A Study Of Heavy Rainfall Events During The 2006/2007 Southern Africa Summer

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Abstract
The main motivation for this study was to investigate the atmospheric conditions that influenced the last Southern Africa rain season (November 2006 to April 2007), by means of NCEP reanalysis, observed rainfall data and satellite estimates (RFE and CMORPH).
Mesoscale convective systems, the Intertropical Convergence Zone (ITCZ), southern cold fronts, upper tropospheric cyclonic vortices and troughs, favored atmospheric instability and rainfall in the southern Africa region.

1. Introduction

Dominant features of the general circulation over southern Africa are the sub tropical semi permanent anticyclones situated over the adjacent oceans (Mascarene high over the southwest Indian Ocean and St Helene high over the Atlantic Ocean), the ITCZ and the larger tropospheric circumpolar vortex of westerly winds within which are embedded a proliferation of perturbation. These features are believed to control the daily weather in Southern Africa. Other rain bearing system includes tropical and sub tropical cyclone and the cut-off lows, accounting for many of the flood-producing rains observed in southern Africa, e.g., Quelimane in the central Mozambican province of Zambezia, January 20th, 2007 figure-1(a) and 1(b).
Since summer precipitation is of extreme importance to most of southern Africa, it was decided to restrict this study to the westerly perturbation waves occurring in summer. In order to identify relationship between the convective systems, the traveling waves and precipitation associated with the mesoscale convective systems (MCS), 34 significant events of heavy rainfall (100 mm in 24 hours or greater) was diagnosed from November 1st to April 15th. The eastern coast of the sub continent was the most affected by these heavy rainfall events with a total of 85.3% of the events being diagnosed in this region. Crimp and Manson (1999) has identified the southwestern Indian Ocean as the moisture source region for the extreme precipitation event over eastern parts of southern Africa. The major oceanographic feature of the South West Indian Ocean is the warm Agulhas Current which flows along the east and south coasts of South Africa and is the most intense western boundary current in the Southern Hemisphere. This study found that 58,8 events occurred in the southeastern parts of the sub continent (32.4% diagnosed in Mozambique and 26.5% in Madagascar). Although the propensity of tropical cyclone over the southeastern part of the sub continent is high, only 5 heavy rainfall events (14.7%) were related to tropical cyclone figure 2 (a) and (b).

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The rain season in the southern Africa extends from October to April, intensifying between December and March, when the atmospheric circulation favors the uplifting of moist air from the Indian Ocean. Within its rain season, the eastern coast experiences extreme rainfall associated to the Tropical Cyclones episodes.
Although the southern part of Africa generally receives below normal rainfall during El Niño years, as happened during this rain season, it can not be concluded as a rule. Southern Africa can be divided into numerous rainfall regions, each one having a different correlation with ENSO.
73,5% of these heavy-to-extreme rainfall occurred between December and February (the most active period).
A number of studies have associated mesoscale convective complexes (MCCs) and Systems (MCSs) with heavy rain and flash floods (e.g., Maddox et al. 1979, 1982; Maddox 1980).

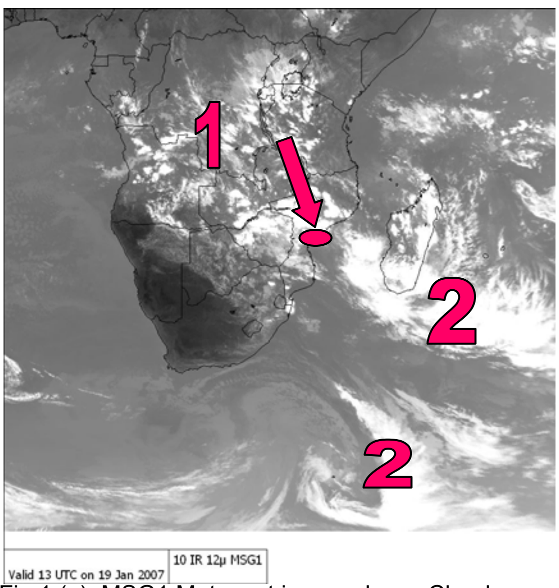


Fig.1 (a): MSG1 Meteosat image shows Cloud bands connecting the ITCZ in region 1 and a upper trough associated with a cold front in region 2. The oval indicated by the arrow points the Quelimane (Coastal) Town which received 339 mm in 24 hrs due to this system.

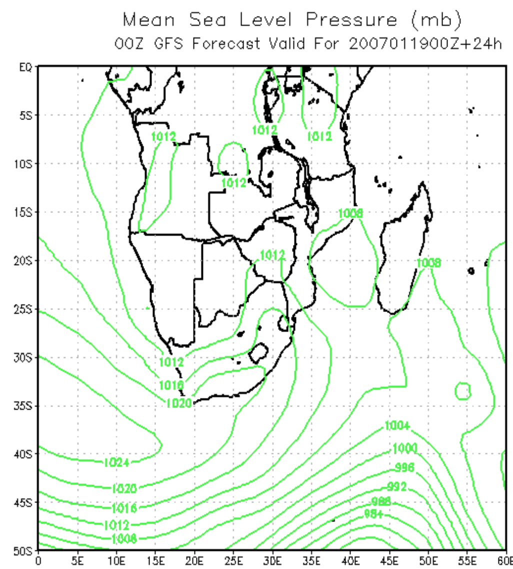
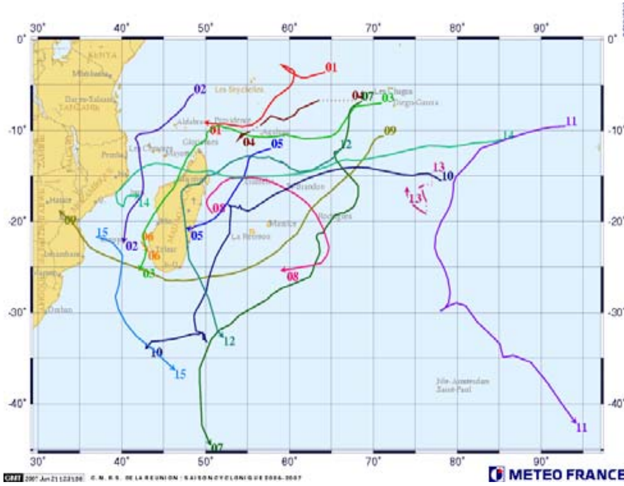


Fig.1 (b): GFS mean sea level pressure, January 20th, 2007 00 UTC. The thermal lows in the northern parts of the sub continent denoting the ITCZ and the 1008 hPa low over the central coast of Mozambique, connected with the cold front to the south of Madagascar.



