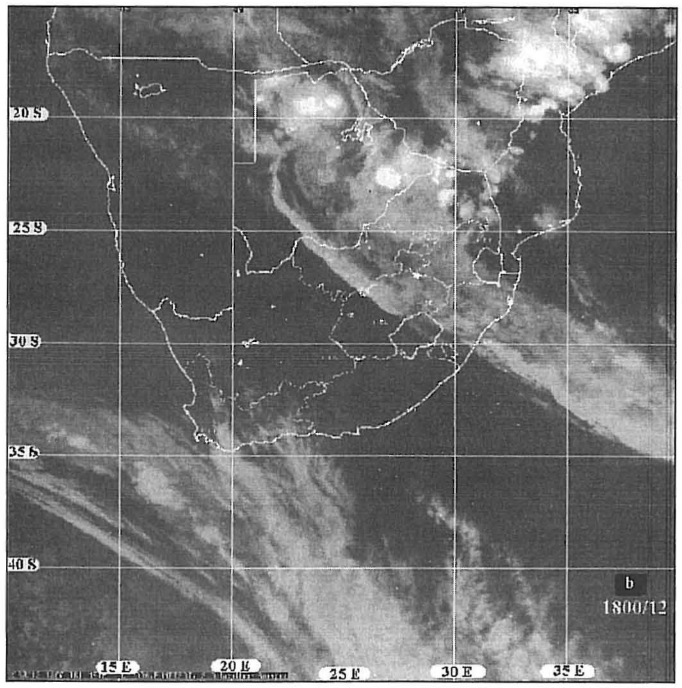


**Fig. 2b.** IR EUMETSAT imagery at 1800 UTC 12 February 1996.

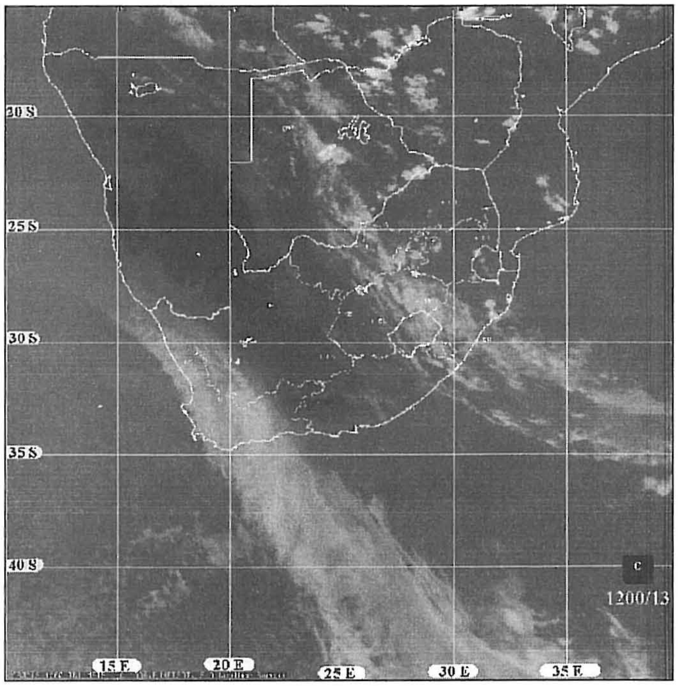


Fig. 2c. IR EUMETSAT at 1200 UTC 13 February 1996.

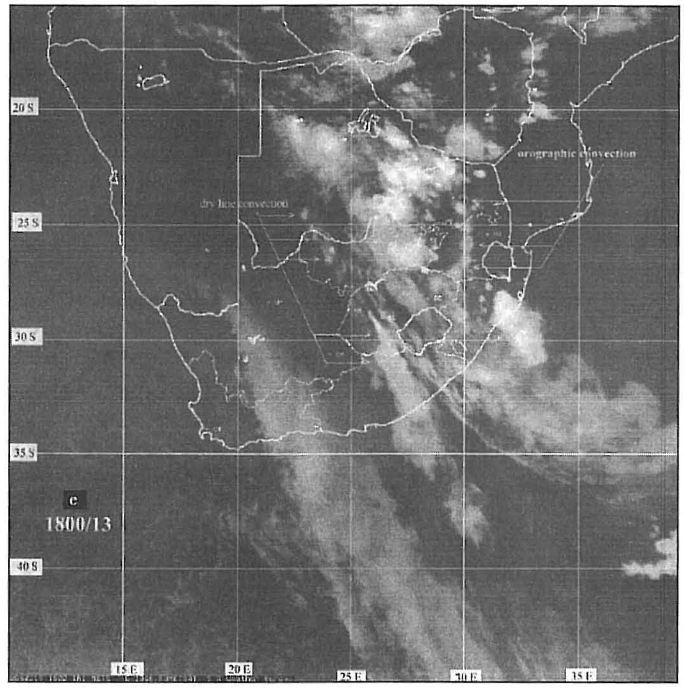


Fig. 2e. IR EUMETSAT imagery at 1800 UTC 13 February 1996.

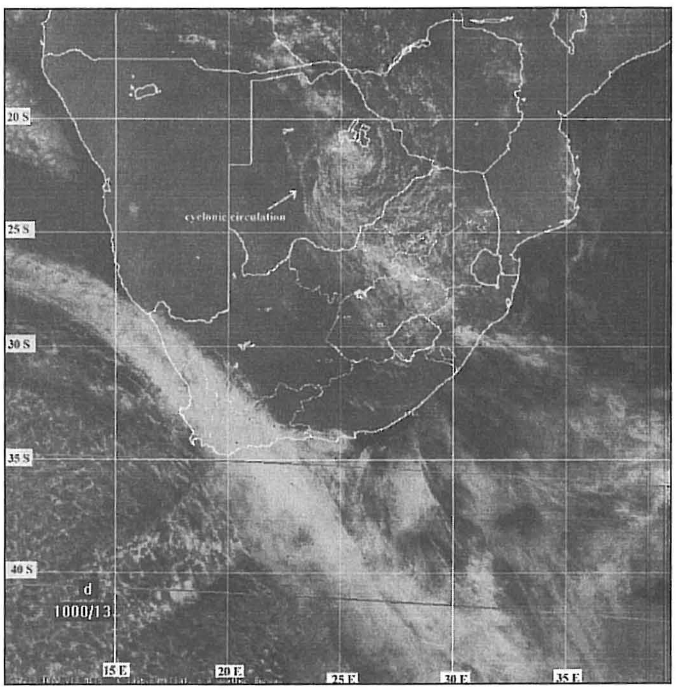


Fig. 2d. Visual (VIS) EUMETSAT imagery at 1000 UTC 13 February 1996.

