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YUNIBESITHI YA PRETORIA

A dynamical forecasting perspective on synoptic scale weather systems over southern Africa.

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A dissertation submitted in part fulfilment
of the requirements for the degree

MASTER OF SCIENCE (METEOROLOGY)

In the

Department of Earth Science
Faculty of Natural and Agricultural Sciences

UNIVERSITY OF PRETORIA

2000

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DISSERTATION SUMMARY

A dynamical forecasting perspective on synoptic scale weather systems over southern Africa.

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Degree: Master of Science (Meteorology)

Keywords: Eta model, NCEP data, Model for the Identification of Tropical Weather Systems (MITS), Tropical Heavy Rainfall Identification System (THERIS), baroclinic atmosphere, precipitable water, total static energy, conditional instability, vertical motion, topography, divergence

Heavy rainfall and flooding often occur over South Africa. A high percentage of the heavy rainfall events occur over the eastern interior of South Africa and generally during the late summer (January to March) when the influence of tropical weather systems becomes dominant. Research into forecasting techniques best suited for tropical weather systems over southern Africa has been neglected since the early 1970's. The aim of this research was to develop a Model for the Identification of Tropical Weather Systems (MITS) as well as a Tropical Heavy Rainfall Identification System (THERIS) for operational use in the weather forecasting offices of Southern Africa. This study explains the dynamical properties of tropical weather systems and identifies those variables, which favour the development of heavy rainfall.

Three case studies are presented to illustrate the dynamical properties of tropical weather systems. THERIS is tested and verified for historical heavy rainfall events over South Africa. The heavy rainfall events of February 2000 over the northern Provinces of South Africa are discussed and both THERIS and MITS are tested for operational functionality.

Results indicate that MITS can be used to identify tropical weather systems and that THERIS determines areas of heavy rainfall. It is recommended that the two products be tested and used operationally.

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SAMEVATTING VAN VERHANDELING

A dynamical forecasting perspective on synoptic scale weather systems over southern Africa.

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Sleutel terme: Eta model, NCEP data, Model for the Identification of Tropical Weather Systems (MITS), Tropical Heavy Rainfall Identification System (THERIS), baroclinic atmosphere, precipitable water, total static energy, conditional instability, vertical motion, topography, divergence

Swaar reën en vloede kom dikwels oor Suid Afrika voor. 'n Groot persentasie van die swaar reën gevalle kom oor die oostelike binneland van Suid Afrika voor en meestal gedurende die laat somer (Januarie tot Maart) wanneer tropiese weerstelsels prominent is. Sedert die vroeë 1970's was baie min navorsing gedoen oor voorspellingstegnieke vir tropiese stelsels oor suidelike Afrika. Die doelwitte van hierdie studie is om 'n model vir die identifikasie van tropiese stelsels (MITS) te ontwikkel sowel as 'n tropiese swaar reën identifikasie sisteem (THERIS). Hierdie twee produkte is ontwikkel vir operasionele gebruik in die weervoorspellingskantore van suidelike Afrika. In hierdie studie word die dinamiese eienskappe van tropiese stelsels behandel en daardie veranderlikes wat gunstig is vir die ontwikkeling van swaar reën word geïdentifiseer.

Drie gevallestudies word gebruik om die dinamiese eienskappe van tropiese stelsels te illustreer terwyl die tropiese swaar reën identifikasie sisteem getoets word op data van bekende swaar reën gevalle wat oor Suid-Afrika voorgekom het. Die buitengewone swaar reën van Februarie 2000 oor die noordelike Provinsies van Suid-Afrika word ook kortliks bespreek en die twee produkte (MITS en THERIS) word getoets vir hul operasionele funksionaliteit.

Resultate toon aan dat MITS goed daarin slaag om tropiese stelsels te identifiseer en dat THERIS areas isoleer waar swaar reën moontlik is. Daar word aanbeveel dat beide die produkte onder operasionele toestande gebruik en getoets word.

Acknowledgements

"I only know that in our choice of friends and lovers and teachers who will change our lives we are guided by forces which have nothing to do with the rationalisations we provide."

Erica Jong

- I would like to extent deep felt appreciation to my study leader Prof. J Van Heerden, for his patience, unwavering support, excellent academic leadership and the many phone calls and e-mails.
- I am also indebted to Eugene Poolman of the South African Weather Bureau for his many useful suggestions on Tropical Meteorology.
- I wish to thank Helen Kenyon who spent a great deal of time taking care of the text, figures and formats. I am very grateful to her not only for this but also for the support she gave me on a personal level.
- Glenda Swart, Colleen de Villiers, Elda Stewart and Karin Marais all from the South African Weather Bureau for supplying me with the required data and being the best librarians in the whole world.
- My family for their support and encouragement.
- Alfred and Belinda Paetzold, Annatjie Taljaard and Isabel Botha, my old friends, who remained my friends even though I hardly spoke to them in the past year.
- The Water Research Commission for financial assistance.
- Evert Scholz, Flip Strydom, Marais Fourie, Roy Vallance, Christo Wolfaardt, Steve Quin, Sakkie Nigrini, Kevin Rae, Michael de Villiers, Michael Edwards, Daryl Myburg, James Fletcher and Roland Royce who embraced me as one of their own when I started working in the central forecasting office. They patiently taught me what they know about weather forecasting and shared with me their passion for the job.
- To the God that I believe in, for believing in me.

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LIST OF SYMBOLS

e_s	Saturation vapour pressure
g	Magnitude of gravity
$\mathbf{g}$	Gravity
p	Atmospheric pressure
q	Specific humidity
r	Mixing ratio
r_s	Saturation mixing ratio
t	Time
w	$=\frac{dz}{dt}$, vertical component of velocity (upward)
z	Geopotential height equal to geometric height for all practical purposes
C_p	$= 1004 \text{ J K}^{-1} \text{ kg}^{-1}$, specific heat of dry air at constant pressure
L	$= 2.5 * 10^6 \text{ J kg}^{-1}$, latent heat of condensation
RH	Relative humidity
R_v	$= 287 \text{ J K}^{-1} \text{ kg}^{-1}$, gas constant for moist air
T	Temperature measured in Kelvin unless otherwise specified
TSE	Total Static Energy
$\overline{V}_g$	Geostrophic wind vector
$\overline{V}_T$	Thermal wind vector
W	Precipitable water
ω	$=\frac{dp}{dt}$, vertical velocity in isobaric coordinates
$\overline{\nabla}p$	$=\bar{i}\frac{\partial}{\partial x}+\bar{j}\frac{\partial}{\partial y}$ Nabla operator at constant pressure

CHAPTER 1

INTRODUCTION

1.1 THE CLIMATE AND TOPOGRAPHY OF SOUTHERN AFRICA.

South Africa is situated on the southern tip of Africa with its northern boundary at approximately 22°S and the southern most point, Cape Agulhas, at approximately 35°S. Namibia, Botswana and Zimbabwe borders South Africa to the north with Mozambique and Swaziland to the east. Over the southeastern interior of South Africa the Mountain Kingdom of Lesotho lies completely surrounded by South Africa (Fig. 1.1). Conforming to the definition provided by Taljaard (1994), the southern subcontinent or southern Africa refers to Africa south of 17° S. The Atlantic Ocean in the west and the Indian Ocean to the south and southeast flank southern Africa (Fig 1.2). In the east the Mozambique Channel lies between Mozambique and Madagascar supplying warm water to the strong Agulhas Current, which runs parallel to the southeast coast. The cooler Benguela Current runs northward off the west coast.

Taljaard (1994) provided a detailed description of the topography of southern Africa. The subcontinent is characterised by a moderately elevated plateau, for the greater part rising to over 1000 m above sea level and to more than 1500 m over extensive areas (Fig 1.2). The plateau rises steeply in most areas over the first 200-300 km from the coast. In the east the main escarpment rises to 1500 m or more. It runs southward from the Soutpansberg, in the north, becoming the Drakensberg of Kwazulu-Natal and the northeastern interior of the Eastern Cape Province. The Maluti Mountains in Lesotho rises to over 3000 m in places.

The geographical distribution of rainfall over southern Africa is highly variable and is, to a large extent, controlled by the topography. Over the western interior the annual average rainfall varies between 100 and 200 mm. Over the remainder of the interior the annual average rainfall fluctuates between 200 to 700 mm with only the elevated mountain areas receiving more than 1000 mm of rain annually (Taljaard, 1996). Schulze (1965) stated that 85% of South Africa receives more than half of its rainfall in summer (October to March). Taljaard (1986) showed that the area of maximum summer rainfall in southern Africa follows a roughly anti-cyclonic circular track. Starting along the East Coast in September, through the four northern provinces of South Africa (Gauteng, Mpumalanga, Northern Province and Northwest Province) by October and November reaching the Northern Cape Province by March. Zimbabwe, the northern parts of Botswana and Namibia also receive most of their rainfall from November to January.

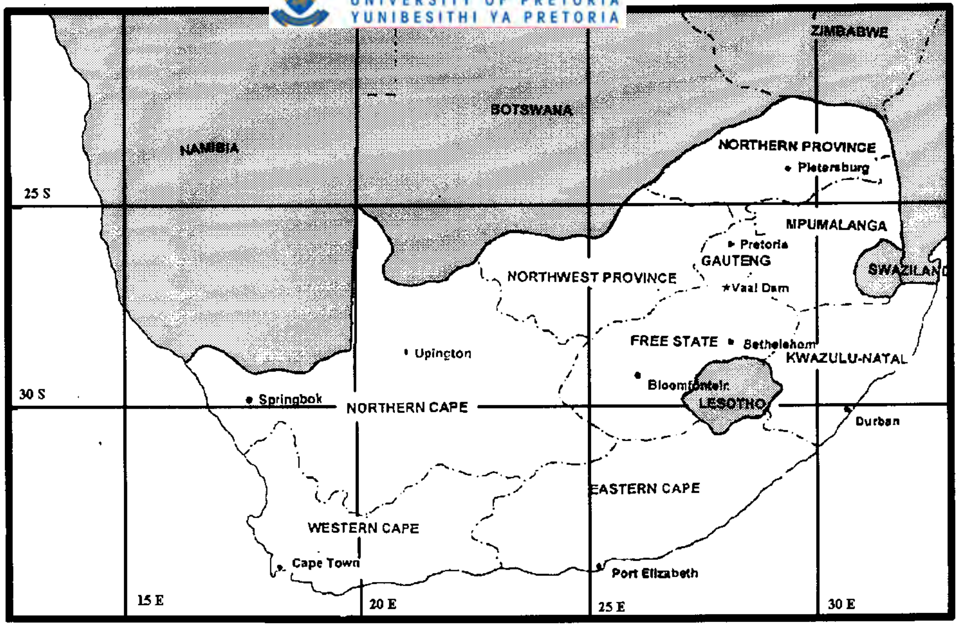

Figure 1.1: The nine provinces of South Africa.

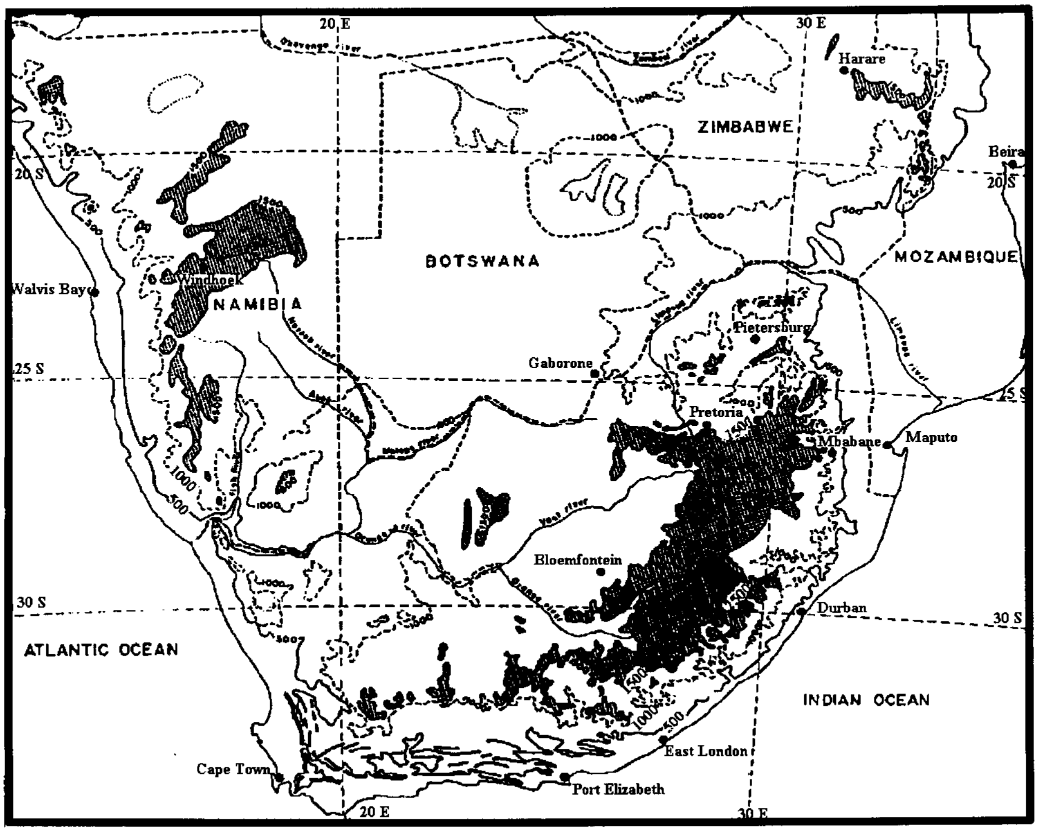

Figure 1.2: Topographical and location map of Southern Africa. Contours are for 500, 1 000, 1 500 and 2 500 m (after Taljaard, 1994).

1.2 WEATHER PATTERNS OF SOUTHERN AFRICA

The weather over the southern subcontinent of Africa is dominated by a high-pressure belt, which is, except for a few winter months, split in two by the continent. The Atlantic Ocean High (AOH) lies to the west and the Indian Ocean High (IOH) to the east. Variations in position and intensity of the two high pressure systems play an important role in the rainfall distribution over South Africa (Shulze, 1965). The mid-latitude westerly circulation, extending northwards to these high pressure systems, controls the weather of South Africa to a large extent. Weather changes are largely influenced by perturbations in the Southern Hemisphere westerly circulation (De Coning, 1997). During the summer months, the influence of the westerly circulation becomes somewhat diminished as the high pressure systems migrate southwards. In the summer the Intertropical Convergence Zone (ITCZ) moves southwards to approximately 17°S (Taljaard, 1994). Van Heerden and Taljaard contributing to Karoly and Vincent (1998) explained that it is during this time of the year that tropical weather systems invade southern Africa from the east in the form of tropical cyclones or easterly waves.

1.3 HEAVY RAINFALL OVER SOUTHERN AFRICA

Rainfall over southern Africa varies considerably from year to year (Schulze, 1965). Below normal rainfall and droughts occur frequently. From time to time heavy rainfall and floods occur over southern Africa and is often associated with large financial losses, damage to infrastructure and loss of life. Viljoen, cited in Alexander and Van Heerden (1991), lists 184 noteworthy flood events during the years from 1911 to 1988. Close to 30% of these flood events occurred over Kwazulu-Natal and 42% over the four northern provinces and the central interior of South Africa.

Alexander and Van Heerden (1991) identified 6 flood classes with the lower end of the scale defining heavy rain events, which could lead to significant river flow but only localised flooding. The top end of the scale is truly significant flood events with disastrous results such as the Kwazulu-Natal floods of 1987 (class 5) and the Free State floods of 1988 (class 4). Considering the six flood classes together Alexander and Van Heerden (1991) found that the month with the highest frequency of floods is February and 67% of these flood events occur during the summer rainfall season (October to March). They also found a dramatic increase of serious floods from 1970 to 1990 and postulated that the possibility of getting serious flood events more frequently must be accepted. Poolman (1999) used the following heavy rainfall classification scheme: more than 25 mm of rain must occur, in 24-hours, over an area greater 20 000 km^2 with rainfall at least one station exceeding 50 mm. This definition differs considerably from the one used by Alexander and

Van Heerden (1991) but the results show similar tendencies. Poolman (1999) found that most of the heavy rainfall events occurred during the summer months with the highest frequency in January and February. The eastern and central parts of South Africa had the most heavy rainfall days. Poolman (1999) also concluded that the number of heavy rainfall events lasting one day only has increased slightly since the mid 1970's but that the frequency of two day, or longer, events have decreased in the same period.

Apart from the tropical weather systems dealt with in detail in this dissertation other systems causing the heavy rainfall over southern Africa are: Tropical Cyclones, the cut-off low (COL), the ridging Atlantic Ocean High behind the cold front and the tropical temperate trough (TTT) (Alexander and Van Heerden, 1991, Preston-White and Tyson, 1993, Riehl, 1979, Taljaard, 1985, Triegaardt el al., 1991 and Van Heerden and Hurry, 1987).

On average 10 – 11 tropical cyclones occur over the Southwest Indian Ocean in summer. Only a small fraction of these cyclones occur in the Mozambique Channel (Kovacs et al., 1985). Between 1950 and 1988 only 10 tropical cyclones invaded southern Africa and had a significant affect on South Africa's rainfall (Alexander and Van Heerden, 1991). It becomes apparent that tropical cyclones making landfall in southern Africa is a rare event, however when it does happen extreme rainfall and flooding results (Poolman and Terblanche, 1984 and Dyson and Van Heerden, 2000).

Many flood events over South Africa were caused by cut-off low (COL) pressure systems (Alexander and Van Heerden, 1991). Taljaard (1985) list at least 10 such events between 1974 and 1981. Amongst them the Laingsburg flood of January 1981 also described by Estie (1981). Treigaardt et al. (1988) showed that a COL, accompanied by a strong surface on-shore, flow caused the extreme rainfall over Kwazulu-Natal during September 1987. When a COL occurs in winter widespread and heavy snowfall can occur. This happened during July 1996 (Strydom and Nel, 1996). Taljaard (1985) stated that considerable confusion exists, even amongst meteorologist, in distinguishing between a COL and a low pressure system in the tropical easterlies. To identify the COL he proposed the following definition: the low (COL) must be located equatorward of the 40° latitude and have a closed circulation in the upper troposphere, extending downwards to the land surface and have a cold core of upper tropospheric temperatures.

The Western Cape Province as well as the coastal zone stretching eastward to Kwazulu-Natal often receive heavy rainfall during the passage of intense mid-latitude weather systems associated with a potent cold front followed by an strong ridge of the AOH. Over the Cape Peninsula and surrounds heavy rainfall generally occurs in the northwesterly flow ahead of the cold front. The southern and southeastern coastal areas usually experience heavy rainfall after the passage of the cold front when a intense ridge of the AOH cause a strong southerly to southwesterly on-shore flow (Alexander and Van Heerden, 1991 and Van Heerden and Hurry, 1987). The escarpment, which rises to approximately 1500 m within 200 – 300 km from the coast, plays a significant role in the production of the heavy rainfall (De Villiers, 1992, Dyson and Van Heerden, 2000, Tennant and Van Heerden, 1994 and Triegaardt et al., 1988). De Villiers (1992) identified 195 heavy rainfall events between 1980 and 1989 over Kwazulu-Natal. Triegaardt et al. (1988) showed that the heavy rainfall over the Kwazulu-Natal is predominantly due to a strong surface on-shore flow.

Crimp et al. (1997) and Harrison (1983,1986) provided a thorough explanation of the importance of the tropical-temperate trough (TTT) in producing rainfall over South Africa. They estimated that approximately 39% of the mean annual rainfall can be contributed to the TTT. The TTT is easily identified on satellite imagery as long cloud bands linking tropical convective systems to the mid-latitude (temperate) frontal systems. Lindesay and Jury (1991) and Harrison (1986) explained that a TTT is characterised by a trough linking a low over tropical or sub-tropical Africa with a mid-latitude depression to the south of the subcontinent. The heavy rainfall over the central interior of South Africa during February 1988 (Jury et al., 1993 and Lindesay and Jury, 1991) as well as the extreme rainfall during February of 1996 (de Coning et al, 1998) are two examples of heavy rain- producing TTT's.

1.4 TROPICAL WEATHER SYSTEMS OVER SOUTHERN AFRICA

Research on tropical weather systems, especially the forecasting techniques best suited for these systems, has generally been neglected in South Africa. Some notable exceptions exist. Lindesay and Jury (1991) identified the weather system responsible for heavy rainfall over the central interior of South Africa during February 1988 as a tropical-temperate trough. On the other hand, Triegaardt el al. (1991) made a detailed dynamical analysis of this weather system and stressed the tropical nature of the atmospheric circulation during this event. Taljaard (1985) in discussing the COL provided a brief description of the tropical easterly low over southern Africa. Preston-White and Tyson (1993) proposed that an easterly wave can be distinguished from an easterly low by considering the level of maximum wind divergence. In the latter case wind divergence should occur at higher levels in the troposphere.

Van Heerden and Taljaard contributing to Karoly and Vincent (1998) discussed circulation systems over tropical and subtropical southern Africa. They identified three types of low pressure systems (tropical cyclones, tropical lows and heat lows) which are common over the low latitudes of continental sub Sahara Africa. Although the tropical cyclone was briefly dealt with here it is important to mention that the observed dynamical characteristics of a tropical cyclone changes significantly when it moves inland from the Mozambique Channel (Poolman, 2000). Van Heerden and Taljaard contributing to Karoly and Vincent (1998) explained how a tropical low over the interior of southern Africa can be identified on loops of half-hourly geostationary satellite images by considering the low-level cyclonic circulation and anti-cyclonic upper tropospheric circulation depicted by the cloud motion. These systems generally move from east to west over the subcontinent but very rarely reach the African west coast. The third type of low, which frequents the lower latitudes, is the so-called heat low. These are shallow low pressure systems and form because of the intense heating of the lower few hundred metres of air in contact with the hot land surface.

Despite this body of evidence very little recent and practical research results exist which can aid an operational meteorologist in identifying and predicting areas of rainfall. This is especially true in the case of heavy rainfall from tropical weather systems. The years 1940 to 1970 were dubbed the golden period of African tropical meteorology. Meteorologist of the British school in East Africa, the Rhodesias (now Zimbabwe and Zambia) as well as the French school in equatorial western Africa all researched the circulation systems favouring rainfall in the region (Van Heerden and Taljaard contributing to Karoly and Vincent, 1998). Forsdyke (1949) expressed the hope that tropical meteorology in Africa would develop faster and further after the Second World War. History has, alas, proven him wrong. Forsdyke (1949) considered that forecasting in the tropics requires different techniques from those employed in temperate latitudes. The quasi-geostrophic theory (Holton, 1992) is less amenable because the geostrophic wind relationship no longer holds and the flow becomes generally across the isobars. Furthermore he also suggested that streamline analysis be used to research tropical circulation and be employed to prepare forecasts. Thompson (1957) and Riehl (1979) supported this approach. At present streamline analysis is used in many countries where tropical weather systems are common such as the Northern Territory in Australia. Streamline analysis is however not in common use by forecasters in South Africa. Riehl (1979) found that upper air winds, surface pressure anomalies, 12 and 24-hour pressure changes, 24-hour changes in of the height of upper isobaric surfaces and a plot of temperature and specific humidity are essential parameters for tropical weather forecasting. Forsdyke (1949) and Thompson (1957) found upper air ascents to be fundamental in tropical forecasting. They found that when the environmental lapse rate is greater than the saturated adiabatic and high levels of humidity exist up to the freezing level widespread or general precipitation is likely. Riehl (1979) explained how a vertical profile of total static energy could be used to identify an unstable atmosphere. This parameter is vital in identifying tropical systems and will be dealt with thoroughly in subsequent chapters.

1.5 AIMS OF THIS STUDY

The first objective of this research is to develop a **Model** for the **Identification** of **Tropical Weather Systems (MITS)** over the interior of southern Africa. MITS should be available to operational meteorologists to aid them in distinguishing between tropical and baroclinic weather systems.

A second aim of this study is to isolate those areas where heavy rainfall is likely from tropical weather systems. The **Tropical Heavy Rainfall Identification System (THERIS)** should also be designed for use in an operational environment.

To achieve these aims research can be subdivided into the following steps detailed per chapter in the dissertation.

Chapter 2 describes the numerical weather predication models and rainfall data used in the research. A brief description is also provided on the calculation of the relevant variables such as specific humidity, total static energy and precipitable water. In chapter 3 a detailed discussion is provided on the design of MITS and THERIS. In MITS it is illustrated how five basic principles may be used to lead the weather forecaster or other user through the dynamical properties of a tropical atmosphere; the simultaneous occurrence determines where convective rainfall is probable. MITS and THERIS go hand in hand but more stringent conditions apply for THERIS, which isolates a single field of potentially heavy rainfall areas.

Three case studies are described in chapter 4 to illustrate how MITS can be used to isolate tropical circulation patterns. THERIS is also tested on historical heavy rainfall days and the results detailed.

The heavy rainfall and floods over the northeastern interior of South Africa during February 2000 is elaborated on in chapter 5. In this case MITS and THERIS are tested using the South African Weather Bureau Eta model data. Emphasis is placed on making the results accessible to operational meteorologists.

Chapter 6 contains the conclusions and suggested further research as well as suggested practical applications of MITS and THERIS.

CHAPTER 2

NUMERICAL WEATHER PREDICTION AND RAINFALL DATA

2.1 National Center for Environmental Prediction (NCEP) Data

The National Center for Environmental Prediction (NCEP) re-analysis data is used in the completion of the case studies as discussed in chapter 4. NCEP data is generally considered being of a high quality. In all three case studies detailed in chapter 4 the 1200 UTC analysis of the NCEP data is used.

The NCEP data used here has a horizontal resolution of 2.5 degrees and has 17 levels in the vertical. The average height of the interior of South Africa is approximately 1500 m above mean sea level and it is therefore common practice in the forecasting offices in South Africa to use the geopotential heights of the 850hPa level to represent the surface synoptic circulation. The station pressure measured at synoptic weather stations over southern Africa is converted to 850hPa geopotential heights, which are then plotted on synoptic weather maps used for analysis. The 850hPa-geopotential heights are also used as the surface level when studying numerical weather prediction (NWP) fields. The same method is employed in this dissertation. One of the principle aims of this research is to develop an early warning system for heavy rainfall from tropical weather systems, specifically for the interior of South Africa. For this reason only 8 of the 17 vertical levels available in the NCEP data set are utilized namely the 850-, 700-, 600-, 500-, 400-, 300-, 250- and 200hPa levels.

The horizontal and vertical resolution of the NCEP data is ideal to research weather systems on the synoptic scale. Small or mesoscale features will not be adequately identified by this data set. To identify synoptic scale tropical weather systems as well as widespread heavy rainfall caused by these weather systems the NCEP data proved to be quite adequate.

2.2 Eta Model Data

The SAWB runs a Limited Area Model (LAM) referred to as the Eta model. In order to make these research results available to the operational meteorologist it is important that the Model for the Identification of Tropical Weather Systems (MITS) and the Tropical Heavy Rainfall Identification System (THERIS) is tested and operates on the Eta model prognostic fields. This was done for the heavy rainfall, which occurred over northeastern South Africa during February 2000 and is described in chapter 5.

The current operational South African Eta model has a horizontal resolution of half a degree (approximately 50 km) and has 38 levels in the vertical. MITS and THERIS were originally developed using the NCEP data set and therefore only those vertical levels also available in the NCEP data are used here. Eta is available on the display system PCGRIDDS in the geographical area bounded by 10° S to 50° S and 5° W to 55° E. A comprehensive description of the Eta model is provided by Mesinger et al., (1988). De Coning (1997) and De Coning et al. (1998) also used the Eta model for research on heavy rainfall events over South Africa.