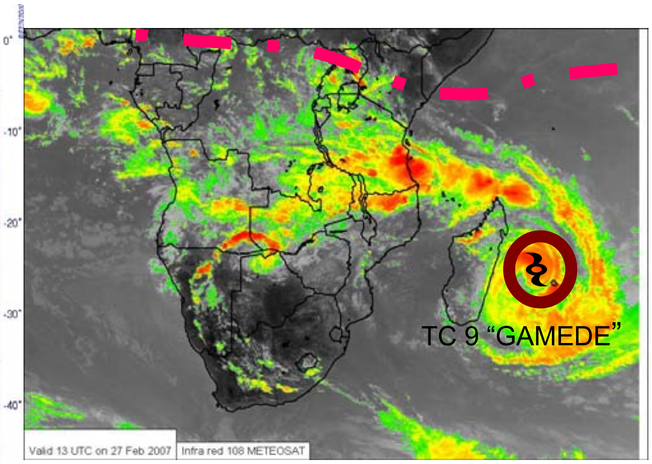


Fig.2 (a): Total number of tropical disturbance or tropical cyclone in southwestern Indian basin, season 2006-2007. Meteo France

Fig.2 (b): MSG1 Meteosat image shows Cloud bands connecting the ITCZ to the north of Mozambique and tropical cyclone “GAMEDE”

2. Datasets

The National Center for Environmental Prediction (NCEP) GFS (Global Forecast System) reanalyzes and GDAS with a 1^{o} latitude x 1^{o} longitude resolution were used to draw 4 times a day map of mean sea level pressure, wind (925 mb, 850 mb, 500 mb and 200 mb), geopotential height, vertical velocity, moisture convergence, relative humidity, precipitation, lifted index, CAPE, temperature, equivalent potential temperature, K-index and vorticity, during the significant rain events.
The advantageous quality of the NCEP reanalyzed meteorological fields are described in detail in Kalnay et al. (1996) and Riel et al. (2001). Global Telecommunication System (GTS) data were accessed to obtain 24 hours total precipitation data.
The use of rainfall estimation (RFE) allowed the determination of the precipitation coverage due to the lack of information. The relationship between the westerly perturbation and the ITCZ in the most extreme case (339 mm in 24 hours) was identified using METEOSAT IR image.

3. Methodology

The synoptic analysis of the meteorological fields was visualized using GRADS (Grid Analysis and Display System). The main purpose was to carefully verify the temporal and spatial evolution of the MCCs or MCSs.

The scarcity and infrequence of the station data have limited the usefulness of some heavy rainfall data to this study figure 3 (a) and (b).
The RFE is used for the rainfall confirmation over the stations reported on GTS. Although the data coverage did not allow a better discussion of the satellite data, it has proven to be a useful tool for the forecasters.

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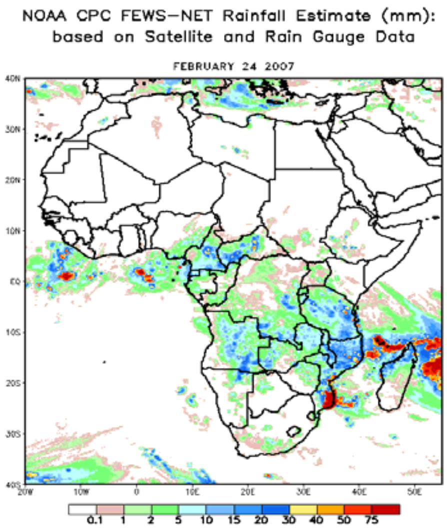


Fig.3 (a): February 24th, 2007 Rainfall Estimate precipitation showing the intensity of precipitation to the northeast of the coast of Mozambique and also over southeastern coast.

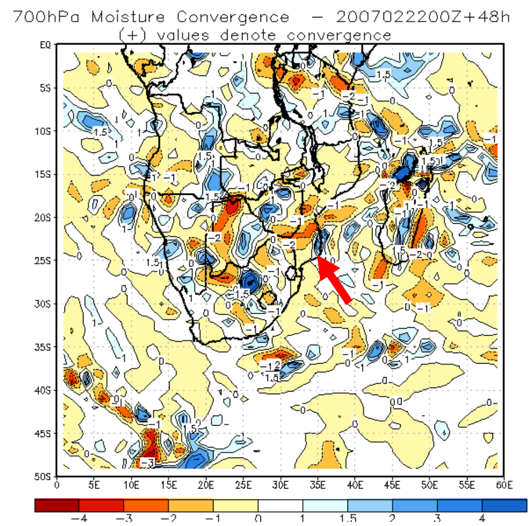


Fig.3 (b): Moisture convergence over the same regions mentioned on 3 (a). A ground station, Inhambane, in the southeastern coast of Mozambique (see arrow), reported 91.9 mm in 24 hrs.

Fig.4: Maximum displacement away from the Equator of the ITCZ during summer in southern hemisphere (January) and Northern hemisphere (July)

4. Synoptic Setting

The intensification of the heavy rainfall events during December, January and February enhanced the theory of connection between the ITCZ (which reaches its maximum displacement away from the Equator in the southern hemisphere in January, figure 4), the westerly waves and troughs and also the MCSs, as shown in figure 1(a) and 2(b). The most extreme events occurred during this phase. For all the discussed events, the flow at 200, 500 and at 850 hPa also the vorticity at 300, 700 and 850 hPa, showed divergence in upper level sustaining convergence in lower levels.
The sub tropical semi permanent anticyclones over the Atlantic and Indian Ocean played a role in the intensification of the rainfall by advection of moisture from the Indian Ocean over the eastern coast of the sub continent.

4.1 – Mean Sea level Pressure Fields.

The mean seal level pressure fields for almost of the events show essential the same features across the entire region. The perturbation of the pressure field is not a local or mesoscale feature (Orlanski, 1975), but has horizontal dimensions in excess of 10^3 km figure 5. The propagation of the troughs (fronts) from west to east is clearly evident in this case study.

