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

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Abstract: Mid-tropospheric cut-off low (COL) pressure systems are linked to severe weather, heavy rainfall and extreme cold conditions over South Africa. They occur during all the above and often result in floods and snowfalls during the winter months, disrupting economic activities and causing extensive damage to infrastructure. This paper examines the evolution and circulation patterns associated with cases of 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 (SAWS) to simulate daily rainfall. Circulation variables and precipitation simulated by the UM were compared against European Centre for Medium-Range Weather Forecast's (ECMWF's) ERA Interim re-analyses and GPM precipitation at 24-hour timesteps. We present five recent severe COLs, which occurred between 2016 and 2019, that had high impact and found a 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 simulated the precipitation differently during the different stages of development and location of the systems. This is mainly due to inaccurate placing of COL centers. 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 (COLs) [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, South African COLs occur throughout the year, with observed maxima in frequency of occurrence 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 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]. They are characterized by a cold-cored depression that is produced by a westerly trough. This trough usually develops in the upper westerlies 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 may also be associated with cold weather as they are often accompanied by ridging anticyclones that steer a cold southerly airflow, facilitating moisture transport from the South West Indian Ocean [21–23].

Several studies have detailed a climatology of COLs over southern Africa including their geographical distribution, seasonality and frequency (e.g., [7,8,15,16]). A total of about 11 COLs per year has been estimated to occur over southern Africa (24), often associated with strong surface wind convergence and rising vertical motions, leading to high impact rainfall events causing floods. They can produce 24-h rainfall totals which exceed the climatological monthly rainfall averages of an area [24]. 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 [25]. The study by [24] analysed a severe COL event over the south coast of South Africa which caused heavy rainfall and flooding. They produced simulations of the event using the Fifth-Generation Mesoscale Model (MM5) and found that warm sea surface temperature enhanced low-level cyclogenesis whilst the coastal topography provided additional lifting.

In other parts of the world, such as the European continent, the Mediterranean, Asia and Australia, COLs are also associated with heavy precipitation which may persist for several days [26]. For instance, [27] found that most of the anomalous regional convective events which occur over northern China are 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 [28]. Over West Africa, a COL system led to rainfall of up to 116 mm in 24 h during the cool season from 9 to 11 January 1981 [16].

Fewer COL studies have been undertaken in the Southern Hemisphere compared to the Northern Hemisphere (e.g., [18]). This includes the lack of studies that have considered the effects of topography as well as the influence of mid-latitude storms on COLs, which have been investigated in different locations in the Northern Hemisphere (e.g., [29]). These aspects of COLs have not been considered in South Africa, particularly in respect of operational model context. This has led to a lack of understanding of the reasons that underpin the inaccuracies associated with operational model forecasts over the country.

The deep moist convection that is associated with COLs may lead to heavy rainfall and cold conditions. It is therefore important to accurately forecast the area of deep moist convection in COLs with adequate lead time in order to provide ample warning to the public and disaster management authorities to prevent loss of life. 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. The latest generation of global NWP systems used for this time range are currently running with grid spacings of less than 20 km at 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 [30]). All these have been shown to predict COLs with improved accuracy from the generation of NWP models that precede them, which had a larger grid spacing.

The reason for the above is that high-resolution models are able to resolve mesoscale features and with convection being represented explicitly instead of parameterization schemes. Several studies have demonstrated better representation of convectional weather systems as the grid space is reduced towards 1 km [31,32]. Although regional NWP models can provide improved forecasts, there is still a need to improve the realistic capability of these models to simulate cumulus convection accurately mostly over the steep topography and regions of South Africa [33]. 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., [34]).

Sharma et al. [35] established that the UM overestimates the Indian monsoon summer rainfall due to a greater number of rainy days. They also found the events to be displaced towards the west or south west by an average 1° distance in the south west region of India. Sharma et al. [35] determined that the UMs with a grid length of 4 and 1 km initiate convection later than the 12 km model, which initiated convection about 1 to 2 hours earlier than observed. They found too few and too large cells in the 4 km, which they attributed to convection not being resolved. Chan et al. [36] found the UM with a grid spacing of 1.5 km to reproduce the heavy rainfall events in the UK better than the 12km model which tended to produce "grid-point" storms. Prakash et al. [37] showed that reducing the global model grid spacing from 22 km to 17 km improved the simulation of the Indian monsoon rainfall. Stein et al. [38] evaluated the performance of the UM with a grid spacing of 10, 4.4 and 1.5 km over South Africa and found the 4.4 model to delay in simulating clouds by 1 to 2 hours compared to the 1.5 km model. They found the 4.4 and 1.5 km models to perform better than the 10 km one in terms of rainfall spatial patterns, rainfall rate distribution and diurnal cycle, and additionally to be largely indistinguishable when considering the temporal and spatial scales of rainfall.

When analyzing the systematic properties of the 12, 4 and 1 km UM resolutions in simulating rainfall over convective cases over southern England, [39] found that 4 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 [39]. 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 the 1.5 km model [40]. 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 [41].

The aim of this study is to analyze cases of severe COLs that were forecast by the operational NWP system at the South African Weather Service in order to identify reasons for the inaccuracies in the forecasts, with the aim of eventually improving this system. The paper is structured as follows: in Section 2 the Data and Methods are presented and the analysis of the COLs cases is provided in Section 3. Section 4 gives the conclusions.

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 [42]. Reanalysis datasets from the European Centre for Medium-Range Weather Forecasts (referred to as ERA Interim) were used to analyze COL characteristics over South Africa for the period 2016–2019. We analysed circulation variables from the ERA Interim reanalysis [43] 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 (omega, 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 omega 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 during the five COL events.

2.3. Model Description and Forecasts

The SAWS runs the UKMO UM [44] as its main operational NWP model, which is driven by initial and lateral boundary conditions from the Met Office global 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. The SAWS updates the UM forecasts four times daily, with the 00h00, 06h00, 12h00 and 18h00 UTC analyses forced by data from the Global Atmosphere (GA) version 6.1 (GA6.1) [30]. The science suite used is similar to the one used by the Met Office in the European regional model (Euro4) [45]. The configuration uses a convection scheme based [46] in a restricted way, while the microphysics scheme is based on an adaptation of [47], which includes prognostic rain and graupel [48]. 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 12 UTC analyses. The 24-hour precipitation simulations from the 4.4 km UM are compared with the GPM calibrated precipitation estimates using the visual inspection technique. This technique involves comparing simulations with observation all together to determine the accuracy of the model [49]. The study focuses on the performance of the model based on amount, location and timing of geopotential heights and extreme rainfall associated with COLs.

