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Forecasting Intense Cut-Off Lows in South Africa Using the 4.4 Km Unified Model

Tshimbiluni P. Muofhe^{1,2*}, Hector Chikoore³, Mary-Jane M. Bopape⁴, Nthaduleni S. Nethengwe¹, Thando Ndarana⁵ and Gift T. Rambuwani⁴

¹ Department of Geography and Geo-Information Sciences, University of Venda, Thohoyandou, South Africa

² Global Change Institute, University of the Witwatersrand, Johannesburg, South Africa

³ Unit for Environmental Sciences and Management, North-West University, Vanderbijlpark, South Africa

⁴ South African Weather Service, Pretoria, South Africa

⁵ Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Pretoria, South Africa

* Correspondence: 2385587@students.wits.ac.za

Abstract: Mid-tropospheric cut-off low (COL) pressure systems are linked to severe weather, heavy rainfall and extreme cold conditions over South Africa. They often result in floods and snowfalls in winter disrupting economic activities. This paper examines the evolution and circulation patterns associated with severe COLs over South Africa. We evaluate the performance of the 4.4 km Unified Model (UM) which is currently used operationally by the South African Weather Service to simulate daily rainfall. Circulation variables and precipitation simulated by the UM were compared against ECMWF's ERA Interim reanalyses and GPM precipitation at 24-hour timesteps. We present five recent (2016-2019) severe COLs that had high impact and found higher model skill when simulating heavy precipitation during the initial stages than the dissipating stages of the systems. A key finding was that the UM underestimated precipitation mainly due to inaccurate placing of COL centers and areas of heavy rainfall by up to 5° of latitude away from the actual location, due to the poor formulating of cumulus and microphysics schemes in the model. Understanding the performance and limitations of the UM model in simulating COL characteristics can benefit severe weather forecasting and contribute to disaster risk reduction in South Africa.

Keywords: cut-off lows; circulation patterns; heavy precipitation; floods; forecast skill; unified model; GPM precipitation

1. Introduction

Some of the major rain-producing weather systems over South Africa include cloud bands in tropical-temperate troughs (TTTs) [1-3], cold fronts [4-6], cut-off lows [7-8], tropical continental lows [9-10], mesoscale convective systems [11] as well as landfalling tropical cyclones [12-14] from the South West Indian Ocean. Whilst most of these systems have strong seasonality, cut-off lows (COLs) can occur throughout the year, although with some peaks during the austral autumn and spring seasons [7, 15]. The peak season for COL events has also been observed to shift from March–May to June–August, with location shifting from southwestern (~34°S) towards the northeast of the subtropical southern Africa since the 1980s [7]. Thus, COL systems may be significant contributors to austral winter rainfall over South Africa.

COLs are important synoptic-scale baroclinic systems typically known for their tempestuous weather often resulting in heavy rainfall events and floods [8, 16]. They tend to form and develop over the mid-latitudes, on the equatorial-side of the tropospheric polar jet-stream ending up as closed cyclones in the middle and upper troposphere. This occurs when the upper air system detaches from the mean westerly flow of the mid-latitudes [17]. A COL is a cold-cored depression produced by a westerly trough that usually develops in the upper westerlies as a trough and deepens to form a closed circulation which may extend to the surface [18-19]. This characteristic closed circulation is induced

by a high potential vorticity (PV) anomaly [20] that is caused by isentropic transport of high PV stratospheric air, which in turn is associated with upper tropospheric Rossby wave breaking processes [15]. Surface depressions may develop below these systems whilst cold air aloft promotes deep convection and cloud development, resulting in persistent heavy rainfall. COLs are associated with cold weather as they are often accompanied by ridging anticyclones that steer cold southerly airflow, facilitating moisture transport from the South West Indian Ocean [21-23].

A small region along the southern coastal region of the country, called the Cape south coast receives rainfall throughout the year [3, 24-25] and much of the rainfall activity over this area is associated with COLs, ridging high pressure systems and TTTs [26]. COLs play a major role in the distribution of rainfall, not only on the Cape south coast region but also across several rainfall regions of the country [8].

COLs are associated with strong surface wind convergence and rising vertical motions, which may lead to high impact rainfall events causing floods. They can produce 24- hour rainfall totals which exceed the climatological monthly rainfall averages of an area [27]. Typically characterized by slow movement, COLs may remain quasi-stationary over a region for several days resulting in persistence of anomalous weather conditions. Often, the persistence and slow-moving character of COLs is due to atmospheric blocking from the Mascarene High pressure system over the South West Indian Ocean [28].

In many regions, such as the European continent, the Mediterranean and Australia, COLs are also associated with heavy precipitation which may persist for several days [29]. [30] found that most of the anomalous regional convective events which occur over northern China are often associated with the occurrence of COLs. In June and August 1998, COL events led to record floods which caused severe damage to infrastructure and disruption of socio-economic activities in northern China [31]. Over West Africa, a COL system led to rainfall of up to 116 mm in 24 hours during the cool season from 9 to 11 January 1981 [16]. In South Africa, on average one in five COLs is associated with flood events, particularly over the southern and eastern coastal belts of the country [8].

Fewer studies have been undertaken on Southern Hemisphere COLs in comparison to their Northern Hemisphere counterparts [e.g., 18]. The effects of topography as well as the influence of mid-latitude storms on COLs have been investigated rigorously in different locations in the Northern Hemisphere [e.g., 32] but not in the South African context. However, there are important differences between the Northern and Southern Hemispheres, which suggests that simply transferring Northern Hemisphere findings about COLs to Southern Hemisphere may be inappropriate. In South Africa, COL events are often dominant over the south west and south coast, and therefore most studies of COLs have focused on these areas than the more northern regions over the country [8].

It is important to accurately forecast the area of deep moist convection in COLs with adequate lead time to warn the public and disaster management authorities of possible heavy rainfall and cold conditions during that are usually associated with these events. Numerical Weather Prediction (NWP) models are the main tools used to forecast weather up to a few days in advance (short to medium term timescale). The spatial resolution used by these models affects the skill with which they can simulate different atmospheric features. Global circulation models used for this time range are currently running with grid spacings of less than 20 km in major international meteorological centers. For example, the European Centre for Medium-Range Weather Forecasts (ECMWF) runs its Integrated Forecasting System (IFS) with a grid spacing of 9 km, while the United Kingdom Met Office (UKMO) runs the Unified Model (UM) Global Atmosphere with a grid spacing of 10 km [33].