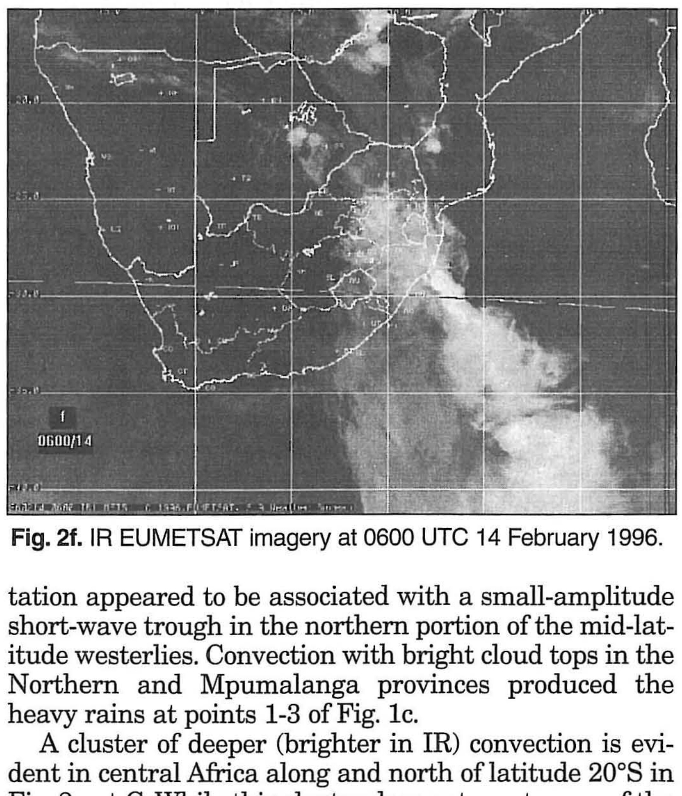


Fig. 2f. IR EUMETSAT imagery at 0600 UTC 14 February 1996.

tographs. The trough and frontal system moved northeastward during the period. Figure 3 is a schematic diagram showing conceptual models of the conveyor belts in Southern Hemisphere weather systems.

The precipitation during the 12-14 February period occurred in several episodes. Clouds associated with one such episode, already underway at 0000 UTC (0700 LST) on 12 February are shown in Fig. 2a. An area of widespread precipitation and embedded convective elements is present within the subtropical moist conveyor belt over northeastern South Africa, near 24°S, 28°E. This precipitation appeared to be associated with a small-amplitude short-wave trough in the northern portion of the mid-latitude westerlies. Convection with bright cloud tops in the Northern and Mpumalanga provinces produced the heavy rains at points 1-3 of Fig. 1c.

A cluster of deeper (brighter in IR) convection is evident in central Africa along and north of latitude 20°S in Fig. 2a at C. While this cluster does not meet some of the criteria for a mesoscale convective complex (MCC; e.g., Maddox 1980), MCC's are not uncommon in Africa (Laing and Fritsch 1993). The evolution of this mesoscale convective system (MCS) during the next 24 hours is of considerable interest in terms of the potential for impacting South Africa's weather on 13 February. Unfortunately, this convective system appeared initially in a data-sparse area, limiting the quantitative analysis of its meteorological features. This MCS appears to be part of a larger-scale subtropical trough which drifts slowly eastward

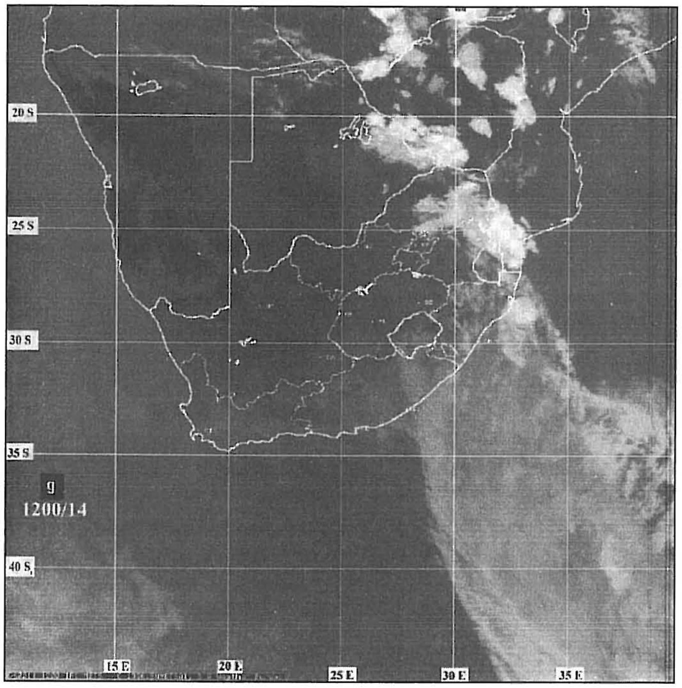


**Fig. 2g.** IR EUMETSAT imagery at 1200 UTC 14 February 1996.

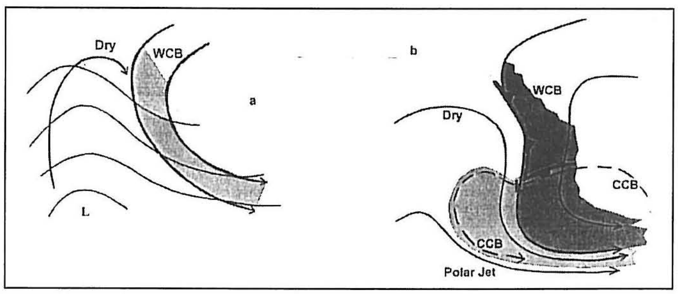


**Fig. 3.** Schematic diagrams of synoptic scale features in the Southern Hemisphere as depicted by relative isentropic streamlines: (a) Warm conveyor belt (WCB) and (b) Cold conveyor belts (CCB) and WCB associated with a mature cyclone. Adapted from Carlson (1980, 1991).