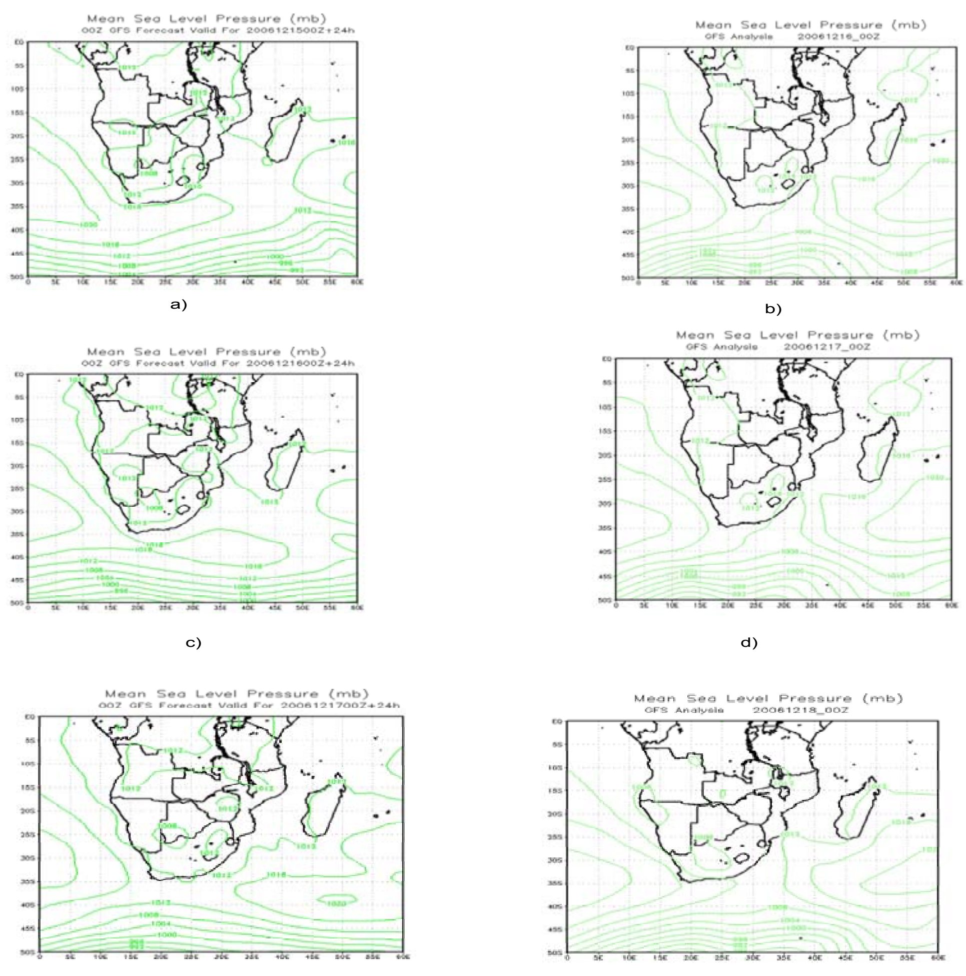


Fig.5 (a to f): Mean sea level pressure, 24 hours forecast (left) and 00Z analysis (right).

On December 16 and 17th a weak cold front was present to the southeast of the sub continent with a heat low over the interior. A well-developed anticyclone was present in the South West Indian Ocean (the Mascarene high) with associated easterly advection of moist air above the Agulhas Current along the southeastern coast. On December 17th, the inland thermal low deepened as it shifted eastward. Interaction between this thermal low, the midlevel trough that tracked over the region on December 16-17 with associated cold air advection aloft and the low level inflow of warm moist air from the Agulhas Current produced very favorable conditions for intense storm development.
MCSs develop in connection with warm air, therefore they can be found in front of or within the leading parts of Cold Fronts. CB clouds develop at the rear parts of Cold Fronts or in the cold air and they have different synoptic environments.

The GFS accurately represents the mean sea level pressure fields, except when the event is related to a small scale development (e.g., eastern South Africa, December 16 and 17th, figure 6), where underestimation of intensity can been seen in the mean sea level fields.

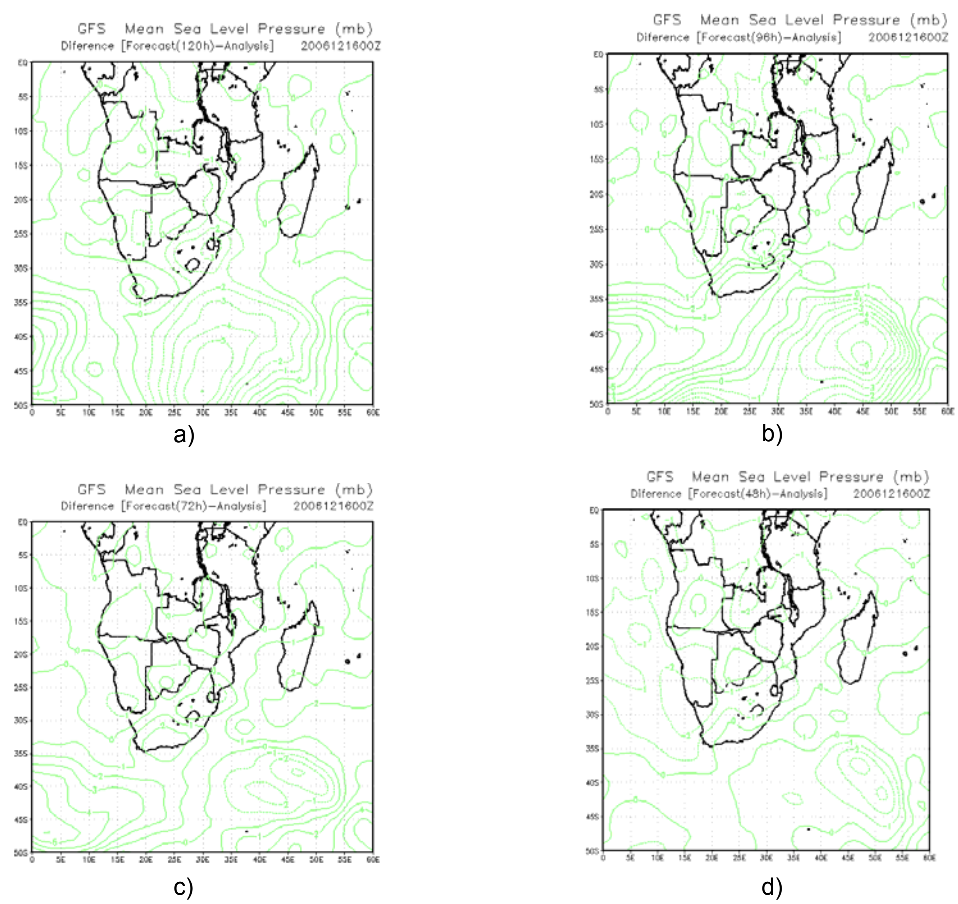
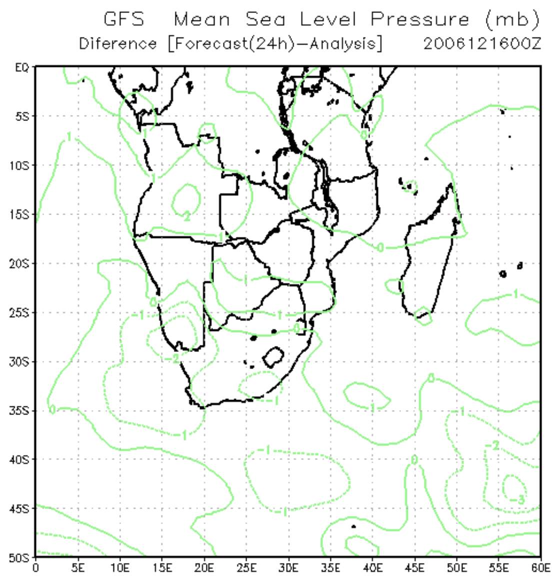


Fig.6 - Difference between: 120h forecast and analysis (a), 96h forecast and analysis (b), 72h forecast and analysis (c) and 48h forecast minus analysis.



e)

Fig.6 (e): Shows a good agreement between 24h forecast and analysis over eastern South Africa, December 16th. 2006 at 00 UTC.

During the propagation of the cold front and intensification of the thermal low over the southern parts of the sub continent, the GFS model did a god job on the 72, 48 and 24 hours forecast of the features that prevailed over the region. Although the model underestimated 1 hPa in 48 and 72 hours forecast figures 6-c and 6-d, the interaction between the inland thermal low deepening over eastern parts of South Africa, the cold front to the southeast, the mid level trough that tracked over the region on December 16-17 with associated moisture advection from the Agulhas Current was a clear signal given by the model about the favorable conditions for instability and storm development.
The 96 and 120 hours forecast underestimated the mean sea level fields up to 3 hPa.