Dynamical regional climate models (RCMs) are preferable tools to simulate atmospheric processes and rainfall at the regional scale. There is still a need to improve the realistic capability of the RCMs to simulate cumulus convection mostly over the steep topography and regional regions of South

Africa [34]. Simulation of convective rainfall by NWP models is known to have relatively large biases which may lead to inaccurate forecasts. Known challenges include the overestimation of rainfall over complex topography, early convection initiation and a lack of severity in simulated thunderstorms [e.g. 35]. South Africa is characterized by a complex topography which can influence the atmospheric circulation and modify characteristics of COL events.

When analyzing systematic properties of the 12 km, 4 km and 1 km UM resolutions in simulating rainfall over convective cases over southern England, [36] found that 4 km and 1 km resolutions simulate more realistic-looking precipitation as convection is represented explicitly instead of being parameterized. However, the 4 km model tends to perform differently depending on whether the convective parameterization scheme is present or not. Without convective parameterization, the model delayed convective initiation but produced too much rainfall later due to the large grid length which was unable to reproduce the convection explicitly. When the standard convective parameterization is included, the model tends to underestimate the intensity of rainfall as the parameterization may remove instability in the showers [36]. When analyzing the amount of rainfall over the Indian summer monsoon region, the 4 km model simulated higher rainfall when compared with Global Precipitation Measurement (GPM) and 1.5 km [37]. Inaccurate simulation of rainfall in the 4 km when compared with 1.5 km has been possibly associated with poor moisture conservation promoting extreme rainfall [38].

In this paper, we analyzed the circulation patterns of five recent COL events over South Africa whilst evaluating the skill of the NWP models used operationally by SAWS in simulating these events. The study is motivated by the impact of the recent COLs, damage to property and loss of lives which often result from inaccurate placing of COL centers, location of deep moist convection resulting in underestimates of precipitation. Recently, a deep COL in April 2019 dumped over 180 mm in 48 hours and caused loss of at least 85 lives in southeast South Africa. Whilst most NWP models predicted rainfall due to the approaching COL, the amounts were underestimated and simulated slightly later affecting early warning systems and disaster management over the areas affected by heavy precipitation.

2. Data and Methods

2.1 Methodology

We present the structure, evolution and characteristics of COLs over South Africa using case studies. To evaluate the performance of the UM in simulating the location of deep moist convection and heavy rainfall, this paper examined five recent (2016-2019) severe COL events which were associated with anomalous meteorological structures, extreme rainfall and high impacts.

2.2 Observed and reanalysis data

Key variables associated with the study of COLs include precipitation, mean sea level pressure, geopotential heights, winds, vertical velocities, divergence and potential vorticity [39]. Reanalysis datasets from the European Centre for Medium-Range Weather Forecasts (ECMWF) were used to analyse COL characteristics over South Africa for the period 2016-2019. We analysed circulation variables from the ECMWF ERA Interim reanalysis [40] which are available at a spatial resolution of about 80 km. Daily geopotential height fields in the mid-troposphere (~500 hPa) were used to identify closed centers associated with the occurrence of COLs. Daily fields of vertical velocity (ω , DP/Dt) were used to investigate the location of rising motion in the COL to account for the skill of the model. Areas of negative values of ω coincide with regions where uplift is taking place. GPM data from the National Aeronautics and Space Administration (NASA) was used to evaluate the performance of the model in simulating the location and amounts of rainfall associated with deep moist convection

during the five COL events. The GPM which is an extension of the Tropical Rain Measuring Mission (TRMM) is largely based on microwave measurements which are better than IR-based estimates [41] and the data are available at a resolution of $0.1^\circ \times 0.1^\circ$. Not only does GPM provide more accurate precipitation estimates than TRMM, it also covers a larger domain (68°N/S) compared to TRMM which was limited to (37°N/S) [14], and also updates every 30 minutes.

2.3 Model description and forecasts

SAWS runs the UKMO UM [42] as its main operational NWP model. The regional model is run with a grid spacing 4.4 km over the southern Africa domain. The UM outputs (from the equator to 38°S) are also available to national met services in southern Africa for their own severe weather forecasting under a WMO initiated Severe Weather Forecasting Demonstration Project. SAWS updates the UM forecasts four times daily, with the 00h00, 06h00, 12h00 and 18h00 UTC analyses. In addition to describing the event from the observations, simulations from the UM are also evaluated in this study. Since these simulations are produced on an operational basis at SAWS, they are part of the actual input information that forecasters used to forecast and inform the public about these COL events.

We analysed the model simulated geopotential heights at 500 hPa and precipitation from simulations initiated with the 12Z analyses. The 24-hour precipitation simulations from the 4.4 km UM are compared with the GPM calibrated precipitation estimates using the eyeball verification technique. The study focuses on the performance of the model based on amount, location and timing of geopotential heights and extreme rainfall associated with COLs.

3. Results

3.1 Event of 13-15 May 2016

A cut-off low system was observed over South Africa between the 13-15th of May 2016, and this is confirmed by the satellite imagery [43]. The core and upper level circulation associated with the system was well observed in by the satellite image over the north western parts of the country [44]. The weather system led to heavy rainfall of between 25 and 100 mm over the northern and central parts of the country as it remained quasi-stationary during its development stages [44]. The system also led to the cool to cold conditions over the eastern half of the sub-continent.