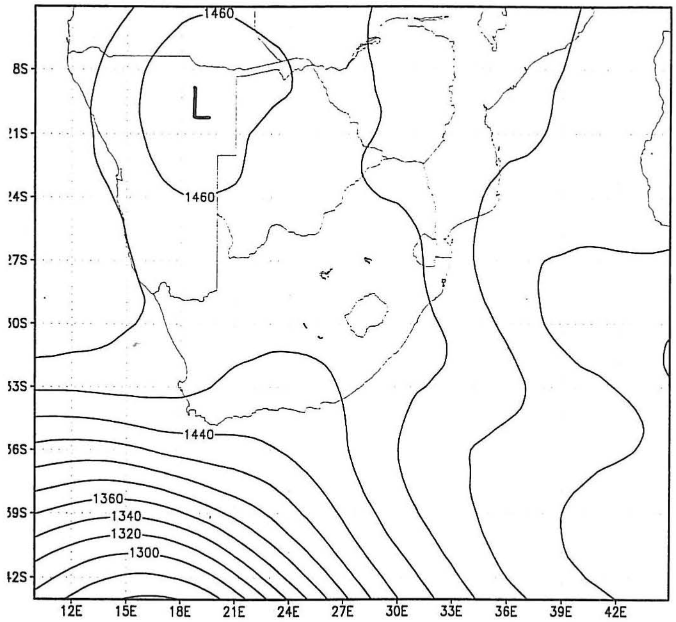


**Fig. 4a.** 850 hPa height analysis of 12-h Eta model predictions valid for 1200 UTC 12 February 1996.

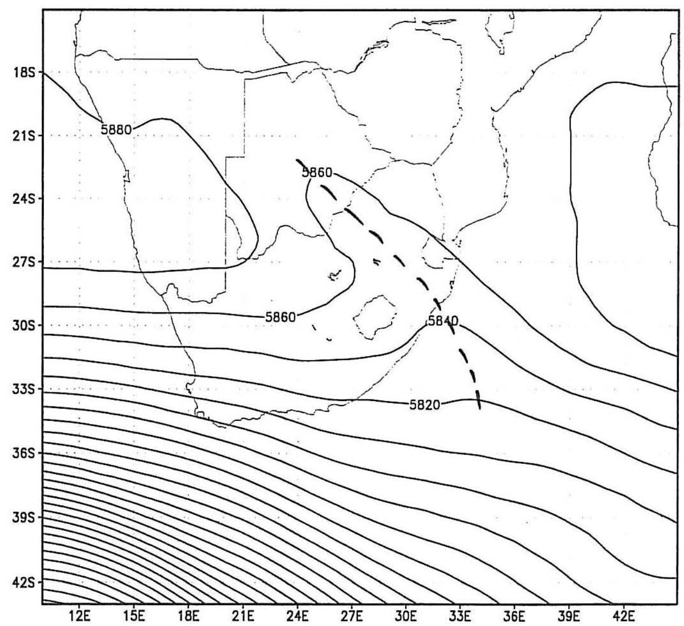


**Fig. 4b.** 500 hPa height analysis of 12-h Eta model predictions valid for 1200 UTC 12 February 1996.

throughout the period. Most of the nocturnal convective activity in cluster C, Fig. 2a, died out during the daytime on the 12th, a characteristic common to many United States MCSs (e.g., Maddox 1980). Similarly, the convection redeveloped on the evening of the 12th (Fig. 2b).

Figure 4 shows 12-h Eta model forecasts of the large-scale at 850 (Fig. 4a) and 500 hPa (Fig. 4b) geopotential height fields at 1200 UTC. The 850 hPa chart (Fig. 4a) depicts a subtropical low over Botswana and Namibia (for locations see Fig. 1b). To the east of this low, moist tropical air was flowing southward over the central parts of the country. Pretoria's precipitable water (derived from the upper-air sounding) at this time was 34 mm or 129% of normal. The synoptic conditions together with the available moisture were setting the stage for the heavy convective rainfalls over South Africa on the 12th (see Fig. 1c). Normal values for precipitable water were computed by Louw (1983).

The 500 hPa pattern shows a mid-latitude trough over the Atlantic ocean still approaching the country (to the SW of Fig. 4b), which subsequently moved northeastward over the next 48 hours. Figure 4b shows a minor short-wave trough of mid-latitude origin over the southeastern part of the country. The vertical motion east of the trough axis triggered the convective episode on the 12th. The development of this convection can be seen in Fig. 2b.

By 1200 UTC on 13 February (Fig. 2c), most of the deep nocturnal convection within the moist tropical plume again died out during the daytime. In the visible imagery, however, such as at 1000 UTC in Fig. 2d, a cyclonic (clockwise in the Southern Hemisphere) circulation in the cloud bands is visible in the shallow convective cloud street pattern near 27°S, 26°E. This cyclonic circulation is similar to a mesoscale convective vortex (MCV)

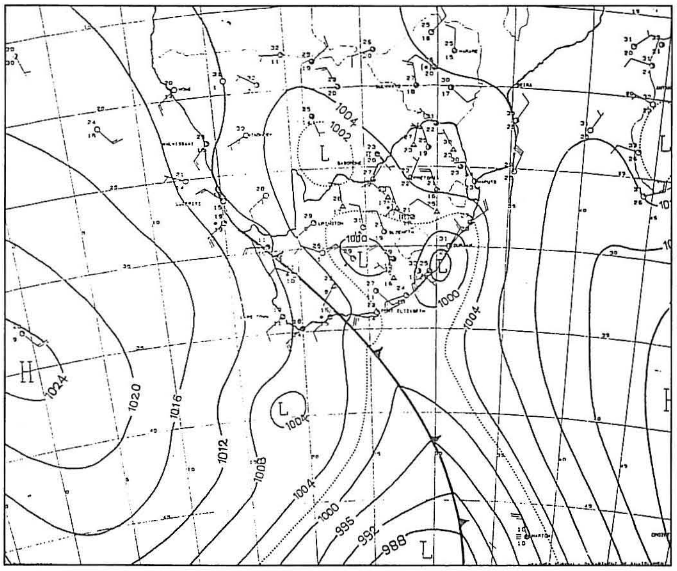


**Fig. 5.** SAWB official surface analysis map valid 1200 UTC 13 February 1996.

that has been reported in the United States by various researchers (e.g., Johnston 1982; Zhang and Fritsch 1988; Menard and Fritsch 1989; Johnson and Bartels 1992). These researchers have documented that the MCV develops in association with a mesoscale convective system and can persist even after the dissipation of the deep convection in the MCS. Upward motion and low-level convergence associated with the MCV can contribute to the formation of subsequent thunderstorms.

The MCV in Fig. 2d played an important part in the development of the heavy precipitation on the 13th. The origin of this MCV can be traced back to the MCS labelled C in Fig. 2a. It has slowly drifted southeastward during the intervening 36 hours, while undergoing diurnal modulation in intensity. The cyclonic circulation around the MCV can be seen on the surface map of February 13th (Fig. 5), east of the analyzed low-pressure center (which could have been positioned more accurately through better use of satellite imagery). Also visible on Fig. 5 is the northerly and northeasterly flow ahead of the MCV enhanced advection of moist tropical air into South Africa.

Figure 6a depicts the 850 hPa height field at 1200 UTC 13 February, using 12-h forecasts from the Eta model. The subtropical low-pressure system is still present over Namibia and Botswana and has intensified somewhat. It thus maintained the southward flow of moisture crucial for development of deep convection on the 13th. A cold front, associated with the trough on the south coast, has passed over southwestern South Africa bringing colder weather and rain to the southern interior.