2.3 Rainfall Data

All the rainfall data used was obtained from the Directorate of Climate of the South African Weather Bureau (SAWB). During the 1980's (the period of case studies 1 and 3) approximately 2500 rainfall stations recorded daily rainfall over South Africa. The number of reporting rainfall stations has steadily decreased to approximately 1500 by the 1990's. Rainfall data is used in two ways:

Firstly daily rainfall charts, indicating the geographical distribution of the rainfall are generated using the interpolation scheme of Rautenbach (1996). This interpolation scheme has some disadvantages in that if rainfall occurs at a single rainfall station, geographical distant from other rainfall stations the isolated rainfall is not adequately captured by this interpolation scheme. Furthermore, if rainfall at a single station is significantly greater than rainfall at other nearby stations the interpolation scheme tends to smooth the rainfall field. Information on isolated heavy rainfall events is lost in this way. Another problem with the interpolation scheme is the fact that in the generation of the rainfall chart the 0-mm isohyet is not indicated and the first plotted isohyet is the same as the contour interval of the isohyets. If for instance the contour interval is 50 mm (as is the case in figure 4.1.1) the first isohyet indicated on the figure is 50 mm, all rainfall less than 50 mm is not shown. In this research the focus point is widespread heavy rainfall and despite the disadvantages of the interpolation scheme, the author is nevertheless convinced that the interpolation scheme captures most widespread heavy rainfall events adequately. The rainfall maps are used only as a graphical presentation of rainfall and the evaluation of THERIS is performed by the methods described below.

The second application of the rainfall data is to evaluate THERIS results. This is done by calculating the average rainfall in the areas isolated by THERIS as well as the percentage of rainfall stations reporting more than 0 mm, 10 mm, 20 mm and 50 mm of rain. Because the rainfall stations have an irregular geographical distribution the weighted average method designed by Tennant (1999) is used to calculate the statistics. Tennant's method is used operationally at the SAWB and a full description is provided by Pienaar et al. (2000). The weighted average rainfall and weighted percentages were computed by taking the geographical position of each station relative to the other stations into consideration. The following weighting function (Tennant, 1999) was applied to all the stations to calculate the weighted percentage of stations reporting rainfall.

$$Wgt = \frac{\sum_{m=1}^{N-1} l_m}{(N-1)l_{\max}}$$

Where Wgt is the weight assigned to a station, $\sum_{m=1}^{N-1} l_m$ is the sum of the distance between the specific station and all other stations, $l_{\max}$ is the maximum distance between the specific station and any other station and N the total number of stations.

When rainfall stations are distributed evenly over an area Tennant's method renders results very close to the mathematical average. The use of the weighting method becomes important when the rainfall stations are not distributed evenly over an area. A rainfall station, which is geographically distant (close) to other stations will have a larger (smaller) weight factor and will therefore contribute more (less) in the computation of the average and percentages.

2.4 Calculating the relevant meteorological parameters.

A number of parameters generated by Numerical Weather Prediction models (NWP) are used by MITS and THERIS. The following meteorological parameters were not available as a model output in the NCEP and Eta data and are dealt with below.

a. Specific Humidity (q)

Specific humidity, the ratio of the mass of water vapour to the total mass, per unit volume, (Gordon et al., 1998), is not available in the NCEP data set. Specific humidity is required for the calculation of precipitable water as well as the total static energy. Gordon et al. (1998) provides the following expression for the computation of specific humidity.

$$q = \frac{r}{1+r} \qquad (1)$$

where r is the mixing ratio defined as the ratio of the mass of water vapour to the mass of dry air per unit volume (Huscke, 1959).

Relative humidity (RH) is one of the variables available in the NCEP and Eta data sets and is used to calculate specific humidity. Relative humidity is defined as the ratio of the actual vapour pressure of air to the saturation vapour pressure, at the same temperature and the following expression from Wallace and Hobbs (1977) is used to compute the RH.

$$RH = \frac{r}{r_s}$$

$$\therefore \qquad r = RH\ r_s$$

Where r_s is the saturation mixing ratio.

By substituting this relationship into equation (1) gives:

$$q = \frac{r_s\ RH}{1 + r_s\ RH} \qquad (2)$$

Relative humidity is a variable available from the NCEP and Eta fields and the next step in the calculation of specific humidity is to find an expression for the saturation mixing ratio. Wallace and Hobbs (1977) provides the following expression.

$$r_s = 0{,}622 \frac{e_s}{p} \qquad (3)$$

where e_s is the saturation vapour pressure and p pressure. It is accepted here that $p \rangle\rangle e_s$ for observed temperatures in the earth's atmosphere.

All that remains to be done is to find an expression for the saturation vapour pressure. The Clausius-Clapeyron equation from Wallace and Hobbs (1977) is used here. It also shows that the saturation vapour pressure is a function of temperature (T) alone, which in turn is available in the model fields.

$$e_s = 611\ \exp\left(\frac{L}{R_v}\left(\frac{1}{273.16} - \frac{1}{T}\right)\right) \qquad (4)$$

Where $L = 2464759\ \ J\,kg^{-1}$

$R_v = 461.48\ \ J\,kg^{-1}\,k^{-1}$

T= temperature in Kelvin.

Substituting equation (3) and (4) into equation (2) gives an expression to calculate specific humidity on a pressure level.

b. Precipitable Water (W)

Huschke (1959) defines precipitable water (W) as the total mass of water contained in a vertical atmospheric column if all the water vapour in the column were to condense out. Although precipitable water is one of the variables provided by the NWP models, in this study preciptable water is defined as above but the 850hPa to 300hPa levels bound the vertical column.

$$W = \frac{1}{g}\int_{p_1}^{p_2} q\,dp$$

Where $g = 9.8ms^{-2}$, p_1 = 300-, p_2 = 850hPa.

The following algorithm is used to calculate W

$$W = \frac{1}{g}\sum_{i=850\,hPa}^{i=400hPa} \frac{q(p_i)+q(p_{i+1})}{2}(p_i - p_{i+1})$$

In Chapter 5 MITS and THERIS is tested on the prognostic fields of the ETA model. In this instance W is computed between 800hPa and 300hPa. Huschke (1959) states that the specific humidity (q) may be approximated by the mixing ratio (r) because both are very small quantities and can be considered the same for all practical purposes. The mixing ratio is one of the variables available in the Eta model data and W is computed by replacing the specific humidity by the mixing ratio.

c. Total Static Energy (TSE)

The Total Static Energy (TSE), is the total energy within an atmospheric parcel of air without taking the small kinetic energy (due to macroscopic motion) into account (Triegaardt et al., 1991). Mathematically TSE is expressed by:

$$TSE = C_pT + gz + Lq$$

Where $C_p = 1004.64 J\,K^{-1}\,kg^{-1}$ and z is the geopotential height and the term gz is the geopotential if it is accepted that g does not vary in the vertical column. The right hand terms represents respectively the enthalpy, geopotential and latent energy of the parcel. The average TSE in the troposphere is calculated between the 850hPa and 300hPa levels using data from the NCEP and Eta data sets.

The vertical profile of TSE is used to determine if the atmosphere is conditionally unstable. In all of the case studies described in this dissertation the surface value of TSE is taken as the 850hPa value. To calculate the level of conditional instability (LCI) the following formula is used: $LCI = TSE_{850} - TSE_i$ where i vary between 700hPa and 400hPa. For the atmosphere to be conditionally unstable up to 400hPa (a requirement of MITS) the LCI must be positive for i = 700hPa to 400hPa. In THERIS it is required that the LCI must be positive up to at least 300hPa.

d. Average upper tropopheric wind divergence

Using scaling arguments for synoptic scale flow Holton (1992) showed that the scale value of wind divergence is in the order 10^{-6} s^{-1}. Wind divergence is very sensitive to small changes in wind direction and strength. To remove small spurious wind perturbations in the wind field the average wind in the 200hPa to 300hPa layer is used to compute the average wind divergence.

2.5 Summary

Two numerical model data sets are used in this dissertation, NCEP re-analysis data and prognostic fields from the SAWB Eta model. The two data sets differ considerably in horizontal and vertical resolution. As far as possible the same vertical levels were used in the design of MITS and THERIS in both data sets. All rainfall data was obtained from the SAWB and is used to display the geographical distribution of daily rainfall as well as to calculate the weighted average and weighted percentages for heavy rainfall areas isolated by THERIS.

CHAPTER 3

THE DESIGN OF MITS AND THERIS

3.1 MODEL FOR THE IDENTIFICATION OF TROPICAL WEATHER SYSTEMS (MITS).

The first aim of this dissertation is to develop a Model for the Identification of Tropical Weather Systems (MITS). An important component of MITS is to provide operational meteorologists with a tool, which they can use in an operational environment to promptly identify tropical circulation patterns. MITS can also be used as an aid to issue timely and accurate rainfall forecast by identifying areas where tropical convection is possible. The design of MITS is based on atmospheric dynamics but will be put at the disposal of the forecaster without bothering them with the complex dynamics. However, the theoretical basis will be made available to the operational meteorologist who can reflect on it at leisure. The forecaster will in fact be encouraged to do so. MITS will also be used in the training of forecasters, which will ensure that young operational meteorologists will be well versed in the basic principles governing tropical circulation.

MITS consists of five components. First the vertical displacement of low and high-pressure systems with height is investigated. Then the relationship between upper tropospheric temperatures and large-scale synoptic systems are detailed. The third component is to identify a moist diverging high in the upper troposphere. The fourth factor to consider is the average values of TSE throughout the troposphere. The fifth component is the conditional instability of the atmosphere as determined from the vertical distribution of TSE. Upward motion in the lower and middle troposphere is of paramount importance for the production of widespread rainfall and areas where this upward motion exists are located by MITS. The final and probably most important product of MITS is to provide the operational meteorologist with a single field, which indicates where rainfall in a tropical atmosphere is likely to occur.

3.1.1 Vertical integrity of low and high-pressure systems.

The low must be upright from 850 to 400hPa and should be displaced by a ridge of high pressure at 200hPa.

Unless otherwise stated the co-ordinate system used in the text is the so-called (x, y, p, t) system with x the west east-, y the south north-, p the pressure co-ordinate and t time. However the actual horizontal derivations were performed in spherical co-ordinates on constant pressure levels.

Holton (1992) defines a barotropic atmosphere as one in which the density is a function of pressure alone. This means that isobaric surfaces are also surfaces of constant temperature so that $\overline{\nabla}_p T = 0$. Where $\overline{\nabla}_p = \bar{i}\frac{\partial}{\partial x} + \bar{j}\frac{\partial}{\partial y}$ and T is temperature. In the absence of a temperature gradient on a specific pressure level the thermal wind will be zero. The thermal wind represents the vertical geostrophic wind shear and can be expressed by $\overline{V}_T = \overline{V}_g(p_1) - \overline{V}_g(p_0)$. Where $\overline{V}_T$ is the thermal wind and $\overline{V}_g$ the geostrophic wind at pressure levels p_1 and p_0 ($p_1 < p_0$). When the thermal wind is equal to zero the geostrophic wind will not change with height. Therefore in such a theoretical barotropic atmosphere the gradient of geopotential remains constant with height. Synoptic scale high and low pressure systems will in this ideal situation "stand upright" with height.

Holton (1992) further states that barotrophy provides very strong constraints on the motions in a rotating fluid and is in fact never achieved in the atmosphere. Nevertheless in a tropical atmosphere the circulation will tend towards this ideal situation. In the precipitation zone of equatorial wave disturbances in the Western Pacific convergence, associated with low-pressure systems, extends up to nearly 400hPa (Holton, 1992). The first component of MITS is therefore to look for a low-pressure system, which stands approximately upright with height from the surface (850hPa) up to 400hPa.

In the real tropical atmosphere strong surface and middle tropospheric convergence occurs in the association with the "upright" low-pressure system. As will be dealt with in paragraph 3.1.5 this convergence in turn results in upward motion and, if adequate water vapour is available, convective cloud or so-called "hot towers" will develop. Riehl (1979) explains the process by which the hot towers act as energy tubes through which energy from the lower troposphere is transported to the upper troposphere where it is distributed horizontally by the upper air divergence. The condensation releases a large amount of latent heat, which is in turn responsible for above normal upper tropospheric temperatures (Triegaardt et al., 1991). The latent heat release therefore, quickly results in a warm core developing above the lower level low (Taljaard, 1985). Holton (1992) shows that the geopotential thickness of a layer is directly proportional to the average column temperature with the result that an upper tropospheric high-pressure system forms above the surface low.

3.1.2 Average column temperatures in the 500-300hPa layer

A core of high average column temperatures should be present in the 500-300hPa layer.

Paragraph 3.1.1 details how the upper tropospheric high develops because of the above normal temperatures in the upper troposphere, which in turn come in to existence because of the release of latent heat. The average column temperatures in the 500-300hPa layer are therefore used as the second component of MITS. The warm core in the column underneath the 200hPa high (component 1 of MITS) is fundamental to the identification of tropical weather systems (Poolman, 1997)

The horizontal temperature gradient of the column temperatures can also be used to determine the baroclinicity of the atmosphere. As dealt with in the previous paragraph the absence of such a temperature gradient is indicative of a barotropic atmosphere. It was also stipulated that this ideal theoretical situation is never achieved in the real atmosphere. A weak temperature gradient can nevertheless be used to identify a 'tropical atmosphere'.

3.1.3 Moist diverging high in the upper troposphere

Precipitable water values in the troposphere should exceed 20 kg m^{-2} *and be in the same geographical position as the 200hPa ridge of high-pressure and upper tropospheric wind divergence.*

It is common practise in the forecasting offices of the SAWB to use relative humidity to identify areas of high water vapour content. However relative humidity in itself does not specify the mass of water vapour present in the atmosphere. In this dissertation precipitable water will be used as the moisture parameter. Huschke (1959) defines precipitable water (W) as the total water vapour contained in a vertical column extending between two specified levels. A fundamental component in the development of the upper tropospheric high-pressure system is the release of latent heat through condensation. High values of precipitable water at the same location as the 200hPa high-pressure system show that abundant water vapour is available to enhance this process.

The developing upper tropospheric high causes horizontal wind divergence. This divergence removes air horizontally in the upper troposphere. It is because of this wind divergence that the vertical integrity of the tropical system can be maintained. Without the upper tropospheric divergence the system would fill up because of the lower level convergence and latent heat release. As dealt with in chapter 2 in MITS the average wind is first computed in the 200-300hPa layer before divergence is calculated. The average 200-300hPa wind is used here to smooth the wind field before divergence is calculated.

3.1.4 Average total static energy (TSE).

*Average TSE in the 850-300hPa layer should exceed 330 * 10^3 J kg^{-1}. Tight horizontal gradients of TSE identify a zone of air mass change.*

It is common practice for forecasters to use the equivalent potential temperature to pinpoint areas where the properties of an air mass are changing by searching for tight gradients of equivalent potential temperatures. This is used with particular success in identifying and forecasting cold fronts invading South Africa from the southwest. Holton (1992) states that an alternative to the equivalent potential temperatures is TSE (also referred to as moist static energy). This is particularly applicable when convection is studied. TSE is the total energy within an atmospheric parcel of air but neglecting the small kinetic energy value (Triegaardt et al., 1991) and is computed by: $TSE = C_pT + gz + Lq$, where C_p is the specific heat of dry air, z is the geopotential height, L the latent heat of condensation and q the specific humidity. The first term on the right hand side of the equation represents the enthalpy, the second term the geopotential and the third term the latent energy. In an atmosphere where above normal upper tropospheric temperatures occur, as is the case in a tropical atmosphere, the contribution of the enthalpy will be to increase the TSE values. The high geopotential heights in the upper troposphere in a tropical weather system will in turn increase the geopotential. The contribution of the latent energy in a tropical atmosphere will also be to increase the TSE because of the high moisture content of the air. In MITS the average TSE is computed in the 850-300hPa layer. This is done in order to capture the contribution of the water vapour in the lower troposphere, as well as the contribution of the above normal temperatures and geopotential heights in the upper troposphere. Research for this dissertation has shown that TSE values greater than 330 * 10^3 J kg^{-1} is indicative of tropical circulation over southern Africa.

3.1.5 Deep cumulus convection and vertical motion.

Upward motion ought to be present from 700 to 400hPa, the atmosphere should be conditionally unstable up to 400hPa and precipitable water values exceed 20 kg m^{-2}.

Holton (1992) reported that in Pacific Ocean equatorial disturbances convergence occurs up to 400hPa and is then replaced by strong wind divergence above this level. The continuity equation (Holton, 1992) expresses the relationship between horizontal wind divergence and change of omega ($\omega = \frac{dp}{dt}$) with pressure $\frac{\partial \omega}{\partial p} = -\overline{\nabla}_p \bullet \overline{V}$. If $\overline{\nabla}_p \bullet \overline{V} < 0$ (convergence) then $\frac{\partial \omega}{\partial p} > 0$ which means that ω decreases (increases) with height (pressure). Where convergence occurs in the lower and middle troposphere ω should decrease with height, which means, that because of the negative relationship, upward motion must increase with height. Above 400hPa ω increases with height in association with the upper tropospheric divergence. An important component of MITS is to isolate those areas where upward motion exists from 700hPa to 400hPa. The interior of South Africa is approximately 1500 m above sea level which means that the 700hPa level is approximately 1500 m above the surface and is still representative of the lower troposphere. The 700hPa level is also close to the summer convective cloud base level.

The vertical distribution of TSE is used to investigate the conditional instability of the atmosphere. Harrison (1988) explained that a conditional unstable atmosphere is required for deep cumulus convection. A typical vertical profile of TSE indicating conditional instability is depicted by figure 3.1. TSE decreases from the surface up to approximately 500hPa and then increase steadily with height. The dashed line in figure 3.1 is the surface value of TSE and is reached again only as high as at the 200hPa level. This means that the atmosphere is conditionally unstable and deep cumulus convection is possible up to 200hPa. In MITS it is required that deep convective development should be possible up to at least 400hPa and that the surface value of TSE is the value at 850hPa.

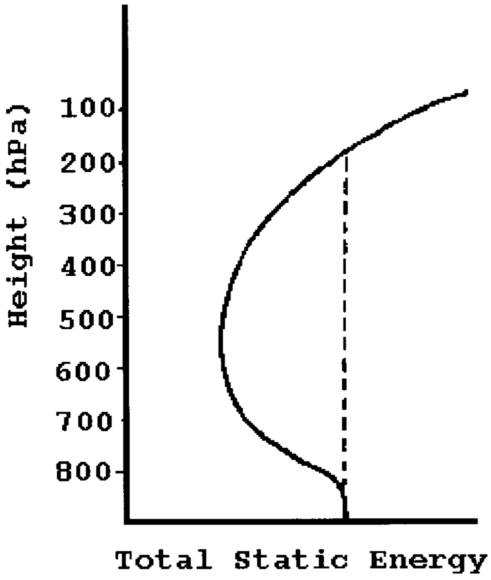

Figure 3.1: **A typical vertical profile of total static energy associated with deep convection. The dashed line is the upward projection of the surface energy value (after Harrison, 1988).**

When the atmosphere is conditionally unstable up to 400hPa and upward motion occurs in the 700-400hPa layer, atmospheric conditions are favourable for the development of extensive convective precipitation. Experimental results obtained in this research indicate that if the other two parameters, discussed in this paragraph, are favourable rainfall is probable from tropical weather systems when precipitable water in the 850-300hPa layer exceeds 20 kg m^{-2}. Therefore when the three variables mentioned here occur simultaneously convective rainfall is likely.

3.1.6 Summary

A great deal of interaction exists between the five components of MITS. It may seem like duplication to use all of them. There are two reasons why this is done. Firstly one has to consider that MITS was developed for operational meteorologists and it is important to make sure that the dynamical properties of a tropical atmosphere is illustrated in a manner which is easy to understand. A 200hPa high probably exists somewhere over Southern Africa each day (and will necessarily be associated with above normal column temperatures). However only a few upper tropospheric highs are tropical and develop because of latent heat release. It is illustrated to the forecasters, by various means, that if this high is associated with high water vapour, high values of TSE and conditional instability tropical circulation dominates. The second reason for the inclusion of all five components in MITS is to lead the forecaster step by step to the final component where a single field is generated which indicates areas where convective rainfall is probable. In the Tropical Heavy Rainfall Identification System (THERIS), discussed in the next section of this chapter, a similar approach is followed. It is important that the forecasters are made aware of the principles underlying the design of THERIS so that it can be used with confidence. MITS is discussed in some detail in chapter 4. A practical operational example of MITS is provided in chapter 5.

3.2 TROPICAL HEAVY RAINFALL INDENTIFICATION SYSTEM (THERIS).

The second aim of the dissertation is to identify areas where heavy rainfall is likely when tropical weather systems dominate the atmospheric circulation. Poolman (1999) has shown that most heavy rainfall events in South Africa occur over the eastern half of the country and during the summer rainfall season (October to March). It is during this time of the year that the Inter Tropical Convergence Zone (ITCZ) extends southwards over Africa and tropical weather systems frequently invade South Africa (Taljaard, 1994). Numerous examples of tropical weather systems causing heavy rainfall and floods over South Africa exist. Such were the tropical temperate troughs of February 1988 (Triegaardt et al., 1991) and 1996 (De Coning et al., 1998) as well as in 1984 when tropical cyclones Domonia and Imboa caused exceptional rainfall over Kwazulu-Natal and

Swaziland (Poolman and Terblanche, 1984). As recently as February 2000 two tropical weather systems caused unprecedented rain over northeastern South Africa and Mozambique (Dyson and Van Heerden, 2000). Independent research by Alexander and Van Heerden (1991) and Poolman (1999) has shown that the frequency of heavy rainfall events over South Africa has increased towards the end of the 20th century. It is therefore imperative to design an early warning system for heavy rainfall associated with tropical weather systems over South Africa.

During a severe weather event tremendous pressure is placed on the operational meteorologist in the central forecasting office (CFO) in Pretoria. It is the responsibility of the senior forecaster in CFO to issue forecasts for South Africa and neighbouring countries (Swaziland, Lesotho, Botswana and Namibia). During the occurrence of severe weather events there is a tremendous increase in telephonic enquiries and requests for weather forecasts. As a result a great deal of the operational meteorologist time is taken up by these peripheral duties leaving a very small amount of time for the analysis of model products and weather maps in order to issue forecasts. During the heavy rainfall of February 2000 forecasters in CFO also had to issue aviation forecasts for the rescue efforts conducted in Mozambique by the international community (Scholz, 2000).

The Tropical Heavy Rainfall Identification System (THERIS) was designed to give the operational meteorologist immediate access to a single field where areas of forecast heavy rainfall are likely. THERIS, to a large extent, makes use of the same principles used in the design of MITS but placing additional constraints on the atmospheric dynamics to isolate those areas where heavy rainfall from tropical weather systems are likely. THERIS applies the following conditions referred to here as 'components'.

1. The precipitable water values in the troposphere should exceed 20 kg m^{-2}.
2. Wind divergence must be present in the upper troposphere.
3. Average TSE values in the troposphere should exceed 335 * 10^3 J kg^{-1}.
4. The atmosphere must also be conditionally unstable up to at least 300hPa
5. Upward motion must exist from 700hPa to 300hPa.
6. Maximum upward vertical motion should occur below the 300hPa level.

A single field is generated to isolate areas where all these conditions are met simultaneously. It is important that the components are not considered individually to identify areas of heavy rainfall. Although all the components do play an important role in the production of heavy rainfall, research conducted for this dissertation indicated that it is only in those areas where all the components co-exist that heavy rainfall is likely to occur.

3.2.1 Precipitable water values in the troposphere should exceed 20 kg m^{-2}.

Precipitable water was dealt with in the previous section of this chapter. The critical value of 20 kg m^{-2} was determined by experiments conducted during this research. It should be kept in mind that this variable alone does not identify heavy rainfall areas.

3.2.2 Average wind divergence in the 300-200hPa layer.

In paragraph 3.1.3 the average wind in the 300-200hPa layer is computed before the wind divergence is calculated. This average wind divergence is responsible for maintenance of the vertical integrity of a tropical weather system. In THERIS the average wind divergence in the upper troposphere points to the probability of tropical circulation but is also a mechanisms for maintaining and enhancing the upward motion in the lower and middle troposphere.

3.2.3 Average TSE values in the troposphere should exceed 335 * 10^3 J kg^{-1}.

In MITS (3.1.4) it was stipulated that an average TSE value exceeding 330 * 10^3 J kg^{-1} is indicative of tropical circulation. In THERIS the average value of TSE is set somewhat higher and should exceed 335*10^3 J kg^{-1}. This additional condition on the average TSE value in the troposphere is stipulated to isolate those areas where the combination of the entrophy, geopotential and latent energy peaks. Experimental results obtained by the author show that the critical value of 335 * 10^3 J kg^{-1} could be applied to assist in identifying areas of heavy rainfall.

3.2.4 The atmosphere must be conditionally unstable up to at least 300hPa.

As was the case in MITS the vertical profile of TSE can be used to identify a conditionally unstable atmosphere. In THERIS it is expected that the atmosphere is conditionally unstable up to at least the 300hPa level, this is 100hPa higher than the level stipulated in MITS. If the atmosphere is conditionally unstable up to 300hPa then deep cumulus convection is possible up to the upper troposphere and convective cloud developing under these conditions will probably extend vertically to the tropopause. This is exactly what needs to be achieved for the development of heavy rainfall from a tropical system. Rodgers and Yau (1989) stated that the likelihood of precipitation in cumulus clouds increases with cloud thickness. Also, Triegaardt et al., (1991) found that in the areas of heavy rainfall in February of 1988 the atmosphere was conditionally unstable up to the 100hPa level.

3.2.5 Upward motion should exists from 700 to 300hPa.

As in the case with conditional instability in THERIS it is required that upward motion should exist up the 300hPa level. In MITS it is stipulated that upward motion only up to the 400hPa level is adequate. To sustain the upper tropospheric high pressure in the 200-300hPa layer it is important that heat is transported in the vertical by Riehl's (1979) 'energy tubes'. Experimental results in this dissertation indicate that convective showers are still possible even if upward motion stops between 400hPa and 300hPa. These clouds can still produce significant rain but the heavy rainfall generally occurs in isolated pockets.

In order to provide an environment favourable for the development and sustenance of hot towers extending up to near the tropopause requires that synoptic scale upward motion exist up to and above the 300hPa level. Examples of the vertical distribution of omega depicted by figures 4.2.7 and 4.3.7b show a deep mid–tropospheric layer with negative values of ω or small values of $\frac{\partial \omega}{\partial p}$.

From the continuity equation small values of $\frac{\partial \omega}{\partial p}$ means that small values of the horizontal wind divergence exist in this layer. However both of these figures as well as figure 4.1.7 have negative omega values extending to beyond the 200hPa level. More importantly in all of these figures the values of $\frac{\partial \omega}{\partial p}$ are minimised (rapid decrease of upward motion with height) to well above the 300hPa level. This requires that horizontal wind divergence starts from the 400hPa level and reach maximum values at levels above the 300hPa level. The hot towers provide the sensible heat sustaining the upper tropospheric high while the horizontal wind divergence, at these levels, provides the mechanism to maintain the system's vertical integrity and the upward motion required for copious rainfall.

3.2.6 Maximum uplift should occur below the 300hPa level.

Following the arguments presented in paragraph 3.2.5 it can be reasoned that in order to have a deep upper tropospheric diverging layer requires large negative values of $\frac{\partial \omega}{\partial p}$ in this layer. It therefore follows that the minimum value of ω should occur below the 300hPa level in order to satisfy the requirement $\frac{\partial \omega}{\partial p} << 0$ above 300hPa. However if the minimum ω values occur above the

300hPa level the depth of the upper tropospheric diverging layer will decrease. If this happens it is argued that the horizontal wind divergence may fail to remove sufficient heat and mass from the upper troposphere, which will result in the lower tropospheric low filling up. This should result in a rapid decrease of upward motion and a collapse of the tropical system.

3.2.7 Summary

The six components of THERIS were chosen to identify heavy rainfall in a tropical atmosphere. All the components should co-exist before an area of heavy rainfall is predicted. The constraints placed on the atmospheric dynamics by the six components are strict and because of these constraints not all of the areas where heavy rainfall occur are positively identified. Although this is not the ideal situation one of the aims of THERIS was to limit the number of false alarms of heavy rainfall. This is achieved to a large extent as will be discussed in the subsequent chapters.

To summarise it can be stated that this research indicated that the production of heavy rainfall in a tropical atmosphere is very sensitive to upward motion and wind divergence in the layer above 400hPa. The author is of the opinion that decreasing upward motion and associated horizontal wind divergence is required to maintain the vertical integrity of the tropical system. The minimum value of omega should also be reached below the 300hPa level.