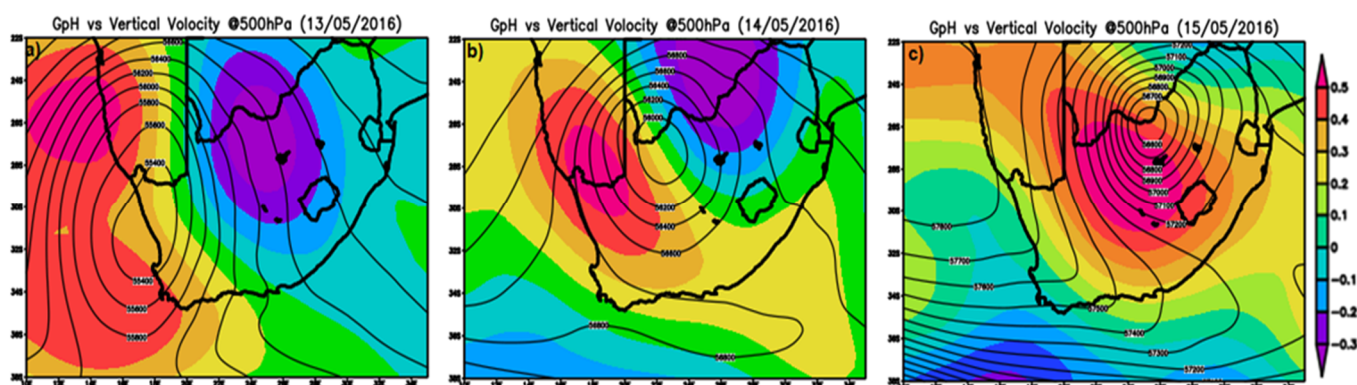
Through the use of the reanalysis geopotential height at 500 hPa, the core of the system was clearly identified covering the north western parts of the country on the 13th of May, extending into the Atlantic Ocean (Figure 1a). Over its eastern flank, the system was accompanied by negative values of vertical velocity (~ -0.3 Pa/s) indicating an area of low-level convergence and uplift of moisture. The model simulated the center of the system covering the most north western parts of the country (Figure 1d). Rainfall amounts between 10 and 38 mm associated with the system were observed over the central and northern parts of the country, spreading to the south-eastern parts of Botswana (Figure 1g). The model simulated rainfall of between 10 and 40 mm over the central parts of South Africa (Fig. 1d). Over the area of deep moist convection and rainfall between 38°S and 20°S , and along the 25°E longitude, the model simulated the diurnal cycle rainfall peak of 38 mm between 29°S and 31°S (Figure 1j). At the same time, the highest observed rainfall of 40 mm was observed between 27°S and 29°S (Figure 1j). This suggests that the UM model slightly underestimated the rainfall by about 2 mm and placed it 2° southward than the actual longitudinal co-ordinate.

The core of the COL shifted eastwards to lie over the far central northern parts of the country on 14th May (Figure 1b). At this stage, the system was characterized by enhanced uplift over its eastern side. The UM simulation for the 14 May located the core of the system over the northern parts of the country as observed (Figure 1e). The model simulated rainfall of between 30 and 64 mm over central parts whilst the actual rainfall was observed shifted over the far north-eastern parts of the country (Figure e, h). When tracing the point of the highest rainfall associated with system between 20°S and

38°S, and along the 27°E longitude, the model simulated maximum rainfall located between 26°S and 28°S while the actual observed rainfall of 58 mm was located between 21°S and 24°S (Figure 1 k).

The COL shifted to the north central parts of the country on the 15th of May (Figure c). The location of the center of the system was simulated over the north-eastern parts of the country at this stage (Figure 1f). The model simulated some rainfall activity towards the eastern parts of the country (Figure 1f) although little rainfall activity was observed over the south eastern side of the COL (Figure i). As a result, the observed rainfall had two peaks, over the southern coast (33°S and 30°E) and over the tip of the far north eastern part of the country (22°S and 30°E) (Figure 1l). The model placed the peak of the rainfall at 26°S and 30°E.

During all the three days of the event, the model simulated the location of the highest rainfall south of the actual location of the observed rainfall by 2°, 3° and 4°, respectively. The difference between the simulated and observed rainfall was less than 10 mm except for the last day where the model overestimated the rainfall by approximately 40 mm.