Thermodynamic analyses of the upper-air sounding (not shown) indicate that precipitable water for Pretoria was 34 mm (129% of normal) at this time and Showalter indices (e.g., Showalter 1953; Preston-Whyte and Tyson 1988) indicate greater instability over the eastern interior of South Africa than on the previous day. This is partly the result of the MCV-related moisture advection. At 500 hPa (Fig. 6b) a weak perturbation is present over the

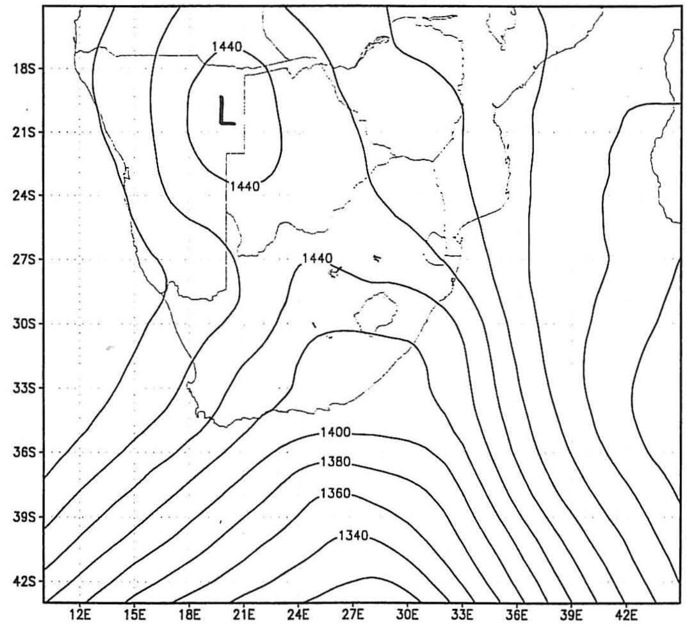


**Fig. 6a.** 850 hPa height analysis of 12-h Eta model predictions valid for 1200 UTC 13 February 1996.

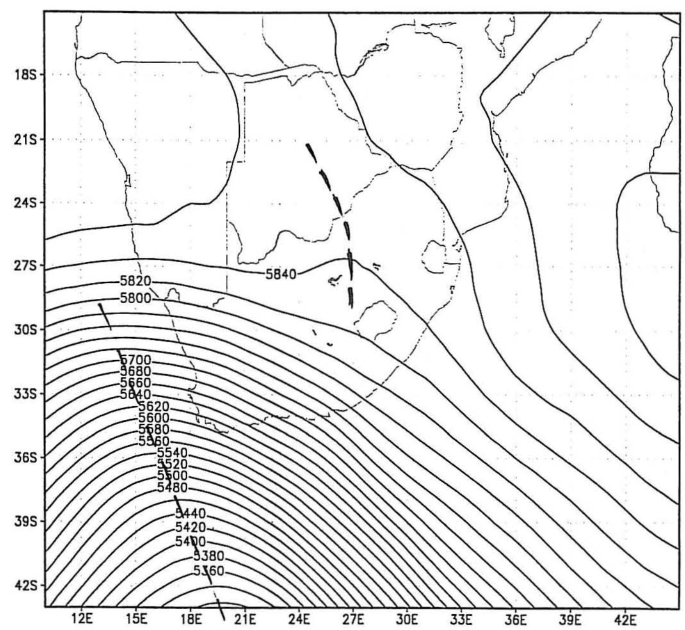


**Fig. 6b.** 500 hPa height analysis of 12-h Eta model predictions valid for 1200 UTC 13 February 1996.

eastern part of the country whereas the mid-latitude trough of Fig. 4b has moved somewhat eastward. The Eta model showed a band of upward motion at 500 hPa (Fig. 7) east of the mid-latitude trough axis over the southwestern parts of the country, and another in association with the tropical moist plume in the northeast. Deep convection developed within the latter band where it intersected the moist northerly flow induced by the MCV.

Figure 8 shows the sounding from Pietersburg (68174) at 1200 UTC. This sounding shows the moist, unstable character of the air mass southeast of the MCV. A parcel of air lifted from the surface would result in deep convection with an equilibrium level above 150 hPa (using parcel theory). In addition to large scale ascent over northern