4.2 – Streamlines and Relative Vorticity

Strong upper level divergence (figure 7) and moisture transport suggests a pattern favoring the formation of MCSs.
The axis of the heaviest rainfall in this study usually occurred within an area of 300 hPa divergence but in the gradient to the south of the highest values (figure 8).
In this study a number of similarities have been noted between the most extreme events, similarities of moisture and wind which can allows the forecasters to anticipate the development of an extreme event.
The fact that a broad area of 300hPa divergence was present during the most extreme events, therefore, is not unexpected. However, forecasters should note that the location of the heaviest rainfall usually is found in the gradient south of the maximum values of 300hPa divergence (figure 7-a and 7-b). This finding is probably related to sloped ascent that takes place as potentially unstable parcels are lifted along a boundary toward the upper level divergence.

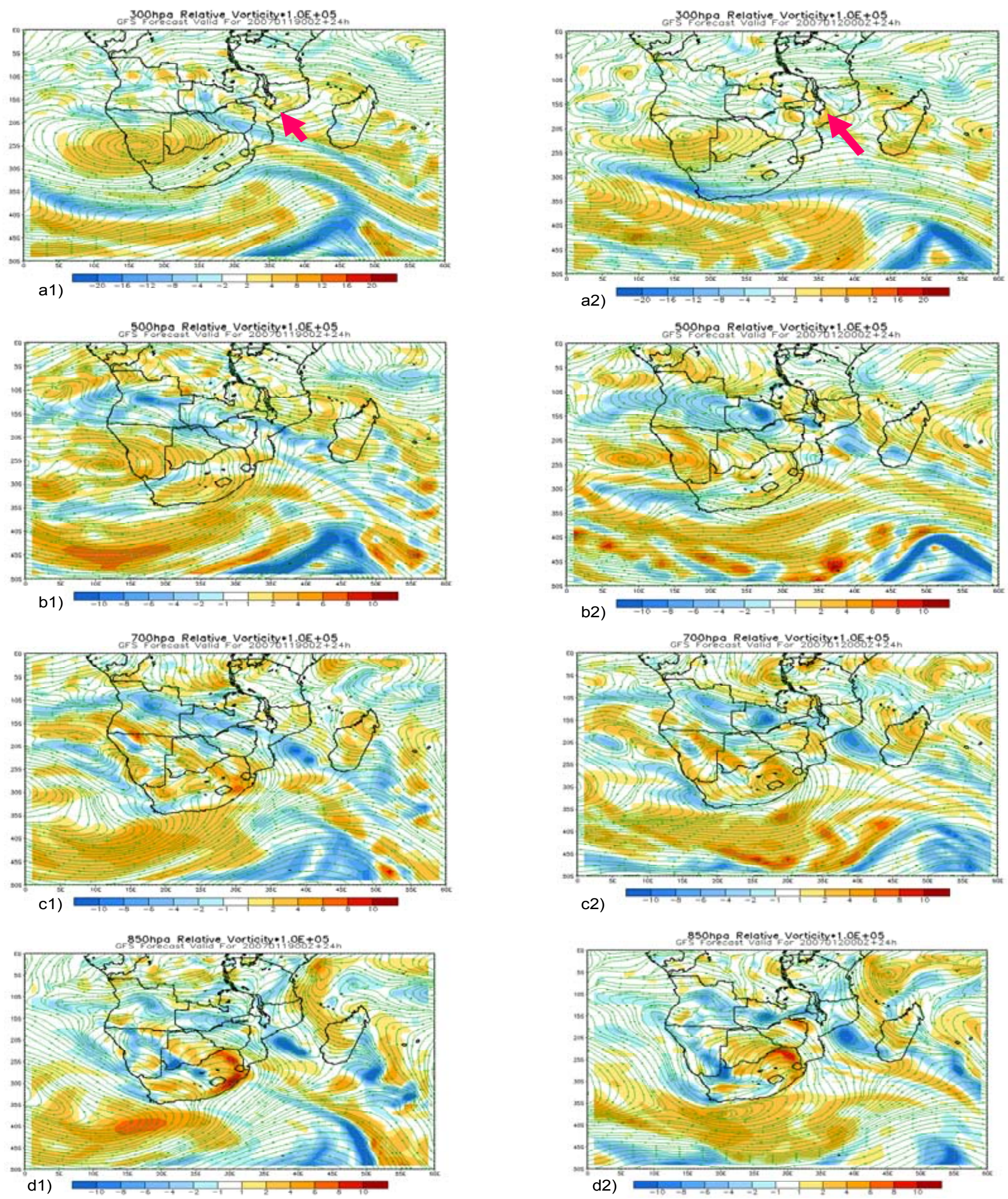


Fig.7 (a to d): Relative vorticity and streamlines at 300hPa (a), 500hPa (b), 700hPa (c) and 850hPa (d). On the left side (1), January 1900Z +24 hrs forecast and January 2000Z +24hrs forecast on the right side (2).

In general negative values of relative vorticity (cyclonic) in lower levels were observed in most of the events leading to the intensification of the instability.

The upper level troughs are clearly shown in figure 7 (b and c). This study found that the convective system associated with the wave appears to the west of the wave axis.

4.3 – Relative Humidity

The synopticians empirically determine that (heavy) rainfall typically is associated with high values of relative humidity. Although relatively large amounts of moisture is found in the tropics, a forecaster needs to ensure the presence of high values of relative humidity in the upper levels, 700 up to 500 hPa (figure 8-a and 8-b), to assure the probability of heavy rainfall.
The most extreme events occurred within the axis of highest relative humidity and were associated with high values of relative humidity (figure 8).
The scale and intensity of rainfall associated with convective systems at least in part seemed to be modulated by the relative humidity. Some less extreme events however occurred with high value of relative humidity indicating that other factors also modulate the scale of a MCS.