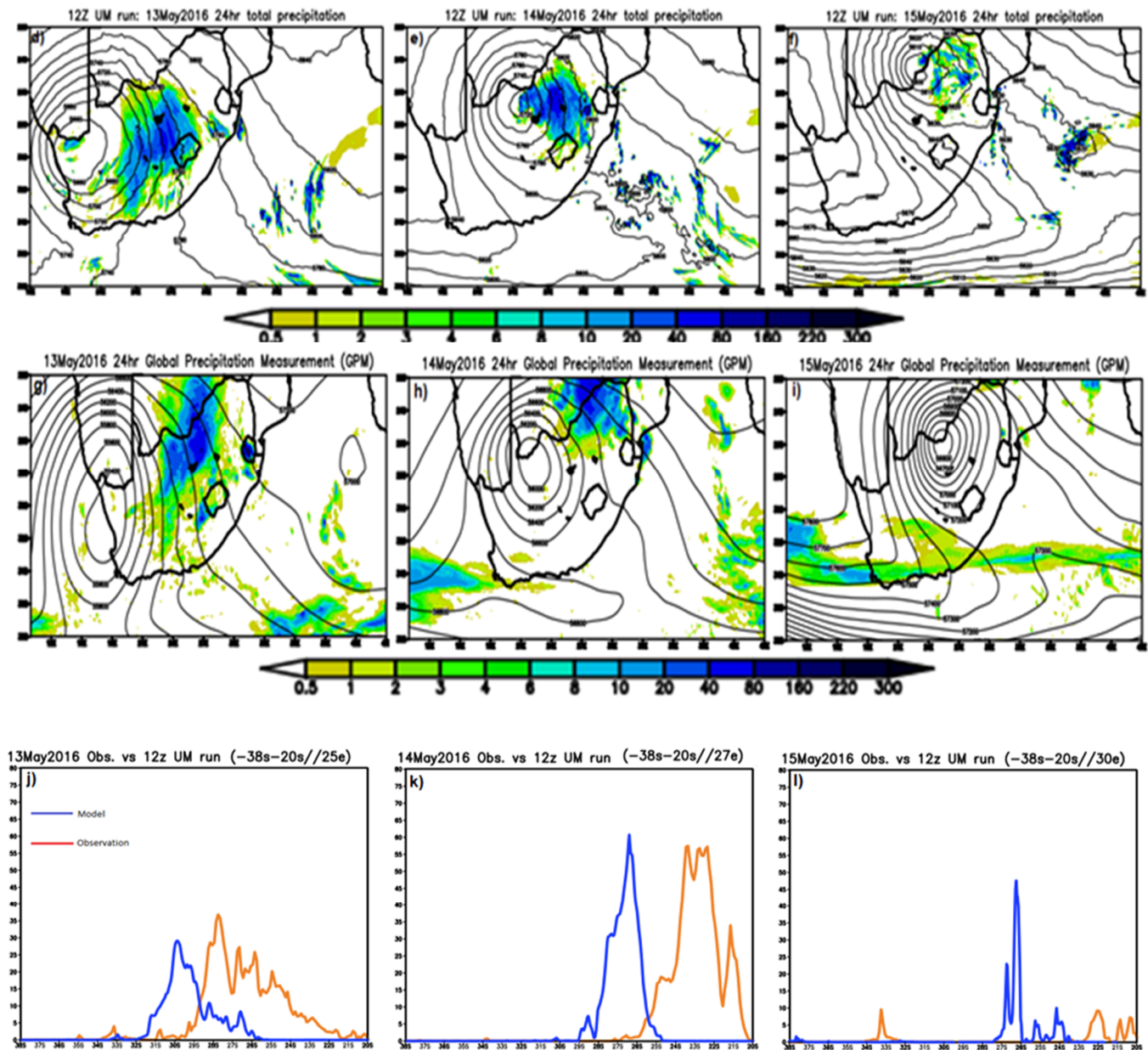


Figure 1: Geopotential Height (hPa) @ 500 (hPa) vs Vertical velocity (a, b and c), 12Z UM 24hr. Total precipitation vs Geopotential Height (hPa) @ 500 (hPa) (d, e and f), 24hr. Total Precipitation vs Geopotential Height (hPa) @ 500 (hPa) Observations (g, h and i) and Model vs Observation diurnal cycle precipitation (j, k and l) from 13th to 15th May 2016, respectively.

3.2 Event of the 25-27 July 2016

Between 25 and 27 July 2016, a COL system was associated with strong winds over the central parts of the country. The system was also associated with persistent cold conditions over the western parts of the country as well as light snowfalls over the Nuweveld and Swartberg Mountain ranges [45]. Extreme weather conditions damaged vehicles, uprooted roofs and more than 200 people were treated for injuries in the country's central Gauteng Province. Over the south east coast in KwaZulu-Natal, the COL was associated with heavy rains and flash floods which caused mudslides, car accidents and also flooded and collapsed several houses. About three people were discovered buried beneath 2 m of mud as several shacks were flattened by landslides [46].

The core of the COL was located over the western parts of the country on the 25th July 2016 as shown in the geopotential height plot at 500 hPa level (Figure 2a). The system was accompanied by moisture uplift over its eastern side as indicated by negative values of vertical velocity (Figure 2a). As observed, the model simulated the core of the system covering the northern and western parts of the country (Figure d). As complemented by negative values of vertical velocity over the eastern side of the system, the model accurately simulated the area associated with deep convection and heavy rainfalls (Figure d). Rainfall amounts of between 40 to 120 mm were simulated over the central and south-eastern parts of the country (Figure 2d) whilst the actual rainfall observed was also located over the same regions of the country (Figure 2g). The precipitation timing plot for the first day between 38°S and 20°S, and along the 26°E longitude, indicates that the model placed the rainfall peak of 220 mm between 34°S and 36°S while the actual rainfall peak of 120 mm was experienced at 31°S and 33°S (Figure 2j).

On 26th July 2016, the centre of COL was observed over the most northern parts of the country (Figure 2b). The model simulated the centre of the system more south compared to the observations (Figure 2e, h). Coinciding with areas of enhanced uplift (Figure 2b), rainfall of between 60 mm to 220 mm was simulated over the eastern and southern parts of the country (Figure 2e). The observation showed rainfall amounts of between 100 to 300 mm over the eastern and southern parts with high figures over the northern, central and the east southern parts of the country as well as in Lesotho (Figure 2h). When analysing the area which was associated with heavy precipitation between 38°S and 20°S, and the 28°E longitude, the model simulated the peak of the 220 mm rainfall between 34°S and 36°S whilst the actual peak of the of more than 300 mm rainfall was observed between 29°S and 31°S (Figure 2k).

On 27th July 2016, the core of the system was located over the south-western and central parts of the country, with the area where the most uplift is expected located over the south Indian ocean (Figure 2c). The GPM rainfall estimate indicates the highest amount of rainfall over Mozambique, with rainfall extending south into South Africa, where rainfall is observed over most of the southern half of the country (Figure 2i). The model simulated the center of the system slightly covering the south-western and eastern parts of the country with rainfall amounts of between 60 to 180 mm over the central interior and western parts of the country (Figure 2f). When tracing the location of high rainfall between 20°S and 38°S, and along the 30°E longitude, the model placed the peak of 180 mm rainfall at 33°S while the peak of about 100 mm actual rainfall was observed at 30°S (Figure 2l).

During the occurrence of this system the model also placed the location of the highest rainfall south of the actual rainfall location by 3°, 4°, 3° for all three days, respectively. The model underestimated the rainfall over the areas identified with highest figures within the country for the first two days but overestimated the rainfall during the last day of the event. The UM simulated rainfall over the adjacent oceans that according to GPM is observed over land for both the 26 and 27th of July 2016. This shows the likely effect on the types of warnings forecasters issue where sometimes warnings are issued for the locations or not issued at all because of the wrong placement of systems and rainfall in the model simulations.