2.4. Topography

South Africa is characterized by a complex topography which can influence the atmospheric circulation and modify characteristics of COL events. From the north there is a steep escarpment, which runs from the Soutpansberg region, becoming Drakensberg over the south eastern regions, and the northern parts of the Eastern Cape Province (Figure 1). Over Lesotho there are the Maluti Mountains, which peak at altitudes of over 3 km. This sharp escarpment gives rise to enhanced orographic lifting of surface winds and plays a significant role when COLs are located above these large topographic gradients. The eastern escarpment of South Africa and Lesotho can interact with a low-level flow of westerly waves and enhance the ascent of moist air through topographic lift [50]. When the frontal systems move near or over complex terrain, the poleward flow of warm-sector air tends to rise leading to the development of precipitating cloud with high rainfall over the ridges and lower in the valleys [51]. The precipitation is often accelerated by the moist air from low-level pressure ahead of the system. As a result, the eastern escarpment region is often characterized by deep convection and high annual rainfall totals [33]. Whilst the UM model topography closely resembles the reality, some local peaks are not very well resolved (Figure 1b).

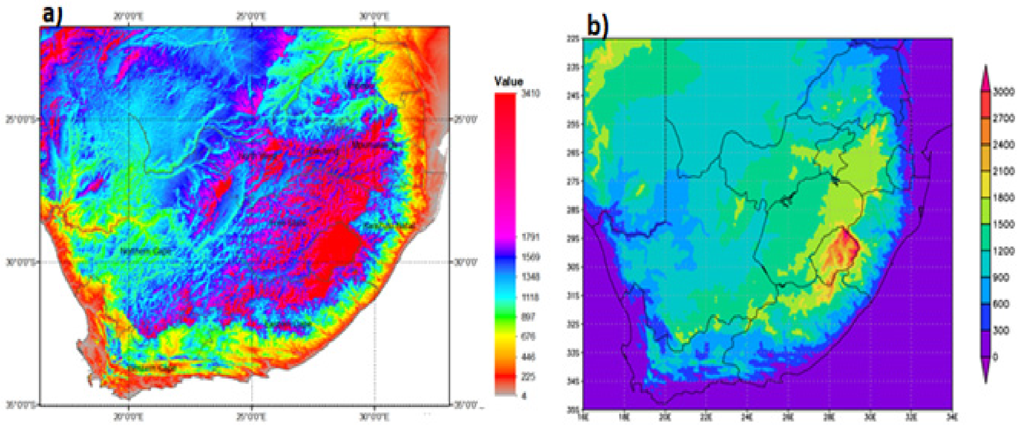

Figure 1. The Shuttle Radar Topography Mission (SRTM) from NASA (**a**) vs. Unified Model (UM) topography (**b**) (in meters) over South Africa.

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 [52]. The core and upper level circulation associated with the system was well observed by the satellite image over the north western parts of the country. 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. 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 2a). 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 2d). 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 2g). The model simulated rainfall of between 10 and 40 mm over the central parts of South Africa (Figure 2d). 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 2j). At the same time, the highest observed rainfall of 40 mm was observed between 27° S and 29° S (Figure 2j). 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 14 May (Figure 2b). 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 2e). 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 2e,h). When tracing the point of the highest rainfall associated with the 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 2k).

The COL shifted to the north central parts of the country on the 15th of May (Figure 2c). The location of the center of the system was simulated over the north-eastern parts of the country at this stage (Figure 2f). The model simulated some rainfall activity towards the eastern parts of the country (Figure 2f) although little rainfall activity was observed over the south eastern side of the COL (Figure 2i). 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 2l). The model placed the peak of the rainfall at 26° S and 30° E.

