



RESEARCH ARTICLE

Sensitivity of Botswana Ex-Tropical Cyclone Dineo rainfall simulations to cloud microphysics scheme [version 1; peer review: 2 approved with reservations]

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Abstract

Background: Numerical weather and climate models rely on the use of microphysics schemes to simulate clouds and produce precipitation at convective scales. It is important that we understand how different microphysics schemes perform when simulating high impact weather to inform operational forecasting.

Methods: Simulations a heavy rainfall event from 17-20 February 2017 over Botswana were made with the Weather Research and Forecasting (WRF) model using four different microphysics schemes. The schemes used were the Weather Research and Forecasting Single Moment 6-class scheme (WSM6); Weather Research and Forecasting Single Moment 5-class scheme (WSM5); Stony Brook University scheme (SBU-YLIN); and Thompson scheme. WSM5 is considered as the least sophisticated of the four schemes, while Thompson is the most sophisticated. Simulations were initialized and forced by the Global Forecast System (GFS), and configured with a grid spacing of 9km over an outer domain and 3km for a nested inner domain without the convection parameterization. The simulations were produced using the University of Botswana and the Centre for High Performance Computing (CHPC) High Performance Computing (HPC) systems.

Results: WSM5 and WSM6 simulations are mostly similar; the presence of graupel in WSM6 did not result in large differences in the rainfall simulations. SBU-YLIN simulated the least amount of rainfall, followed by Thompson. All the schemes captured the north-south rainfall gradient observed on 17 February, but with all simulations

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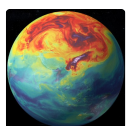
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rainfall is simulated slightly south of where it was observed. All the schemes overestimated rainfall on 18 February over the central parts of Botswana, and underestimated rainfall on 19 February over most of Botswana.

Conclusions: Simulations with different microphysics looked more similar to each other, than to observations. Future studies will test WRF configurations including a single nest over Botswana to determine the best configuration for operational forecasting by the Botswana Department of Meteorological Services.

Keywords

Weather forecasting, early warnings, cloud microphysics, flooding, high impact weather, climate change



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Introduction

Extreme weather events can have both positive and negative impacts on society. One such event is the Ex-Tropical cyclone Dineo which resulted in torrential rainfall over Botswana with flooding in some areas, while filling up the Gaborone dam which was at its lowest in over 35 years of its existence¹. The adverse impacts of extreme weather and climate events on society can be reduced in the presence of accurate and actionable early warnings². The provision of the weather and climate services in Botswana is a mandate that is given to the Botswana Department of Meteorological Services (BDMS).

Botswana has a semi-arid climate attributed largely to its position at the centre of southern Africa plateau which makes the country naturally prone to droughts. A historical perspective of drought draws back as far as the 1950s, in which Botswana has experienced multiple, multi-year droughts and their return period has shortened while the severity has increased³. An analysis of rainfall over the whole of Botswana indicates a decrease in rainfall over the whole country, which is associated with a decrease in the number of rain days⁴. Droughts affect all economic sectors and have dire consequences mostly on water and agricultural sectors⁵ and subsequently on communities' livelihoods. The rainfall season for Botswana starts around October and ends in March the following year⁶. The south-western parts of the country receive the lowest amount of rainfall annually (250mm), while the northern parts receive the highest (600 mm)⁷.

To provide weather forecasts, BDMS runs two regional numerical weather prediction (NWP) models, namely the Weather Research and Forecasting (WRF)⁸ and Consortium for Small-Scale Modeling (COSMO)⁹ systems, and these models have been running since 2010 and 2016, respectively. The resolutions for WRF and COSMO models are 14km and 20km respectively, and the two models run on a BDMS server. Forecasters also have access to Meteo France APERGE (Action de Recherche Petite Echelle Grande Echelle)¹⁰ and United Kingdom Met office (UKMO) Unified Model (UM)¹¹ model outputs through a PUMA 2015 forecaster workstation. In addition forecasters also use output from the Global Forecast System (GFS)¹² and European Center for Medium range Weather Forecast (ECMWF) Integrated Forecasting System (IFS)¹³ global products via the internet¹.

A number of current regional NWP models run with a grid spacing of less than 5km¹⁴, especially in big meteorological centres. The general expectation is that the higher the resolution, the better the forecast^{15,16}. Spatial resolution has been increasing in models over the past years, and the forecast skill has been improving in parallel¹⁷. The spatial resolution used in models is informed by the available computational resources. Currently the ECMWF and UKMO which host large super-computers run global NWP models with a grid spacing of 9km and 10km respectively. The Deutscher Wetterdienst (DWD) which provides forcing fields for COSMO runs the Icosahedral Non-hydrostatic (ICON) model with a grid spacing of 13km^{18,19}. This means the resolution used by the three global models

mentioned above is higher than that used by the regional models run at BDMS. It may also be noted that COSMO running as a LAM at BDMS runs with a lower resolution than ICON which provides the lateral boundary conditions (LBCs). It is therefore important that BDMS starts taking steps to prepare to run regional NWP models with spatial resolutions that are higher than what is provided by global models.

To prepare to run regional NWP models with a spatial resolution that is higher than what is provided by the 14 and 20km simulations, BDMS has to test available models at higher resolution. The available computational resources of BDMS are, however, used to meet the operational responsibilities of the organisation. Through the Southern African Development Community (SADC) Cyber-Infrastructure (CI) Framework, High Performance Computing (HPC) systems have been deployed in a number of countries within SADC^{20,21}, including Botswana. HPC systems make it possible for weather and climate models to run over larger domains with high resolution and produce results faster than when running on a small server. The HPC system in Botswana is hosted by the University of Botswana, and this system is used for the current study²². The model that is tested in this study is WRF which is used widely across the globe because it is open source, and there is open data available to provide LBCs.