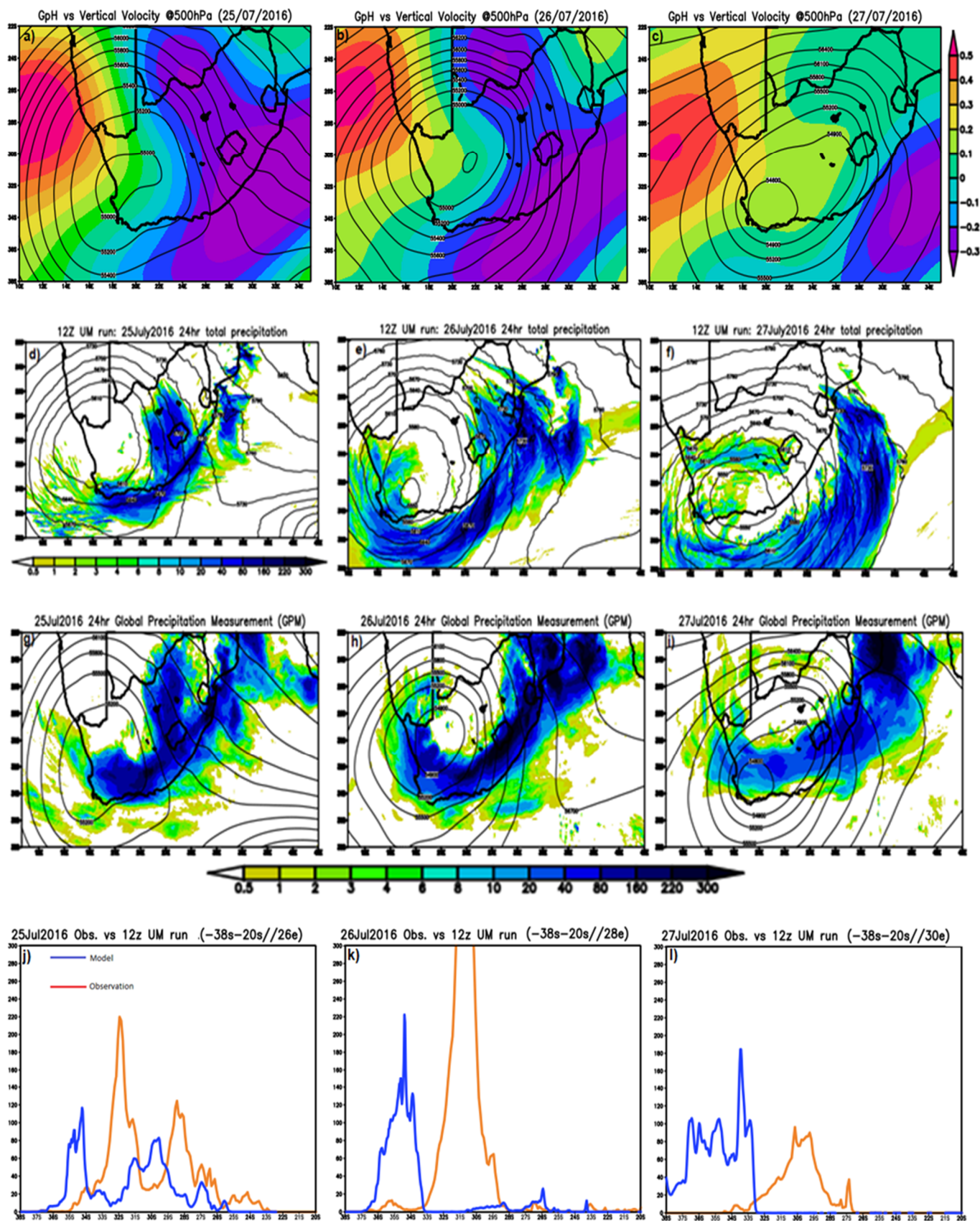


Figure 2: Geopotential Height (hPa) @ 500 (hPa) vs Vertical velocity (a, b and c), 12Z UM 24hr. Total precipitation vs Geopotential Height (hPa) @ 500 (d, e and f), 24hr. Total Precipitation vs Geopotential Height (hPa) @ 500 (hPa) Observations (g, h and i) and Model vs Observation diurnal cycle precipitation (j, k and l) from 25th to 27th July 2016, respectively.

3.3 Event of 10-11 October 2017

On 10th October 2017, a COL system associated with gale force winds up to 90 km/hr and heavy rainfall flooded houses and roads, delayed flights, submerged cars and caused sink holes and accidents over the most parts of the south eastern country, in KwaZulu-Natal [47]. This system was clearly identified as a COL by closed geopotential heights at 500 hPa located over the central parts of the country (Figure 3a). The uplift activity was observed in the eastern part of the COL which covered the eastern coastal area of the country as well as the South Indian Ocean (Figure 3a). The UM model simulated an upper-air trough covering the central and eastern parts of the country. Rainfall of between 10 and 60 mm was simulated spreading from the south-eastern parts of the country through Lesotho to the Indian Ocean (Figure 3c). With a clearly visible low, observations also indicated high rainfall over the eastern parts of the country extending to Mozambique and the Indian Ocean (Figure 3e). High rainfall activity was observed located over the Indian Ocean (Figure 3e). When analysing the location of the highest precipitation within the country between 20°S and 38°S and the 30°E longitude, the model simulated the peak of 80 mm rainfall located between 29°S and 32°S whilst the actual rainfall was also observed between 30°S and 31°S (Figure 3g).

On 11 October, the COL shifted to the South Indian Ocean (Figure 3b) as the model simulated the upper trough over the Indian Ocean but with no rainfall over the country (Fig. 3d). Most of the rainfall activity was observed over the Indian Ocean during this stage (Figure 3f). Tracing the area associated with deep convection and rainfall over the South Indian Ocean between 20°S and 38°S, and along the 40°E longitude, the model simulated the highest rainfall of 85 mm between 31°S and 32°S while the observed rainfall peak of 80 mm was located between 28°S and 30°S (Figure 3h).

During this event, the model placed the peak of the precipitation closer to the observation during the first day but simulated the peak of the precipitation 3° south in relation to the actual location for the observed peak. For the rainfall amount over the area of deep convection and rainfall, the model overestimated the rainfall by 40 mm in the first day and by 5 mm in the second day (Figure 3g & h).