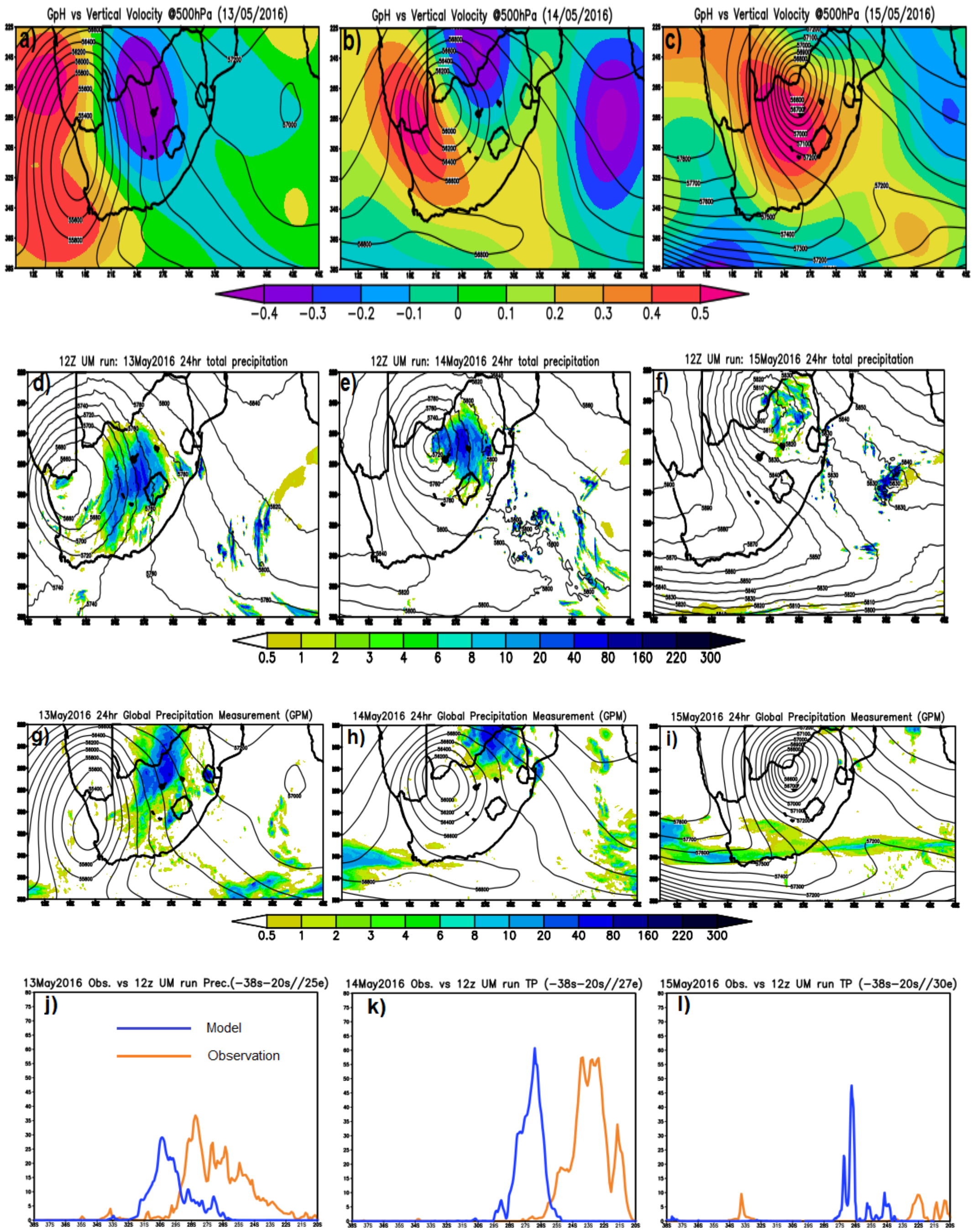

Figure 2. Geopotential height at 500 hPa (thin black contours) together vertical velocity (shaded) (**a**–**c**), at 12Z UM 24 h on the 13th, 14th and 15th May 2016. The second-row panels (**d**–**f**) show total precipitation (shaded) and geopotential height at 500 hPa, at the same as time as in the top panels. The third-row panels (**g**–**i**) show the total precipitation and geopotential height at 500 hPa for the ERA Interim for the same time as in (**a**–**c**). The bottom panels (**j**–**l**) show model (blue curve) and observation (orange curve) diurnal cycle precipitation for the same times as in (**a**–**c**).

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. Further, a comparison between convective and non-convective precipitation in the UM shows that a large percentage of the total precipitation is from the non-convective precipitation. This shows that for this COL case the total precipitation is influenced by the large scale vertical synoptic scale vertical uplift in the model (see top panels in Figure 2 than it is influenced by the convection scheme (Figure 3). This suggests that the precipitation in the model is produced by means of microphysical processes in this case. Therefore, the microphysics scheme of the model is more important than the cumulus convection scheme, and so to improve the biases observed in Figure 2j–l the former would have to be adjusted to suite local South African conditions.

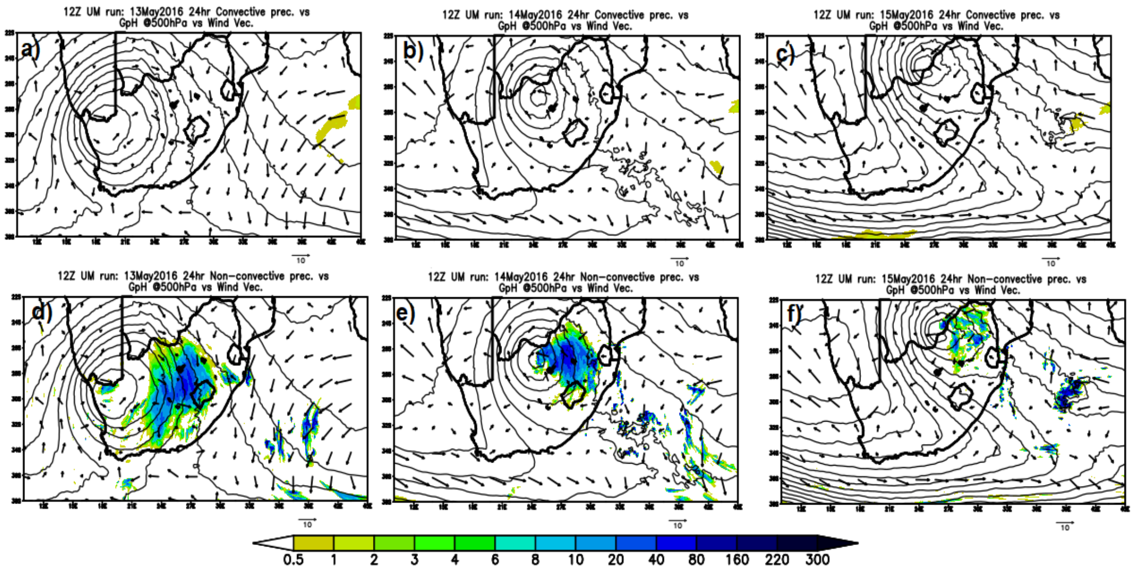

Figure 3. Geopotential heights at 500 hPa (thin contours) together with convection precipitation (**a**–**c**) at 12Z UM 24 h on the 13th, 14th and 15th May 2016. Bottom panels (**d**–**f**) are for the same time as in (**a**–**c**) but for non-convective precipitation. The vectors represent the wind vectors at 10 m above the ground.

Note that topography does not appear to be playing a critical role in this case because of the location of the vertical motion, which is largely located to the west of the escarpment (see Figure 1). To attest to this observation, the rainfall amounts (bottom panels of Figure 2) are similar, it is the timing of their occurrence that is different.

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 [53]. 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. Approximately three people were discovered buried beneath 2 m of mud as several shacks were flattened by landslides [54].

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 4a). The system was accompanied by moisture uplift over its eastern side as indicated by negative values of vertical velocity (Figure 4a). As observed, the model simulated the core of the system covering the northern and western parts of the country (Figure 4d). 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 4d). Rainfall amounts of between 40 to 120 mm were simulated over the central and south-eastern parts of the country (Figure 4d) whilst the actual rainfall observed was also located over the same regions of the country (Figure 4g). 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 4j).