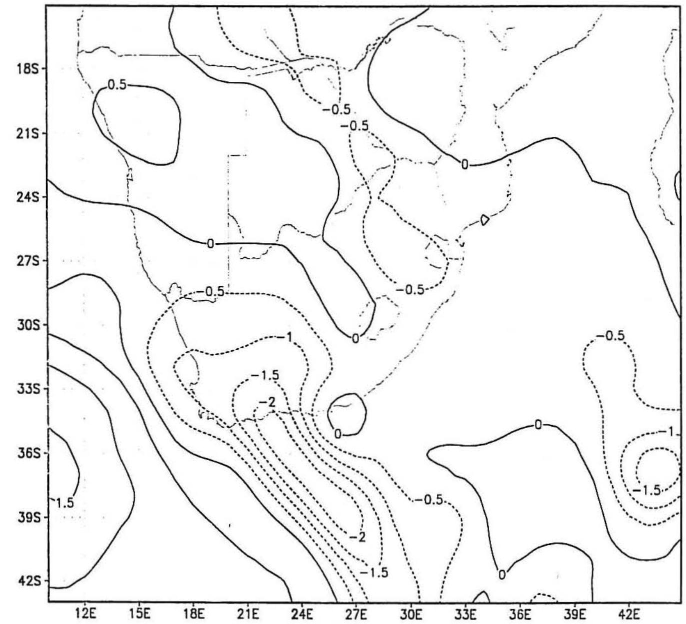


**Fig. 7.** 12-h Eta model forecasted omega field (Pa $s^{-1}$) at 500 hPa valid for 1200 UTC 13 February 1996.

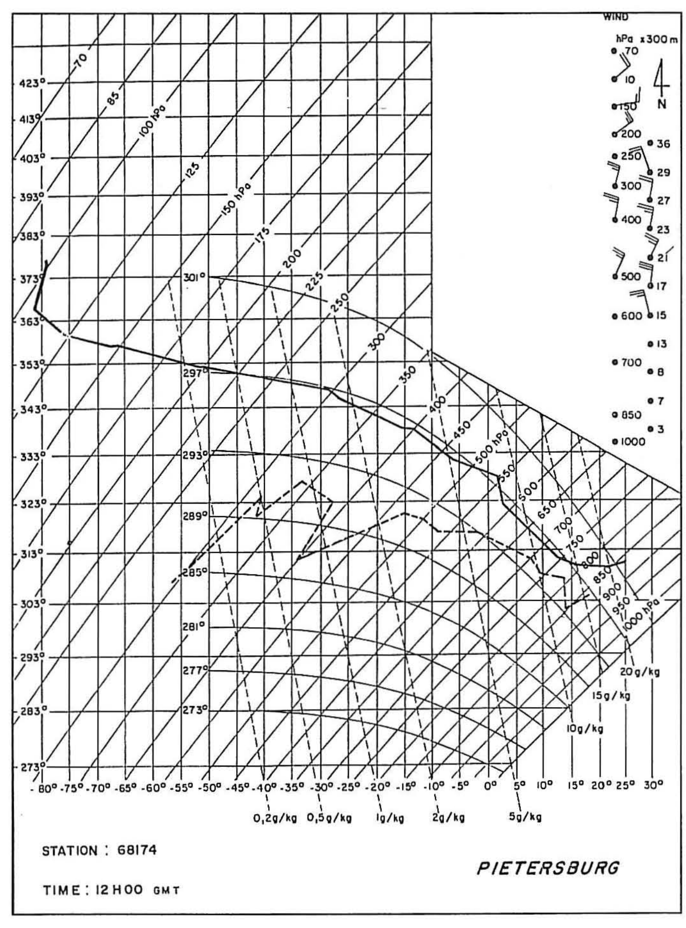


**Fig. 8.** Sounding at Pietersburg (68174) at 1200 UTC 13 February 1996.

South Africa, strong low-level lifting was also provided as the northerly flow (Fig. 5) ascended the northern slopes of the mountain ranges in the northern parts of South Africa. The deep convection in this episode appeared to be

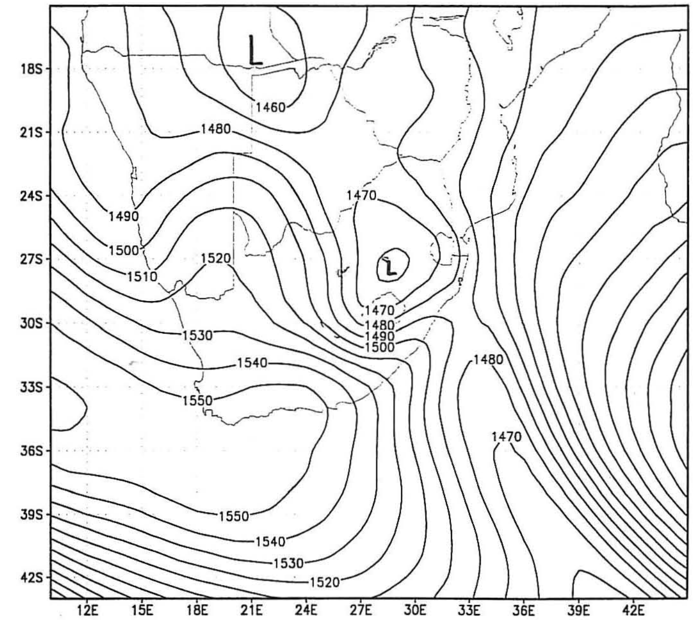


**Fig. 9a.** 850 hPa height analysis of 12-h Eta model predictions valid for 1200 UTC 14 February 1996.

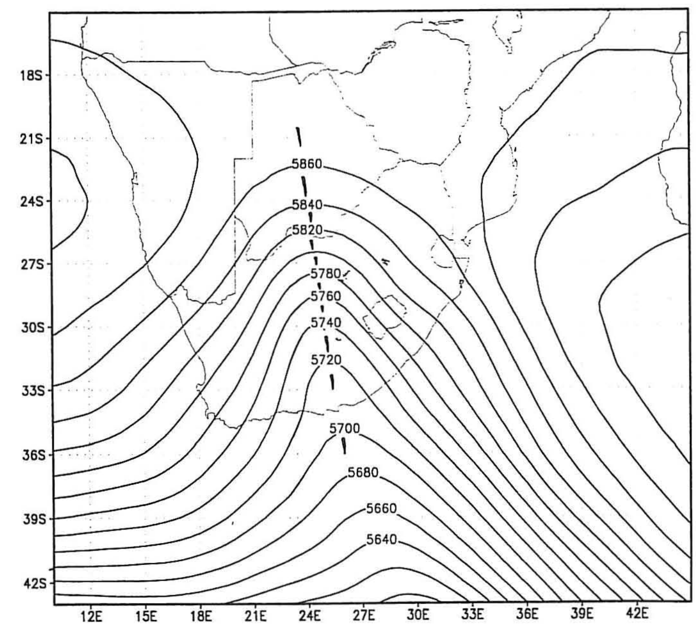


**Fig. 9b.** 500 hPa height analysis of 12-h Eta model predictions valid for 1200 UTC 14 February 1996.

most strongly related to orographic lift of the moist tropical plume ahead of the MCV.

By 1800 UTC 13 February, as shown in Fig. 2e, multiple clusters of convection have developed within the northerly flow east and southeast of the MCV shown in Fig. 2d. This convection continued to move southeastward (Fig. 2f) and resulted in areas of heavy rain over northeastern parts of the country (points 4-6, A and B of Fig. 1c). Farther to the southwest, a broken line of smaller convective clouds has developed along a dry line (Fig. 2e), which separates dry air in the central interior of South Africa from the tropical air mass in the northeast.

The convection over the Northwest Province in Fig. 2f continued to drift southeastward, causing heavy rain

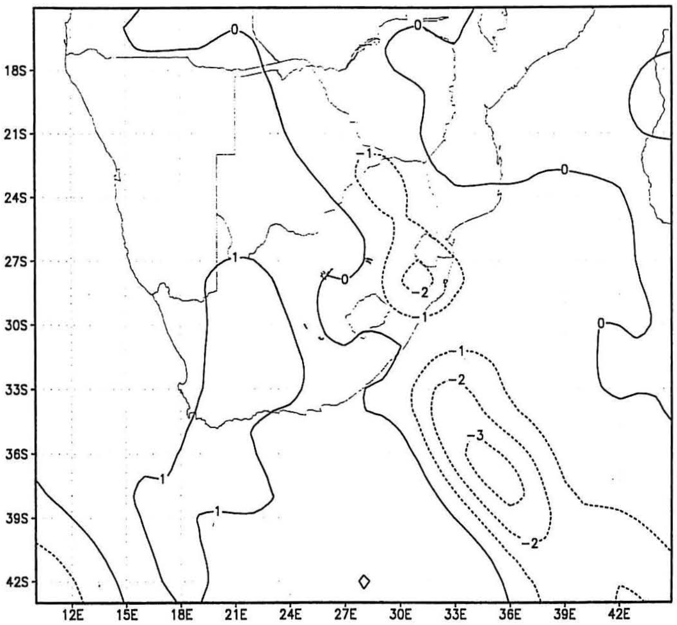


**Fig. 10.** 12-h Eta model forecasted omega field (Pa s$^{-1}$) at 500 hPa valid for 1200 UTC 14 February 1996.

over Johannesburg early on the 14th (point 7 of Fig. 1c). Convective development also occurred along the eastern escarpment and resulted in heavy rainfall in these areas (points 8 and 9, Fig. 1c). Remnants of the earlier convection are concentrated northeast of Swaziland (see Fig. 1c) and along the east coast at 1200 UTC (Fig. 2g) on the 14th. Most of South Africa was now under the influence of colder, more stable air behind the cold front.