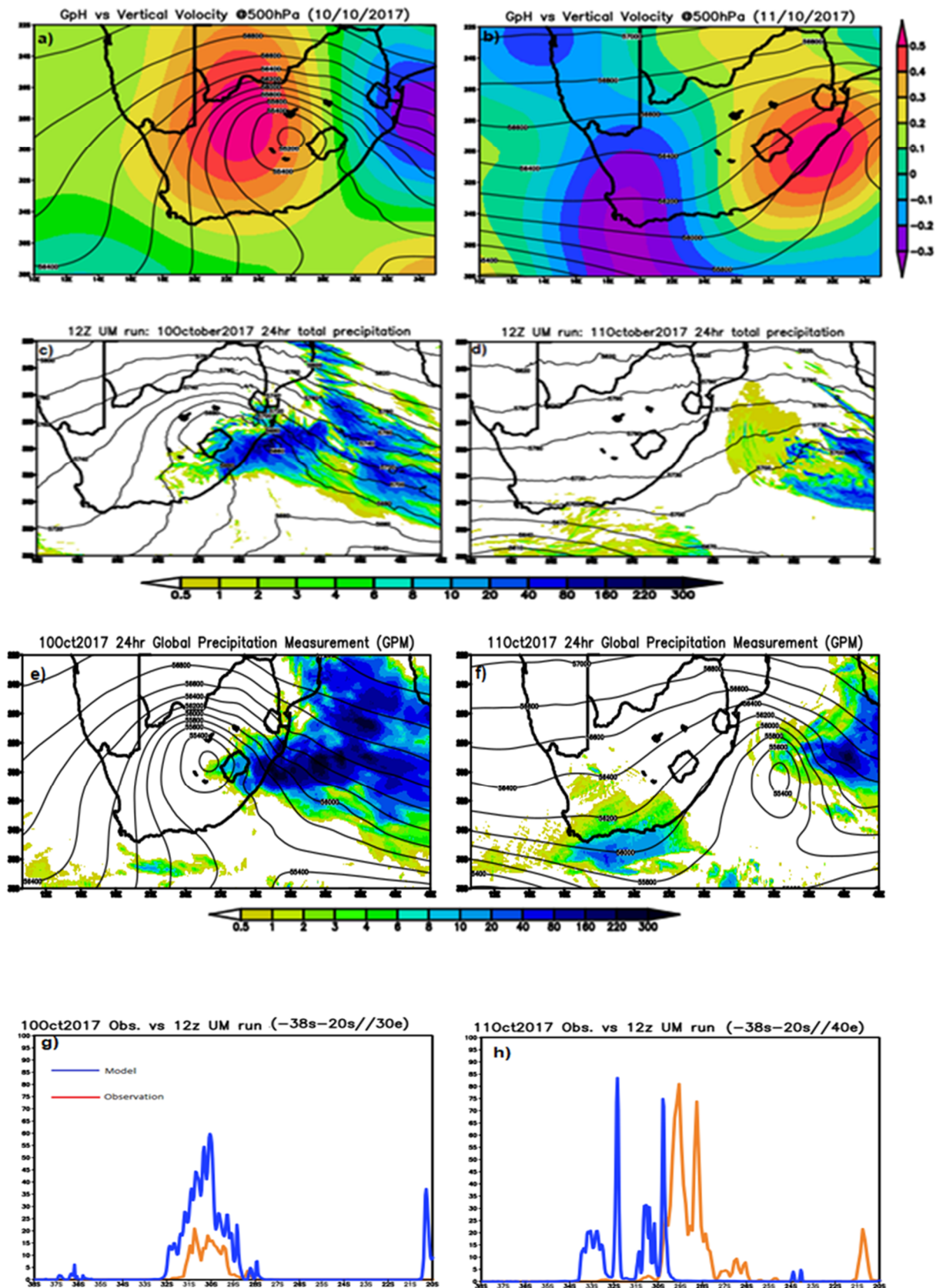


Figure 3: Geopotential Height (hPa) @ 500 (hPa) vs Vertical velocity (a, b), 12Z UM 24hr. Total precipitation vs Geopotential Height (hPa) @ 500 (c, d), 24hr. Total Precipitation vs Geopotential Height (hPa) @ 500 (hPa) Observations (e, f) and Model vs Observation diurnal cycle precipitation (g and h) from 10th to 11th October 2017, respectively.

3.4 The event of 15-17 November 2017

On 15th November 2017, a deep upper-air trough was observed over the western parts of South Africa (Figure 4a, g). This event was associated with rainfall activity to its east (10 to 50 mm), with most of South Africa receiving rainfall triggered by this system (Figure 4g). The model simulated closed geopotential heights over the central, interior of the country, with the centre of the system extending to the borders of Botswana and Namibia (Figure 4d). Although the rainfall activity was also observed over the eastern parts of the country, high rainfall was observed over the South Indian Ocean, spreading to Mozambique (Figure 4g). When analysing the performance of the model in simulating rainfall over the location of deep convection, the model simulated a rainfall peak of 50 mm which is almost similar to the observation, and the model also captured the location of the event well (Figure 4.j).

On the 16th November, the core of the COL was observed over the central parts of the country. This enhanced the establishment of rising motion over the eastern coastal parts of the country (Figure 4b). Rainfall amounts of between 10 and 20 mm were observed over the southern and eastern parts of the country extending to the Mozambique Channel with higher falls over the South Indian Ocean (Figure 4h). The model simulated the center of the system located over the central interior towards the south-east of the country (Figure 4e). Rainfall of between 10 and 30 mm was simulated by the model over the south-eastern coastal parts of the country into the Indian Ocean (Figure 4e). Over the area associated with deep convection, the model overestimated the peak of the observed rainfall by up to 20 mm (Figure 4k).

On 17th November, the center of the COL was observed closer to the south east coastal areas of the country (Figure 4c). At this stage, the model also simulated the system located over the South Indian Ocean with rainfall amounts of between 10 to 80 mm near the center of the system covering the western side of Madagascar (Figure 4f). The system was associated with rainfall amounts of between 8 to 20 mm observed over the south-eastern coastal belts of South Africa. High rainfall amounts of about 10 mm were also observed over the south east (Figure 4i). When analysing rainfall over the area of deep moist convection between 20°S and 38°S, and along the 33°E longitude, the model simulated the peak of 10 mm between 35°S and 37°S while the maximum rainfall was observed between 30°S and 32°S (Figure 4l).

During this event, the model accurately simulated the location of the maximum precipitation against the observation except for the last day when the system was located over the ocean. The model simulated the exact amount of the maximum rainfall over the area of deep convection during the first day of the event. However, the model overestimated rainfall over the south-east belt during the second day when the system was moving towards the ocean.