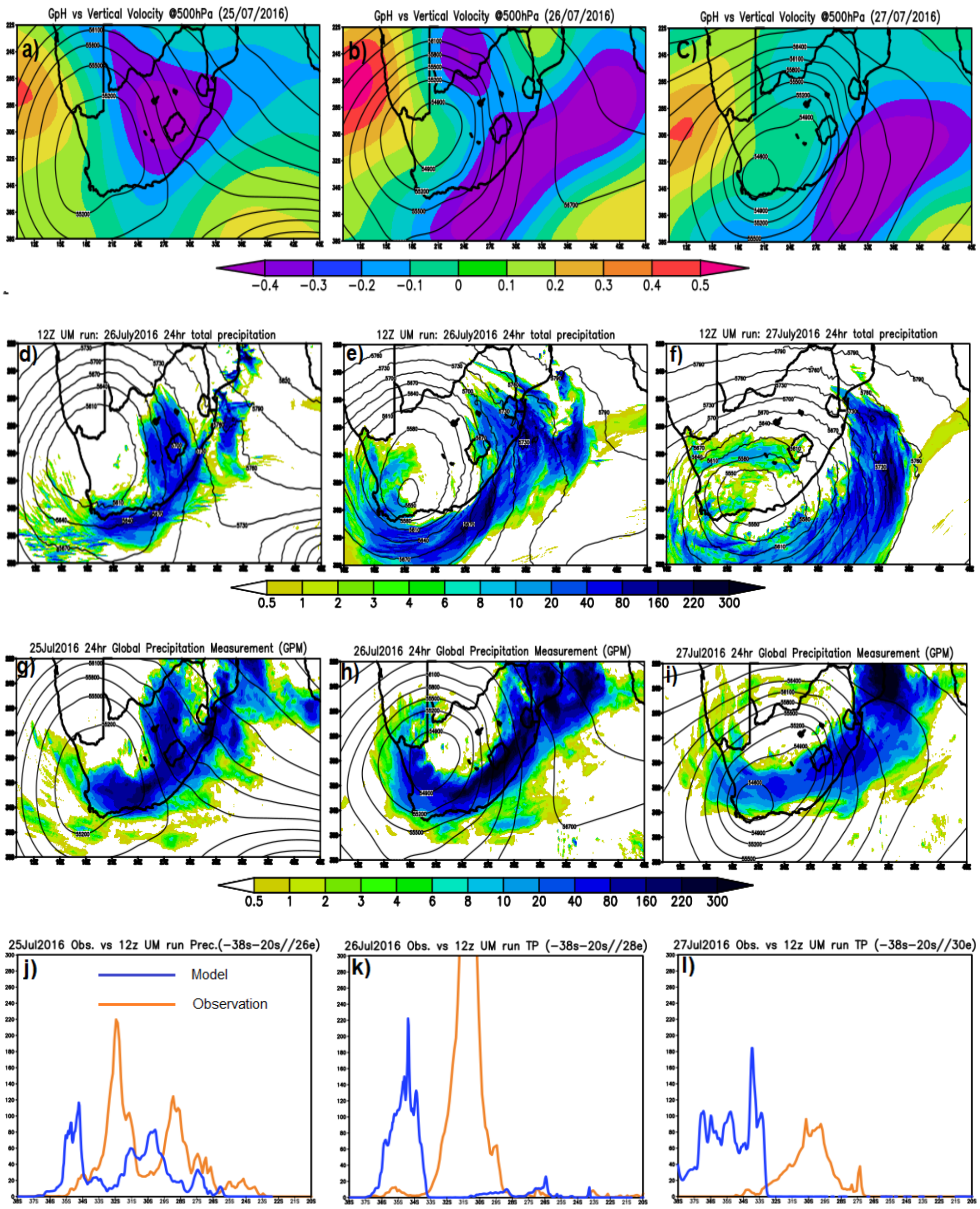

Figure 4. Geopotential height at 500 hPa (thin black contours) together vertical velocity (shaded) (**a**–**c**), at 12Z UM 24 h on the 25th, 26th and 27th July 2016. The second-row panels (**d**–**f**) show UM total precipitation (shaded) and geopotential height at 500 hPa, at the same as time as in the top panels. The third-row panels (**g**–**i**) show the total precipitation and geopotential height at 500 hPa for the ERA Interim for the same time as in (**a**–**c**). The bottom panels (**j**–**l**) show model (blue curve) and observation (orange curve) diurnal cycle precipitation for the same times as in (**a**–**c**).

On 26th July 2016, the center of COL was observed over the most northern parts of the country (Figure 4b). The model simulated the center of the system more south compared to the observations (Figure 4e,h). Coinciding with areas of enhanced uplift (Figure 4b), rainfall of between 60 to 220 mm was simulated over the eastern and southern parts of the country (Figure 4e). 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 4h). When analyzing 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 more than 300 mm rainfall was observed between 29° S and 31° S (Figure 4k).

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 4c). 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 4i). 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 4f). 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 4l).

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. This event also shows that the contribution of convective precipitation is too small in this event relative to non-convective precipitation (Figure 5). It is also significant that all the convective rainfall is being simulated off shore, over the southwest Indian Ocean.

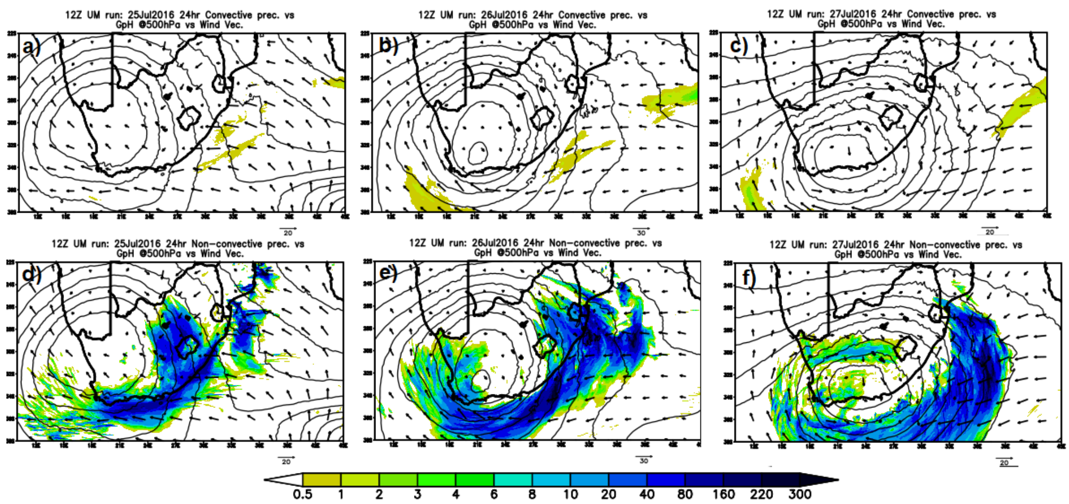

Figure 5. Geopotential heights at 500 hPa (thin contours) together with convection precipitation (**a**–**c**) at 12Z UM 24 h on the 25th, 26th and 27th July 2016. Bottom panels (**d**–**f**) are for the same time as in (**a**–**c**) but for non-convective precipitation. The vectors represent the wind vectors at 10 m above the ground.