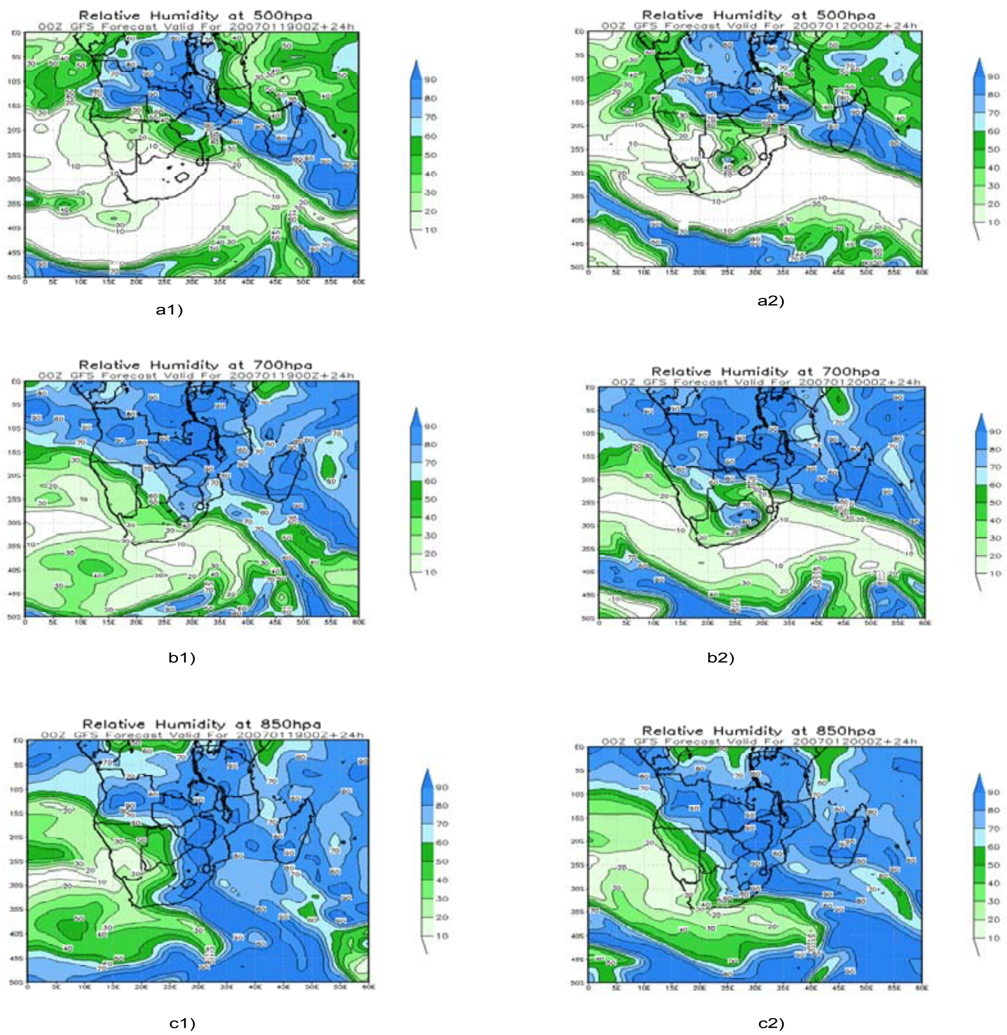


Fig.8 (a to c): Relative humidity at 500hPa (a), 700hPa (b) and 850hPa (c).
On the left side (1), January 1900Z +24 hrs forecast and January 2000Z +24hrs forecast on the right side (2).

At the 500 hPa (figure 8-a1 and 8-a2) the relative humidity over Mozambique which is seen at 700 and 850 hPa, is only higher in the central region. It proves that chance of heavy rainfall is just centered over central Mozambique, as found in the station data.

4.4 – Moisture convergence

The heavy rainfall events were more likely when the axis of the strongest low level moisture convergence was parallel to the wind flow and where moisture convergence is also present in the upper level (figure 9-c2 region A).
When the boundary and major axis of the associated moisture convergence were more frequently aligned perpendicularly to the wind flow (figure 11-c2), lower observed rainfall was reported (figure 9-c2 region B).
When relative humidity values are higher new cells form in the area of moisture convergence, prolonging the duration of heavy rainfall and increasing ultimate rainfall amount. Heavy rainfall also was located just to the southeast of an axis of strong 850 hPa moisture convergence region (figure 9-b1). This observation probably can be attributed to the initial development of convection near the zone of surface convergence but south of the 850 hPa convergence and to the eastward shift of the moisture convergence with the flow.
Early studies (Hudson 1971, Doswell 1985) noted that development of surface moisture convergence usually precedes convective initiation, making it a useful forecast tool.

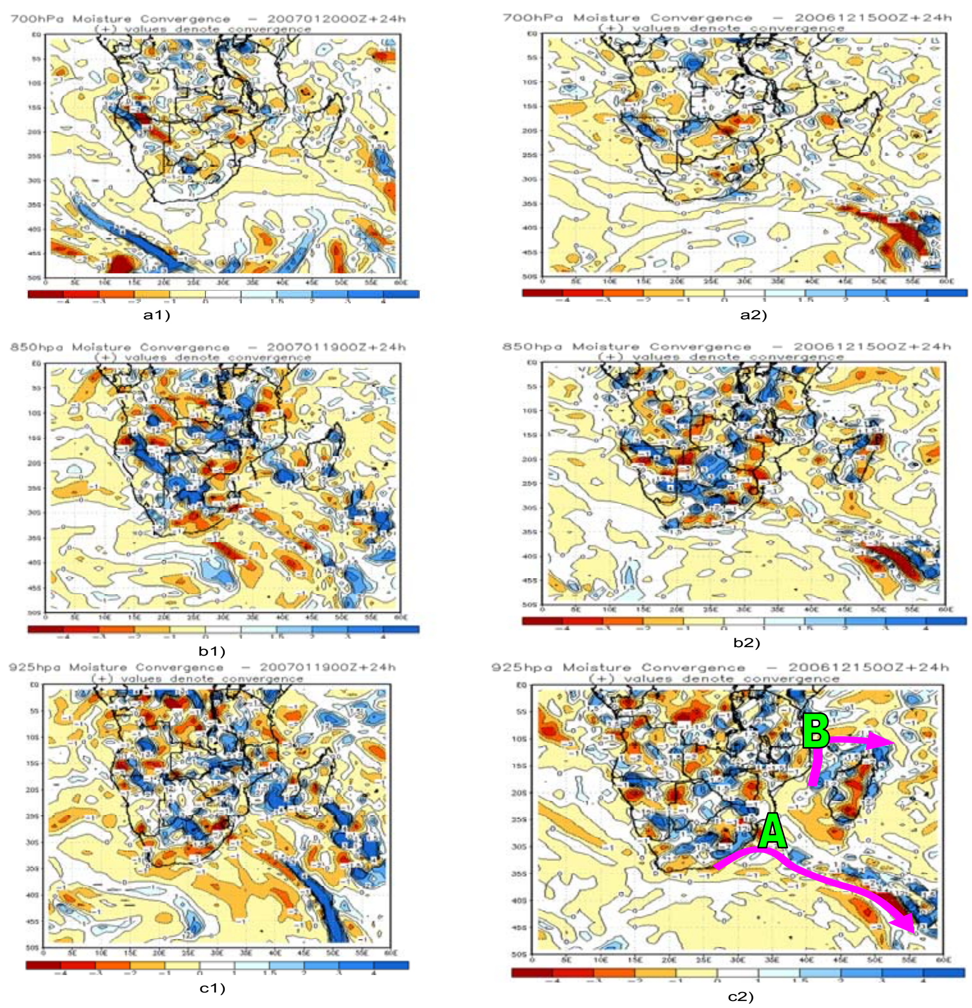


Fig.9 (a to c): Moisture convergence at 700hPa (a), 850hPa (b) and 925hPa (c). On the left side (1), January 1900Z +24 hrs forecast and December 1600Z +24hrs forecast on the right side (2). Note the presence of moisture convergence at 850 and 700 hPa over central coast of Mozambique (left) and eastern South Africa (right).

4.5 – Vertical Velocity

Almost all events were associated with weak to moderate vertical speed shear and with winds that veered with height (figure 10).

The data also suggest that heavy-to-extreme rainfall events can occur with much less vertical wind speed shear than is usually associated with most other severe weather threats (e.g. wind storms and hail). For example, the heavy rainfall over eastern South Africa on December 16 and 17th, occurred with weak 850 hPa flow, implying that only weak vertical speed shear was present. However, the wind veered considerable with height, especially at low levels.