Figure 9 shows large-scale Eta model 12-h forecasts for 850 (Fig. 9a) and 500 hPa (Fig. 9b) at 1200 UTC 14 February. The cold front and associated mid-latitude trough have swept across most of South Africa generating very low, minimum temperatures and setting some minimum temperature records for this time of the year. The vertical velocity pattern (Fig. 10) of the Eta model at 500 hPa is now primarily in a single band associated with the frontal zone and upper-air trough. Heavy precipitation developed within the area of strongest upward motion along the coast, where the remnants of the tropical moist plume were being lifted by the front.

## 4. Isentropic Analysis

Researchers (e.g., Anderson 1984) have shown that isentropic analyses (i.e., on potential temperature surfaces) actually provide more useful information on a few charts than do a large array of charts produced on isobaric surfaces. While certainly not a replacement for current model output fields, isentropic surface charts can, with practice, help forecasters to gain an understanding of the three dimensional structure of the synoptic-scale atmosphere that is hard to equal using isobaric charts. Uccellini (1979), Moore (1993) and others have discussed various applications of isentropic analysis in weather analysis and forecasting for the United States.

An adiabatic process is defined as one in which a parcel of air will experience no heat exchange with its environment and no heat gain or loss due to phase changes of

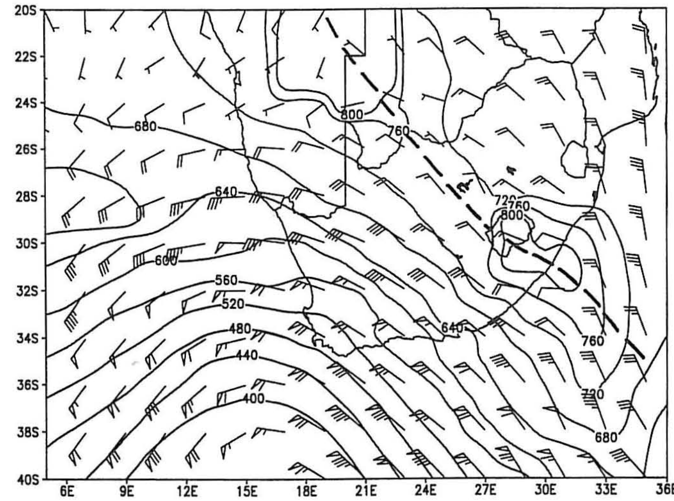


**Fig. 11a.** Isentropic analysis valid 1200 UTC 13 February 1996 for pressure (hPa) and horizontal winds (knots) on the 315 K isentropic surface, from 12-h Eta model predictions. Limiting streamline is indicated in thick dashed line.

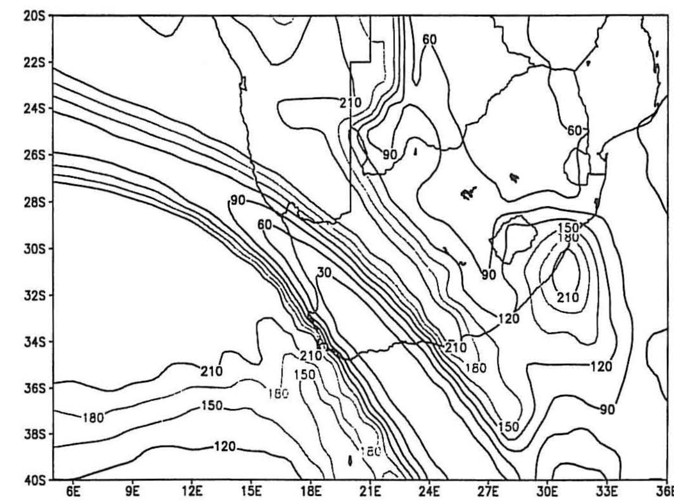


**Fig. 11b.** Isentropic analysis valid 1200 UTC 13 February 1996 for condensation pressure difference (hPa) on the 315 K isentropic surface, from 12-h Eta model predictions.

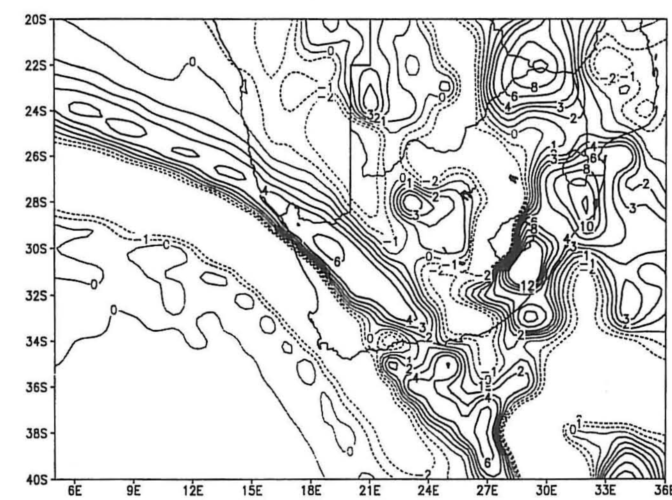


**Fig. 11c.** Isentropic analysis valid 1200 UTC 13 February 1996 for moisture flux convergence (tenths of g kg$^{-1}$ h$^{-1}$) on the 315 K isentropic surface, from 12-h Eta model predictions.

water. Diabatic (non-adiabatic) processes such as condensation, evaporation, radiation and sensible heat fluxes are excluded. Under adiabatic conditions, isentropic charts act as material surfaces, meaning that air parcels are thermodynamically bound to their isentropic surfaces in the absence of diabatic processes. Winds and pressure on isentropic surfaces, therefore, depict the three dimensional adiabatic motion using a single chart. Condensation, if present, will cause air to rise to a higher potential surface, giving the parcel a larger, upward vertical velocity than indicated by the isentropic analysis. Examination of numerical model output on isentropic surfaces, therefore, effectively provides a third dimension to diagnosis of the forecast and, since the atmosphere is three-dimensional, gives a more realistic picture of large-scale atmospheric motion.

Isentropic interpretation of weather data was not operational in South Africa at the time of the February 1996 flood event. However, with archived Eta model output data it was possible to get an idea of how isentropic analysis could have helped the forecaster to make a short-term forecast. Isentropic analysis is used here to diagnose the large-scale environments of the heavy rainfall events that occurred on 13-14 February 1996. The methodology not only provides insights into the thermodynamics of this particular episode, but serves as a model for future operational use by the South African Weather Bureau. (A more comprehensive study with isentropic analysis in several case studies over South Africa can be found in De Coning 1997).