For this case the role of topography is quite clear as indicated by the large differences in the maximum rainfall amounts. Because of the location of the vertical motion, relative to the escarpment and the westward direction of the flow, vertical motion would be expected to be a combination of synoptic dynamical processes and orographic uplift. The fact that the UM topography does not match that which is observed, as it is less steep, means that the vertical motion in the model would be expected to be weaker than observed. For that reason, the rainfall would be weaker. Therefore, precipitation forecasts are affected by the model microphysics and topography for COLs whose vertical uplift is located east of the escarpment.

3.3. Event of 10–11 October 2017

On 10th October 2017, a COL system associated with gale force winds up to 90 km/h and heavy rainfall flooded houses and roads, delayed flights, submerged cars and caused sink holes and accidents across much of the south eastern country, in KwaZulu-Natal [55]. This system was clearly identified as a COL by closed geopotential heights at 500 hPa located over the central parts of the country (Figure 6a). 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 6a). 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 6c). 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 6e). High rainfall activity was observed located over the Indian Ocean (Figure 6e). When analyzing 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 6g).

On 11 October, the COL shifted to the South Indian Ocean (Figure 6b) as the model simulated the upper trough over the Indian Ocean but with no rainfall over the country (Figure 6d). Most of the rainfall activity was observed over the Indian Ocean during this stage (Figure 6f). 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 6h).

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 6g,h). Again, the convective precipitation was simulated over the Indian Ocean (Figure 7), with non over the land, most of the total precipitation was simulated due to non-convective or dynamic processes.

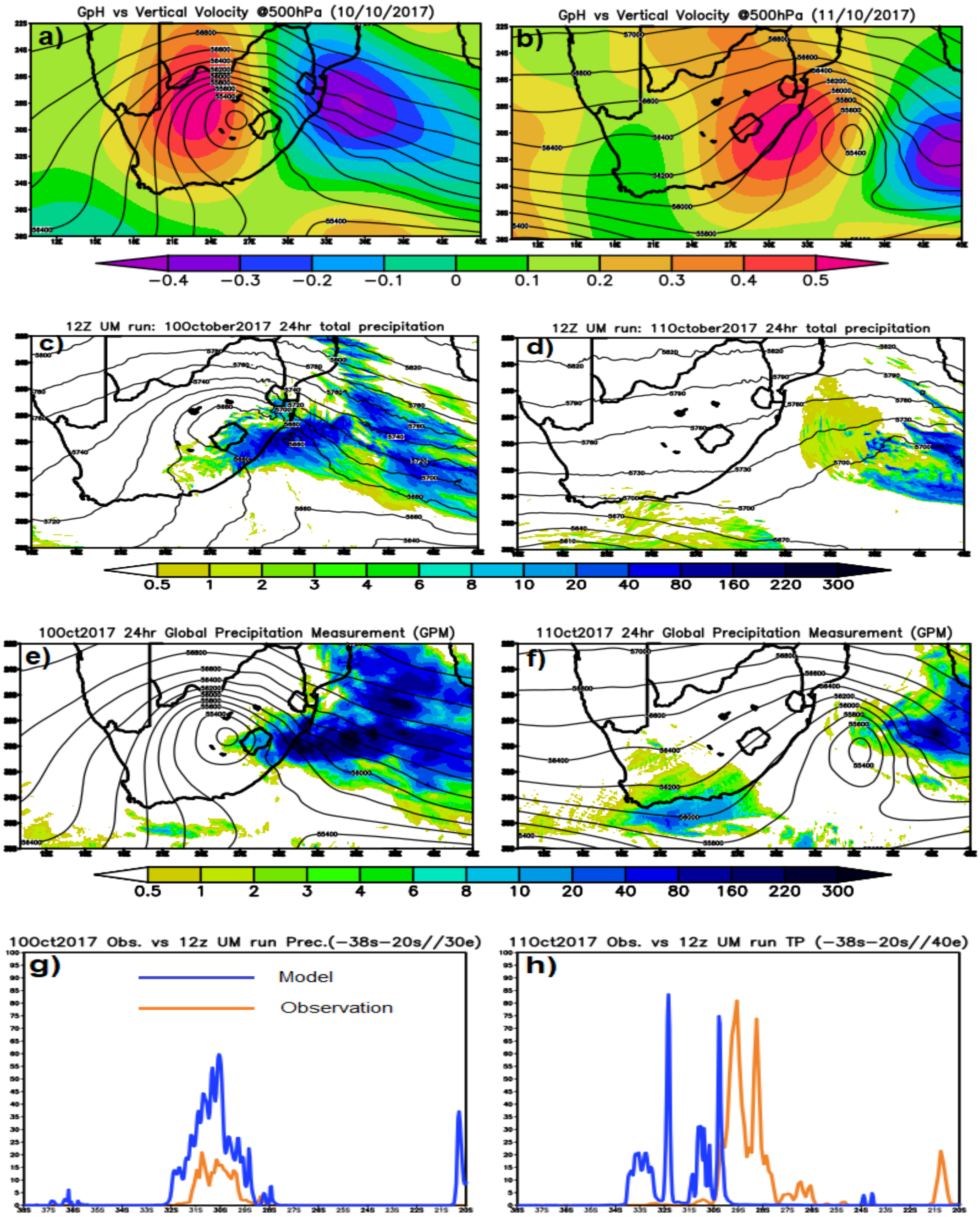

Figure 6. Geopotential height at 500 hPa (thin black contours) together vertical velocity (shaded) (**a**,**b**), at 12Z UM 24 h on the 10th and 11th October 2017. The second-row panels (**c**,**d**) show UM total precipitation (shaded) and geopotential height at 500 hPa, at the same as time as in the top panels. The third-row panels (**e**,**f**) show the total precipitation and geopotential height at 500 hPa for the ERA Interim for the same time as in (**a**,**b**). The bottom panels (**g**,**h**) show model (blue curve) and observation (orange curve) diurnal cycle precipitation for the same times as in (**a**,**b**).