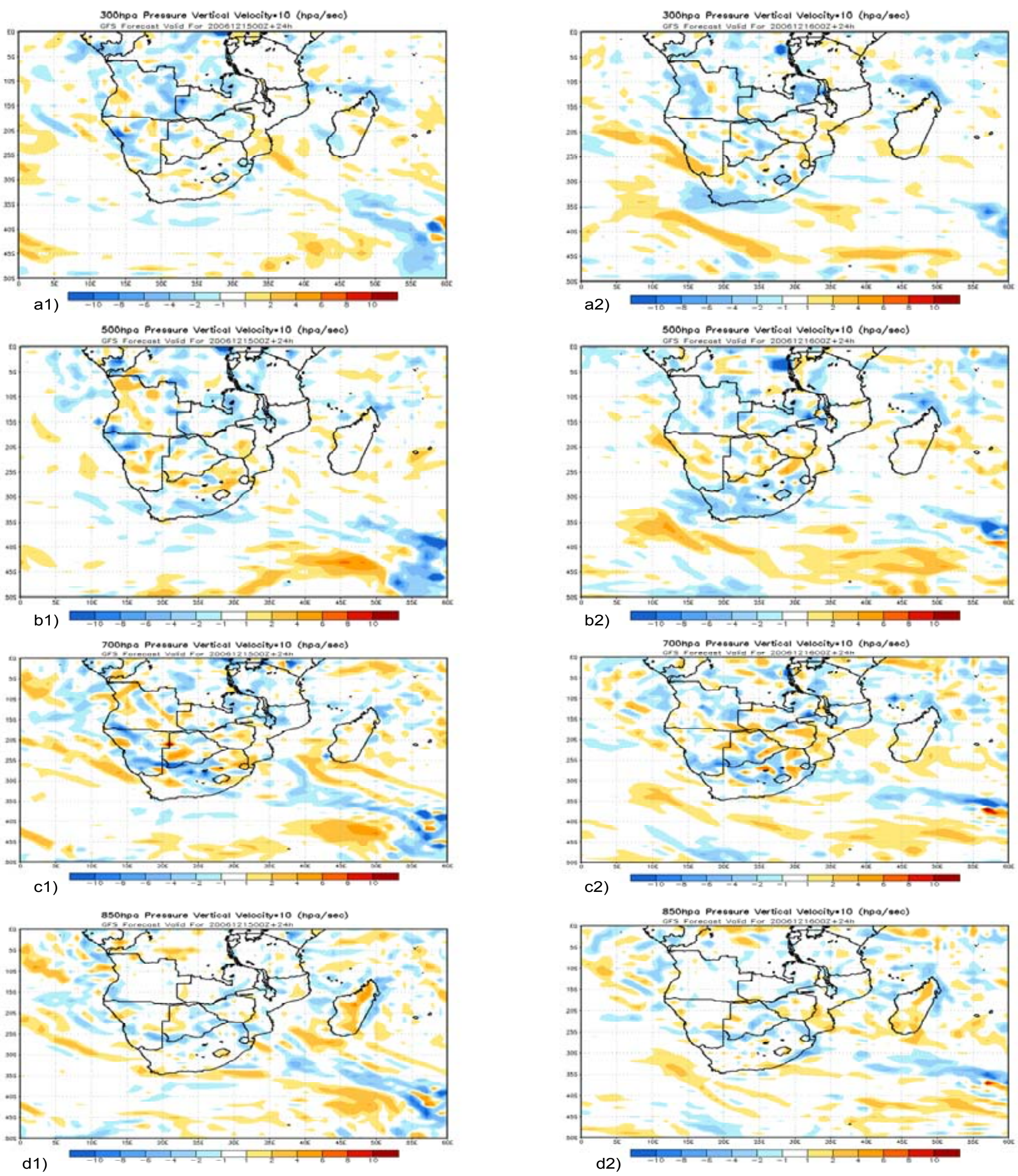


Fig.10 (a to d): Vertical velocity at 300hPa (a), 500hPa (b), 700hPa (c) and 850 hPa (d). On the left side (1), December 1500Z +24 hrs forecast and December 1600Z +24hrs forecast on the right side (2).

4.6 - Wind

The maximum rainfall for the majority of the cases was found to the north-northwest of an area of relatively strong 850 hPa wind flow (figure 11).

High southeast to northwesterly 850 hPa wind and moisture transport, and also strong upper level divergence were present over central western portion of Mozambique and central Madagascar favoring the formation of MCSs.