CHAPTER 4
CASE STUDIES

Three case studies are detailed here to illustrate the association and differences between tropical and baroclinic weather systems over South Africa by concentrating on their individual dynamical characteristics. Case studies described are 21 February 1988, 7 July 1996 and 25 January 1981. The three case studies are representative of weather systems causing heavy rainfall and other severe weather conditions over the southern part of the African subcontinent. With the exception of the 7th of July 1996 case study the weather events have been documented and analysed thoroughly by others. The aim of this research is not to do a detailed analysis of the synoptic circulation patterns responsible for the heavy rainfall. Nevertheless, a short summary of the rainfall distribution, as well as the atmospheric circulation patterns which prevailed, is provided. The emphasis of this research is placed on the dynamical properties of the heavy rain producing weather system with a view to making these parameters accessible to an operational meteorologist. MITS (Model for the Identification of Tropical Weather Systems) is described while THERIS (Tropical Heavy Rainfall Identification System) is tested and verified against actual rainfall data. This product should greatly enhance the operational meteorologist's ability to pinpoint areas where heavy precipitation is possible.

The first case study, 21 February 1988, illustrates the tropical nature of the atmospheric dynamics while the second case study, 7 July 1996, will give insight into a typical baroclinic weather system, in this case a COL. The third case study, 25 February 1981, depicts the interaction between tropical and baroclinic weather systems when a COL was situated off the southwestern coast of South Africa while tropical air dominated the circulation over the central parts of the subcontinent.

4.1 CASE STUDY 1: THE TROPICAL SYSTEM OF 21 FEBRUARY 1988.

4.1.1 Introduction.

This case study illustrates that if all the appropriate dynamical parameters are taken into consideration then areas of heavy precipitation in a tropical atmosphere can in fact be pinpointed. The atmospheric circulation in case study 1 is a classical example of a tropical weather system. MITS parameters (described in chapter 3) are applied in considerable detail here. THERIS is also tested on the circulation prevailing on the19th - 21st of February 1988.

During February of 1988 extreme rainfall occurred over large areas of Southern Africa. Widespread flooding occurred and Bloemfontein was isolated from the outside world, except by air, as connecting routes were washed away or flooded (Triegaardt et al., 1991). Almost the entire summer rainfall area of South Africa received well above the average February rainfall. Over the central interior rainfall was exceptionally heavy with the recorded monthly rainfall between 4 and 6 times the mean February rainfall. Bloemfontein Airport received 530 mm of rain during February 1988. Over the southern Free State, De Wetsdorp reported 442 mm, Trompsburg 417 mm, Jamestown 461 mm, Buffelsfontein 409 mm and Danielskuil 512 mm. Unprecedented heavy rain also fell over the Northwest Province (Stella 448 mm) and Northern Cape. The flood producing rainfall occurred in a relatively short period from the 19th to 22nd of February 1988 (Triegaardt et al., 1991).

Jury et al. (1993) and Lindesay and Jury (1991) speculated that the weather system responsible for the heavy rainfall was a tropical-temperate trough. The sea surface Indian Ocean High (IOH) was situated to the east of the southern subcontinent with a deep low-pressure system over Botswana. These systems extended vertically throughout most of the troposphere and were responsible for maintaining an anomalous easterly flow over the eastern parts of the subcontinent and through most of the troposphere. The atmospheric circulation during the period 19th to 22nd February is a typical example of moist tropical air advected at the surface beneath a low in the upper air. A very important feature for the production of the heavy rainfall from the 19th to 22nd of February was that the prevailing weather systems remained virtually stationary during this period. The low-pressure system over the central interior only started to weaken when a mid-latitude trough moved south of the country on the 23rd (Lindesay and Jury, 1991 and Triegaardt et al., 1991).

The synoptic circulation on the 21st of February 1988 is considered representative of the atmospheric circulation during this heavy rainfall event and is used here to illustrate the tropical nature of the atmospheric dynamics.

4.1.2 Rainfall.

Table 4.1.1 lists 24-hour rainfall totals on the 21st of February 1988 at a few rainfall stations. Two of them in Bloemfontein had rainfall in excess of 300 mm. The other 7 stations all had more than 200 mm and are close to Bloemfontein. Figure 4.1.1 displays the geographical distribution of the rainfall. On this day the central interior received widespread rainfall with 24-hour rainfall totals in excess of 50 mm mainly over the western Free State and surrounding areas. The escarpment of the Eastern

Cape, Kwazulu-Natal and Mpumalanga Provinces also had significant falls but only in isolated patches.

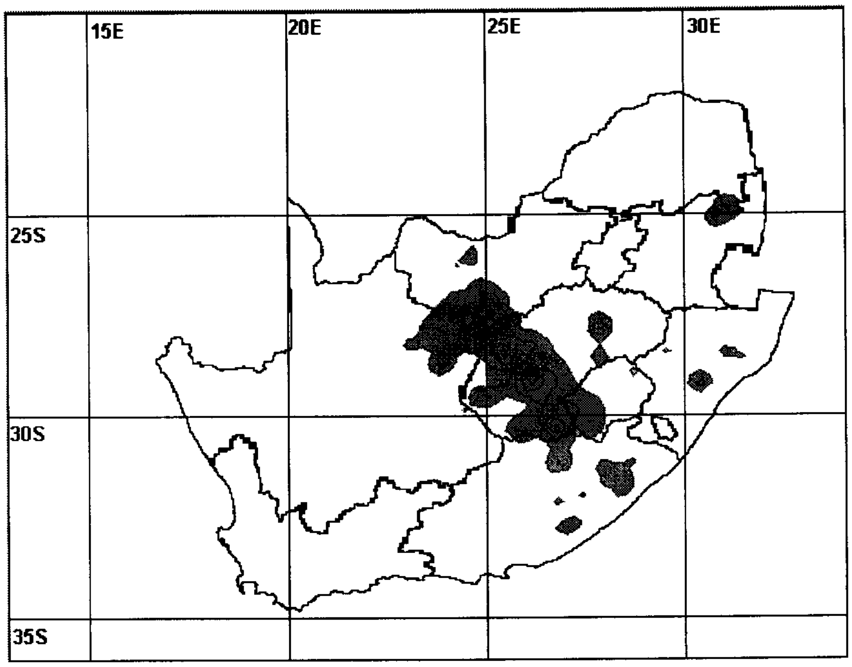

Figure 4.1.1: Rainfall totals, in mm, over South Africa for 21 February 1988. Isohyet spacing is 50 mm.

Latitude (° S)	Longitude (° E)	Rainfall (mm)	Place
29.1	26.2	311	Bloemfontein Hamilton
29.1	26.2	310	Bloemfontein Zoo
28.7	25.8	284	Dealesville
29.0	26.1	283	Bainsvlei
30.4	26.8	266	Rouxville
29.5	26.6	259	Baden
27.8	24.7	246	Pampierstad
30.2	26.5	237	Smithfield
27.7	25.4	210	Holfontein

Table 4.1.1: 24-hour rainfall exceeding 200 mm for 21 February 1988

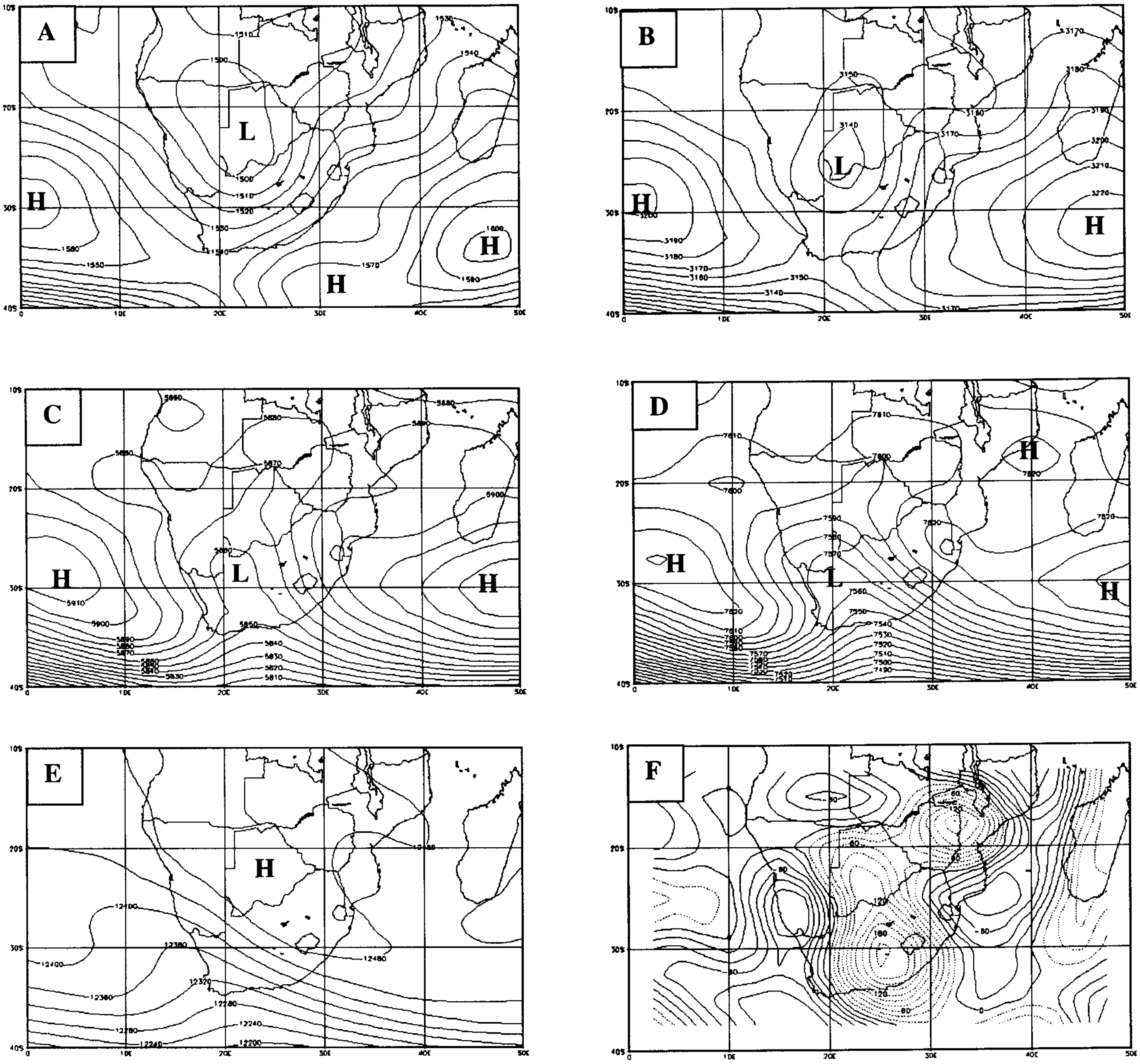

Figure 4.1.2: The topography of the 850, 700, 500, 400 and 200 hPa pressure surfaces for 21 February 1988, shown in A, B, C, D and E respectively. The contours are labelled in geopotential meters. Figure F displays the wind convergence (solid lines) and divergence (dashed lines) at the 200 hPa pressure surface, units multiplied by 10^{-6} meters per second.

4.1.3 Synoptic circulation and dynamical characteristics.

Figure 4.1.2 depicts the low, middle and upper air circulation pattern on 21 February. The main feature is the closed low centred over Botswana on the 850hPa level (Fig. 4.1.2a). The IOH to the southeast of Southern Africa is advecting moist tropical air from the Mozambique Channel to the eastern and central interior of South Africa. The inflow of tropical moist air below the upper air divergence (Fig. 4.1.2f) was of paramount importance in the production of the heavy rainfall. Figure 4.1.2b shows that the closed low is maintained at 700hPa although it is displaced slightly southward. At 500hPa (Fig. 4.1.2c) and 400hPa (Fig. 4.1.2d) the low becomes a sharp trough and continues its southwestward displacement as it becomes entrained in the westerly flow extending northwards from the mid-latitudes. However, at the 500hPa and 400hPa pressure levels a secondary trough is extending northeastwards over Botswana and at approximately the same position as the closed low at 850hPa. Figure 4.1.2e shows that the 200hPa upper air trough is west of South Africa while a strong ridge over central Botswana displaces the closed low at 850hPa. The first criterion of MITS as detailed in chapter 3 is met over Botswana.

Figure 4.1.2f portrays the wind divergence at 200hPa. Large values of wind divergence, indicated by the dotted lines, is present over the central parts of the southern subcontinent with a maximum value (200^*10^{-6} s^{-1}) at approximately 30°S 25°E, directly above the area of maximum rainfall (Table 4.1.1). Synoptic scale values of wind divergence are in the order of 10^{-6} s^{-1} (Holton 1992). Here we are dealing with divergence at last two orders of magnitude larger. Furthermore a comparison between the 200hPa wind divergence (Fig 4.1.2f) and geopotential heights (Fig. 4.1.2e) shows that the wind divergence reached a maximum east of the 200hPa upper trough with a secondary maximum near the ridgeline, which is situated over Botswana.

Considering the 500-300hPa average column temperatures (Fig. 4.1.3) it is noteworthy that the highest average temperatures (greater than –16° C) occurred in the vicinity of the 200hPa upper air ridge. There is a rapid drop in average column temperatures towards the southwestern coast where temperatures are less than –20 °C and these corresponding to the position of the 200hPa upper air trough illustrated in figure 4.1.2. A tight gradient of column average temperature exists between the warm core over Botswana and the cold core over the southwestern Cape. According to Holton (1992) the existence of a strong horizontal temperature gradient is required to maintain the thermal wind and the existence of a thermal wind is indicative of a baroclinic atmosphere. On the other hand the average column temperature gradient eastwards between the warm core over Botswana and Mozambican regions is considerably less. Although the atmosphere must in the

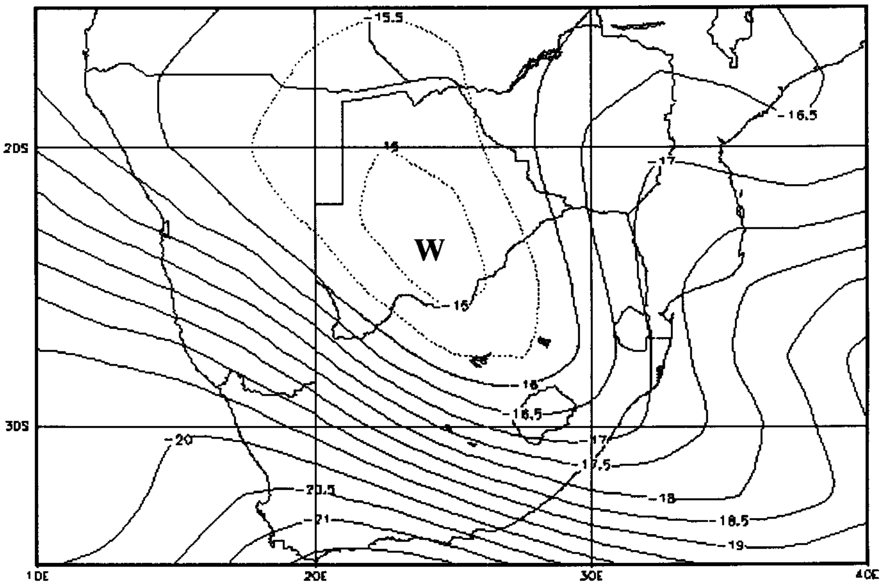

Figure 4.1.3: Average 500-300 hPa column temperatures on 21 February 1988. Temperatures are in degrees Centigrade. Dashed lines indicate temperatures greater than -16 degrees Centigrade.

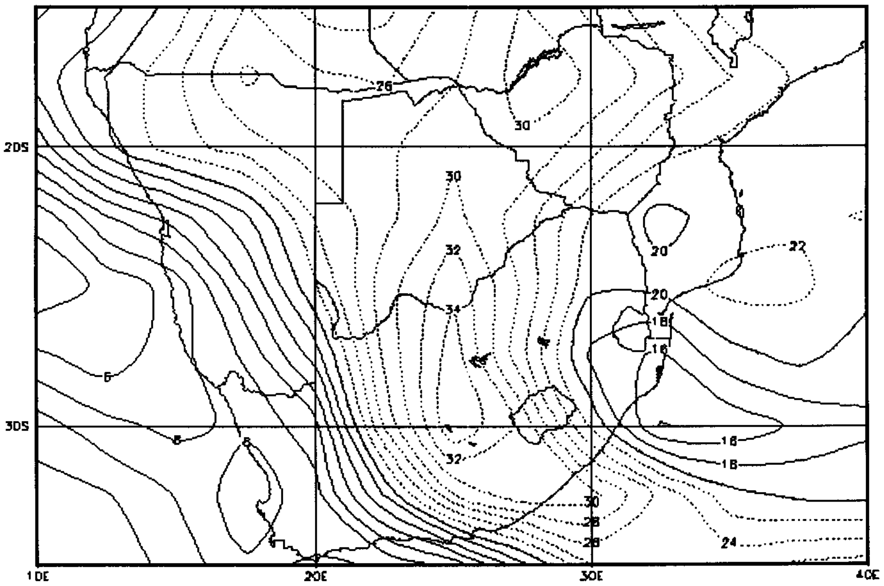

Figure 4.1.4: Precipitable water in the 850-300 hPa layer on 21 February 1988 in units of kg m^{-2}. Dashed lines indicate precipitable water values greater than 20 kg m^{-2}.

strictest sense still be classified as baroclinic over this area it is clear from the weak average column temperature gradient distribution that the atmosphere is becoming less baroclinic. This is so despite the fact that a reversal of flow occurs between the 400- and 200hPa levels over the eastern sub-tropical regions. The second criterion of MITS is met and is clearly illustrated by figure 4.1.3

The pricipitable water (in units of kg m $^{-2}$) in the layer bounded by 850hPa and 300hPa is shown in figure 4.1.4. Values greater than 20 kg m $^{-2}$ (indicated by dotted lines) shows a remarkable correspondence to the positive wind divergence at 200hPa (Fig. 4.1.2f). The maximum values of pricipitable water occur in a band over the central interior of South Africa extending a tongue into southern Botswana. Comparing this to figure 4.1.1 it is apparent that the maximum rainfall occurred in the same band. This distribution of the high values of pricipitable water is understood if figures 4.1.2a and b are compared. They show the transport of low-level moist tropical air into the central interior of South Africa from the northeast. Considering the position of the ridge of high pressure at 200hPa (Fig 4.1.2e) in association with the positive wind divergence (Fig 4. 1.2f), and the high values of precipitable water, it is clear that this warm thermal high can also be classed as a moist diverging high. The third criterion of MITS is also satisfied.

The average total static energy (TSE) of the 850-300hPa layer is shown in figure 4.1.5. Values larger than 335 $*10^3$ J kg^{-1} (dotted lines) occur over the central interior of South Africa, Botswana and Zimbabwe. In chapter 3 the TSE is defined as the sum of the enthalpy, geopotential and latent heat. The high values of average TSE on the 21st of February 1988 are due to a combination of the presence of the moist air in circulation (potential of latent heat release), anomalously high temperatures in the upper troposphere (enthalpy) and the upper tropospheric ridge of high pressure (geopotential). The fourth MITS criterion stating that the average TSE values in the troposphere should exceed 330 $* 10^3$ J kg^{-1} is therefore also met.

Figure 4.1.6 portrays the vertical distribution of TSE at Bloemfontein (more than 300 mm rain in 24-hours). This vertical distribution of TSE is a typical example of a conditionally unstable atmosphere (Triegaardt et al., 1991). The TSE decreases with height up to 500hPa although there is an insignificant increase in TSE values between 700 and 600hPa. From 500 to 300hPa there is a steady increase in TSE but the value at 850hPa remains greater than the 300hPa value. This means that the layer of deep convection is higher than the 300hPa level and is indicative of atmospheric conditions favourable for the development of convective cloud.

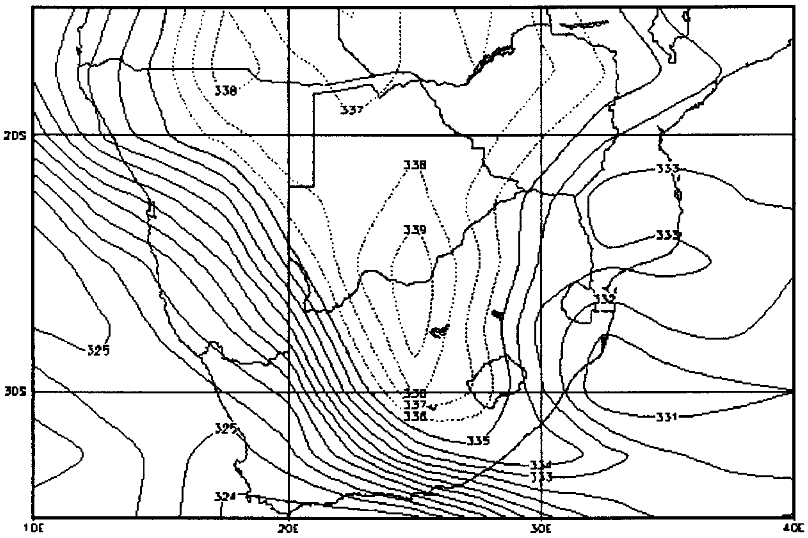

Figure 4.1.5: Average total static energy of the 850-300 hPa layer on 21 February 1988, in units of 10^3 J kg $^{-1}$. Dashed lines indicate values greater than 335 * 10^3 J kg^{-1}.

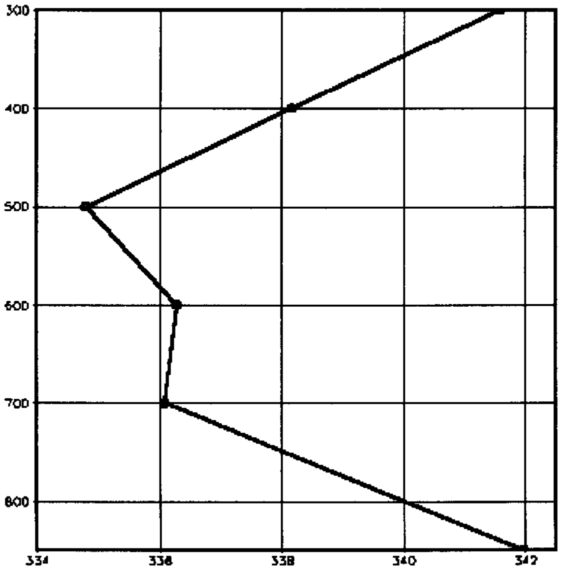

Figure 4.1.6: Vertical distribution of total static energy (10^3 J kg^{-1}) on 21 February 1988 at 29° S 26° E (near Bloemfontein).

The vertical distribution of omega (pseudo vertical motion), near Bloemfontein, as illustrated by figure 4.1.7, is a further indication of favourable atmospheric conditions for the development of rain producing cloud structures. The air is ascending throughout the troposphere with values close to zero at the surface (850hPa) as well as at 100hPa. Maximum uplift occurs at 400hPa with a value of approximately –0.4 Pa s^{-1}. An investigation of figures 4.1.3, 4.1.6 and 4.1.7 show that the 5th criterion of MITS exists. Convective development did indeed take place in the area close to Bloemfontein, as was indicated by MITS.

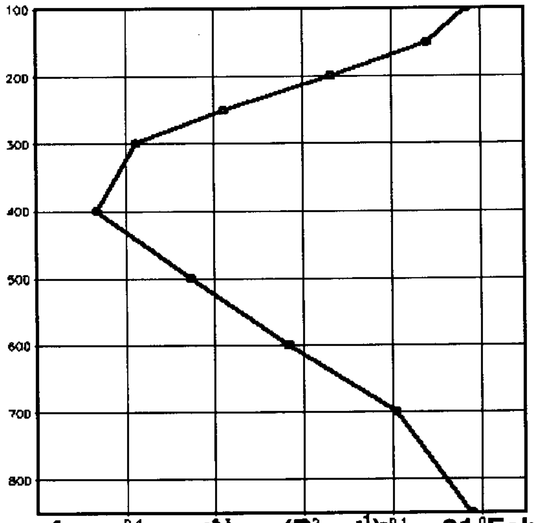

Figure 4.1.7: Vertical distribution of omega values (Pa s^{-1}) on 21 February 1988 at 29° S 26° E (near Bloemfontein).

4.1.4 Performance of THERIS.

The result of the Tropical Heavy Rainfall Identification System (THERIS) as described in chapter 3 is depicted in figure 4.1.8. The areas where heavy rainfall is predicted are indicated by the shaded rectangles. Two regions of potential heavy rainfall are identified. The first region stretches from northeastern Namibia over western Botswana to the central interior of South Africa. The second region extends across western Zimbabwe. Failure to obtain rainfall data for regions outside of South Africa made it impossible to evaluate THERIS outside South Africa. The heavy rainfall area (indicated by 1 on Fig. 4.1.8) but within the borders South Africa will be used to evaluate THERIS.

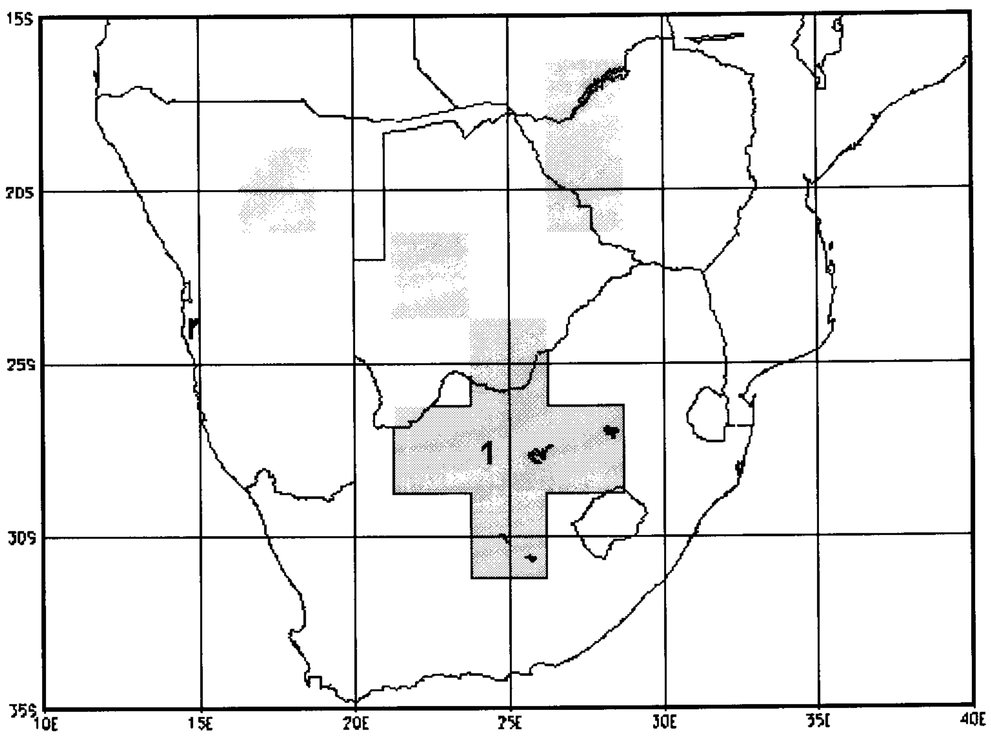

Figure 4.1.8: THERIS results for 21 February 1988. The shaded blocks indicate areas where heavy rainfall is predicted.

Weighted average rainfall	34 mm
Weighted percentages of stations with more than 0mm of rainfall	84 %
Weighted percentages of stations with more than 10mm of rainfall	64 %
Weighted percentages of stations with more than 20mm of rainfall	50%
Weighted percentages of stations with more than 50mm of rainfall	24 %

Table 4.1.2: Weighted average rainfall and weighted percentages for Area 1 on 21 February 1988.

Area 1 in figure 4.1.8 encompasses the Northwest Province (with the exception of the northeastern parts), the western and northern Free State as well as the extreme eastern parts of the Northern Cape. The weighted average rainfall in area 1 as well as the weighted percentages as described in chapter 2 is shown in Table 4.1.2. The weighted average rainfall over area 1 is 34 mm with 84% of the stations in the area getting rain. 64% of the all the stations had more than 10 mm rain with 50% of the stations getting more than 20 mm. At 24% of the stations more than 50 mm of rain fell. Comparing these results with figure 4.1.1 it becomes clear that the area of predicted heavy rainfall is validated. However rainfall over the northern Free State was generally light and occurred in isolated patches.