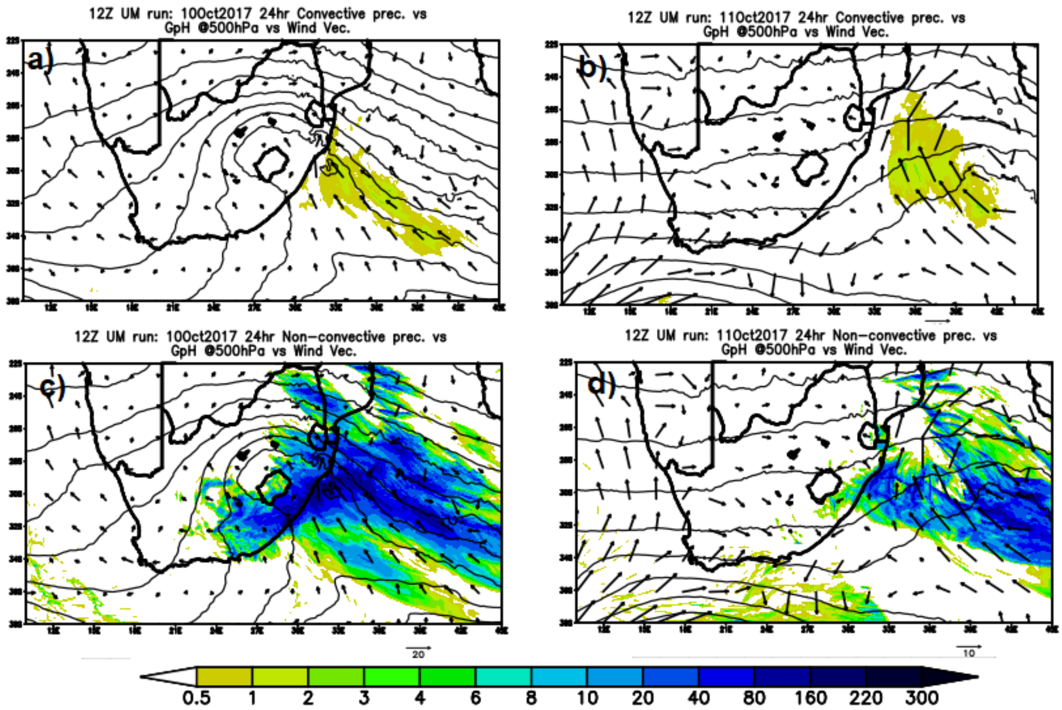

Figure 7. Geopotential heights at 500 hPa (thin contours) together with convection precipitation (**a**,**b**), at 12Z UM 24 h on the 10th and 11th Oct. 2017. Bottom panels (**c**,**d**) are for the same time as in (**a**,**b**) but for non-convective precipitation. The vectors represent the wind vectors at 10 m above the ground.

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 8a,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 8g). The model simulated closed geopotential heights over the central, interior of the country, with the center of the system extending to the borders of Botswana and Namibia (Figure 8d). 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 8g). When analyzing 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 8j).

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 8b). 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 8e). 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 8e). Over the area associated with deep convection, the model overestimated the peak of the observed rainfall by up to 20 mm (Figure 8k).

On 17th November, the center of the COL was observed closer to the south east coastal areas of the country (Figure 8c). 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 8f). The system was associated with rainfall amounts of between 8 to 20 mm observed over the south-eastern coastal belts of South Africa. Rainfall amounts of about 10 mm were also observed over the south east (Figure 8i). When analyzing 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 8l).

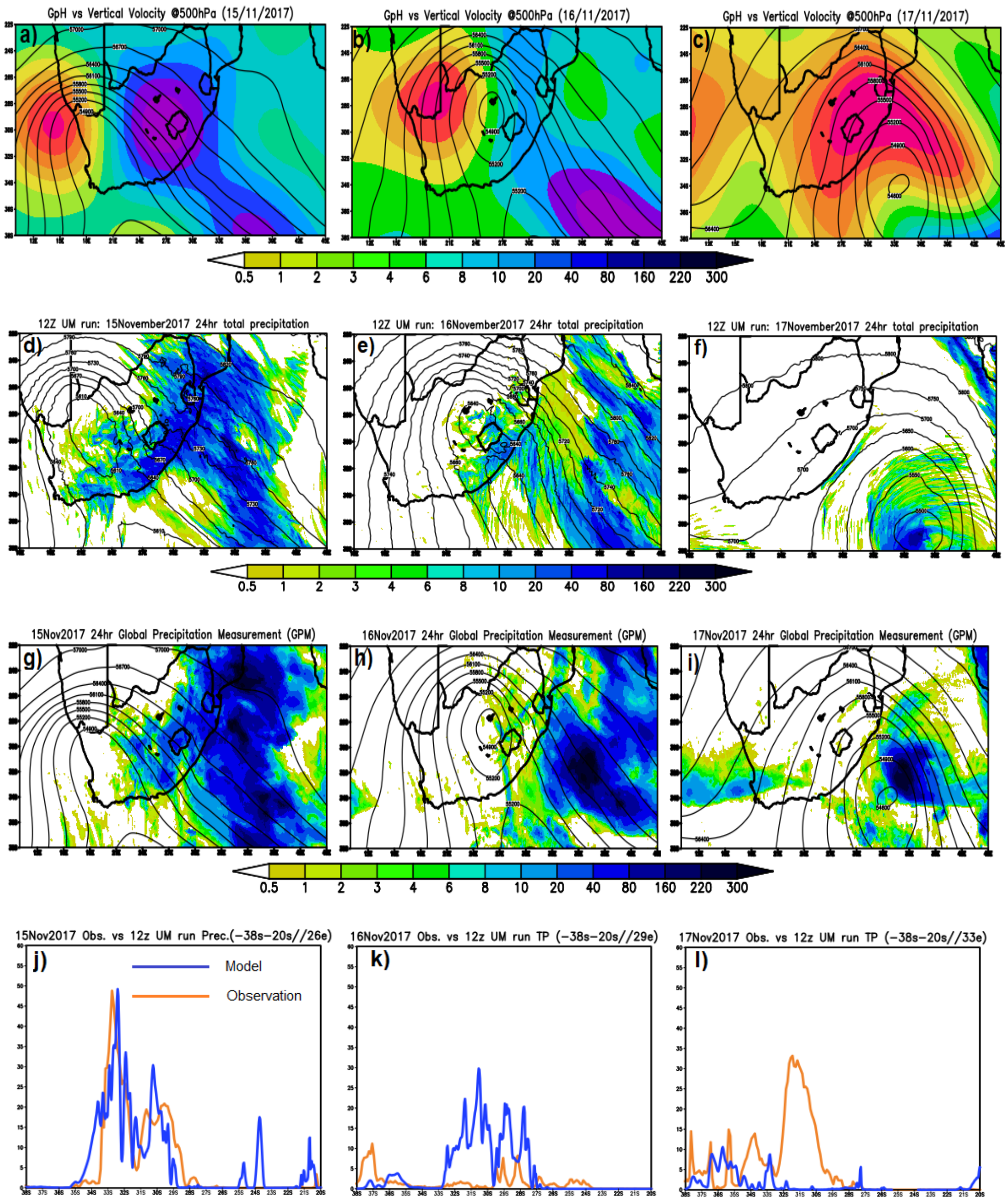

Figure 8. Geopotential height at 500 hPa (thin black contours) together vertical velocity (shaded) (**a**–**c**), at 12Z UM 24 h on the 15th, 16th and 17th November 2017. The second-row panels (**d**–**f**) show UM total precipitation (shaded) and geopotential height at 500 hPa, at the same as time as in the top panels. The third-row panels (**g**–**i**) show the total precipitation and geopotential height at 500 hPa for the ERA Interim for the same time as in (**a**–**c**). The bottom panels show model (**j**–**l**) (blue curve) and observation (orange curve) diurnal cycle precipitation for the same times as in (**a**–**c**).