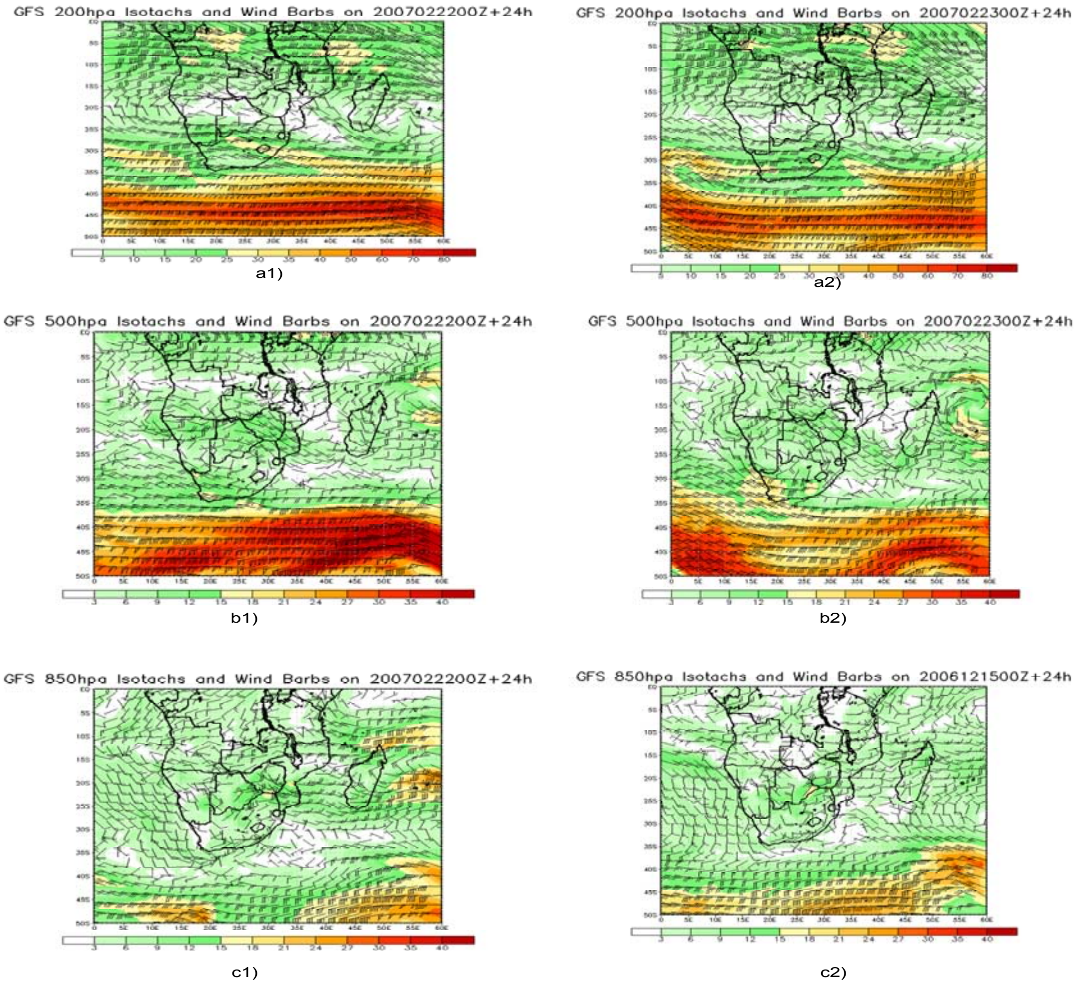


Fig.11 (a to d): Wind field at 200hPa (a), 500hPa (b) and 850 hPa (c).
The heavy rain usually was centered along the axis of strongest 850 hPa but slightly
To the northwest of the wind maximum. Tropical Cyclone GAMEDE in b1 and b2.

4.7 – CAPE, K-Index and (850/700 hPa) Temperature

The Convective Available Potential Energy (CAPE) is simple the sum (integration) of the energy that a parcel would have throughout its vertical “life”, once convection is released. The greater the excess in temperature (unstable parcel), then the greater the energy available, resulting in stronger upward motion, potentially more “severe” conditions (downdraft gust, heavy precipitation, larger hail, tornadic threat and etc…). The maximum cape (>2250 J) occurred on January 20th over central coast of Mozambique (figure 12-a) and on November 28th (figure 12-b) to the north of Mozambican Channel (associated with a disorganized convection that followed the Tropical Depression 02 “Anita”, figure 2-a). These CAPE values were due to the relatively humid air in the lower level and subsequent drop in environmental temperature from 850 hPa and above.

The presence of a low level warm, moist layer overlain by a cold, dry layer of air is a profile highly conductive to instability. In this study, no heavy-to-extreme convective rainfall event occurred at 700 hPa temperature above 12^{o}C. However less intense ones did occur.

Forecasters routinely use K-Index values as an indicator of the potential for thunderstorms and heavy rainfall.

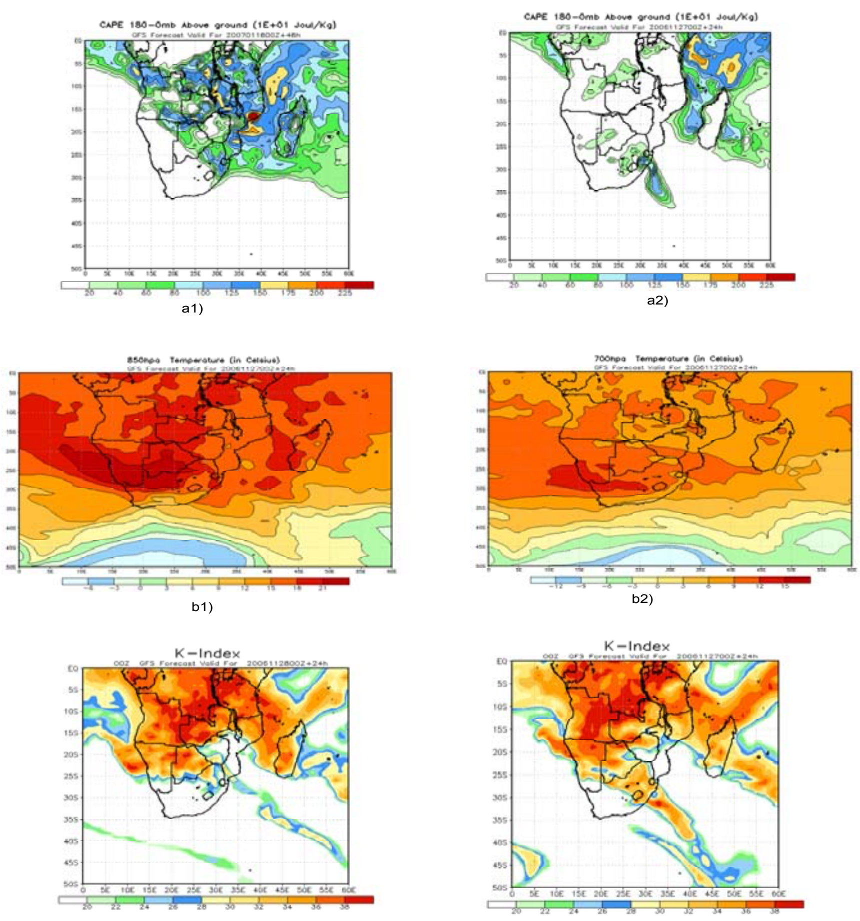


Fig.12: Cape over central coast of Mozambique, January 19, 2007 (a1) and to the north of Mozambican Channel, November 28 (a2). Temperature at 850 and 700 hPa, November 28 (b1 and b2). K-Index values for November 28 and 29, 2006.

4.8 – Equivalent Potential temperature (θe) and Thickness.

The θe is a useful quantity because it is calculated taking the humidity content of the air into account, thus a better tracer of air-mass property (at 700 hPa).
High values of θe shoes areas of warmer, potential more humid air (tropical maritime or modified continental air-masses).
In this study, the area of heavy rain is located to the north-northeast of the axis of highest 850 hPa θe (warmer temperature). Not all warmest θe coincides with heavy rainfall, but all heavy rainfall occurred on area of warmer 700 hPa θe.
This signal suggests that θe can also be used to predict where the heaviest rainfall is likely to fall.
Thickness is a useful tracer of warmer and cold air in the lower “half” of the troposphere (surface to about 500 hPa). In particular, areas where the thermal contrast is increasing are regions of potential baroclinic development (figure 13-b).

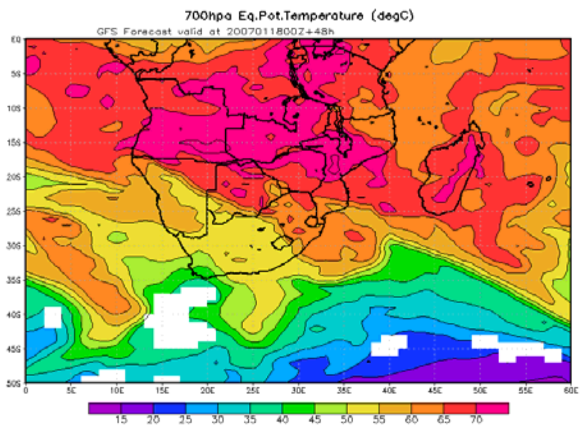


Fig.13 (a): Equivalent potential temperature at 700 hPa showing high values (orange) over central Mozambique (January 20, 2007), implying more tropical maritime air was advected to the region, thus guiding the forecaster to high probability of extreme event which was underestimated by the GFS model rain.