Rainfall totals in excess 50 mm over the escarpment of the Eastern Cape, Kwazulu-Natal and Mpumalanga are not identified by THERIS. The rainfall in these areas is most probably due to orographic uplift and not because of the tropical circulation alone.

4.1.5 Summary and conclusions

The heavy rainfall over the central interior of South Africa on the 21st of February 1988 was due to a combination of abundant water vapour carried by the tropical air at the surface underneath the maximum upper air divergence and in a conditionally unstable atmosphere.

Figure 4.1.2 illustrates the interaction between the tropical circulation over the central interior and the mid latitude weather system over the southwestern Cape in the upper troposphere. The steep 200hPa-geopotential gradient between the approaching trough and the thermal high over the central interior was responsible for the high values of positive wind divergence at this level. However, the tropical nature of the atmospheric circulation was maintained over the central interior as is illustrated with the low over Botswana maintaining its identity in the vertical up to 400hPa and becoming a ridge of high pressure at 200hPa, typical of tropical weather systems. This high developed because of the release of latent heat of condensation resulting in above normal temperatures in the upper troposphere. High values of precipitable water in a conditionally unstable atmosphere made conditions favourable for the development and maintenance of the deep convective cloud system.

The tropical and dynamically induced heavy rainfall over the central parts of South Africa was captured quite well by THERIS.

4.1.6 Performance of THERIS on the 19th and 20th of February 1988.

Figure 4.1.9a and b depicts the result of THERIS on the 19th and 20th of February respectively. On the 19th an extensive area of potential heavy rainfall is identified from Namibia, over Botswana to the central interior of South Africa. The area indicated by 1 on figure 4.1.9a, confined within the borders of South Africa, is compared with actual rainfall data. The weighted average and weighted percentages are given in table 4.1.3a. The average rainfall in area 1 is 28 mm and 72% of all the stations received rain. At 51% of the stations more than 20 mm of rain fell and 19% of the stations reported more than 50 mm rain.

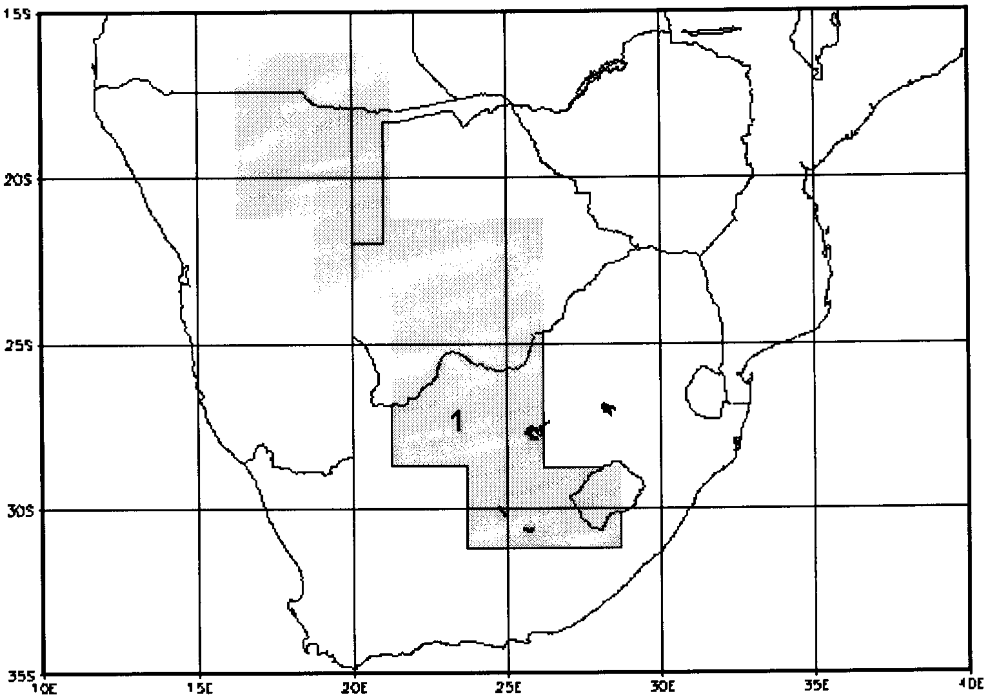

Figure 4.1.9a: THERIS results for 19 February 1988. The shaded blocks indicate areas where heavy rainfall is predicted.

Weighted average rainfall	28 mm
Weighted percentages of stations with more than 0mm of rainfall	72 %
Weighted percentages of stations with more than 10mm of rainfall	57 %
Weighted percentages of stations with more than 20mm of rainfall	51%
Weighted percentages of stations with more than 50mm of rainfall	19 %

Table 4.1.3a: Weighted average rainfall and weighted percentages for Area 1 on 19 February 1988.

On 20 February the predicted heavy rainfall area shifted slightly eastwards now covering most of Botswana. Over South Africa the area of potential heavy rainfall was virtually the same as on the

19th of February. A new area of potential heavy rainfall was also indicated over northern Zimbabwe. Table 4.1.3b list the weighted average rainfall and percentages for area 1 on figure 4.1.9b. Extensive and heavy rainfall occurred in area 1 on the 20th of February. The weighted average rainfall in area 1 was 50 mm with close to 90% of the stations getting some rain. 64% of the stations received rain in excess of 20 mm and at 40% of the stations more than 50 mm of rain fell.

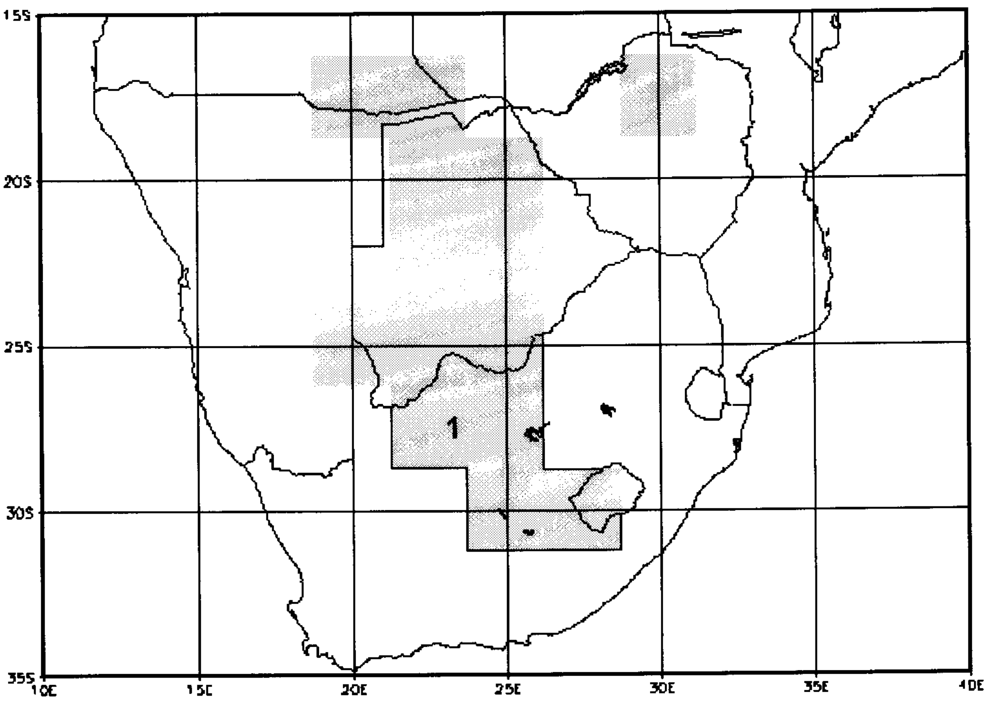

Figure 4.1.9b: **THERIS results for 20 February 1988. The shaded blocks indicate areas where heavy rainfall is predicted.**

Weighted average rainfall	50 mm
Weighted percentages of stations with more than 0mm of rainfall	88 %
Weighted percentages of stations with more than 10mm of rainfall	73 %
Weighted percentages of stations with more than 20mm of rainfall	64%
Weighted percentages of stations with more than 50mm of rainfall	40 %

Table 4.1.3b: Weighted average rainfall and weighted percentages for Area 1 on 20 February 1988.

THERIS faired quite well on the 21st did very well on the 19th but the results on the 20th were excellent, exceeding all expectations. The reason for the devastating floods over the central interior of South Africa is also understood if figures 4.1.8 and 4.1.9 are analysed. For at least three days the area where heavy rainfall was predicted over central South Africa remained more or less the same. The average rainfall over the areas identified by THERIS for the three days varied between 28 and 50 mm.

4.2 CASE STUDY 2: THE WINTER BAROCLINIC SYSTEM OF 7 JULY 1996.

4.2.1 Introduction.

This case study is indicative of a baroclinic weather system. The differences between tropical and baroclinic circulations are clearly illustrated by comparing the dynamical characteristics of this case study with the first case study. It is shown how the criteria of MITS are generally not met. No doubts remain in identifying the baroclinic nature of the weather system.

July 1996 was ranked as the coldest and wettest winter month over South Africa for at least ten years (Strydom and Nel, 1996). Widespread rainfall occurred over the entire country with large areas of the subcontinent receiving more than twice the mean July rainfall. The monthly rainfall totals over the eastern interior varied between 20 mm and 30 mm, which can in no way be classified as heavy rainfall except that this is a summer rainfall area. Pietersburg, in the Northern Province, had 28 mm rain with a long-term average rainfall for July of only 5 mm (South African Weather Bureau, 1984). Bloemfontein, in the Free State, where 33 mm rain occurred has a July average of 9 mm (South African Weather Bureau, 1984). However monthly rainfall totals greater than 50 mm were confined to Kwazulu-Natal and the eastern Free State. Durban and Bethlehem had 261 mm and 58 mm respectively.

Heavy snowfalls occurred on the 6th and 7th over the Maluti and Drakensburg mountains. The snow covered a wide area. The high ground over Kwazulu-Natal was covered with snow and the trans-escarpment road routes were all closed. The escarpment of Mpumalanga and the Northern Province also had exceptional snowfall. Tzaneen, in the Northern Province, lies in a subtropical climatic region (Schulze, 1965) and is known for its mild winter temperatures. Snow on the mountains close to Tzaneen is a very rare and noteworthy event (Strydom and Nel, 1996).

The severe weather events on the 6th and 7th of July were caused by a mid-latitude cyclone containing a potent cold front moving over South Africa with a strong (1032hPa) Atlantic Ocean

High (AOH) ridging eastward south of the country behind this front. Very cold maritime air was advected over South Africa ahead and beneath a COL in the upper troposphere. This interaction resulted in the deepening of the COL and provided mechanisms for widespread rain- and snowfalls (Strydom and Nel, 1996).

Heavy rainfall over Kwazulu-Natal generally occurs when a strong AOH is situated south of Durban causing a sustained inflow of moist maritime air over the southeastern parts of South Africa. Triegaardt et al., (1988) suggested that this on-shore flow is the main factor responsible for heavy rainfall in this area, irrespective of the upper tropospheric circulation. In a modelling study by Tennant and Van Heerden (1994) they showed that the unique topographical features of Kwazulu-Natal (the escarpment rises to 3000m within 170km of the coast) plays a dominant role in the development of a COL, its associated surface convergence, upper air divergence and mid-tropospheric vertical motion. De Villiers (1992) did a detailed analysis of heavy rainfall events over Kwazulu-Natal and stressed the importance of the AOH south of the country when a COL moves or develops over the central interior of South Africa. Precisely this situation existed on the 7th of July 1996.

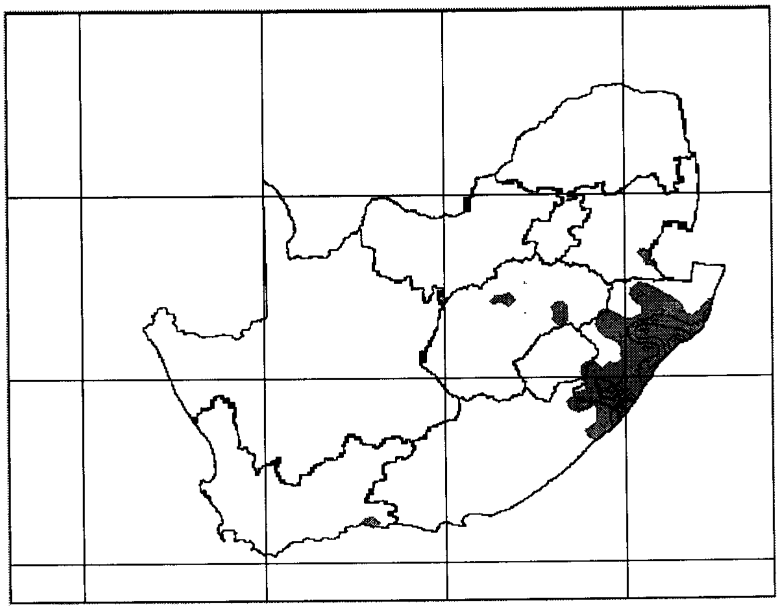

Figure 4.2.1: Rainfall totals, in mm, over South Africa for 7 July 1996. Isohyet spacing is 20 mm.

Latitude (° S)	Longitude (°E)	Rainfall (mm)	Station
30.7	30.0	154	Eureka
29.1	31.4	137	Mandini
28.9	31.8	131	Port Durnford
29.9	31.0	120	Durban Bluff
30.9	30.3	115	Glen Doone
29.9	30.9	115	Queensburg
30.0	30.9	111	Amanzimtoti
30.0	31.0	106	Durban
30.3	30.8	104	Scottburgh
29.2	30.4	104	Newark
28.4	32.4	102	St Lucia Estuary

Table 4.2.1: 24-hour rainfall exceeding 100 mm for 7 July 1996.

4.2.2 Rainfall.

Figure 4.2.1 shows the geographical distribution of rainfall on 7 July 1996. Kwazulu-Natal received widespread rainfall with rainfall totals generally above 50 mm. Rainfall of between 10 mm and 20 mm occurred over the eastern Free State and the southern parts of Mpumalanga. Table 4.2.1 lists the 24-hour rainfall totals exceeding 100 mm over Kwazulu-Natal. Eureka, in the south of this Province, received the most rain at 154 mm. Mandini had 137 mm and Port Dunford 131 mm. Heavy rainfall also occurred over the northern parts of the province with St Lucia Estuary getting 102 mm.

4.2.3 Synoptic circulation and dynamical characteristics.

Figure 4.2.2a depicts the 850hPa AOH south of South Africa. The maritime air circulating anti clockwise around this high becomes a perpendicular on-shore flow over the southeast coast. A trough of low pressure lies over southeastern Botswana on this level. A closed low is visible at 700hPa and is situated over the central interior, but slightly to the southwest of the 850hPa trough. The high south of the continent extends in the vertical to the mid-troposphere (Fig. 4.2.1b). From 500 to 200hPa (Fig. 4.2.2c, d and e) the dominant feature is the low-pressure system over the central interior. The 500-300hPa average column temperatures also show a cold pool over the southeastern parts of South Africa (Fig. 4.2.3). It is clear that the prerequisites for a COL as defined by Taljaard (1985) exist. However this COL is slanting southeastwards in the vertical, which, if the analysis is correct and the quasi-geostrophic theory expounded by Holton (1992) holds, the system should be filling up. The first criterion of MITS, as described in chapter 3 is not satisfied as the low lies southeastward with height and is still evident on the 200hPa level.

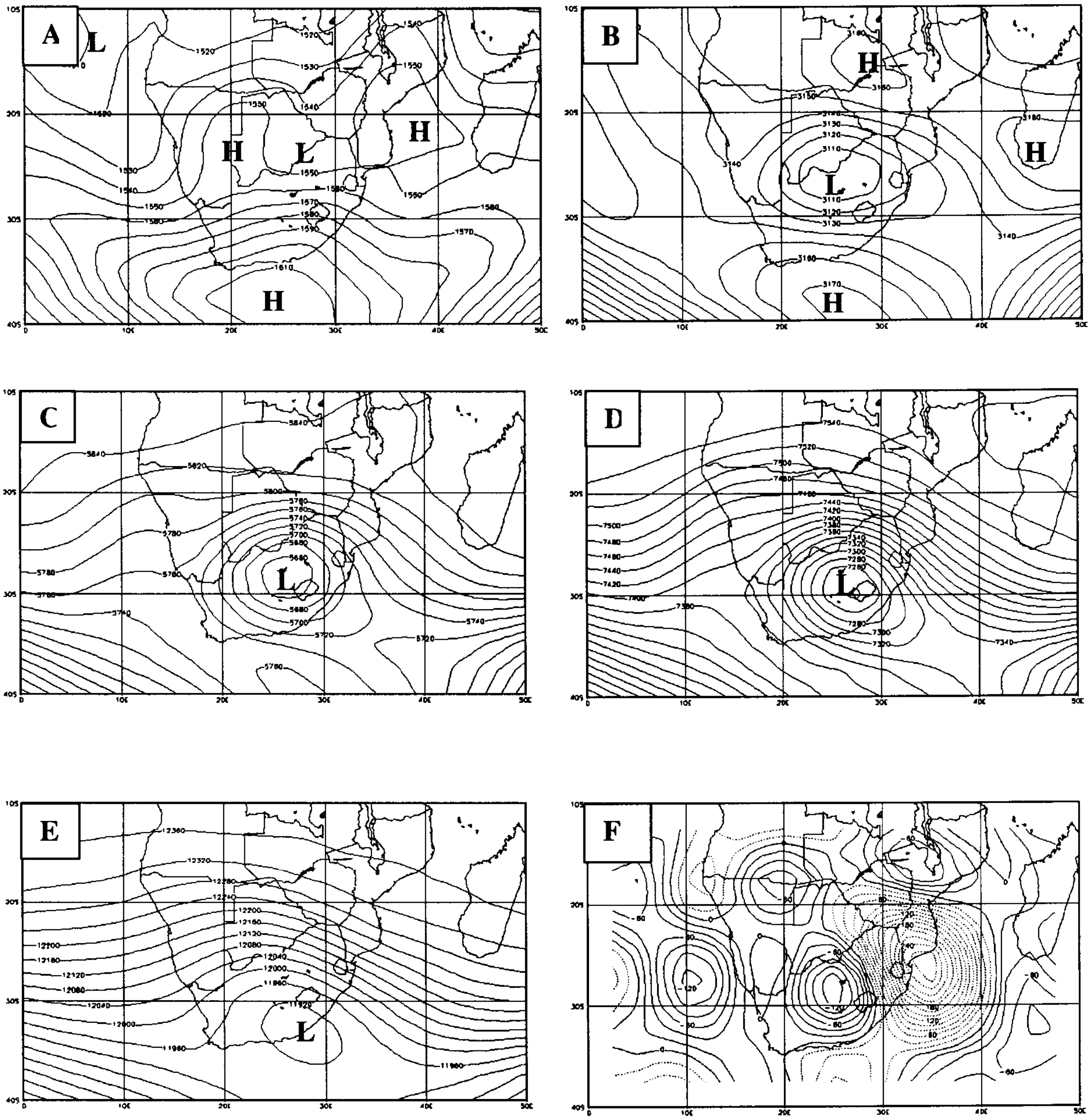

Figure 4.2.2: **The topography of the 850, 700, 500, 400 and 200 hPa pressure surfaces for 7 July 1996, shown in A, B, C, D and E respectively. The contours are labelled in geopotential meters. Figure F displays the wind convergence (solid lines) and divergence (dashed lines) at the 200 hPa pressure surface, units multiplied by 10 $^{-6}$ meters per second.**

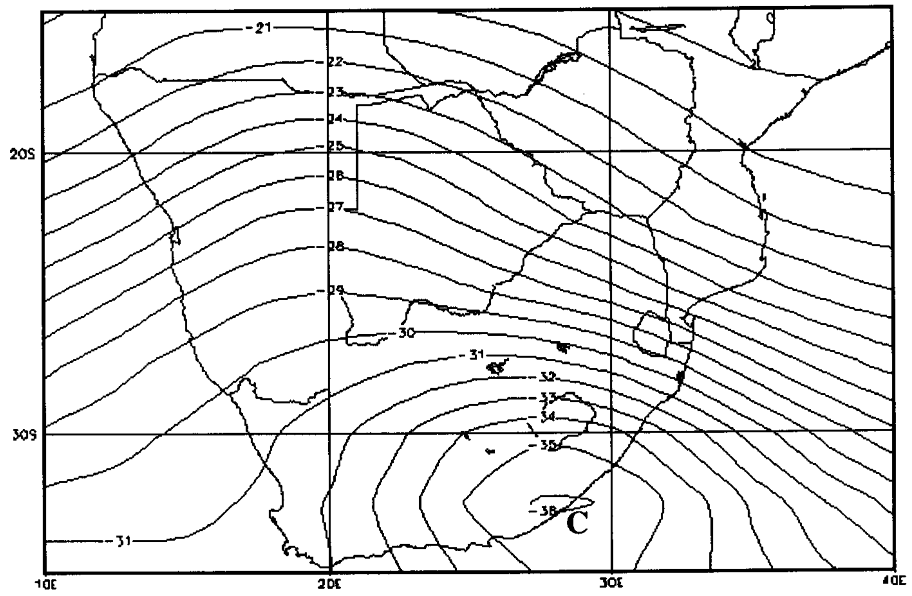

Figure 4.2.3: Average 500-300 hPa column temperatures on 7 July 1996. Temperatures are in degrees Centigrade.

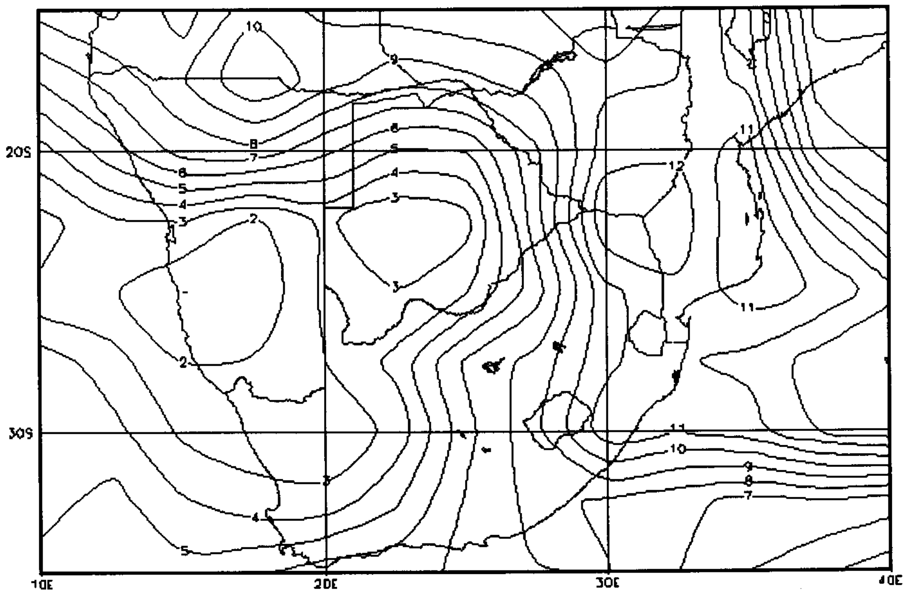

Figure 4.2.4: Precipitable water in the 850-300 hPa layer on 7 July 1996 in units of kg m $^{-2}$.

Positive wind divergence is present to the east of the low at 200hPa with a maximum value of 260 * 10^{-6} s^{-1} over Mozambique (Fig 4.2.2f). The rainfall as depicted in figure 4.2.1 corresponds well to positive values of wind divergence over South Africa. Although rainfall totals over the northeastern Free State, Mpumalanga and the Northern Province was only 10 to 20 mm it were over these areas where heavy snowfalls occurred on the 7th of July.

Figure 4.2.3 shows the cold pool (temperatures < -38 °C) over the Eastern Cape corresponds to the position of the 200hPa low (Fig 4.2.2e). A tight temperature gradient extends northwards from the periphery of this low. The strong temperature gradient is indicative of the existence of a significant thermal wind and is in turn is representative of a baroclinic atmosphere (Holton, 1992). In the 2nd criterion of MITS it is stipulated that a warm core of temperatures should exist in the 500-300hPa layer. Exactly the opposite happened here.

The precipitable water in the 850-300hPa layer is depicted in figure 4.2.4. The maximum value of 12 kg m^{-2} occurs over the Northern Province with values in excess of 10 kg m^{-2} over the eastern interior where most of the rain- and snowfalls occurred. The maximum values of precipitable water on the 21st of February 1988 (Fig. 4.1.4) were three times larger than the maximum values on the 7th of July 1996. A comparison between table 4.1.1 and table 4.2.1 shows that the rainfall in the first case study was also significantly greater than on the 7th of July 1996. The third MITS criterion, a moist diverging upper tropospheric high, did not occur on 7 July 1996. The maximum value of precipitable water is only 12 kg m^{-2} while it is stipulated in MITS that in a tropical atmosphere it should exceed 20 kg m^{-2}.

As shown in figure 4.2.5 the average 850-300hPa TSE reached a minimum value over the central interior at 308 * 10^3 J kg^{-1}. This conforms to the position of the low in the middle and upper troposphere (Fig. 4.2.2). The relatively low moisture content of the air, low temperatures and the low geopotential heights in the upper troposphere results in the low values of TSE. The values of average TSE on the 7th of July 1996 are not comparable to the values stipulated in MITS (330 * 10^3 J kg^{-1}).

The vertical distribution of TSE at 30°S 30°E is depicted in fig 4.2.6. Table 4.2.1 lists the heavy rainfall at this geographical position. Due to the very cold surface conditions it is no wonder that the 850hPa TSE was less than 308 * 10^3 J kg^{-1}. At 700hPa the value of TSE increased slightly but then remained constant up to 500hPa after which there was a steady increase up to 300hPa. The vertical profile of TSE at this location is not conducive to the development of convective cloud systems. With convective development suppressed the importance of the topography of Kwazulu-Natal for the production of steady rainfall when strong onshore flow is maintained is apparent.

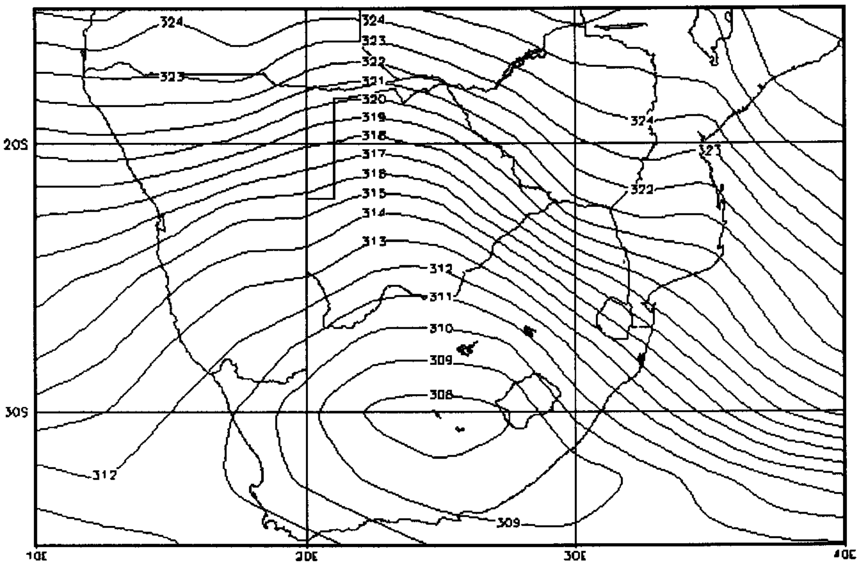

Figure 4.2.5: **Average total static energy of the 850-300hPa layer on 7 July 1996, in units of 10^3 J kg $^{-1}$.**

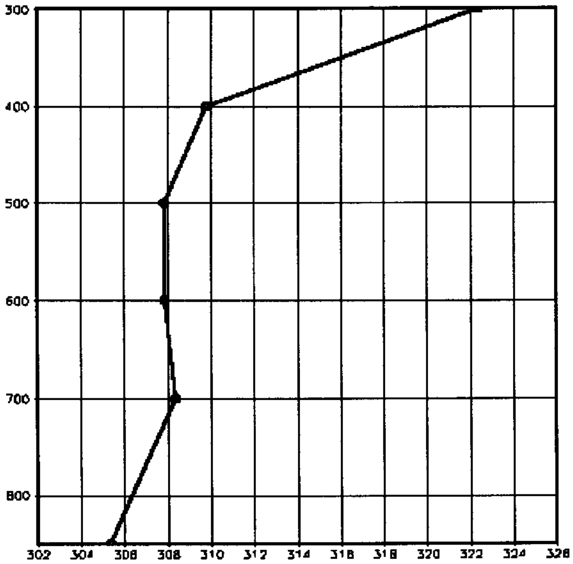

Figure 4.2.6: **Vertical distribution of total static energy (10^3 J kg^{-1}) on 7 July 1996 at 30° S 30° E.**

Omega values decrease steadily with height up to 500hPa where the minimum value of –0.35 Pa s^{-1} (7 cm s^{-1}) is reached (Fig. 4.2.7). From 500hPa to 100hPa there is a steady increase in omega becoming near zero at 100hPa. This profile mimics figure 4.1.7 to a large extent with the exception that on the 21st of February the maximum uplift occurred at 400hPa. In the first case study the maximum value of omega was close to 0.1 Pa s^{-1} larger than on the 7th of July 1996. From figure 4.2.6 and 4.2.7 it is clear that the fifth criterion of MITS is also not realised. It is significant, however, that the vertical distribution of omega is still quite favourable for rainfall. A fact, which needs due consideration when developing a heavy rainfall identification system for baroclinic, weather systems.