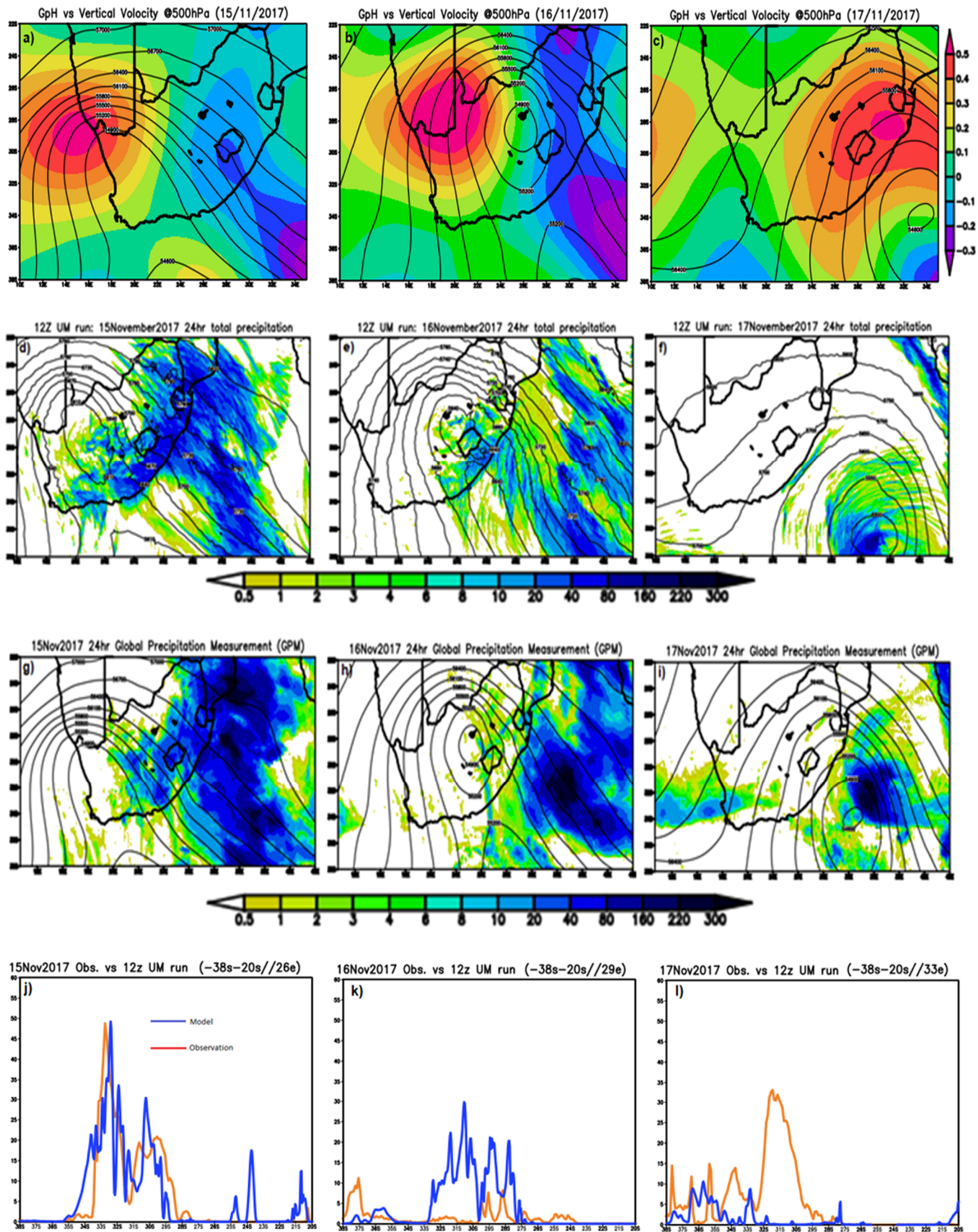


Figure 4: Geopotential Height (hPa) @ 500 (hPa) vs Vertical velocity (a, b and c), 12Z UM 24hr. Total precipitation vs Geopotential Height (hPa) @ 500 (hPa) (d, e and f), 24hr. Total Precipitation vs Geopotential Height (hPa) @ 500 (hPa) Observations (g, h and i) and Model vs Observation diurnal cycle precipitation (j, k and l) from 15th to 17th November 2017, respectively.

3.5 The event of 22-24 April 2019

During the 2019 Easter weekend, the south eastern areas of South Africa in the vicinity of the coastal city of Durban experienced severe flooding associated with a COL weather system. The system led to extreme rainfall of between 150 to 200 mm within 48-hours [48], resulting in landslides, busting of the river banks and collapsed buildings with more than 70 people losing their lives [49]. The storm damaged water pipes, washed away walls, uprooted electric poles and damaged health facilities with the repair cost estimated at R650 000 000 [50]. The weather system was also associated with snow falls over the Maluti Mountains on the border of Lesotho and South Africa with extremely low temperatures over the central parts of the country [51].

The development of this COL was firstly identified by the closed geopotential heights at 500 hPa located over the western parts of South Africa on the 22nd of April 2019. The system was characterized by negative values of vertical velocity of between -0.1 to -0.3 Pa/s indicating uplift of moisture over the system's eastern flank (Figure 5a). The model simulated the core of the system located over the north-western parts of the country, extending into Namibia (Figure 5d). The simulated rainfall associated with the system was between 60 and 130 mm over the central interior of the country, into Botswana extending to the Indian Ocean coast (Figure 5d). The observed spatial distribution of the rainfall is however larger than the simulated one (Figure 5g).

When analysing the rainfall over the area of deep convection as experienced on 22nd April between 38°S and 20°S, and along the 27°E longitude, the model simulated the maximum rainfall of 130 mm to occur between 26°S and 27°S while the actual maximum rainfall of 120 mm was observed between 25°S and 26°S (Figure 5j). Even though the model simulation almost matches that in the observation, the peak is higher in the model simulation. This indicates that the model overestimated rainfall at this stage. The observed rainfall is also more long-lived, compared with to the simulated one (Figure 5j).

On 23 April 2019, the core of the COL was located over the northern and western parts of South Africa. Enhanced vertical motion associated with the development of complex cumulus congestus and heavy rain showers was observed over the central parts of the country (Figure 5h). As shown by observation, the center of the system was simulated over the western parts of the country. The pattern of simulated rainfall was slightly different when compared to the observed (Figure 5e & h). Although the model did not place the maximum rainfall over the observed location, the model simulated almost the same amount of maximum rainfall to the observation between 38°S and 20°S, and along the 29°E longitude (Figure 5k).

The core of the system shifted to lie over the western and central parts of the country on 24 April 2019 (Figure 5c). The system was associated with the persistence of south easterly winds at a speed of about 20 knots which also promoted convergence and enhanced upliftment at this stage. The model simulated the center of the system over south-eastern parts of the country and rainfall which was closer to the observed rainfall pattern (Figure 5f, i). High rainfall amounts of between 30 and 80 mm were simulated over the central interior and south-eastern parts of the country (Figure 5f). When tracing the area of deep moist convection and rainfall between 38°S and 20°S and the 33°E longitude, the model placed the peak of 110 mm at 33°S whilst the actual maximum rainfall was observed between 28°S and 30°S. At this stage, the model run overestimated rainfall (Figure 5l).

For all three days the model placed the maximum rainfall south of the actual location of the observed rainfall by 1°, 4° and 4°, respectively. For the first and second days, the model overestimated rainfall by about 10 and 5 mm, respectively whilst overestimated rainfall by 50 mm during the last day of the event (Figure 5 j, k & l).