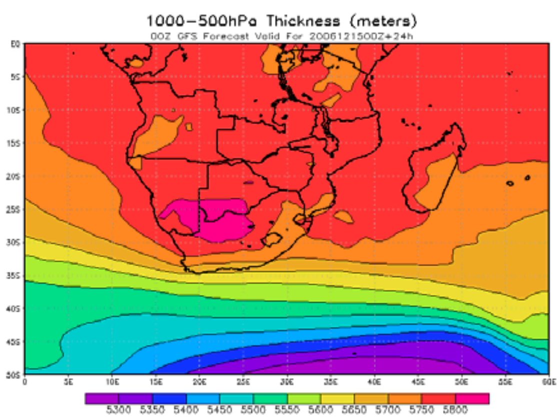


Fig.13 (b): 1000 – 500 hPa Thickness, on December 16th, 2006 over eastern South Africa. The contrast over the region is clearly seen. Consequently troughs associated with a low pressure (mid-latitude cyclones) and frontal boundaries can be found over the region.

4.9 - Precipitation

The underestimation of pressure fields during a MCS by the GFS, led to an underestimation of relative humidity and consequently the precipitation amount.
In fact, station data has shown that the NCEP-GFS model precipitation is significantly underestimated over eastern coast of South Africa, central coast of Mozambique but the model did a good job to the north of Mozambican Channel (Comoro).
The GFS precipitation over the first two regions is lower than the observations.
In situ observed precipitation during the studied events also revealed significant underestimation in the corresponding RFE data (figure 14 on the right).
As a result of these underestimations, is believed that the contribution of the smaller moisture source, mainly the narrow core of the Agulhas current which is only about 100 km wide, is not adequately resolved by the GFS.

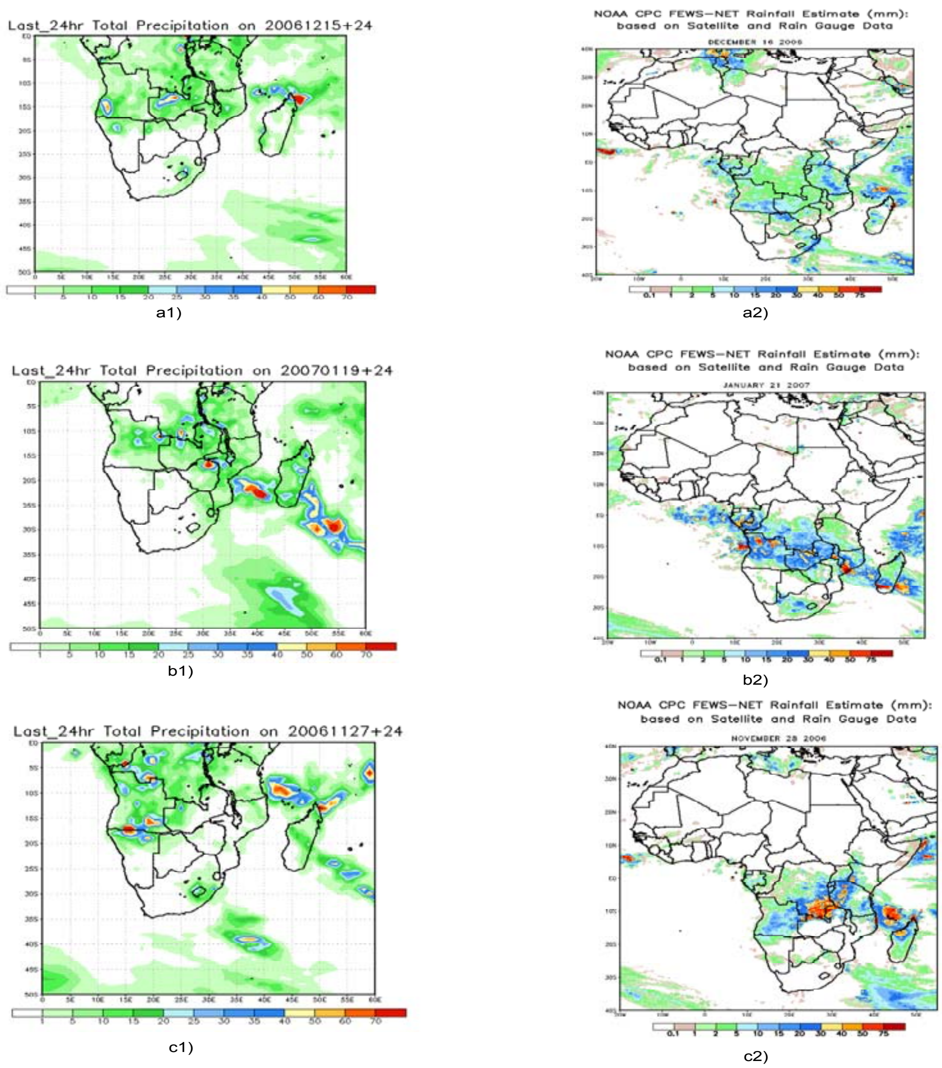


Fig.14 (a to c): 24 hours Accumulated precipitation left (1), GFS model on December 16 (a1), January 21 (b1) and November 28 (c1). Rainfall estimation based on satellite and rain gauge data (2) for the corresponding days on left.

5. Discussion

The similarities in all the dynamic and thermodynamic fields for most of the 34 heavy rainfall events instilled confidence in the diagnostic analysis of the westerly wave's propagation along southern Africa during the 2006 / 2007 summer and also highlighted the consistence nature of this perturbation.

The surface pressure fields in the post-trough stages produce a strong onshore flow along the southeastern coast of the sub continent.

The breadth, location, and movement of the axis of stronger moisture flux convergence values appeared to play a role in modulating the rainfall.

NCEP data and Meteosat pictures suggest that most of the events resulted from interaction between a continental thermal low (mostly associated with ITCZ), the sub tropical high pressure systems and midlevel troughs approaching from the west.

It is quite possible that the significance of the warm Agulhas current as a moisture source for the heavy rainfall events that occurred over southeastern parts of the sub continent may be underestimated by the NCEP re-analysis examined in this study.

6. Conclusion

This study demonstrated that even in absence of radar or dense radiosond networks and satellite remote sensing, model data can be extremely useful for case study research or even heavy rainfall forecasting. The data used were downloaded freely after often being displayed through the internet. *This is a particular importance to underdeveloped countries whose resources for costly data are often limited.*
The study also confirmed that the factors that govern whether a convective event becomes extreme are:

- Slow system movement
- Prolonged heavy-to-intense rainfall rates
- Areal coverage of the intense rainfall rates

The small scale of the core of the heaviest rainfall within the extreme convective events, many of which produced severe flash flooding, argues for a probabilistic approach to forecast flash floods.

This study suggests that forecasters may be able to develop some skills in predicting when an extreme event is likely, but they probably would not be able to predict the precise location with the accuracy needed to determine which area, river basin or sub basin would flood with much lead time.

A more realistic approach might be to predict the probability of occurrence (ensemble prediction system) of heavier rainfall within a predefined region over a specified time period (i.e., 6, 12 or 24 hours).
Such an approach would provide information about the uncertainty of the scale and location of the core of heavy rains that are associated with flash floods.

7. Acknowledgement

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The compliments are also extended to the Mozambican Institute of Meteorology for the station data provided.

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