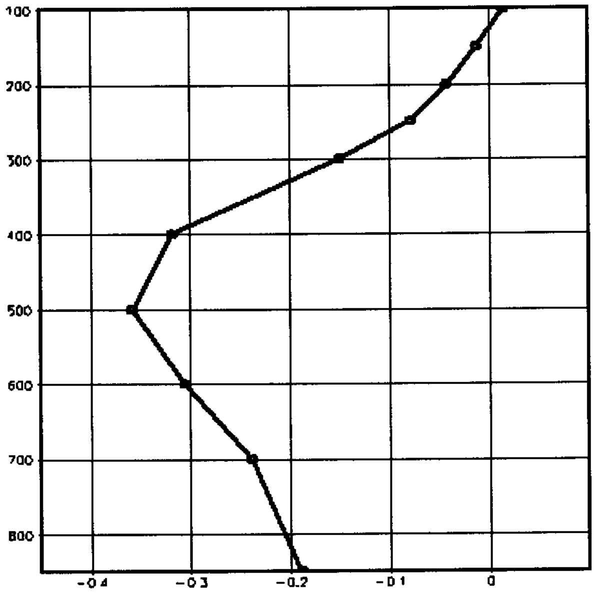

Figure 4.2.7: Vertical distribution of omega values (Pa s^{-1}) on 7 July 1996 at 30° S 30° E.

4.2.4 Performance of THERIS.

THERIS, as described in chapter 3, was designed to identify areas of heavy rainfall in an atmosphere considered to have a tropical circulation. It is therefore no surprise that the identification scheme failed to identify areas of heavy rainfall on the 7th of July 1996. However, De Villiers (1992) lists at least 195 heavy rainfall events between 1980 and 1989 over Kwazulu-Natal. Considering that some 20 of these events occur each year over Kwazulu-Natal and with the increasing urbanising of the population as well as the tremendous increase in informal settlements on flood plains it becomes imperative that an early warning system for heavy rainfall become operational in this area.

4.2.5 Summary and conclusions.

The heavy rainfall over Kwazulu-Natal was caused by a combination of the inflow of moist maritime air over the province and the surface topography providing the necessary uplift to initiate widespread heavy rainfall. The COL in the upper troposphere provided the wind divergence required to maintain synoptic scale vertical motion over the eastern interior resulting in heavy snowfalls over the northeastern highlands.

Figure 4.2.2 illustrates the baroclinic nature of the atmospheric circulation as the low is displaced southwestward in the vertical between 850hPa and 700hPa and then southeastward up to 200hPa. The closed cyclonic circulation associated with the cold core of temperatures in the upper troposphere identifies the COL (Taljaard, 1985). The low values of precipitable water as well as below normal average TSE are also useful to identify a baroclinic circulation system.

4.3 CASE STUDY 3: THE MIXED SYSTEM OF 25 JANUARY 1981.

4.3.1 Introduction.

In this case study the dominant weather system is a COL over the southwestern parts of the country. However the properties of the air mass over the northeastern interior was quite different. This case study illustrates the value of MITS in identifying tropical circulation even though the COL dominates. It is also an example of how sensitive the production of heavy rainfall is to the vertical distribution of omega and wind divergence. In addition THERIS is tested on the 24th and 26th of January 1981.

On the 25th of January 1981 disaster struck Laingsburg, a small town in the Great Karoo, when the Buffels River came down in flood and literally washed away a large part of the town. Hundreds of people lost their lives (Estie, 1981). The January 1981 rainfall over the South Western Cape Province was far above normal. Most of the province received 6 times the mean January rainfall. Normal to above normal rainfall also occurred over large parts of South Africa. The Northern Province, central Free State and the North West Province all had twice the January mean rainfall. The heavy rainfall over the southwestern parts of the country occurred in a three-day period namely from the 24th to the 26th of January.

Crimp et al. (1997) made a detailed analysis of the synoptic circulation for the four-day period up to the 25th of January and identified a tropical temperate trough as the main feature dominating the synoptic circulation. Taljaard (1985) described the weather systems responsible for the heavy rainfall on the 25th of January 1981 as a COL. Estie (1981) referred to the synoptic circulation as a typical "black southeaster". A black southeaster occurs when a strong high south of the continent feeds in warm moist maritime air to a low-pressure system over the southern interior. This low must also extend to the upper troposphere in the form of a COL. In summer the wind direction over the southwest coast is predominantly southeasterly (Taljaard, 1995) and is associated with fair weather conditions. But the black southeaster is normally associated with moderate to heavy rainfall. The presence of a COL in association with a strong surface southeasterly wind is a well-known feature of the South African south and eastern coastal regions. Virtually all the major floods along these coasts were due to these systems. Notable amongst them were the Port Elizabeth deluge of September 1968, East London and environs in 1970 and the Eastern Cape in 1971 (Alexander and Van Heerden, 1991).

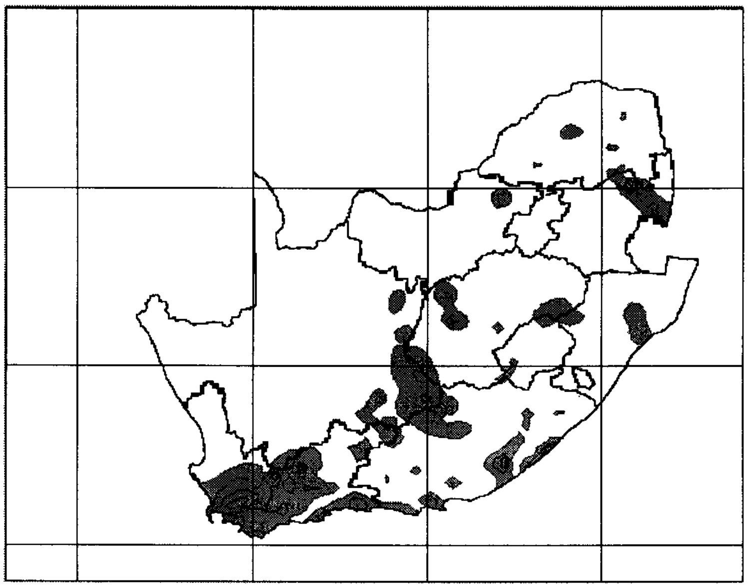

Figure 4.3.1: Rainfall totals, in mm, over South Africa for 25 January 1981. Isohyet spacing is 30 mm.

4.3.2 Rainfall.

Table 4.3.1 lists 24-hour rainfall totals on the 25th of January 1981 at a few stations. In the southwestern Cape stations with more than 200 mm rain were Jonkersnek (337 mm), Disavlei (333 mm), Dassieshoek (242 mm) and Witfontein (223 mm). Over the northeastern interior Pretoria had 71 mm and Saulspoort 58 mm. The geographical distribution of the rainfall on the 25th of January is shown in figure 4.3.1. Rainfall totals greater than 100 mm were confined to the southwestern Cape with isolated areas over the central and eastern interior getting rainfall in excess of 30 mm.

Latitude (° S)	Longitude (° E)	Rainfall (mm)	Station
34.0	19.0	337	Jonkersnek
34.0	19.0	333	Disavlei
33.7	19.9	242	Dassieshoek
33.9	22.4	223	Witfontein
25.8	28.1	71	Pretoria
25.2	27.2	58	Saulspoort

Table 4.3.1: 24-hour rainfall 25 January 1981

4.3.3 Synoptic circulation and dynamical characteristics.

The closed surface low (850hPa) is situated over Bushmansland in the Northern Cape Province (Fig. 4.3.2a). A tight geopotential height gradient existed between this low and the south coast. Warm, subtropical air was advected from the Mozambique Channel and Indian Ocean to the central and southern interior of South Africa recurving to the West Coast. The closed low leans westward in the vertical between 850 and 700hPa (Fig. 4.3.2a and b). The IOH, situated south of Madagascar is maintaining the inflow of subtropical air into South Africa up to approximately 3 000 m above sea level. Figure 4.3.2c shows the 500hPa closed low right above the 700hPa closed low. A trough is extending southwards from the equatorial regions to southern Zimbabwe at both the 500- and 400hPa levels (Fig. 4.3.2c and d). However the dominant feature remains the closed low over the West Coast, which is leaning slightly west from the 500hPa to the 200hPa, levels (Fig. 4.3.2e). A high-pressure ridge at 200hPa replaces the equatorial trough over southern Zimbabwe on the lower levels. Although not apparent at first glance this satisfies the first criterion of MITS: an upright low up to 400hPa replaced by a 200hPa high exists over Zimbabwe. However, the circulation is clearly baroclinic over the western parts. The indistinct low, especially in the lower troposphere, illustrates that if a single criterion of MITS is not immediately apparent, the tropical nature of the atmospheric circulation should not be rejected out of hand.

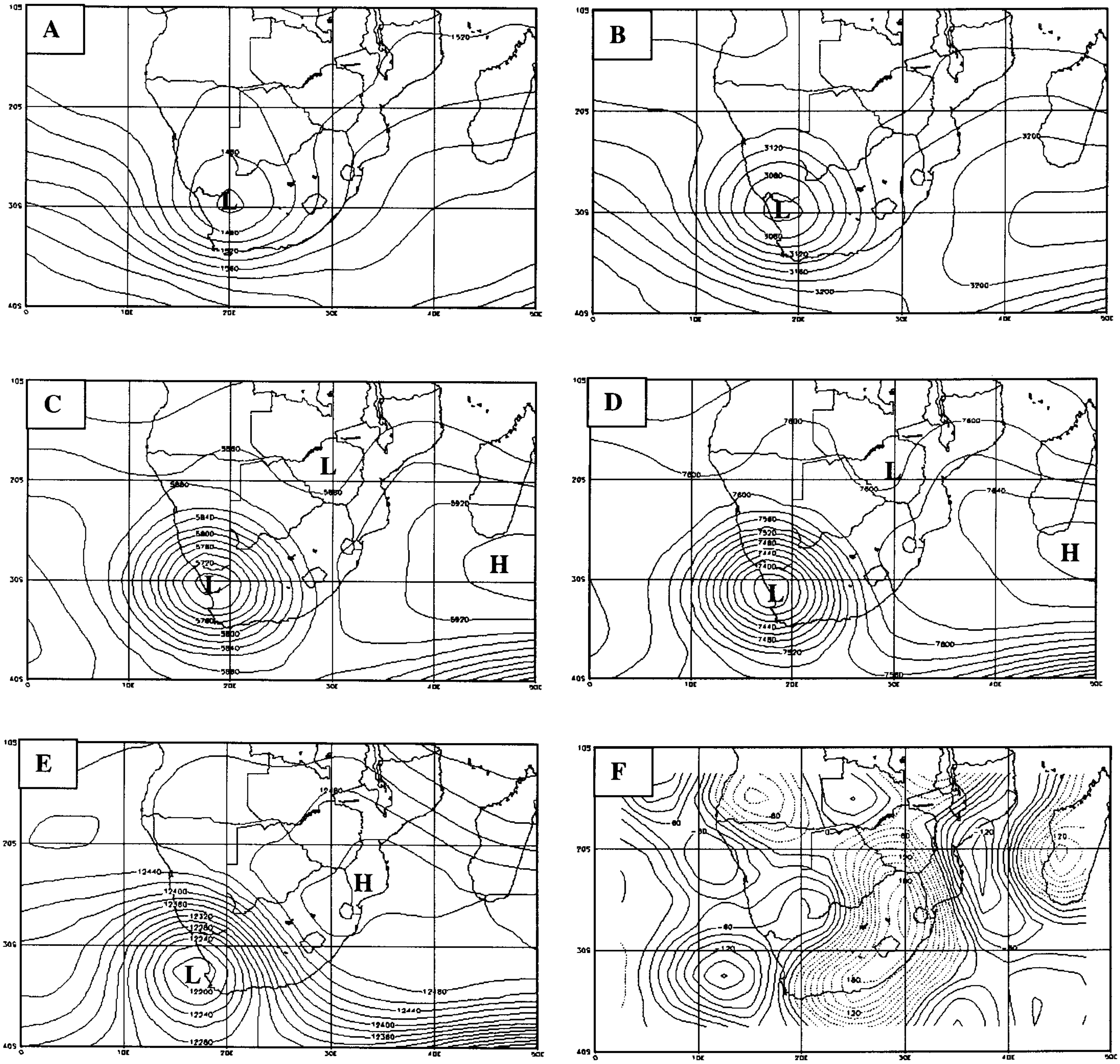

Figure 4.3.2: The topography of the 850, 700, 500, 400 and 200 hPa pressure surfaces for 25 January 1981, shown in A, B, C, D and E respectively. The contours are labelled in geopotential meters. Figure F displays the wind convergence (solid lines) and divergence (dashed lines) at the 200 hPa pressure surface, units multiplied by 10^{-6} meters per second.

In many respects the 200hPa wind divergence field (Fig. 4.3.2f) reminds one of the wind divergence in the first case study (Fig 4.1.2f). Maximum wind divergence (200 * 10^{-6} s^{-1}) occurs over the eastern interior somewhat west of the 200hPa high centre. The wind divergence extends northwards into western Zimbabwe with a second leg stretching southwestward to the western Cape. The "banana" shaped tongue of 200hPa positive wind divergence values is associated with the area of strong relative vorticity advection and vertical motion which normally peaks along a line connecting the inflection points between the upper trough and ridge lines (Holton, 1992).

The average 500-300hPa temperatures are displayed by (Fig 4.3.3). The cold pool off the southwest coast corresponds to the position of the low at 200hPa and fulfils the requirement of a COL according to Taljaard (1985). Over the central interior in the vicinity of the 200hPa ridge, temperatures reached a maximum value (–16 °C). A very tight temperature gradient exists between this high and the cold pool in the southwest. Applying the definition provided by Holton (1992) it is quite clear that the atmosphere is highly baroclinic in this area. As was the case on the 21st of February 1988, the temperature gradient between the warm core over central interior and Mozambique is relatively slack indicating a weakening in the baroclinic properties of the atmosphere over these regions. The second criterion if MITS is met but over the northeastern parts alone.

Figure 4.3.4 shows the pricipitable water distribution in the 850-300hPa layer. The maximum value is attained over the central interior (28 kg m^{-2}). A close inspection of figure 4.3.2a and b reveals that the moisture over the central interior originates over the northern regions of the Mozambique Channel. These values measure up to the values achieved on the 21st of February 1988 (Fig 4.1.4). The relative low values east of Maputo are due to the strong subsidence forced by the 200hPa convergence in this region as depicted by figure 4.3.2f. Comparing figure 4.3.2 e, f and 4.3.4 shows that the 3rd criterion of MITS is realised over the northeastern interior.

The maximum precipitable water values over the central parts of the country decrease rapidly towards the southwest. Figure 4.3.2a and b show that the surface moisture over these parts originated south of Madagascar over the Indian Ocean. The tropical properties of the air were therefore modified. More than 300 mm of rain fell over the southwestern interior where the precipitable water values varied between 10 kg m^{-2} and 16 kg m^{-2}. Comparing these precipitable water values to those in case study 2 (Fig. 4.2.4) it follows that areas of maximum rainfall in a baroclinic atmosphere corresponds to precipitable water values of 10 to 15 kg m^{-2}. However, rainfall far exceeds the precipitable water values and a possible explanation for the high rainfall totals is the maintenance of strong inflow of moisture in the lower troposphere, which provides the necessary water vapour, required for the heavy rainfall (Triegaardt et al., 1988).

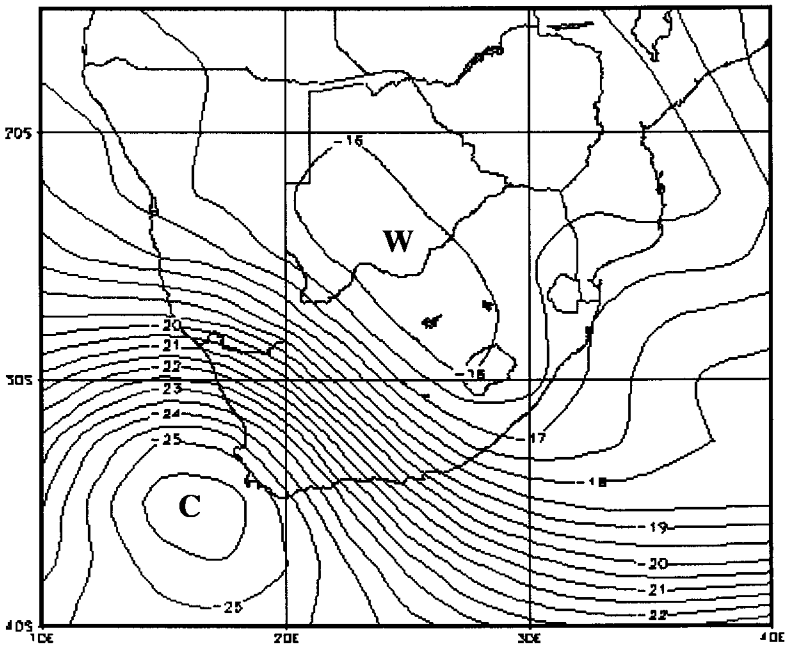

Figure 4.3.3: **Average 500-300hPa column temperatures on 25 January 1981. Temperatures are in degrees Centigrade.**

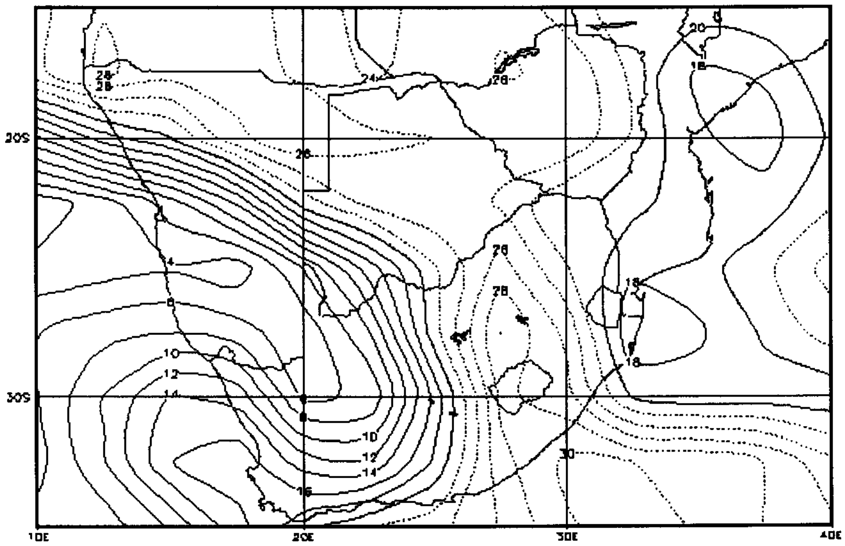

Figure 4.3.4: **Precipitable water in the 850-300 hPa layer on 25 January 1981, in units of kg m $^{-2}$. Dashed lines indicate precipitable water values greater than 20 kg m $^{-2}$.**

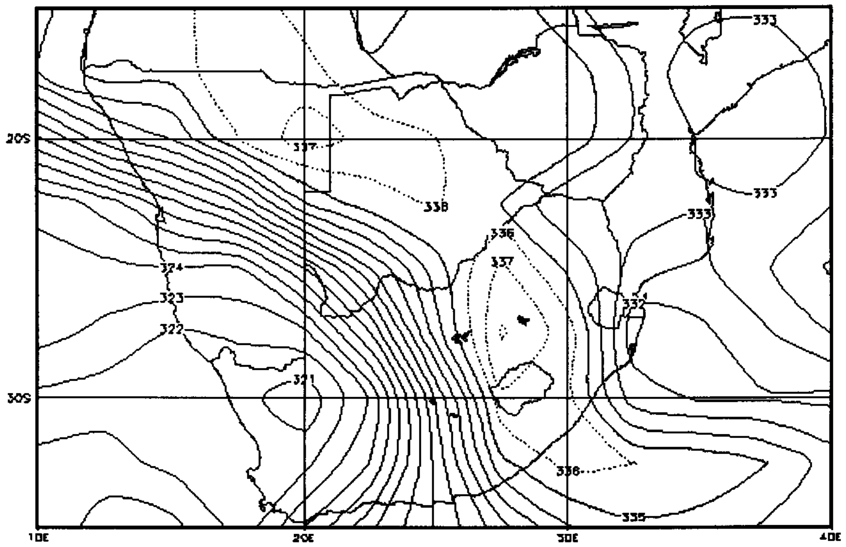

Figure 4.3.5: Average total static energy of the 850-300 hPa layer on 25 January 1981, in units of 10^3 J kg $^{-1}$. Dashed lines indicate values greater than 335 x 10^3 J kg^{-1}

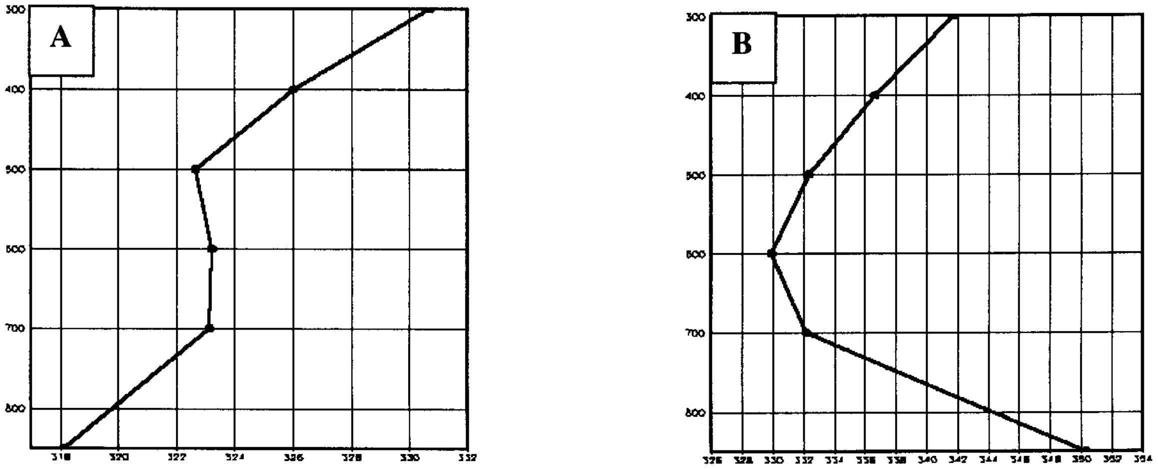

Figure 4.3.6: Vertical distribution of total static energy (10^3 J kg^{-1}) on 25 January 1981 at 34 °S 21 °E (A) and 25 °S 27 °E (B).

The average TSE in the 850-300hPa layer, as depicted in figure 4.3.5, indicates that two distinct air masses with very different properties exists over Southern Africa. In the vicinity of the COL in the southwest, values of average TSE reached a minimum of value (321 * 10^3 J kg^{-1}). Over the eastern and central interior a maximum of 338 * 10^3 J kg^{-1} is reached. The maximum values of average TSE, in this case study, are very similar to the values on the 21st of February 1988 (Fig. 4.1.5). As described in chapter 3 the tight gradient of average TSE over the western and central interior is representative of a change in the properties of the air mass taking place over this area. The values of TSE are exceeding 330 * 10^3 J kg^{-1} in the northeast. This confirms the existence of the 4th MITS criterion.

Figure 4.3.6a depicts the vertical distribution of TSE at 34°S, 21°E where rainfall in excess of 200 mm occurred (Table 4.3.1). The weather system responsible for the rainfall over this area is a COL and the average temperatures in the 500-300hPa layer as well as average TSE in the 850-300 hPa layer would indicate that the atmosphere is highly baroclinic in this area. Although the values of TSE on the 7th of July1996 were much lower than on 25 January 1981 a comparison between figure 4.2.6 and 4.3.6a reveals similar characteristics in the vertical distribution of TSE. In both cases TSE is a minimum at the surface (850hPa) with a slight increase in value at 700hPa. Above 700hPa the value of TSE remains more or less constant, increasing rapidly with height from 400hPa upwards. The vertical distribution of TSE at these two locations did not indicate a conditionally unstable atmosphere and the 5th criterion of MITS therefore do not exist here.

Figure 4.3.6b represents the vertical distribution of TSE at 25°S, 27°E. Rainfall totals in this area were between 50 mm and 70 mm (Table 4.3.1). This distribution of TSE is a classical example of a conditionally unstable atmosphere, conducive to the development of deep convective cloud systems. A comparison with figure 4.1.6 shows a similar vertical distribution of TSE with the exception that on 25th of January 1981 the minimum value occurs at 600hPa, while on 25 February 1988 the minimum value is somewhat higher in the troposphere at 500hPa.

The vertical distribution of omega values in Pa s^{-1} at the above-mentioned positions is depicted in figures 4.3.7a and b. Over the southwestern regions of the Western Cape Province (Fig. 4.3.7a) upward motion is present throughout the troposphere with maximum upward motion at 600hPa (-0.3 Pa s^{-1} or 5 cm s^{-1}). The vertical distribution of omega at 25 °S, 27 °E over the northeastern interior (Fig. 4.3.7b) is interesting. The 24-hour rainfall totals in this area were between 50 mm and 70 mm but considering figure 4.3.1 it is clear that the heavy rainfall developed in isolated convective cloud systems. Upward motion occurred through the entire troposphere but the values of omega were relatively small with the maximum vertical motion as high as 300hPa. Between 600hPa and 400hPa the values of omega remain constant with height. An investigation into the wind divergence at this point between 600hPa and 400hPa (figure not shown) shows wind convergence at both 600hPa and 400hPa but wind divergence at 500hPa. Referring to figure 4.3.2c the positive wind divergence at 500hPa occurs directly east of the COL. This positive wind divergence at 500hPa means that air is removed horizontally from the column of air at this level. Omega values therefore do not decrease at these levels as was the case depicted by figure 4.1.7 (21 February 1988). Figures 4.3.4, 4.3.6b and 4.3.7b indicate that the 5th criterion of MITS is achieved in this area. Although isolated significant falls did occur in this area (table 4.3.1) widespread heavy rain did not. This is probably due to the divergence in the middle troposphere and the maximum upward motion being achieved at the 300hPa level. The significance of this is discussed in some detail in chapter 3.