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. As in previous events, the UM model simulated a small; amount of convective precipitation over the adjacent southwest Indian Ocean (Figure 9). The non-convective component dominated the total precipitation, mainly over the land.

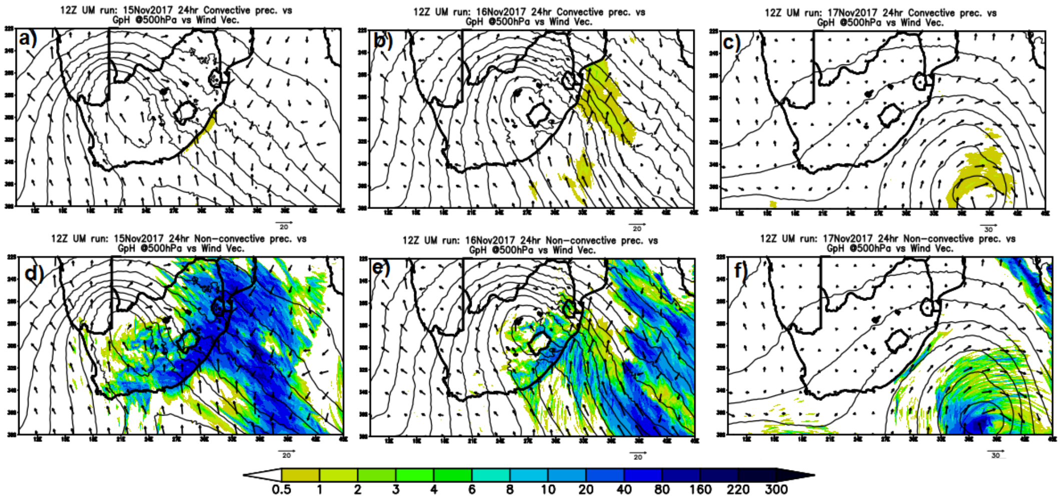

Figure 9. Geopotential heights at 500 hPa (thin contours) together with convection precipitation (**a**–**c**) at 12Z UM 24 h on the 15th, 16th and 17th Nov. 2017. Bottom panels (**d**–**f**) are for the same time as in (**a**–**c**) but for non-convective precipitation. The vectors represent the wind vectors at 10 m above the ground.

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 [56], resulting in landslides, bursting of the river banks and collapsed buildings with more than 70 people losing their lives [57]. The storm damaged water pipes, washed away walls, uprooted electric poles and damaged health facilities with the repair cost estimated at R650 000 000 [58]. 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 [59].

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 10a). The model simulated the core of the system located over the north-western parts of the country, extending into Nambia (Figure 10d). 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 10d). The observed spatial distribution of the rainfall is however larger than the simulated one (Figure 5g).

When analyzing 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 10j). 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 than the simulated rainfall (Figure 10j).