Two isentropic surfaces are selected as representative of the low- and mid-troposphere, respectively. The 315 K isentrope approaches ground level without intercepting it and is used to represent the layer close to the surface. The 325 K isentrope, generally, is at a level just beneath 550 hPa isobaric surface and is chosen to represent the middle troposphere.

Pressure variations on isentropic surfaces correlate well with the average temperature of the atmospheric column below the isentrope (Anderson 1984). This is analogous to recognizing that mid-tropospheric troughs are essentially cold-cored and ridges are warm. Areas of rapid pressure level variation on isentropic surfaces are analogous to frontal zones on isobaric charts. Applying this interpretation to Fig. 11a, it is apparent that the warmest air is found across the central parts of the country where the isentropic surface is at pressures of 720 hPa and higher. Overall, the west edge of the warm air mass is associated approximately with the 680 hPa contour, while the area to the southwest of the central region is in cold air having pressure values of 600 hPa and lower. The pressure ridge separating the tropical air mass in the northeast from the continental and polar air masses in the southwest is essentially a limiting streamline separating the air masses. Little precipitation occurred in the dry airstream west of this limiting streamline, while moderate to heavy rain occurred in the moist tropical air east of it.

Anderson (1984) notes that condensation pressure differences of less than 100 hPa represent areas close to saturation. In this case the air masses close to saturation are located in the southwestern and northeastern portions of the country (Fig. 11b) where the pressure differences are less than 60 hPa, associated with the cold front and the moist tropical plume, respectively. Dry continental air, west of the dry line and east of the cold front shown in Fig. 2e, is located over the western parts of South Africa in association with condensation pressure differences greater than 200 hPa.

Moisture flux convergence as defined on an isentropic surface proved to be a highly complementary product on this occasion. Similarly, Waldstreicher (1988), and many others have found that moisture convergence at the surface and on pressure surfaces is a valuable parameter in convective forecasting. Significant moisture convergence with values exceeding 1 g $kg^{-1}$ $h^{-1}$ on the 315 K surface (Fig. 11c) is evident in the southeastern, eastern and northern parts of South Africa. This is in close agreement with the areas where the heaviest precipitation occurred on 13 February. Thus, moisture convergence, indicative of convergence and advection of moist air predicted by the

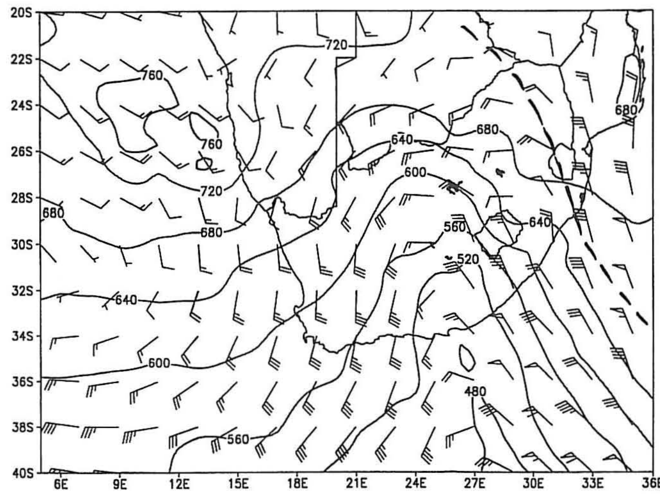


**Fig. 12a.** Isentropic analysis valid 1200 UTC 14 February 1996 for pressure (hPa) and horizontal winds (knots) on the 315 K isentropic surface, from 12-h Eta model predictions. Limiting streamline is indicated in thick dashed line.

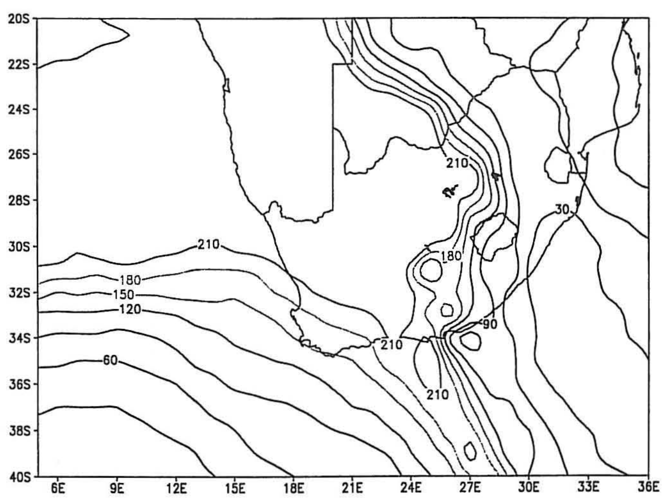


**Fig. 12b.** Isentropic analysis valid 1200 UTC 14 February 1996 for condensation pressure difference (hPa) on the 315 K isentropic surface, from 12-h Eta model predictions.

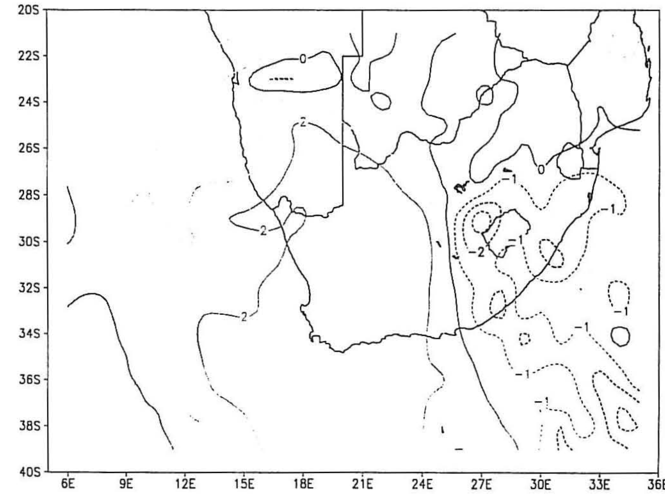


**Fig. 12c.** Isentropic analysis valid 1200 UTC 14 February 1996 for vertical adiabatic motion (microbar s$^{-1}$) on 325 K isentropic surface, from 12-h Eta model predictions.