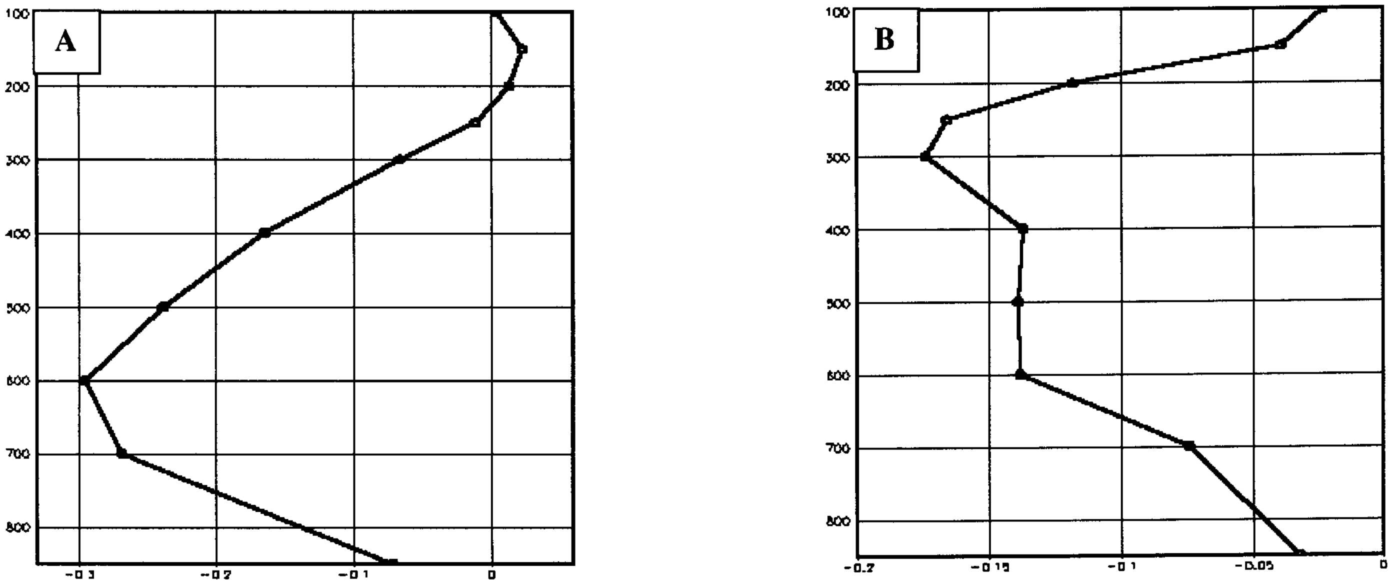

Figure 4.3.7: **Vertical distribution of omega values (Pa s^{-1}) on 25 January 1981 at 34 °S 21 °E (A) and at 25 °S 27 °E (B)**

4.3.4 Performance of THERIS.

THERIS did not identify any heavy rainfall areas on the 25th of January 1981. Comparing this result with figure 4.3.1 it is evident that the heavy rainfall over the southwestern parts of the Western Cape Province is not identified by THERIS. This also holds true for the widespread rain over the western Free State and the Eastern Cape Province. As for case study 2 it should be remembered that THERIS was designed to identify areas of heavy rainfall in an atmosphere with tropical circulation characteristics. In case study 3 the COL dominated the atmospheric circulation over the western interior and the failure of THERIS to pinpoint areas of heavy rainfall is not unexpected.

4.3.5 Summary and conclusions.

A well-developed COL caused the heavy rainfall over the southwestern interior on the 25th of January 1981. The same weather system was also responsible for widespread rainfall over the central interior. The westward leaning low and cold core of temperatures in association with the tight temperature gradient in the upper troposphere illustrates the baroclinic nature of the atmosphere over the southwestern regions of the country.

Over northeastern parts of South Africa the atmosphere had quite different properties. A weak trough over Zimbabwe in the lower troposphere is replaced at 200hPa with a southeastward leaning ridge of high pressure. The warm core in the upper troposphere, high values of average TSE and precipitable water confirms the existence of a tropical atmospheric circulation over these northern parts.

As expected the heavy rainfall over the southwestern and central interior was not captured by THERIS. However it is especially the rainfall over the central interior that deserves special attention as it occurred midway between the tropical circulation in the east and baroclinic atmosphere in the west. Crimp et al. (1997) states that 39% of the mean annual rainfall over South Africa can be contributed to the tropical-temperate trough. If so it is very important to obtain a better understanding of the dynamical processes involved in producing heavy rainfall in the area where the atmosphere exhibits “mixed” properties. As with THERIS described in this dissertation it is of paramount importance that the results are made assessable to the operational meteorologist.

4.3.6 Performance of THERIS on the 24th and 26th of January 1981.

The result of THERIS for the 24th and 26th of January is illustrated in figure 4.3.8a and b respectively. On the 24th of February 2 areas of heavy rainfall are identified. The first area is over northern Zimbabwe. The second area covers a band stretching from the Northwest Province to the interior of Kwazulu-Natal. Table 4.3.2a lists the weighted average rainfall (26 mm) over the two rectangles of area 1. Rain fell at 89% of the stations in this area and at 48% of the stations rainfall of more than 20 mm occurred. At 13% of the stations more than 50 mm rain fell.

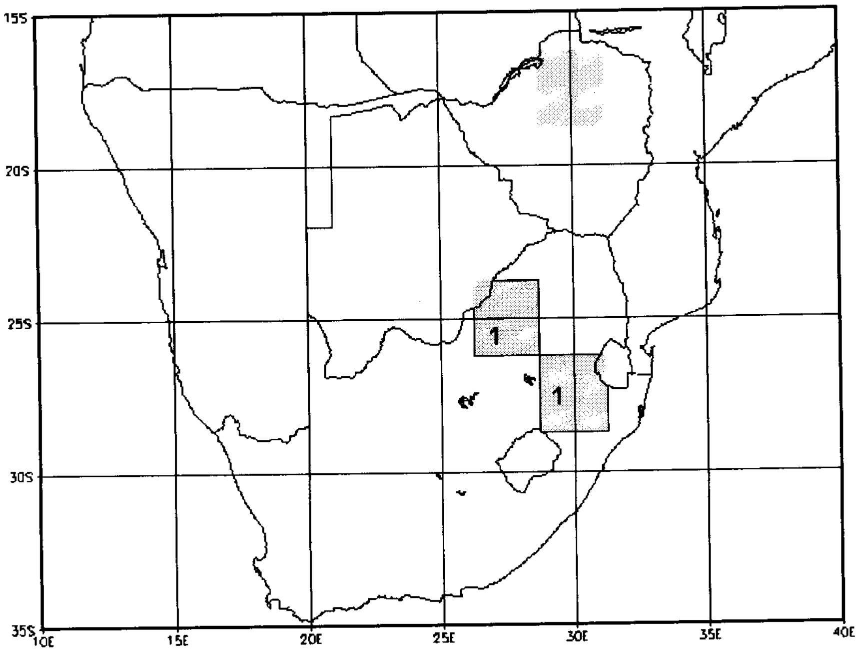

Figure 4.3.8a: **THERIS results for 24 January 1981. The shaded blocks indicate areas where heavy rainfall is predicted.**

Weighted average rainfall	26 mm
Weighted percentages of stations with more than 0mm of rainfall	89 %
Weighted percentages of stations with more than 10mm of rainfall	72 %
Weighted percentages of stations with more than 20mm of rainfall	48 %
Weighted percentages of stations with more than 50mm of rainfall	13 %

Table 4.3.2a: **Weighted average rainfall and weighted percentages for Area 1 on 24 January 1981.**

On the 26th of January THERIS identified areas of heavy rainfall over the central interior of South Africa, northern Zimbabwe as well as northern Namibia (Fig. 4.3.8b). The weighted average rainfall for area 1 is 18 mm. Table 4.3.2b shows that more than 90% of the stations received rainfall while at 68% of the stations more than 10 mm of rain fell. At 33% of the stations more than 20 mm of rain occurred with 4% getting more than 50 mm. Although the average rainfall over the area was relatively low it is encouraging that THERIS identified the area of widespread rainfall (94% of the stations in the area had rain).

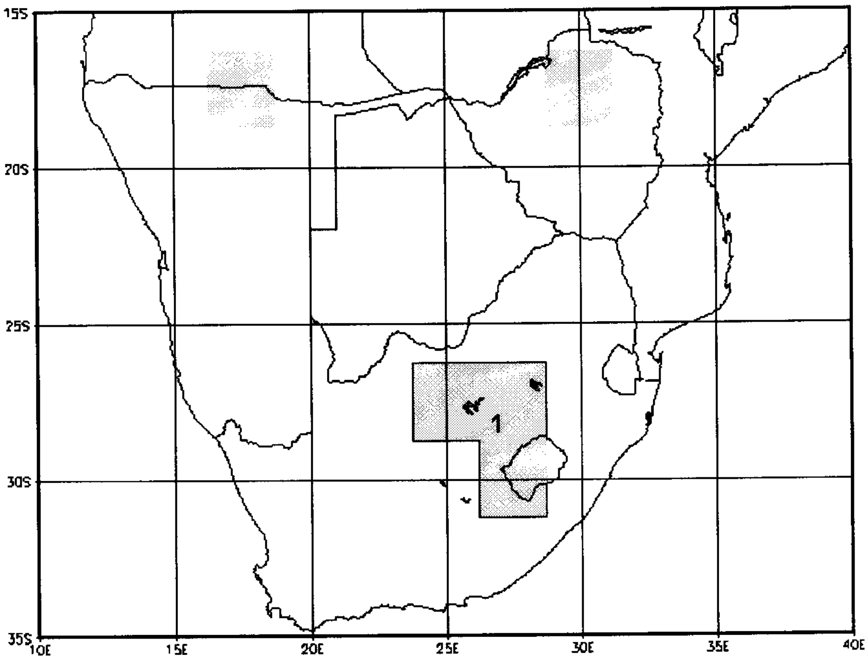

Figure 4.3.8b: **THERIS results for 26 January 1981. The shaded blocks indicate areas where heavy rainfall is predicted.**

Weighted average rainfall	18 mm
Weighted percentages of stations with more than 0mm of rainfall	94 %
Weighted percentages of stations with more than 10mm of rainfall	68 %
Weighted percentages of stations with more than 20mm of rainfall	33 %
Weighted percentages of stations with more than 50mm of rainfall	4 %

Table 4.3.2b: **Weighted average rainfall and weighted percentages for Area 1 on 26 January 1981.**

No areas of potential heavy rainfall were identified by THERIS on the 25th of January but on the 24th of January and the 26th of January areas of likely heavy rainfall were identified. Considering table 4.3.2 it becomes apparent that widespread and even heavy rainfall did occur over the identified areas. It is encouraging that THERIS was capable of identifying tropical rainfall on days on which the atmospheric circulation was dominated by a well defined baroclinic weather system, namely a COL.

CHAPTER 5

THE PERFORMANCE OF THERIS AND MITS DURING FEBRUARY 2000

5.1 INTRODUCTION.

February 2000 will be remembered for the devastating floods, which occurred over the northeastern interior of South Africa, southern Zimbabwe and Mozambique. Unprecedented rains fell over the escarpment of the Northern Province. South African Weather Bureau (1988) shows the annual average rainfall over the Northern Province and Mpumalanga seldom exceeds 1000 mm except at a few locations high up the escarpment, such as Woodbush (1780 mm) and Levubu (1006 mm). Comparing the February 2000 rainfall with the long-term annual averages provides some understanding of the magnitude of the February 2000 rains. Table 5.1 lists monthly rainfall totals of more than 1000 mm (1 meter) of rain. All of the monthly totals exceeded the annual average rainfall. The highest rainfall occurred at Entabeni where 1844.5 mm was recorded. Entabeni is situated at 1376 m above mean sea level (MSL), the second highest of the listed stations. Many of the extreme rainfall totals occurred against, near or on top of the escarpment of the Northern Province. At the two lowest stations listed in Table 5.1, Levubu (706 m) and Thohoyandu (614 m) the rainfall of February 2000 surpassed the previous highest monthly rainfall, which occurred in February of 1996, by some 540 mm at Levubu and 595 mm at Thohoyandou. This is close to double the previous highest rainfall.

More than half of the Northern Province had more than 6 times (600%) the February mean rainfall. Very good rains (200% to 400% of the mean) also occurred over the Northwest- and Gauteng Provinces. The exceptional rains also extended into Zimbabwe, Botswana and Mozambique. Most of the extreme rainfall occurred over the catchment of the Limpopo River. It is no wonder that the coastal flood plains of the Limpopo suffered one of the worst floods ever, bringing Mozambique one of its greatest natural disasters. The Mozambican government estimates that at least 600 people lost their lives due to the floods and hundreds of thousands of people were displaced by the raging waters (Leestemaker, 2000).

There is no doubt that the financial and social impact of the February 2000 floods was severe, most likely the worst in living memory. Van Bladeren and van der Spuy (2000) did a comparison between the flood of February 2000 and earlier flood events. The flood peaks in some rivers were indeed the highest on record. However in many other rivers within the Limpopo River catchment new records were not set. Calculations performed by Van Bladeren and van der Spuy (2000) show that the geographical extent and flood peaks of the February 2000 floods were similar to the floods of 1939 and 1893.

Latitude	Longitude	Rainfall (mm)	Height (m)	Station
23.00	30.27	1844.5	1376	Entabeni
22.98	30.28	1803.0	1311	Matiwa
23.03	30.12	1785.3	1214	LouisTreigaardt/Shefeera
23.80	29.98	1739.2	1555	Tzaneen/Woodbush *
23.88	29.98	1612.2	1350	Tzaneen/Stamblokfontein *
22.97	30.35	1588.3	976	Thsivhasie Tea/Venda
23.05	30.22	1483.5	712	KleinAustralie
22.92	30.40	1466.3	762	Mukumbani Tea/Venda
23.08	30.10	1388.0	811	Louis Triegaardt/Goedehoop
23.75	30.08	1360.4	975	Belvedere
23.73	30.10	1280.2	945	Duiwelskloof/Wesfalia
23.85	30.08	1265.7	1128	Tzaneen/Vergelegen *
23.95	30.15	1230.0	1097	Tzaneen/New Agatha *
23.17	30.05	1173.5	808	Elim
23.00	30.02	1172.2	1065	Roodewal
23.77	30.07	1162.8	893	Tzaneen/Grenshoek *
23.08	30.28	1153.0	706	Levubu
22.97	30.02	1135.0	1295	Vreemdeling
23.78	30.12	1074.3	792	Politzi/Zomerkomst
23.98	30.12	1065.8	914	Mamathola
23.50	30.00	1051.5	1082	Spelonken
23.78	30.13	1036.2	755	Tzaneen/Merensky Agricultural School *
23.93	30.05	1030.7	975	Tzaneen/Letabadrift *
25.00	31.02	1017.5	1376	Pelgrimsrus/Mac Mac
23.07	30.38	1016.0	614	Thohoyandou

Table 5.1: **Monthly rainfall exceeding 1000 mm for February 2000. Stations near Tzaneen are indicated by *.**

Dyson and Van Heerden (2000) investigated the synoptic circulation, which caused the heavy rainfall. They identified two periods in February when most of the rainfall occurred namely 5 to 10 February and 22 to 25 February. In both instances the heavy rainfall was caused by tropical weather systems moving from east to west over the southern subcontinent. They had anomalously long life times. From the 5th to 10th of February a tropical easterly low-pressure system moved from Mozambique to Namibia. From the 22nd to the 25th of February a tropical cyclone named Eline made a landfall in the Beira area. Eline weakened rapidly and moved westward to Zimbabwe producing heavy rainfall over Mozambique, Zimbabwe and the Northern Province. The extreme rainfall totals as listed in table 5.1 occurred over the eastern escarpment of South Africa. Dyson and Van Heerden (2000) stressed the importance of the perpendicular flow of moist air onto the escarpment in producing the heavy rainfall. The air cools, by expansion, as it is forced upward along the escarpment, condensation occurs and orographic rainfall is enhanced. The eastern escarpment is a narrow feature and rises between 500 m and 1000 m above the lowveld. It is very difficult to accurately simulate the sharp escarpment in a numerical weather prediction model. The evaluation of the Eta model prognosis is discussed below. Suffice to mention here that the Eta model underestimated the rainfall totals over the eastern escarpment by some 50% during both rainfall periods. In this dissertation the emphasis will be placed on the heavy rainfall, which occurred over the interior of southern Africa away from the escarpment.

5.2 OBJECTIVES

The weather systems causing the extreme rainfall during February 2000 are classical examples of tropical weather systems producing heavy rainfall. Because of the devastating economic and social effects of the heavy rainfall and floods it is important to know how THERIS performed during this period and to test its usefulness as an early warning system. An operational THERIS will eventually utilise prognostic fields generated by Eta or a similar model. It is important to know how THERIS performs on these fields. THERIS results are verified against SAWB rainfall data. The usefulness of MITS as described in chapter 3, which was developed to identify a tropical atmosphere, will be illustrated. Dyson and Van Heerden (2000) did a detailed analysis of the synoptic sequence of events responsible for the heavy rainfall and it will not be repeated here, however, a short discussion of the synoptic circulation patterns and rainfall is provided.

5.3 DATA

The Directorate of Climate of the SAWB provided the rainfall data as well as the figures depicting the synoptic sequence of events. The SAWB's Eta model is utilised in the analysis and in the production of THERIS and MITS. A discussion of the Eta model is provided in chapter 2.

5.4 ETA MODEL EVALUATION

Most of the research in this chapter is based on prognostic fields computed by the SAWB Eta model and it is therefore important to assess the model's performance during the periods 5 to 10 February and 22 to 25 February 2000. In order to do this the Eta model's sea level pressure (SLP), 850hPa and 500hPa height prognostic fields were compared with the appropriate observed data obtained from the SAWB. It is tragic that the number of upper air ascents over southern Africa has decreased dramatically in recent years. This unfortunately means that a thorough comparison, using the observed data, is impossible. However the author is of opinion that the 0-hour forecast of the Eta model portrayed the real circulation pattern skilfully. This was found to be generally true for both the 12 and 24-hour prognoses of the mean SLP, 850hPa and 500hPa height fields. There were however some notable exceptions. The 12 and 24-hour prognoses of the 0000 UTC run on the 6th failed to pinpoint the position of the tropical low-pressure system accurately. In reality the tropical low was situated over Botswana while the model's height forecast for 850hPa and 500hPa placed the low over Mozambique. The surface pressure of tropical cyclone Eline was also underestimated over the Mozambique Channel early in the second period. De Coning (1997), describing the heavy rainfall of February 1996, found similar anomalous behaviour of the Eta model, and in this case predicting the position of an upper air tropical low.

In general the Eta model simulated the heavy rainfall events, 5 to 10 February 2000 and 22 to 25 February 2000, very well. The model 24-hour rainfall distribution pattern compared well with the observed rainfall pattern. The Eta model predicted rainfall depths, however, were in general considerably less than the observed rainfall. Dyson and Van Heerden (2000) found that on the eastern escarpment of South Africa the rainfall was underestimated by some 50%. This conforms to findings of De Coning et al., (1998) who investigated the heavy rainfall of 12 to 14 February 1996 using the Eta model.

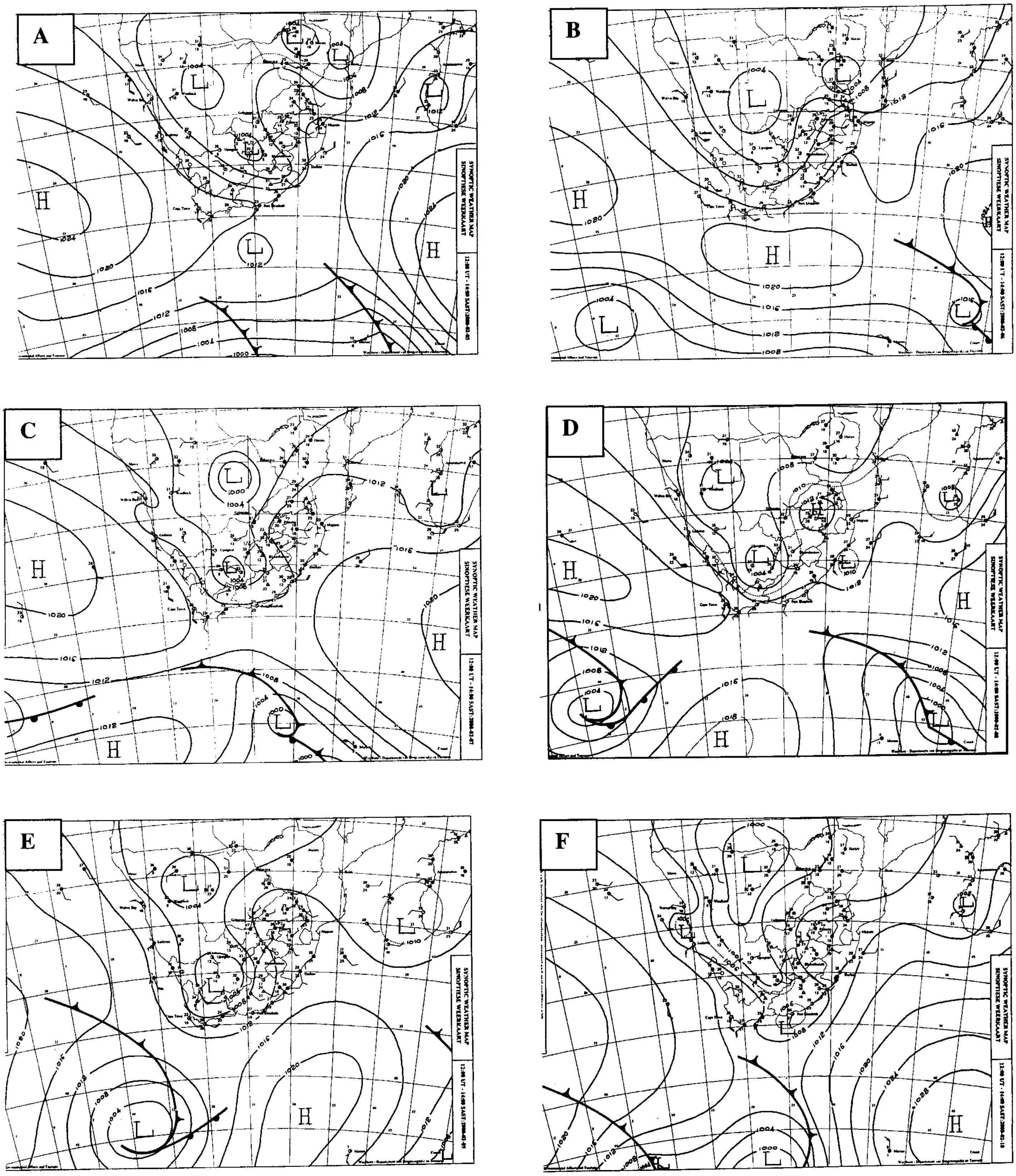

Figure 5.1: Sea level pressure in hPa at 1200 UT during the first period. A: 5 February 2000. B: 6 February 2000. C: 7 February 2000. D: 8 February 2000. E: 9 February 2000. F: 10 February 2000.

5.5 SYNOPTIC SEQUENCE OF EVENTS: 5 TO 10 FEBRUARY 2000

The surface pressure maps for the period 5 to 10 February are depicted by figures 5.1a to 5.1f. The maps were provided by the SAWB and are all regional maps of sea level pressure as observed at 1200 UT during the first period. It should be noted that the isobars over the land are land surface pressures reduced to sea level.

In all of these maps two separate low-pressure systems are evident. One system, depicted as two separate cells, on the 5th is situated over northern Zimbabwe and west of Beira respectively. They are of tropical origin. The other low-pressure system remained over the south central interior during the first period. The tropical surface low first moved southward to the Limpopo valley (6th) and then steadily westwards reaching the Namibia- Botswana border on the 8th where it remained fairly stationary until the end of the first period.

Considering the surface circulation (Figs. 5.1a to 5.1f), it is noteworthy that the Atlantic Ocean High (AOH) extended a weak ridge south of the country till the 9th when a cold front and mid-latitude depression approached the land and passed south of the country on the 10th. During the entire first period moist tropical air circulating westwards around the Indian Ocean High maintained a steady flux of water vapour over the Northern Province, Mozambique, southern parts of Botswana and Zimbabwe.

5.6 SYNOPTIC SEQUENCE OF EVENTS: 22 TO 25 FEBRUARY 2000

Analysis of figure 5.2 reveals that as in the first period a weak surface high-pressure ridge was maintained south of the country. Alexander and Van Heerden (1991) suggested that, when a surface pressure ridge is maintained south of South Africa, the likelihood of a tropical cyclone in the Mozambique Channel making a landfall and moving inland increases. On the 22nd the tropical cyclone Eline was situated near Beira in Mozambique. The infrared Meteosat image for the 22nd (Fig. 5.3) is a classical example of a tropical cyclone with a well-defined eye clearly visible. By 1200 UT on the 23rd (Fig. 5.2b) the cyclone had moved westwards to eastern Zimbabwe and had become a deep tropical low. Figure 5.2c shows that on the 24th the tropical surface low had moved westwards to northeastern Botswana. A separate deep tropical low remained seawards of Beira causing further convective development over Mozambique and the Northern Province.

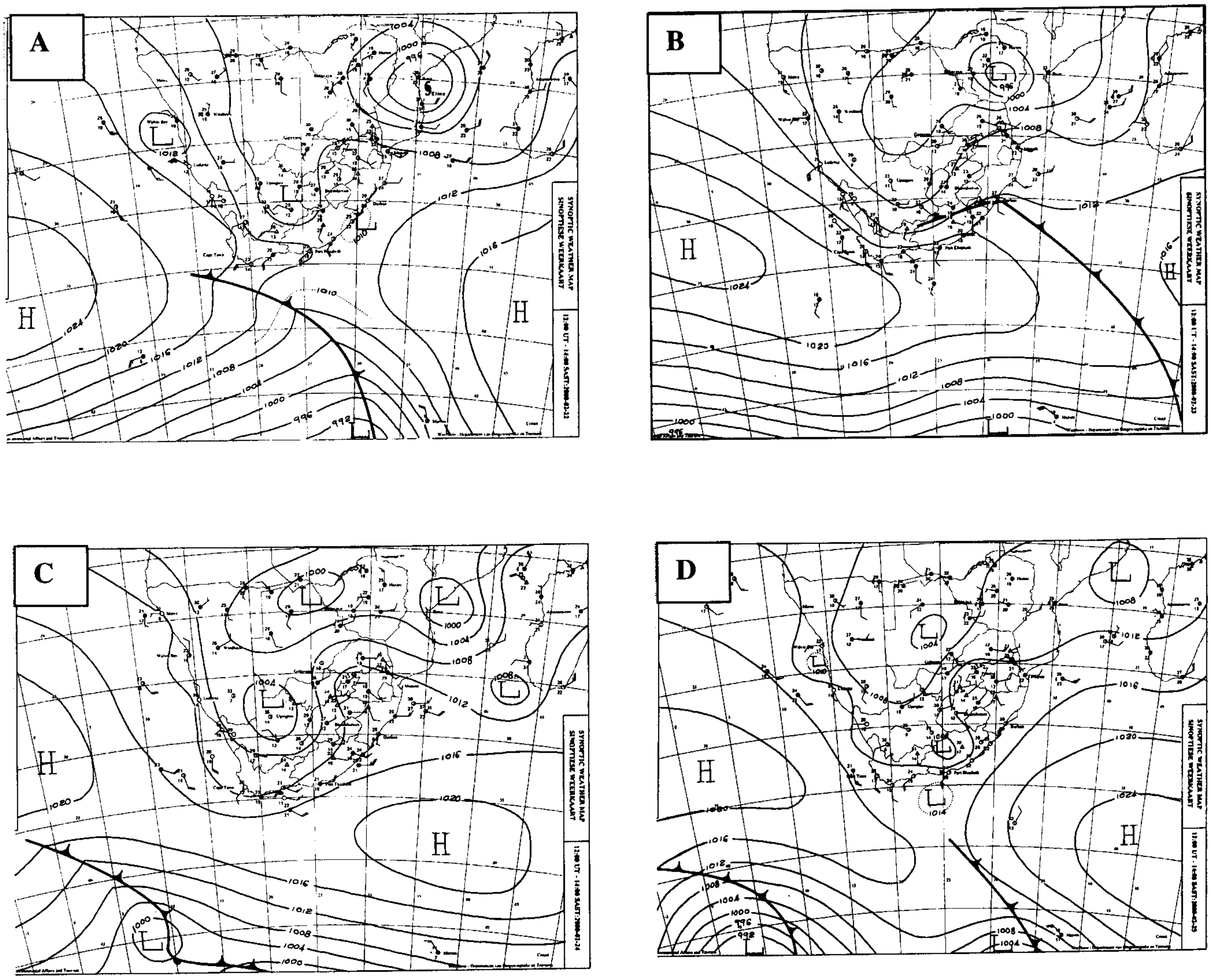

Figure 5.2: Sea level pressure in hPa at 1200 UT during the second period. A: 22 February 2000. B: 23 February 2000. C: 24 February 2000. D: 25 February 2000.