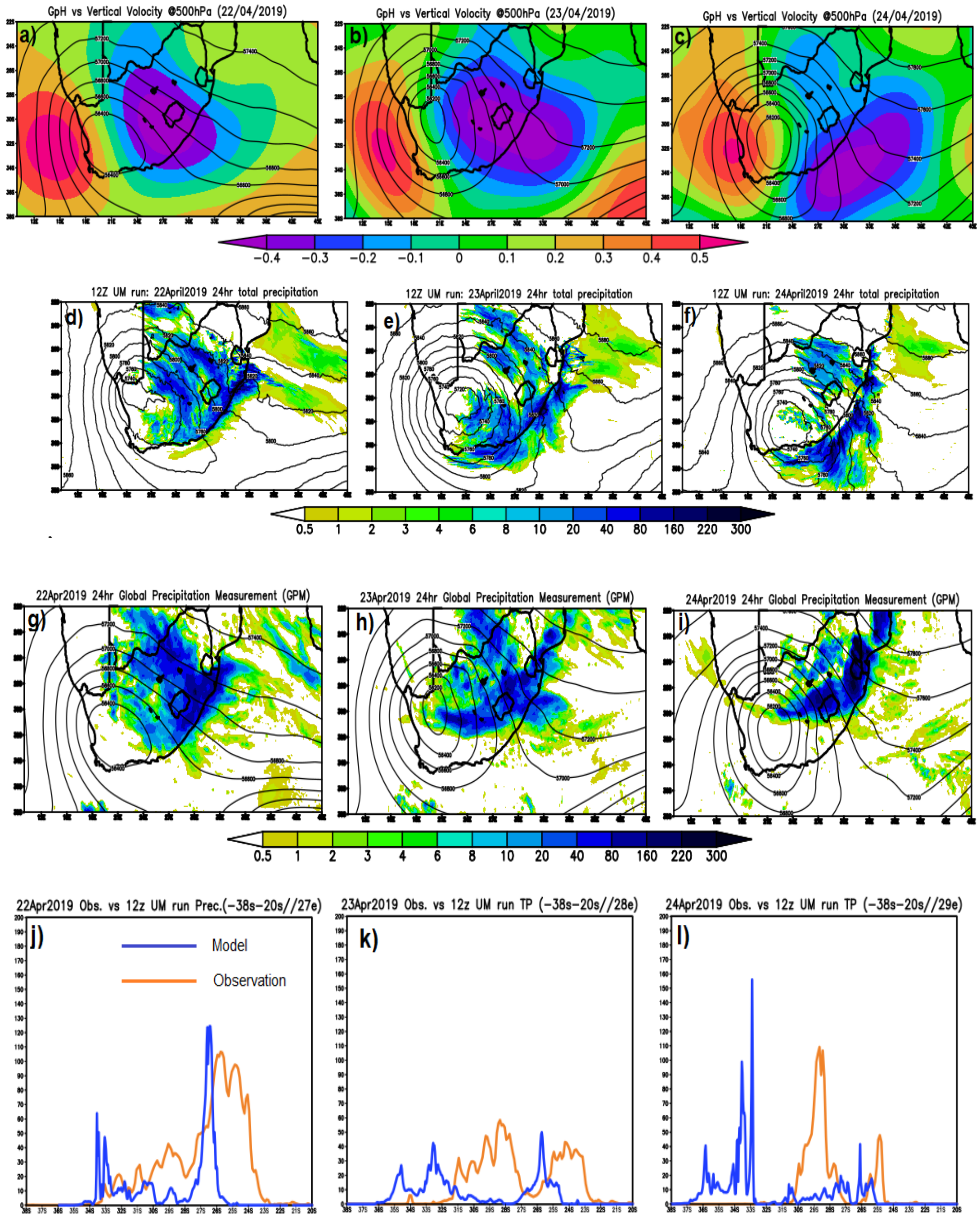

Figure 10. Geopotential height at 500 hPa (thin black contours) together vertical velocity (shaded) (**a**–**c**), at 12Z UM 24 h on the 22nd, 23rd and 24th April 2019. The second-row panels (**d**–**f**) show UM total precipitation (shaded) and geopotential height at 500 hPa, at the same as time as in the top panels. The third-row panels (**g**–**i**) show the total Precipitation and geopotential Height at 500 hPa for the ERA Interim for the same time as in (**a**–**c**). The bottom panels (**j**–**l**) show model (blue curve) and observation (orange curve) diurnal cycle precipitation for the same times as in (**a**–**c**).

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 10h). 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 10e,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 10k).

The core of the system shifted to lie over the western and central parts of the country on 24 April 2019 (Figure 10c). 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 10f,i). High rainfall amounts of between 30 and 80 mm were simulated over the central interior and south-eastern parts of the country (Figure 10f). 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 10l).

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 it overestimated rainfall by 50 mm during the last day of the event (Figure 10j–l). The model simulated convective precipitation running along (offshore) the southeast coast for 22 and 23 April 2019, which was also close to the location of heaviest precipitation (Figure 11). As with the other events, the larger percentage was from non-convective or dynamic processes.

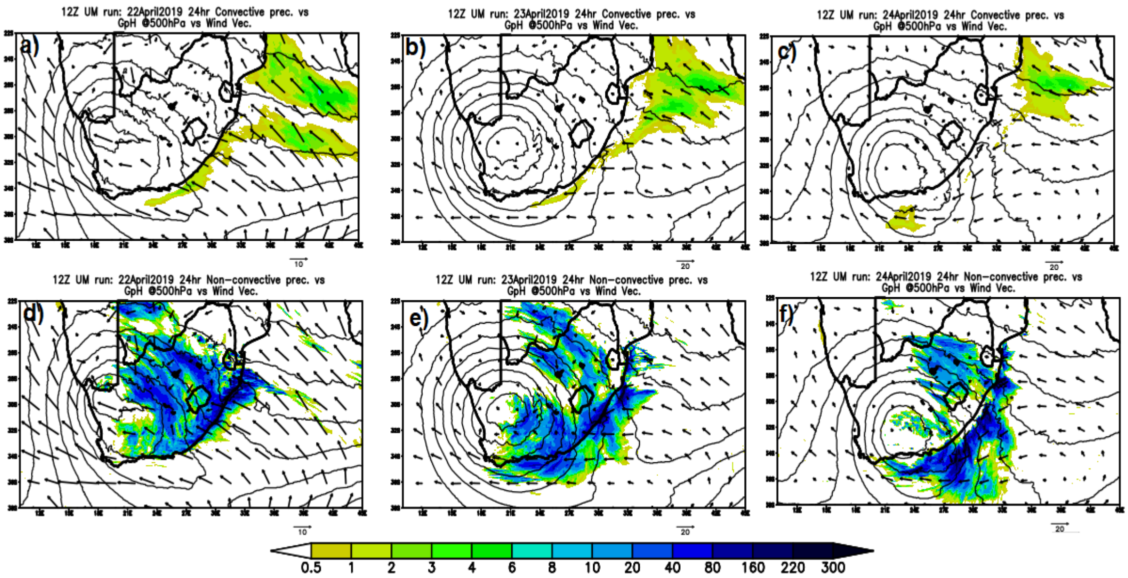

Figure 11. Geopotential heights at 500 hPa (thin contours) together with convection precipitation (**a**–**c**) at 12Z UM 24 h on the 22nd, 23rd and 24th April 2019. Bottom panels (**d**–**f**) are for the same time as in (**a**–**c**) but for non-convective precipitation. The vectors represent the wind vectors at 10 m above the ground.

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 [60], this paper analyzed 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 12 UTC configuration of the 4.4 km UM model in simulating the transit of COLs over parts of South Africa. The visual inspection technique was used to compare the outputs of the UM model against observations from the ECMWF ERA Interim re-analyses 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 the 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 [38]. All the 12 UTC model runs simulated the highest rainfall amounts towards the east of the center of the system as expected. This is because that is where the most convergence is expected at the surface, associated with strong uplift [42].

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. As revealed by other studies (e.g., [39–41]) conducted in different parts of the world for evaluating different resolutions of the UM during for different convectional weather systems, the 4 km model tends to simulate rainfall differently in response to different stages and location of the COLs over South Africa. The location of the maximum rainfall often simulated between 1° and 5° of latitude poleward of the highest observed rainfall during the mature stage. At initialization, the model was skillful in locating the center of the system, but the misplacement occurred mainly during the propagation stages, which may be related to topographic effects. The UM model tends to pick-up precipitation slightly early which is often shorter-lived than observed. The model underestimates the amount of rainfall when the systems transit over the eastern complex topography and coastal regions of the country. Rainfall over these regions is often influenced by warm sea surface temperatures from the surrounding ocean basins which enhances low-level cyclogenesis while escarpments provide additional uplift. As a result, this shows that there is still a need for further improvements for convection representation prescribed in the model for resolving rainfall over the complex topography. In addition, the representation of the topography itself needs to be improved in the model in order to forecast rainfall that is influenced by both synoptic dynamical and orographic uplift.

It was also found that the main problem with the rainfall simulations is with the microphysics scheme of the UM which is contributing most of the total rainfall, with only a small fraction being attributed to the convective scheme. We also realized that the connective rainfall was being simulated at sea, with almost none over the terrestrial environment.

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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