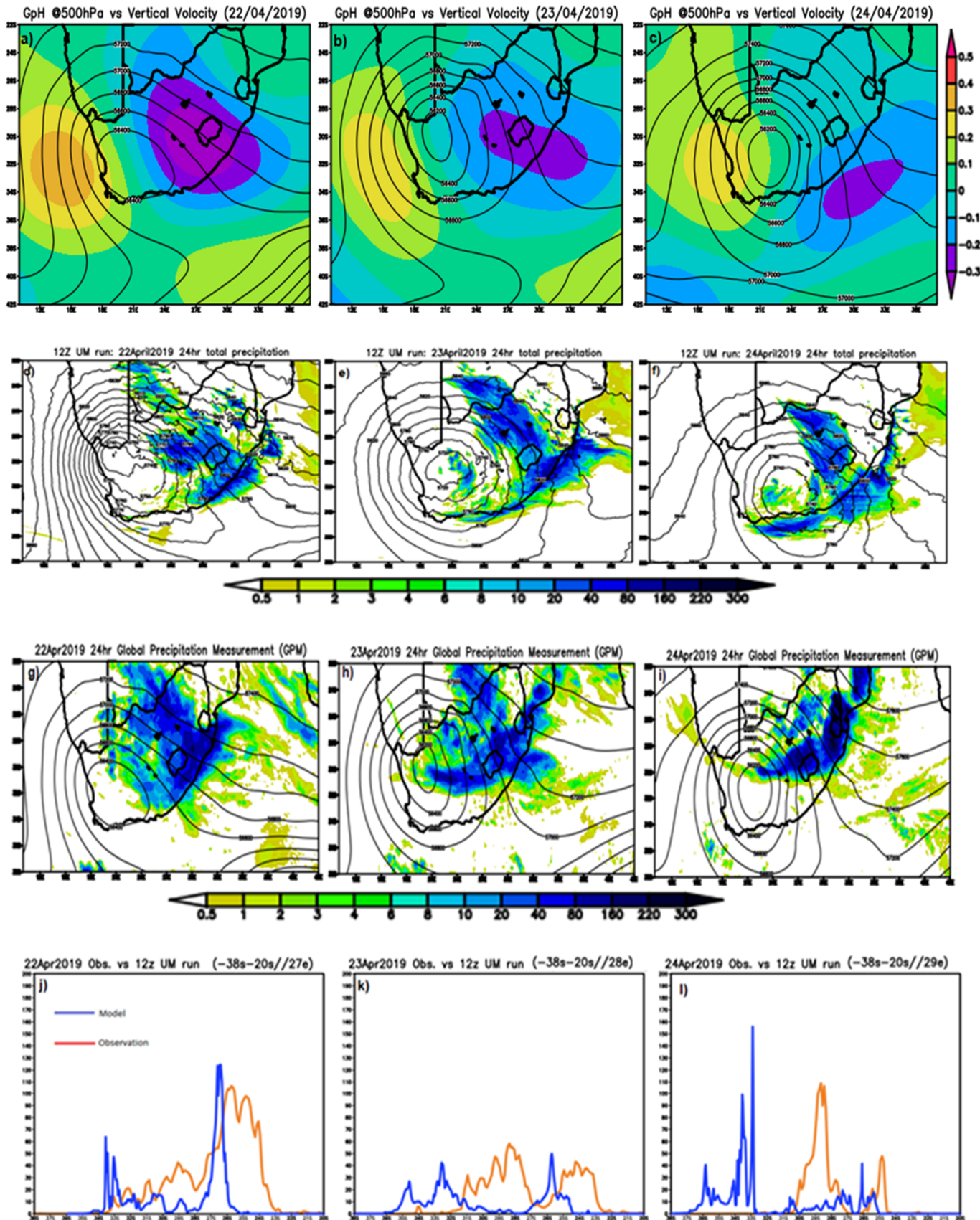


Figure 5: Geopotential Height (hPa) @ 500 (hPa) vs Vertical velocity (a, b and c), 12Z UM 24hr. Total precipitation vs Geopotential Height (hPa) @ 500 (hPa) (d, e and f), 24hr. Total Precipitation vs Geopotential Height (hPa) @ 500 (hPa) Observations (g, h and i) and Model vs Observation diurnal cycle precipitation (j, k and l) from 22nd to 24th April 2019, respectively.

4 Discussion and Conclusions

Mid-tropospheric COL pressure systems are some of the weather systems associated with severe weather conditions, heavy rainfall and flooding over South Africa. It is important to understand COL pressure systems for weather forecasting purposes [15], but also to determine the skill of NWP models used to forecast them. Whilst an average of 11 COLs occur every year over southern Africa [52], this paper analysed five major events which occurred between 2016 to 2019 over South Africa and caused significant damage and loss of lives. We evaluated the performance of the 12Z configuration of the 4.4 km UM model in simulating the transit of COLs over parts of South Africa. The eyeball verification technique was used to compare the outputs of the UM model against observations from the ECMWF ERA Interim reanalyses as well as GPM precipitation.

We found that the UM is able to simulate the location of COL systems over South Africa when using isopleths of constant geopotential height at 500 hPa. However, the location of the center of the systems does not always match with observed, but with better simulations during matured stages of systems with a deepened core. The misplacement of COL centers by the model has a profound impact on the nature of warnings issued by forecasters regarding location and rainfall amounts as happened during the event of 25 - 27 July 2016 [35].

All the 12Z model runs simulated the highest rainfall amounts towards the east of the centre of the system as expected. This is because that is where the most convergence is expected at the surface, associated with strong uplift [39]. The model tends to accurately simulate the location of the maximum rainfall during the first days of the systems, with the location often simulated between 1° and 5° of latitude poleward of the highest observed rainfall during the mature stage. When analysing the amount of rainfall over the area of deep moist convection, the model overestimated the peak of rainfall during the event of 22-24 April 2019 with other events simulated almost exactly with the observation. The UM model tends to pick-up precipitation slightly early which is often short-lived than observed. When the COL is located towards the South Indian Ocean mostly during the dissipating stage, the model poorly resolves the location of maximum rainfall and overestimates rainfall. The model treatment of propagation of weather systems may also be important. The UM underestimated the rainfall due to tropical cyclone Dando in January 2012, as it anticipated peak rainfall north of the actual track of the system [14].

Overall, the results indicate that the UM is a useful tool for forecasting heavy rainfall in COLs, and can help with the provision of early warnings and disaster risk reduction, despite some shortcomings. There are however shortcomings indicated in this study showing a need for further improvements of the cumulus and microphysics schemes that produce rainfall. The findings of this paper can help scientists involved in model development to identify areas for improvement in future upgrades of NWP models. The SAWS uses the UM which was developed by the UK Met Office (UKMO) as its main NWP system and has mandate to provide weather, climate and air quality services to the country for purposes of saving lives and property over land, sea and the air. It is therefore important that the skill of the model used by SAWS in predicting severe weather is well understood. An understanding of model strengths, limitations and biases also helps forecasters to be cautious when interpreting model outputs and generating forecasts and warnings.

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