Analysis of figures 5.2c and 5.2d indicate that on the 24th and the 25th the Indian Ocean High (IOH) had maintained a strong ridge, which extended from the Kwazulu-Natal coast northeastward to eastern Botswana. The strong pressure gradient, which was maintained between this ridge and the tropical low-pressure systems to the north, resulted in a steady flux of water vapour over the Northern Province and across the escarpment on both these days. Comparison of figures 5.2c and 5.2d shows that the IOH was intensifying even as it moved eastwards and this ensured that the strong flow of moist maritime air off the Mozambique Channel was maintained on both days.

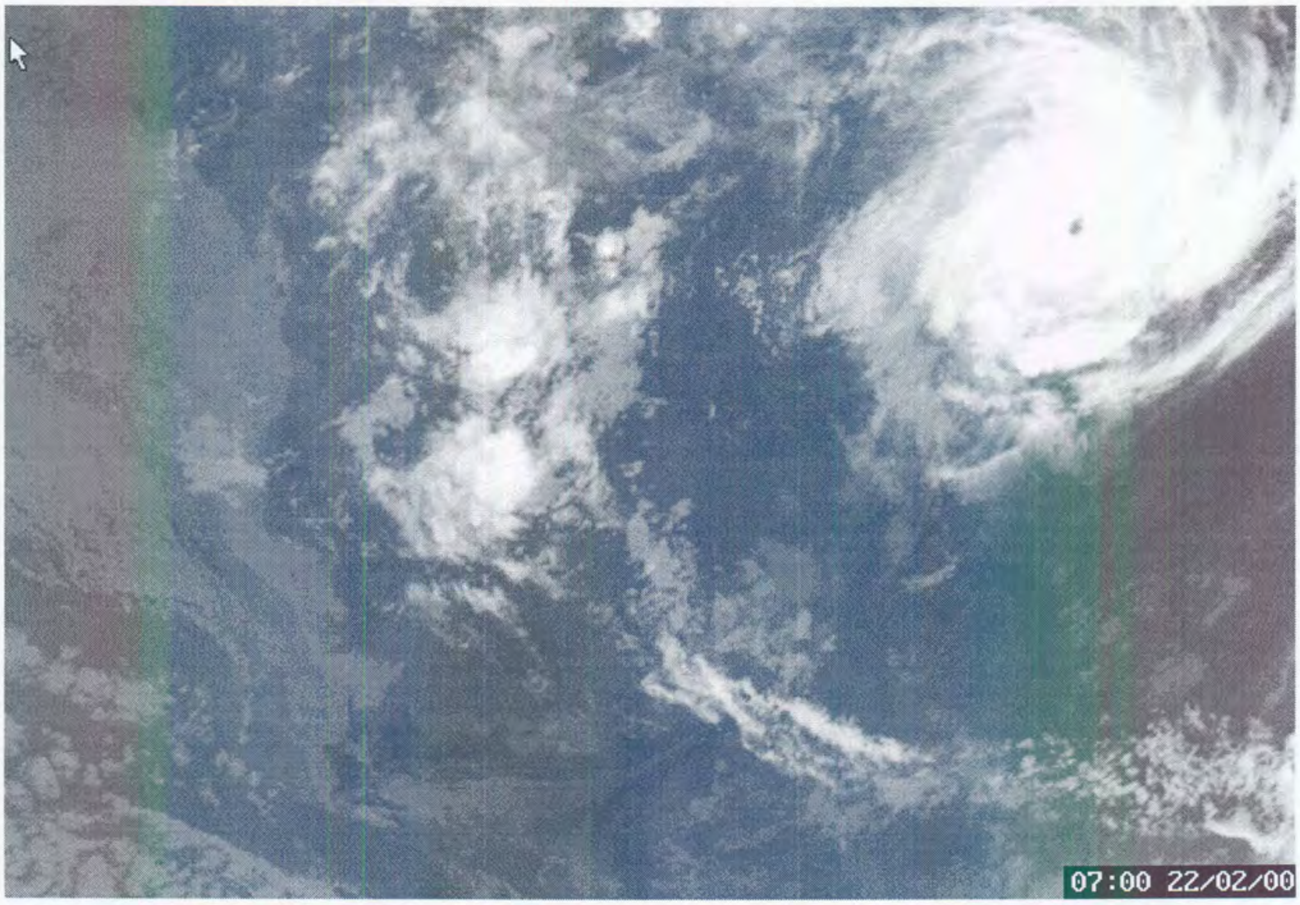

Figure 5.3: **Geostationary satellite Meteosat infrared channel imagery at 0700 UT on 22 February 2000.**

5.7 MITS IN FEBRUARY 2000.

The design and components of MITS are discussed in some detail in chapter 3. A very important principle in the design of MITS is to make it accessible to an operational meteorologist and it therefore has to produce results quickly. MITS is displayed using the graphical display package PCGRIDDS, which is currently used operationally in the forecasting offices of the SAWB. MITS is available in a so-called “macro” which enables the operational forecaster to type in one command and all the fields listed below is displayed automatically

MITS was tested during both heavy rainfall periods in February 2000 and in all cases identified the tropical nature of the atmosphere. The circulation on the 8th of February 2000 is representative of the tropical circulation pattern and the results of MITS will be detailed here. The 12-hour prognosis of the 0000 UTC Eta model run on the 8th of February is used to demonstrate MITS.

5.7.1 Vertical displacement of low and high-pressure systems.

Figure 5.4a (the first image in the macro) represents the 850hPa (blue), 700hPa (magenta) and 500hPa (red) geopotential height fields. The fact that the low is “standing upright” is clearly evident in figure 5.4a. Near the centre of the low the 850-, 700- and 500hPa contours are almost parallel (tangent to each other).

The second image in the macro (Fig. 5.4b) depicts the 400hPa (blue) and 200hPa (green) geopotential heights. A broad weak trough is present at 400hPa in the same geographical position as the low illustrated in figure 5.4a. At 200hPa a closed high-pressure system lies right above the low on the lower levels.

Figures 5.4a and 4b illustrate that the first criteria in MITS are met. These figures clearly portray the upright positioning of the low from 850hPa to 400hPa with a high displacing the low at 200hPa.

5.7.2 Average column temperatures in the 500-300hPa layer

Figure 5.4c depicts the average column temperatures in the 500-300hPa layer. The highest temperatures (-14.5 °C) occur over central Botswana. A Comparison with figure 5.4b shows that the warm core of temperatures is in the same geographical position as the 200hPa high. Comparing the temperature gradient over the Northern Cape Province with the temperature gradient over the Northern Province and Mozambique it is clear that the air in circulation over the eastern parts of the subcontinent represents a tropical circulation system.

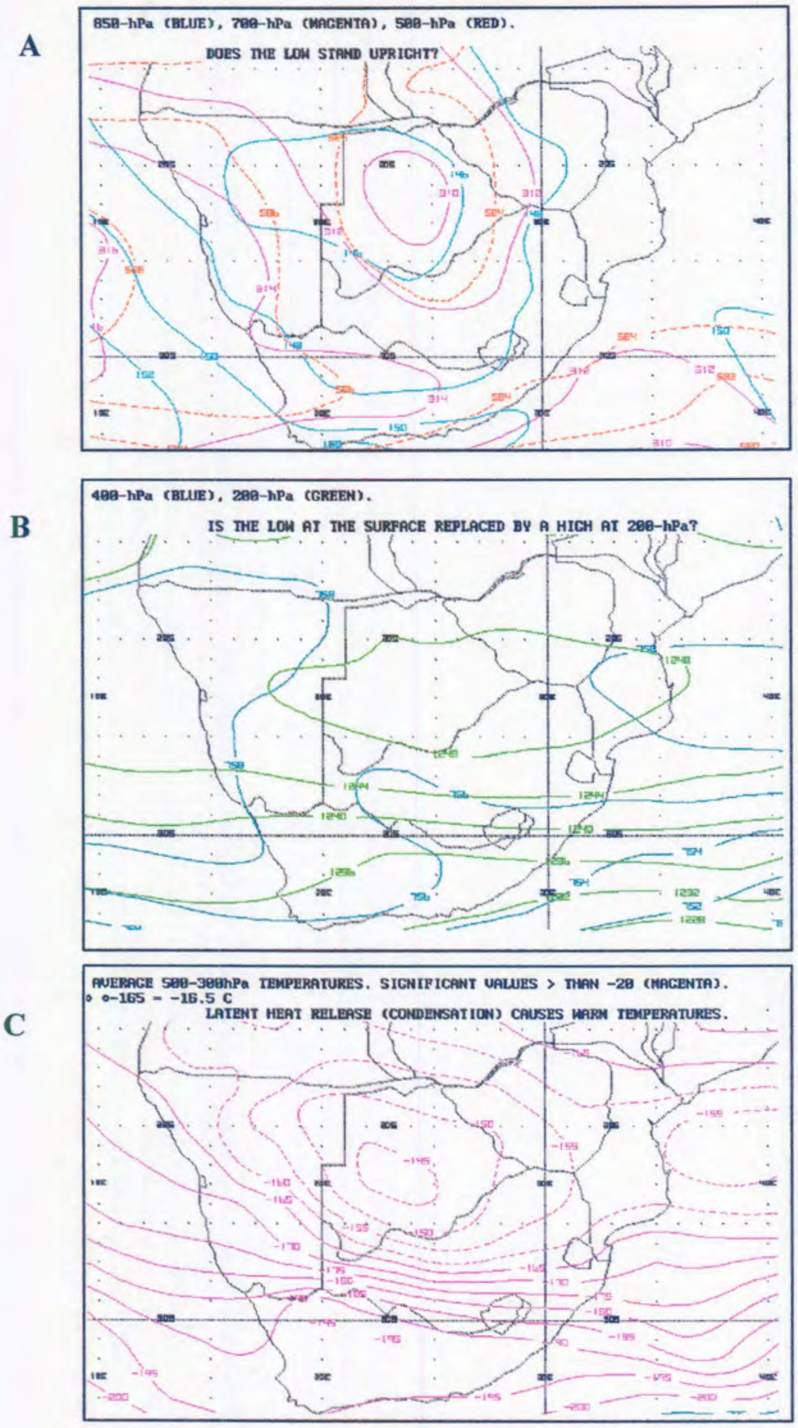

Figure 5.4: **Meteorological fields at 1200 UTC on 8 February 2000. A: Topography in geopotential meter (gpm) of the 850hPa (blue), 700hPa (magenta) and 500hPa (red) pressure surfaces. B: Topography in gpm of the 400hPa (blue) and 200hPa (green) pressure surfaces. C: The average 500-300hPa column temperatures in degrees Centigrade.**

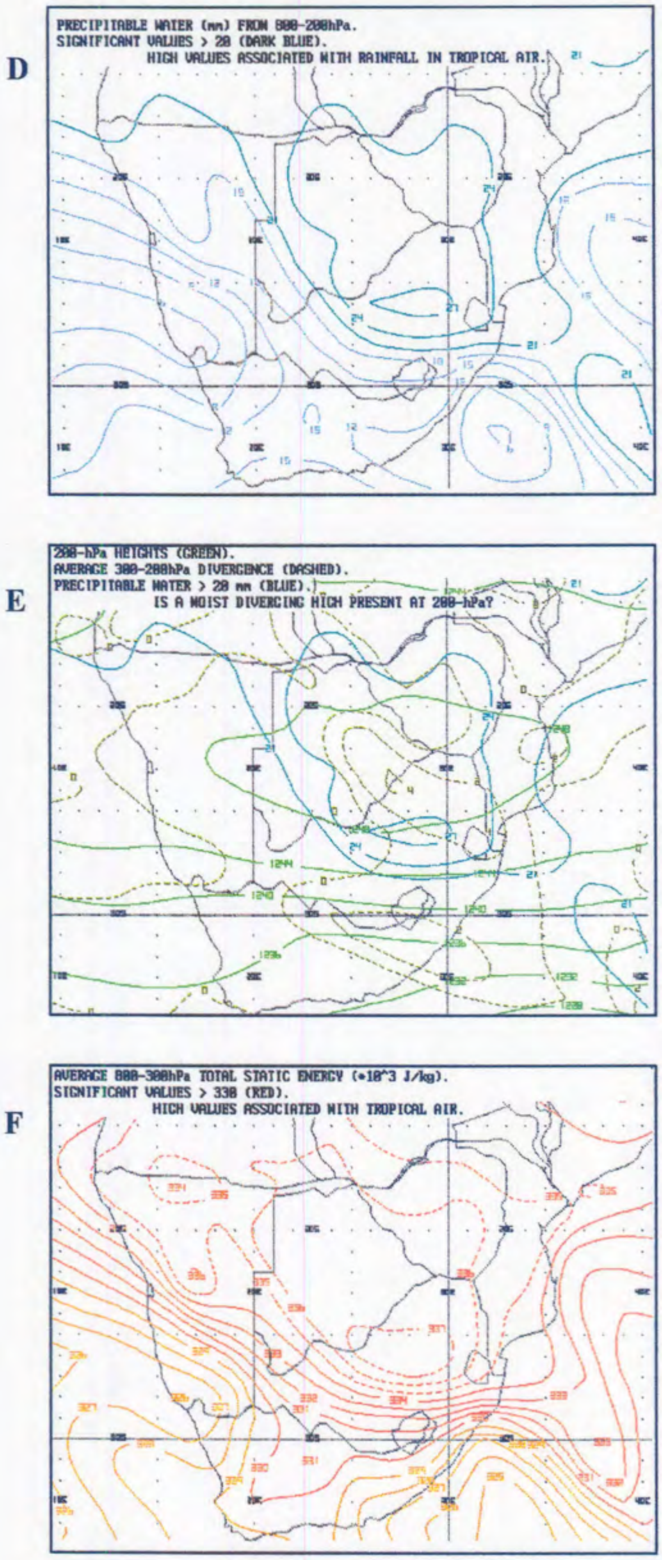

Figure 5.4 (continue): **Meteorological fields at 1200 UTC on 8 February 2000. D: Precipitable water in the 800-300hPa layer in units of kg m $^{-2}$. E: Average 200-300hPa wind divergence (dashed lines), topography in gpm of the 200hPa pressure surface (green) and precipitable water (>20 kg m^{-2}) in the 800-300hPa layer (blue). F: Average total static energy of the 850-300hPa layer in units of 10^3 J kg $^{-1}$.**

5.7.3 Moist diverging high in the upper troposphere

Figure 5.4d shows the precipitable water in the 800-300hPa layer with dark blue contours indicating values greater than 20 kg m^{-2}. As discussed in chapter 4 a good association exists between heavy rainfall and high values of precipitable water in a tropical atmosphere. In figure 5.4e the average 200-300hPa wind divergence (dashed lines) and the 200hPa heights (green) are displayed together with precipitable water values greater than 20 kg m^{-2} (blue). The high values of precipitable water overlap the position of the 200hPa high pressure. Wind divergence occurs over the centre and eastern parts of the 200hPa high coincident with the high values of precipitable water. As was detailed in chapter 3 a moist diverging high in the upper troposphere identifies a tropical weather system.

5.7.4 Average total static energy in the 800-300hPa layer.

The average total static energy (TSE) is depicted in figure 5.4f. The dashed red lines indicate values higher than 335 * 10^3 J kg^{-1}. In chapter 3 the importance of high average TSE values in identifying tropical weather systems was dealt with. The values reached on the 8th of February 2000 are comparable to the values of average TSE reached on the 21st of February 1988 as well as on the 25th of January 1981 all detailed in chapter 4.

5.7.5 Deep cumulus convection and vertical motion.

The green arrows in figure 5.4g indicate areas where the atmosphere is conditionally unstable up to 400hPa, deep cumulus convection is therefore possible up to at least 400hPa. Although conditional instability also occurs in a baroclinic circulation system it was detailed in chapter 3 that when the circulation is considered to be tropical, conditional instability should be high. This field alone therefore cannot be used to identify tropical weather systems.

The brown contours on figure 5.4h indicate those areas where upward motion exists in the column bounded by 700hPa and 400hPa. Where the upward motion field overlaps the green arrows (conditionally unstable atmosphere) conditions are conducive for deep cumulus convection. In figure 5.4i the precipitable water values greater than 20 kg m^{-2} are indicated in blue to remind the forecaster that although atmospheric conditions are favourable for deep cumulus convection, no thundershowers will develop without sufficient water vapour. The magenta arrows in figure 5.4j portray the area where the three fields discussed in figure 5.4i overlap and represent areas of extensive convective development. The forecaster can use this field to identify areas where convective rainfall may develop.

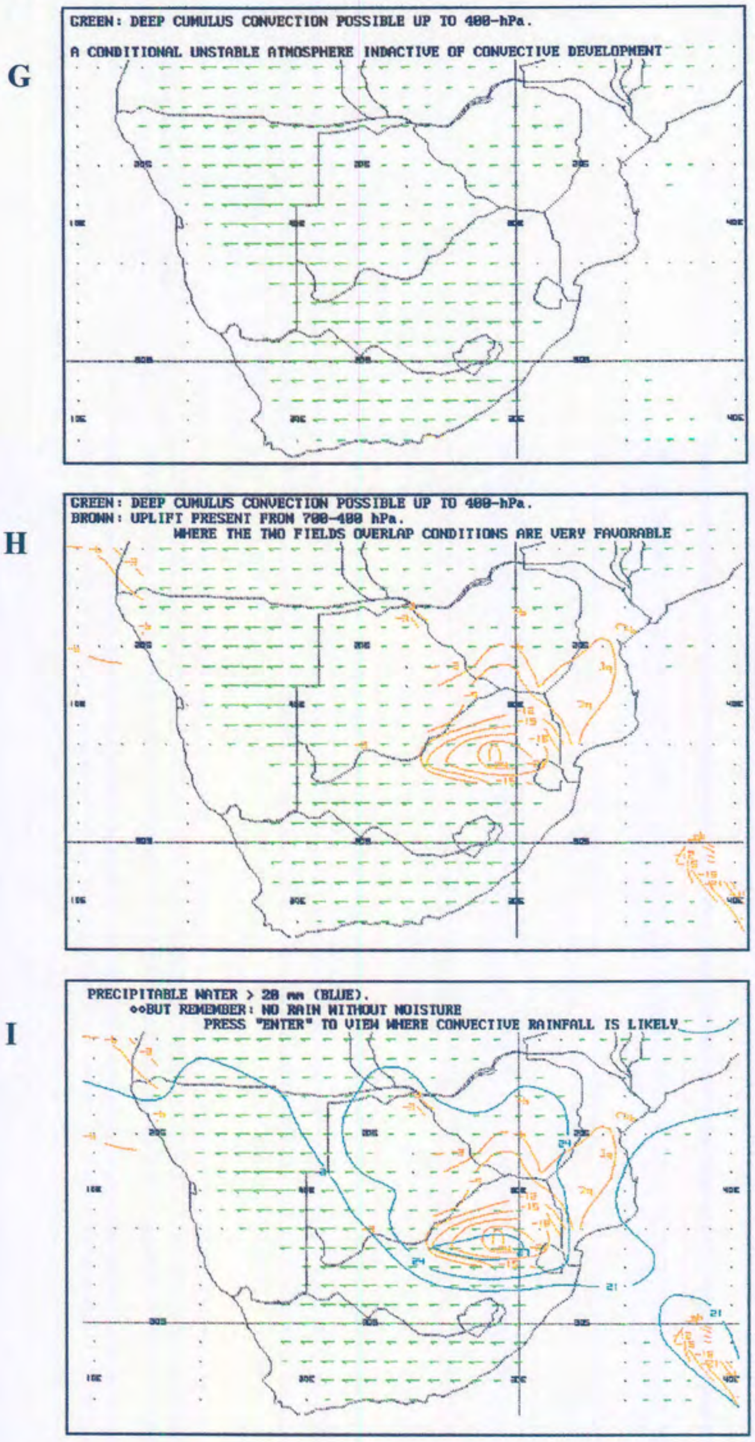

Figure 5.4 (continue): **Meteorological fields at 1200 UTC on 8 February 2000. G: Green arrows indicate areas of conditional instability up to 400hPa. H: Areas of conditional instability (green arrows) and upward motion from 700 to 400hPa (brown contours). I: As G but for precipitable water in the 800-300hPa-layer greater than 20 kg m^{-2} (blue).**

J

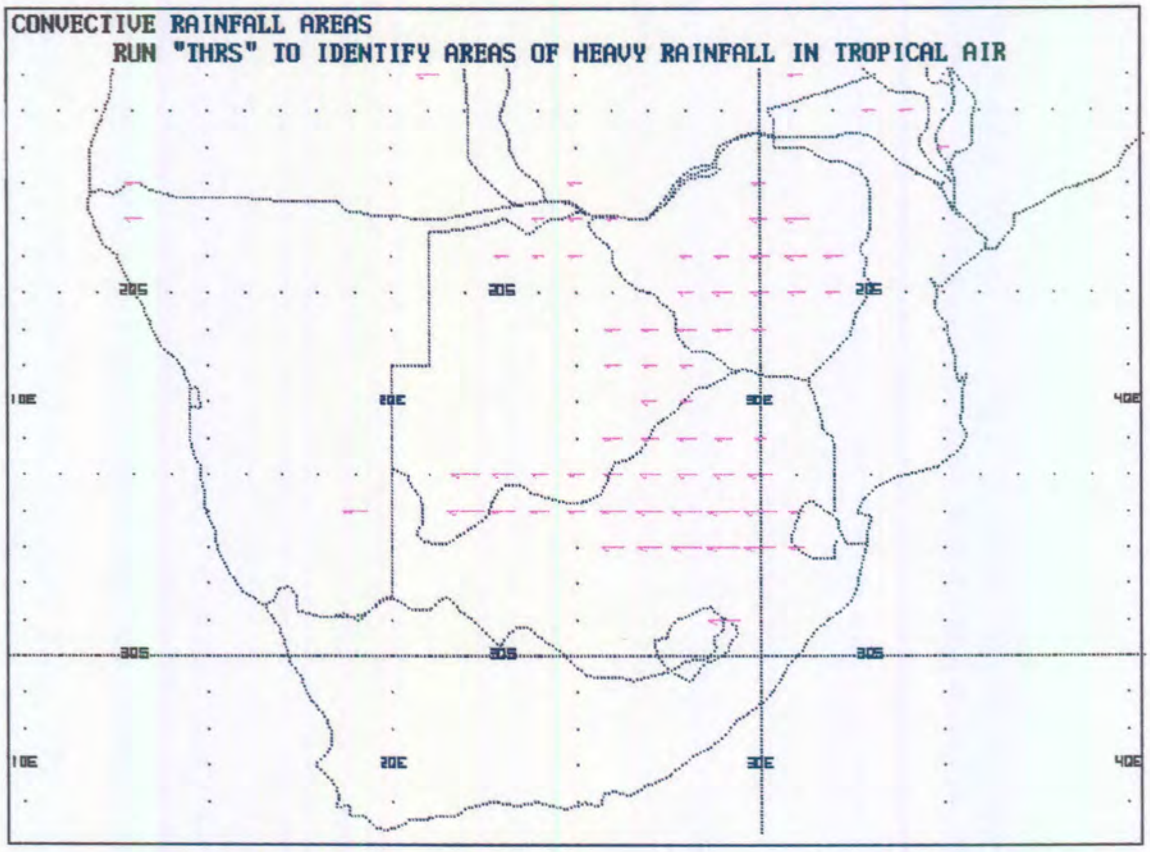

Figure 5.4 (continue): **Meteorological fields at 1200 UTC on 8 February 2000. J: Magenta arrows indicate areas of convective development isolated by MITS.**

5.7.6 Summary and conclusions.

The tropical nature of the atmosphere is illustrated in MITS by using ten basic figures. The low is upright up to 400hPa and is displaced by a high at 200hPa. The high values of average TSE in the 800-300hPa layer together with high upper tropospheric temperatures are indicative of a tropical atmosphere. It was also illustrated that a moist diverging high at 200hPa gives additional evidence of a rain producing tropical system.

An additional product of MITS is that areas where convective rainfall is possible are isolated. This is illustrated by figures 5.4g to 4i where moisture, conditional instability and upward motion through the lower and middle troposphere are pinpointed. Where the three fields overlap (figure 5.4j) atmospheric conditions are very favourable for deep cumulus convection.

5.8 THERIS IN FEBRUARY 2000.

The design of THERIS were dealt with in chapter 3. A THERIS field is created at 6-hourly intervals starting with the 6-hour prognoses of the 0000 UTC Eta run and ending with the 30-hour prognoses. A single field is generated which include all the possible heavy rainfall areas for a 24-hour period ending at 0600Z. This 24-hour period is the same as the 24-hour period, which the SAWB uses for daily rainfall. Close to 1500 SAWB rainfall stations are operational in South Africa at present. The measured rainfall is compared with the areas of predicted heavy rainfall to verify THERIS.

In chapter 2 the shortcomings of the rainfall-contouring package were dealt with. In figure 5.5a the first isohyet is 20 mm. A blank space does not necessarily mean no rain and up to 20 mm rain is possible.

The 0000 UTC runs of the Eta model are utilised in this investigation. The evaluation of the Eta model shows that on the 6th of February 2000 the 12 and 24-hour prognosis of the geopotential height fields misplaced the position of the tropical low over the northeastern parts of southern Africa. Due to the inaccuracy of the Eta model on the 6th of February, the data will not be put to use in this discussion. Furthermore THERIS did not predict any heavy rainfall over South Africa on the 5th, 23rd, 24th or 25th of February 2000. Only those days for which heavy rainfall was predicted are discussed here.

5.8.1 THERIS on the 7th of February 2000.

The result of THERIS on the 7th of February is displayed in figure 5.5a. The shaded areas indicate the geographical distribution of rainfall greater than 20 mm. Two areas of potential heavy rainfall were identified. The first area, bounded by 24°S to 25 °S latitude and 28°E to 29°E longitude, is a small area over the southern parts of the Northern Province and is indicated by 1 on figure 5.5a. The weighted average rainfall as well as the weighted percentages as described in chapter 2 is depicted in table 5.2.1. The weighted average rainfall over area 1 was 51 mm. 94% of all the stations recorded some rainfall, while 66% of the stations received more than 20 mm of rain. More than 50 mm of rain fell at 28% of the stations in area 1.

Area 2 (indicated by 2 on figure 5.5a) lies over the southern extremes of the Northwest Province. Considering the geographical distribution of the rainfall (depicted by the shaded areas in figure 5.5a) and the weighted average rainfall in table 5.2.2 it is clear that area 2 lies south of the area of heavy rainfall. The weighted average rainfall in area 2 was only 2 mm. Rainfall totals over the eastern parts of the Northwest Province was between 30 and 50 mm. In this case THERIS indicated the area of potential heavy rainfall approximately 200 km southwest of where it actually occurred.