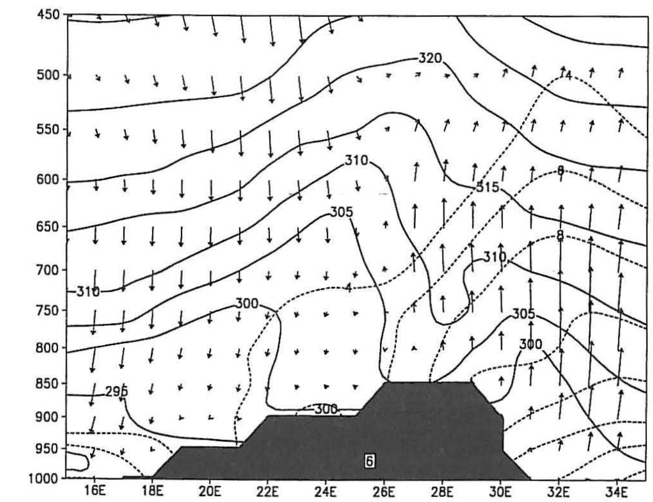


**Fig. 12d.** Isentropic analysis valid 1200 UTC 14 February 1996 for vertical cross section (potential temperature in degrees Kelvin (solid line), specific humidity in g kg$^{-1}$ (dashed line) and winds in m s$^{-1}$) along 30°S from 12-h Eta model predictions.

South African Eta model, played a critical role in the development of convection within the tropical air mass.

By 1200 UTC 14 February, the cold front was situated over the eastern parts of the country. The 315 K pressure values (Fig. 12a) indicate that the warmer air mass has moved eastward and out of South Africa, while cool air associated with the 640 hPa isobar covers most of the country. Very humid air was present in the east where the moist tropical plume was being lifted over the frontal zone, as indicated by the low condensation pressure differences (Fig. 12b). Very dry air over the western parts of the country is associated with subsidence behind the upper-air trough and is depicted by the high condensation pressure differences. Vertical adiabatic motion on the 325 K isentropic surface at 1200 UTC 14 February (Fig. 12c) shows this area of subsidence over the western interior. Also evident is an area of upward motion in the frontal zone east of the upper-air trough axis. This upward motion is associated with the heavy precipitation event on this day on the east coast .

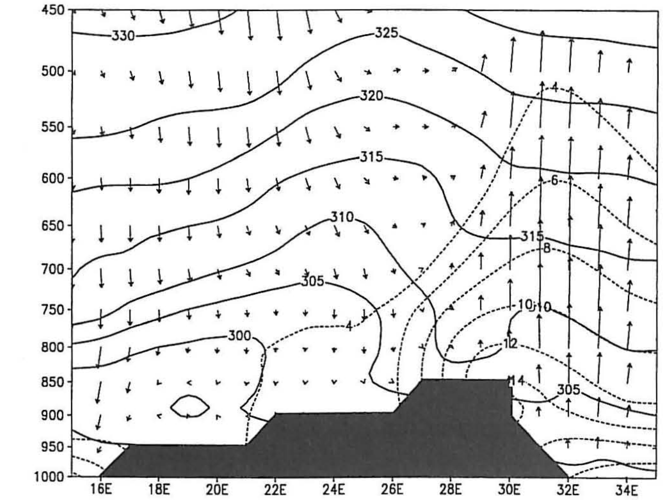


**Fig. 12e.** Isentropic analysis valid 1200 UTC 14 February 1996 for vertical cross section (potential temperature in degrees Kelvin (solid line), specific humidity in g kg$^{-1}$ (dashed line) and winds in m s$^{-1}$) along 28°S from 12-h Eta model predictions.

The extent and depth of the east coast upward motion is evident along the escarpment on cross sections along 30°S (Fig. 12d) and 28°S (Fig. 12e). This uplift is associated with the cold front, upper-air trough and terrain-induced ascent which contributed to the heavier rainfall along the east coast of South Africa on 14 February.

## 5. Discussion and Conclusions

A tropical moist plume present over northeastern South Africa set the stage for the heavy rainfalls and flooding during the 12-14 February 1996 period. Analyses show that the heavy precipitation and flooding occurred as a result of several different triggering mechanisms. Rainfall on the 12th was due to deep convection triggered by a minor short-wave trough in the mid-latitude westerlies passing east-southeastward across the country. On the 13th, deep convection again occurred within the moist conveyor belt, triggered by enhanced, moist northerly flow resulting from an approaching mesoscale convective vortex (MCV). Since much of the heavy rain fell on upwind slopes, orographic ascent appeared to be a factor contributing to convective initiation. Some of this convection continued until early on the 14th. Subsequent heavy precipitation on the 14th, in contrast, was not the result of deep convection within the moist plume, but rather by lifting of the western edge of the moist plume by the cold front and associated mid-latitude trough. Orography, by way of terrain-induced lifting in the escarpments in the east of the country, also played a role in the development and intensity of precipitation. The variety of mechanisms, combined with the sparsity of data over and especially surrounding the region, point out the challenges facing an operational forecaster in South Africa.

Many of the output fields of the South African Weather Bureau Eta model were of value in diagnosing the areas where heavy precipitation occurred. The model's vertical velocity fields revealed mid-tropospheric forcing associated with a mid-latitude trough. Isentropic analyses were useful in revealing dry and moist airstreams, as well as in locating the limiting streamline that separated these airstreams near the dry line. Moisture convergence on isentropic surfaces gave a reliable indication of the regions within the tropical air mass where heavy precipitation developed. Adiabatic vertical velocities on the 325 K isentropic surface, representing the middle layers, provided a reliable presentation of the middle layer ascent ahead of the mid-latitude trough.

This study highlights procedures and difficulties involved in precipitation forecasting during the summer in South Africa. Both tropical and mid-latitude disturbances must be considered since air masses of dry, continental mid-latitude and moist, maritime tropical origins can be present simultaneously. Large variations in terrain aid the development of mesoscale circulations, while existing convective systems can generate mesoscale convective vortices that can impact subsequent storm development. The major topographical influence of the Drakensberg in the east of the country usually acts as a trigger for strong ascent of moist air resulting in the enhancement of rainfall.

Despite the valuable guidance fields provided by the South African version of the Eta model (at 80 km resolution) discussed in this paper, considerable human judgment needs to be applied to pinpoint smaller scale features. Because of the above-mentioned complexities, sophisticated mesoscale numerical models and mesoscale conceptual models developed for South Africa are important for improving the analysis and forecasting of summer regime precipitation.

## Acknowledgments

This paper evolved from Estelle de Coning's M.S. thesis research (from the University of Pretoria) in which the use of isentropic analysis as a forecasting tool in South Africa was addressed. Dr. Forbes was external reviewer of this thesis. Subsequent collaboration to prepare this paper was aided by a travel grant from the Mbeke/Algore Bi-National Commission (agreement between South Africa and the U.S.) and the NOAA International Activities Office, which enabled Dr. Forbes to visit South Africa in 1997. We would like to thank the reviewers, Dr. McNulty and Mr. Brooks, for their valuable comments which helped us to improve the paper.

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