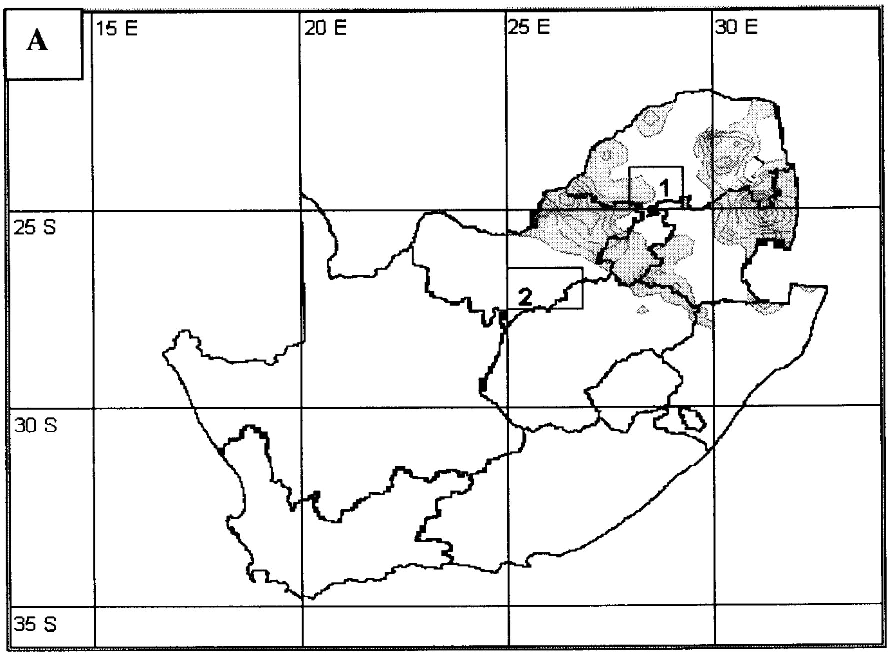

Figure 5.5a: **THERIS results for 7 February 2000. The blocks indicate the areas where heavy precipitation is predicted. The shaded areas are observed rainfall with the first isohyet at 20 mm. Up to 20 mm rain is possible outside the 20 mm isohyet.**

Weighted average rainfall	51 mm
Weighted percentages of stations with more than 0mm of rainfall	94 %
Weighted percentages of stations with more than 10mm of rainfall	72 %
Weighted percentages of stations with more than 20mm of rainfall	66%
Weighted percentages of stations with more than 50mm of rainfall	28 %

Table 5.2.1 **Weighted average rainfall and weighted percentages for the area bounded by 24° to 25°S and 28° to 29°E (area 1) on 7 February 2000.**

Weighted average rainfall	2 mm
Weighted percentages of stations with more than 0mm of rainfall	34 %
Weighted percentages of stations with more than 10mm of rainfall	3 %
Weighted percentages of stations with more than 20mm of rainfall	0 %
Weighted percentages of stations with more than 50mm of rainfall	0 %

Table 5.2.2 **Weighted average rainfall and weighted percentages for the area bounded by 26.5° to 27.5°S and 25° to 27°E (area 2) on 7 February 2000.**

It is interesting that area 1 and 2 lie on both sides of the band of heavy rain stretching southeastwards from Botswana. It should also be noted that that this band of rain lies over the main watershed dividing the western Highveld, the Bankeveld and the Bushveld. The terrain slopes southward and rises some 300 to 400m from the Bushveld to the Highveld regions of the Northwest Province. It could well be that this gentle escarpment played a significant role in the rainfall distribution and caused THERIS to misplace the heavy rainfall areas.

Figure 5.5a indicates a second area of heavy rainfall over the eastern escarpment and lowveld of South Africa. Rossbach, in the mountains of the Northern Province, received 350.5 mm of rain on the 7th of February. THERIS did not isolate this band of very heavy rainfall. A closer investigation into the atmospheric dynamics as illustrated by the Eta model's prognostic field over this area reveals that the atmosphere was not conditionally unstable up to 300hPa and positive wind divergence occurred in the lower and middle troposphere. In chapter 3 it was detailed how sensitive THERIS is to wind divergence in the middle troposphere. The heavy rainfall over the eastern escarpment were therefore not forced by the tropical atmospheric dynamics alone but can be linked to the orographic uplift ensuing from the flow of moist air in the lower troposphere striking the escarpment near perpendicular.

5.8.2 THERIS on the 8th of February 2000.

On the 8th of February widespread and heavy rainfall occurred over the western parts of the Northern Province, Gauteng and the eastern extremities of the Northwest Province (Fig. 5.5b). THERIS identified an area of potential heavy rainfall as indicated by 1 in figure 5.5b. Comparing area 1 with the shaded rainfall areas in figure 5.5b, THERIS extended the heavy rainfall too far towards the west over the Northwest Province. Considering table 5.3 it is obvious that THERIS faired very well in isolating the heavy rainfall area. The weighted average rainfall over area 1 was 30 mm with close to 80% of all the rainfall stations in the area receiving rainfall. 62% of the stations had more than 10 mm of rain with 22% receiving more than 50 mm of rain.

As was the case on the 7th of February 2000 THERIS did not isolate all heavy rainfall areas. On this day the heavy rainfall over the western parts of the Northern Province was not isolated by THERIS. The prognostic fields of the 0000 UTC run of the Eta model reveal that the atmosphere was again not conditionally unstable up to 300hPa and had positive wind divergence in the middle troposphere. The heavy rainfall in this area was probably caused by the strong inflow of surface moisture and relatively large negative values of omega (upward motion) at 500hPa. A comparison with figure 5.4j shows that MITS identified the western part of the Northern Province as an area where convective rainfall is possible. The strict criteria applied in THERIS prevented it from isolating heavy rainfall over this area of the Northern Province.

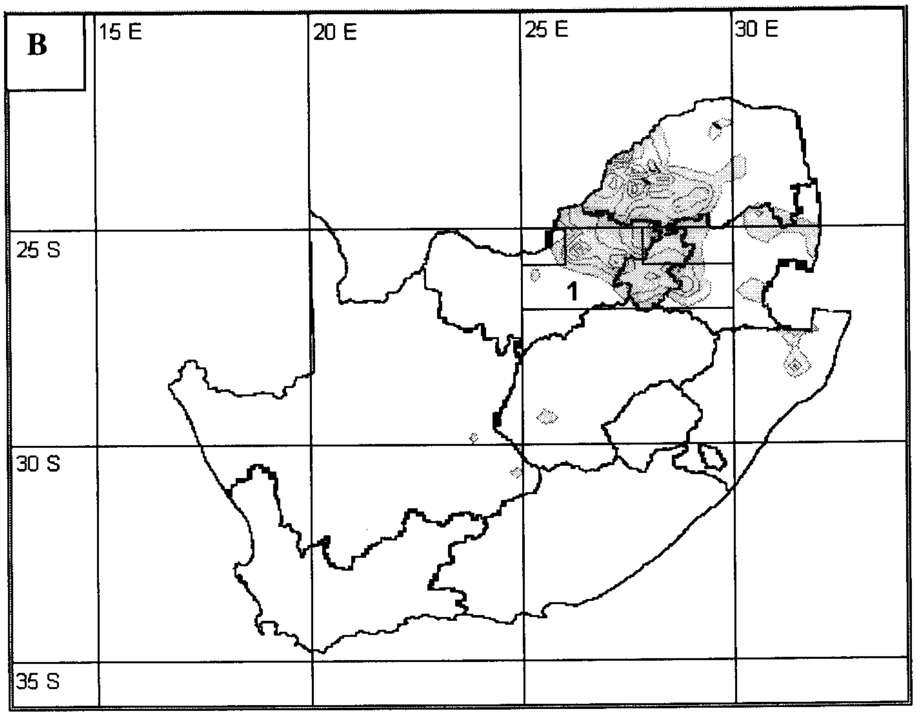

Figure 5.5b: **THERIS results for 8 February 2000. The block indicates the area where heavy precipitation is predicted. The shaded areas are observed rainfall with the first isohyet at 20 mm. Up to 20 mm rain is possible outside the 20 mm isohvet.**

Weighted average rainfall	30 mm
Weighted percentages of stations with more than 0mm of rainfall	79 %
Weighted percentages of stations with more than 10mm of rainfall	62 %
Weighted percentages of stations with more than 20mm of rainfall	47 %
Weighted percentages of stations with more than 50mm of rainfall	22 %

Table 5.3 **Weighted average rainfall and weighted percentages for the predicted heavy rainfall area on 8 February 2000.**

5.8.3 THERIS on the 9th of February 2000.

Figure 5.5c denotes the geographical distribution of the rainfall on the 9th of February 2000. Rainfall totals exceeding 20 mm occurred over the northern parts of the Northwest Province as well as over Gauteng. Area 1 on figure 5.5c indicates the THERIS forecast heavy rainfall area. As was the case on the 8th of February, THERIS identified the heavy rainfall area to the south and west of where it actually happened. The weighted average rainfall for this day (Table 5.4) indicates that the average rainfall over area 1 was only 17 mm. Close to 50% of all the stations had rain with 41% of the stations getting more than 10 mm. Only 7% of the stations in area 1 had rainfall amounts greater than 50 mm.

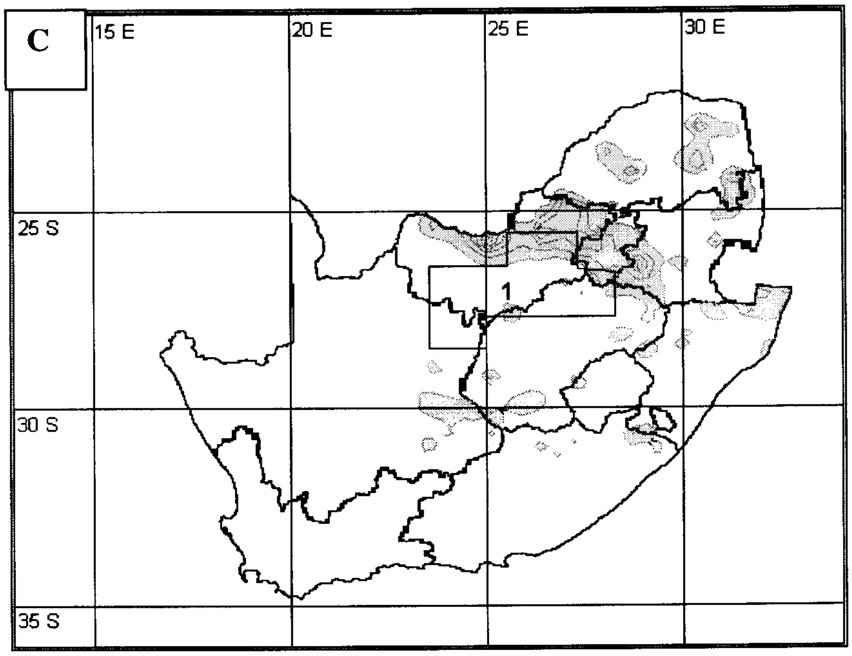

Figure 5.5c: **THERIS results for 9 February 2000. The block indicates the area where heavy precipitation is predicted. The shaded areas are observed rainfall with the first isohyet at 20 mm. Up to 20 mm rain is possible outside the 20 mm isohyet.**

Weighted average rainfall	17 mm
Weighted percentages of stations with more than 0mm of rainfall	47 %
Weighted percentages of stations with more than 10mm of rainfall	41 %
Weighted percentages of stations with more than 20mm of rainfall	24 %
Weighted percentages of stations with more than 50mm of rainfall	7 %

Table 5.4 **Weighted average rainfall and weighted percentages for the predicted heavy rainfall area on 9 February 2000.**

MITS, detailed in 5.7.5, reveals that the area of heavy rainfall over Gauteng and the northern parts of the Northwest province are within in the area of potential rainfall (figure not shown). As was the case on the 7th of February the criteria forming part of THERIS prevented it from isolating this area. As described in 5.8.1 it should also be taken into consideration that the heavy rainfall occurred over the east west running watershed. This topographical feature can supply the necessary uplift to enhance convective development.

5.8.4 THERIS on the 10th of February 2000.

On the 10th of February 2000 THERIS (depicted by 1 on figure 5.5d) isolated a large area of potential heavy rainfall over the eastern half of South Africa. Comparing area 1 to the geographical distribution of rainfall exceeding 20 mm (shaded areas on figure 5.5d) shows that the heavy rainfall did indeed occur over a large part of area 1. THERIS was wrong only over small parts of the northern Free State as well as the southern parts of Kwazulu-Natal. Table 5.5 lists the weighted average and weighted percentages for area 1. The average rainfall over area 1 was 26 mm with close to 80% of all the stations receiving rainfall. Nearly 50% of the stations had more than 20 mm rain and at 19% of the stations more than 50 mm rain fell.

Weighted average rainfall	26 mm
Weighted percentages of stations with more than 0mm of rainfall	77 %
Weighted percentages of stations with more than 10mm of rainfall	60 %
Weighted percentages of stations with more than 20mm of rainfall	48 %
Weighted percentages of stations with more than 50mm of rainfall	19 %

Table 5.5 **Weighted average rainfall and weighted percentages for the predicted heavy rainfall area on 10 February 2000.**

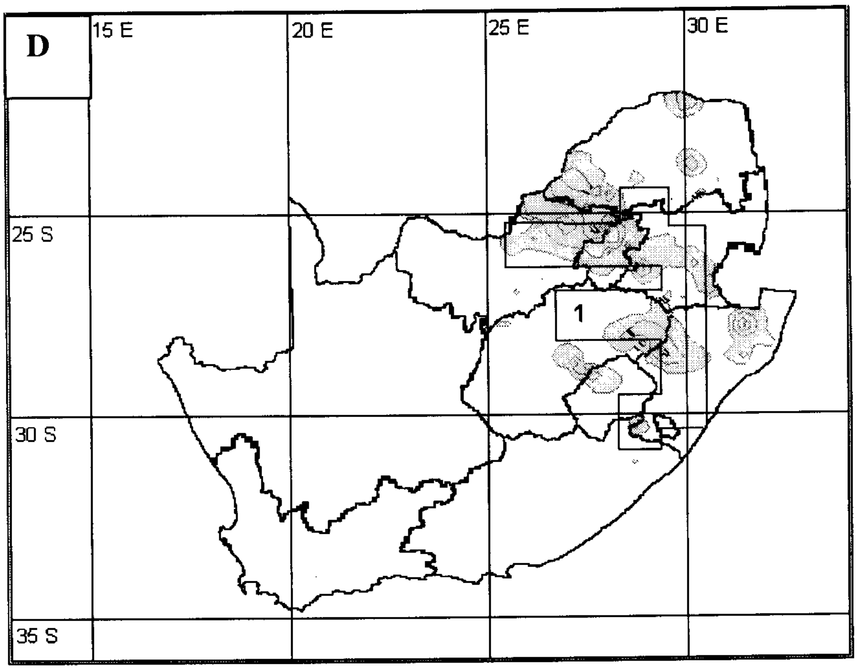

Figure 5.5d: **THERIS results for 10 February 2000. The block indicates the area where heavy precipitation is predicted. The shaded areas are observed rainfall with the first isohyet at 20 mm. Up to 20 mm rain is possible outside the 20 mm isohyet.**

On the 10th of February 2000 the tropical low pressure system was situated over Namibia, extending a trough southward over the central interior of South Africa (figure 5.1f). In the upper troposphere the high pressure dominated the circulation over Botswana and Namibia with a weak westerly trough over the southwestern interior (figure not shown). The significance of the results of THERIS on the 10th of February lies therein that in all probability the operational meteorologist would not have predicted heavy rainfall so far from the dominant tropical low over Namibia. THERIS indicated that the atmospheric circulation over Gauteng and as far south as Kwazulu-Natal was still very much tropical and conducive to the development of heavy rainfall. It is also encouraging that THERIS is capable of isolating heavy rainfall areas when the tropical atmospheric circulation was beginning to decay.

5.8.5 THERIS on the 22nd of February 2000.

On the 22nd of February tropical cyclone Eline was situated over Mozambique as depicted by figure 5.2a. Heavy rainfall occurred over Mozambique (not shown) as well as the northeastern extremes of the Northern Province (Fig. 5.5e). THERIS did not identify the heavy rainfall over these areas.

The Eta model prognosis for this area reveals that most of the criteria stipulated for THERIS were not met. The perceptible water values did not exceed 20 mm, the average TSE was less than 335 $*10^3$ J kg^{-1}, deep cumulus convection was not possible up to 300hPa and uplift was not indicated throughout the middle and upper troposphere. As for the 7th of February 2000 the rainfall in this area can only be linked to the orographic uplift which occurred near the eastern escarpment.

THERIS identified an area (indicated by 1 in figure 5.5e) of heavy rainfall over southern Gauteng and the northeastern Free State. Not one of the SAWB rainfall stations in area 1 had any rainfall. Area 1, isolated by THERIS, is small and refers to conditions at a single grid point. Investing the 0000 UTC Eta model prognoses it became apparent that atmospheric conditions over area 1 were only marginally favourable for heavy rain. Furthermore positive wind divergence occurred in the middle troposphere and this is detrimental to the development of heavy rainfall in a tropical atmosphere. The operational meteorologist will be well advised to be cautious if THERIS isolates heavy rainfall at a single grid point.

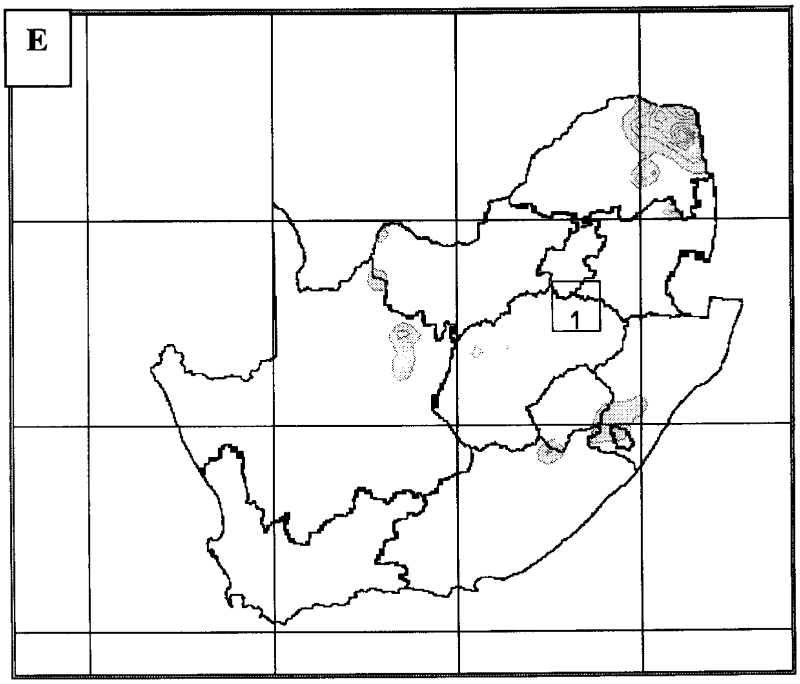

Figure 5.5e: **THERIS results for 22 February 2000. The block indicates the area where heavy precipitation is predicted. The shaded areas are observed rainfall with the first isohyet at 20 mm. Up to 20 mm rain is possible outside the 20 mm isohyet.**

5.8.6 Summary and conclusions.

THERIS was tested on 5 days during February and generally identified areas of heavy rainfall fairly well. THERIS came close to getting it 100% right on the 7th of February 2000. Considering that THERIS used model prognostic fields the results obtained on this day was very satisfying. THERIS results for the 10th February 2000 were the best prognosis of heavy rainfall from a tropical system that was ever made in South Africa. Operational meteorologists very seldom succeed in pinpointing areas of heavy rainfall using conventional methods and model prognoses. That THERIS could do so well is very gratifying.

On the 7th and 9th of February the areas of heavy rainfall occurred to the north and east of the predicted heavy rainfall area. The widespread and heavy rainfall over the eastern escarpment of South Africa was not captured by THERIS. The mechanism responsible for rainfall over these areas was probably orographic uplift. Results indicate that in a tropical atmosphere the development of heavy rainfall is very sensitive to the vertical distribution of wind divergence. The forecaster will be well advised to investigate the wind divergence and be very careful if positive wind divergence starts in the middle troposphere. This is especially true if the heavy rainfall is isolated by THERIS at a single grid point.

The fact that the Eta model's grid resolution as well as the physical parameterisation schemes differs from the NCEP re-analysis data may well require some adjustment of the criteria used in this study. Sensitivity tests should be conducted prior to operational implementation.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 GENERAL SUMMARY

Two products were developed and tested in this study using NCEP re-analysis data as well as the prognostic fields of the SAWB Eta model. The **Model for the Identification of Tropical Weather Systems (MITS)** and the **Tropical Heavy Rainfall Identification System (THERIS)** were described. MITS and THERIS were tested in three case studies (February 1988, July 1996 and January 1981) as well as for February 2000 using the Eta model prognosis. The purpose of the research was to ascertain if MITS could be used to identify areas of predominantly tropical atmospheric circulation and to determine if THERIS could be used to determine areas of heavy rainfall, both over the interior of southern Africa.

6.2 SUMMARY OF RESULTS

A detailed summary of results followed each of the case studies detailed in chapter 4 and 5. A brief summary of the most significant results, in each of the case studies, is presented here in order to illustrate how MITS and THERIS could aid the weather forecaster in the identification of tropical weather systems and areas of heavy rainfall. In the first three case studies NCEP data was used while the February 2000 floods were analysed using the prognostic fields of the Eta model.

6.2.1 February 1988

During February 1988 a classical example of a tropical weather system caused extreme rainfall over the central parts of Southern Africa. The heavy rainfall was caused by the simultaneous occurrence of abundant water vapor carried by the tropical air at the surface underneath the maximum upper tropospheric divergence in a conditionally unstable atmosphere.

Two weather systems with very distinct properties existed over southern Africa with the tropical low dominating the circulation over the central interior while a mid latitude weather system was situated over the southwestern Cape. MITS easily identified the tropical nature of the atmospheric circulation over the central interior.

THERIS was tested on the 19th, 20th and 21st of February 1988 when the heaviest rainfall occurred. This tropical, heavy rainfall, over the central parts of South Africa was captured very well by THERIS. On the 20th of February THERIS performed exceptionally well. The weighted average rainfall over the area isolated by THERIS was 50 mm with close to 90% of all the stations receiving rain.

6.2.2 July 1996

A mid-winter baroclinic cut-off low (COL), situated over the central interior together with near perpendicular surface on-shore flow over the southeastern coastal regions was responsible for the heavy rainfall over Kwazulu-Natal as well as the heavy snowfall which occurred over the elevated areas of the eastern interior.

The baroclinic nature of the atmospheric circulation was clearly illustrated by the southeastward leaning low, cold core of upper tropospheric temperatures and low values of average total static energy (TSE). With the exception of the vertical profile of omega, the other conditions of MITS were not met in this case study. Not unexpectedly THERIS was unable to identify the heavy rainfall over Kwazulu-Natal.

6.2.3 January 1981

A COL was situated over the southwestern Cape causing widespread and heavy rainfall over the southwestern interior ultimately leading to the Laingsburg flood disaster. The atmospheric circulation properties were distinctly different over the northeastern parts of the southern sub-continent. It is therefore encouraging that MITS was able to identify the tropical circulation over the eastern interior even with such a dominant baroclinic weather system in the southwest. It was illustrated here how the identification of the tropical nature of the atmosphere should not be rejected out of hand even when all the MITS components are not evident immediately. In this case study the lower tropospheric cyclonic circulation over Zimbabwe was somewhat obscured but the other four components of MITS did exist.

THERIS was tested on the 24th, 25th and 26th of January 1981 and widespread and heavy rainfall generally did materialize in the areas isolated by THERIS. No heavy rainfall area was isolated by THERIS on the 25th even though extensive rainfall did occur over the central and western interior. On the 24th the weighted average rainfall in the area predicted by THERIS was 26 mm and 18 mm on the 26th.

6.2.4 February 2000

During February 2000 exceptionally heavy rainfall occurred over the northeastern parts of South Africa and adjacent parts of Mozambique, Botswana and Zimbabwe. First (5 - 10 February) a tropical easterly low moved from east to west over the southern sub continent and then (22 – 25 February) tropical cyclone Eline invaded Mozambique causing heavy rainfall over Mozambique, Zimbabwe and the Northern Province of South Africa. This case study illustrated how the operational MITS identified the tropical nature of the atmospheric circulation. MITS also fared well in predicting areas of convective rainfall.

THERIS was tested on all the heavy rainfall days during February 2000 by using the Eta model. THERIS isolated heavy rainfall areas over South Africa on the 7th, 8th, 9th, 10th and 22nd. On the 7th two heavy rainfall areas were isolated and on average 50 mm of rain occurred in the first area. The results in the second area were not as good and it seems as if the heavy rainfall in fact occurred slightly northeast of the THERIS predicted area. The same tendency repeated on the 9th as the area isolated by THERIS was again somewhat south and west of the actual rainfall. The northward slopes of the east-west running watershed, inadequately modeled by Eta, probably played a significant role in the development of the heavy rainfall over these areas. The THERIS results on the 8th and 10th were exceptionally good as the average rainfall which occurred over the areas isolated by THERIS was between 26 and 30 mm and with close to 80% of the stations in the areas reporting some rain. No rainfall occurred on the 22nd in the area isolated by THERIS. The very heavy rainfall over the eastern escarpment of South Africa was not captured by THERIS.

Initial hands-on illustration resulted in positive comments from operational weather forecasting staff, who were keen to test and use both THERIS and MITS thoroughly.

6.3 CONCLUSIONS.

6.3.1 MITS

1. MITS proved to be an efficient system to isolate continental tropical weather systems over southern Africa.
2. Case studies indicate that MITS was effective in delineating areas where convective development will take place.

3. The weather forecaster is taken step by step through the dynamical properties of a tropical system to the eventual conclusion. In this way the forecasters' confidence in the system is enhanced.
4. MITS was incorporated into the display package PCGRIDDS, in daily use by the forecasters. It operates quickly and effectively.
5. MITS is an effective training tool and promotes further investigation and understanding of the dynamical properties of tropical systems over South Africa.
6. MITS identified conditions and parameters derived from the atmospheric dynamics not used in the forecasting offices of South Africa prior to the development of MITS. They are precipitable water, total static energy and conditional instability.

6.3.2 THERIS

1. THERIS succeeded in identifying and pinpointing the geographical areas where heavy rain from tropical weather systems occurred.
2. Case studies indicated a good correlation between predicted heavy rain and the reality.
3. Dynamical circulation parameter thresholds set for THERIS are strict and avoid identifying marginal heavy rainfall areas.
4. THERIS is completely compatible with MITS except that the criteria set are considerable stricter in order to isolate only areas where heavy rainfall should occur.
5. Despite the fact that heavy rainfall producing baroclinic weather systems dominated the circulation, THERIS was able to isolate the tropical sector of the much larger complex baroclinic system (January 1981).
6. THERIS has the capability to assimilate many model prognostic variables, apply strict conditions and identify areas where all are met. No human can do this much simultaneously and in the time available for the production of a rainfall prognosis.
7. Criteria set for THERIS are set so strict that areas of heavy rainfall can be missed especially along the escarpment or where orographic forcing and sub-synoptic processes dominate.
8. THERIS is the first operational system in South Africa to identify areas of heavy rainfall and provides a powerful tool to forecasters.
9. THERIS is the first product available as input for Quantitative Precipitation Forecasts (QPF) in South Africa, which in the long term will be very beneficial to water management in the southern subcontinent.

6.4 RECOMMENDATIONS

1. MITS and THERIS should be implemented operationally immediately to provide feedback for the further tuning of the system.
2. An operational evaluation system should be developed in order to test the quality of the forecast provided by the two products.
3. Research to gain more understanding of the role of topography in producing heavy rainfall is urgently required. Inclusion of orographically driven forcing factors could enhance THERIS considerably.
4. A system similar to THERIS needs to be developed for heavy rain producing baroclinic weather systems over southern Africa.
5. Eta model prognostic products have not been utilized to their full potential. It is recommended that research continue on the improvement on THERIS and MITS by making use of the relatively fine horizontal resolution (50-km) and 38 vertical levels available from the Eta model.
6. Links should be established with researchers in related fields and especially with Meteorology Systems Technology (METSYS) where the development of an integrated daily rain map using RADAR, satellite and rain gauge data is currently taking place under the auspices of the Water Research Commission (WRC).
7. Operational meteorologist involvement in testing MITS and THERIS as well as their participation in future research is of paramount importance to ensure that the systems remain compatible with operational requirements.
8. Provision should be made for continuous training of operational meteorologists throughout southern Africa on the implementation and testing of MITS and THERIS.
9. The research results, as well as hands on experience with MITS and THERIS, should be incorporated into the postgraduate forecasting course available at the University of Pretoria. This is to ensure that young operational meteorologists throughout Africa get exposure to the dynamical properties of tropical weather systems.
10. The rather strict criteria set for both MITS and THERIS needs to be tested and then adjusted for different numerical models.

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