NWP models solve atmospheric equations and also rely on the use of observations to be able to predict weather. The resolution used by the model determines processes that the model is able to capture explicitly. Sub-grid processes that the model is not able to resolve are represented using parameterization schemes²³. Cumulus schemes are used to represent moist convection processes including thunderstorms, and precipitation in models comes out as a by-product of these schemes. When models use a grid spacing of about 3km and less, the cumulus schemes are usually turned off and clouds are thought to be captured explicitly using microphysics schemes²⁴. There is a wide range of microphysics schemes in existence today, with different levels of complexity, and their performance varies with generally poorly quantified uncertainties in all of them^{25,26}. There is also a wide range of bulk microphysics schemes (BMPs) which use a specified functional form for the particle size distribution and predict only the species mass mixing ratios^{27,28}. The schemes range from the simple Kessler²⁹ which is liquid only, the simple ice scheme with no mixed phase, the 5 class and 6 class single moment schemes, to the hybrid, double and triple moment schemes. Generally the more sophisticated the scheme, the increase in computational resources needed.

WRF is a community model and provides a wide range of physics options, with over 15 microphysics schemes⁸. In this study we test the performance of four different microphysics schemes with comparable levels of complexity in simulating a heavy rainfall event that occurred in February 2017. An understanding of the performance of different schemes has implications on operational forecasting and hence early warnings because the best available and affordable scheme has to be

used. The sensitivity tests are conducted on ex-tropical cyclone Dineo which resulted in torrential rains over most parts of Botswana from the 18th February to 27 February 2017. The comparison is made for three days, from 17 February to 19 February. Moses and Ramotonto¹ compared the performance of the ECMWF IFS and GFS systems in simulating the event, and found IFS to outperform GFS in simulating the maximum rainfall values, location and intensity of the ex-tropical cyclone Dineo and its remnant low. GFS outperformed ECMWF in forecasting the location of maximum rainfall, overall rainfall amount and the cloud band associated with the system.

Methods

Model and simulations description

The **Advanced Research WRF (ARW) model** version 4.1.2⁸ is used in this study, with four different microphysics schemes described below. WRF solves fully compressible, non-hydrostatic equations, and it also has a hydrostatic option. The model can therefore be used to simulate processes with different scales from large eddies to global. WRF is an open source community model, and has a wide range of physics options introduced by the model development community. The physics used is the WRF tropical suite which includes the Rapid Radiative Transfer Model (RRTM) for both short and long wave radiation³⁰, the YSU planetary boundary layer (PBL) scheme³¹, and Tiedke cumulus scheme^{32,33}. The version of WRF used for this study has 19 microphysics schemes with different levels of complexity. The microphysics schemes provide the simulated heat and moisture tendencies, distribution of hydrometeor species, microphysical process rates, and surface precipitation within a grid box. In this study we tested four different schemes of approximately similar levels of complexity. The four schemes are 1) Weather Research and Forecasting Single Momentum 6-class scheme (WSM6)³⁴; 2) Weather Research and Forecasting Single Momentum 5-class scheme (WSM5)³⁵; 3) Stone Brook University (SBU-YLIN)³⁶; and 4) Thompson³⁷.

WRF is initialized with GFS data which has a horizontal grid spacing of 0.25°. The GFS data provides both initial conditions and time-dependent LBCs every three hour simulation time. WRF is run from 17 February 2017 at 00:00 UTC until 20 February 2020 00:00 UTC, giving a simulation period of 72 hours. A one-way nesting technique is employed, where a 3km grid spacing domain is nested within the 9km model. The model runs with 33 levels in the vertical and 50hPa level model top. The 9km parent domain spans 18°- 31° E; and 30°-16° S, while the 3km domain is located over 23°- 27° E; 26°-20° S. **Figure 1** topography on the 9km domain, while the 3km model smaller domain is shown by a red rectangle inside the 9km domain.

Computational resources

Simulations were conducted on the University of Botswana (UB) HPC system as well as the South African Centre for High Performance Computing (CHPC) Dell cluster. The UB HPC system is based on Racks of compute nodes that were a donation from the 2013 decommissioning of a Texas

Advanced Computer Center's (TACC) Ranger supercomputer²⁰, and was commissioned at UB in 2015. The system has:

- 4 Racks (1 commissioned, others for spares);
- Compute Node with AMD Opteron microprocessors;
- 1 Rack has 48 Compute Nodes – each node has 16 Cores & up to 64GB RAM;
- DELL PowerEdge R730d 27TB Storage over NFS; and
- 48 Port Gig Ethernet Managed Switch.

The CHPC Lengau system was launched on 7 June 2016. The peta-scale system consists of Dell servers, powered by Intel processors, using FDR InfiniBand by Mellanox and is managed by the Bright Cluster Manager. The system has 1368 nodes with 24 cores each, and therefore has a total of 32832 cores, and a total storage of 4PB shared by South African scientists and collaborators across Africa. The model simulations and observations were analysed with the Grid Analysis and Display System (GrADS) version 2.1.a2. The score function in GrADS is used to calculate the spatial correlation between observations and simulations.

Observations used

The observations discussed in this study include the ECMWF Reanalysis Version 5 (ERA5) which is the latest climate reanalysis of ECMWF³⁸. The data provides hourly data on many variables, and the data is also available on different pressure levels with a grid spacing of 0.25. ERA5 combines vast amounts of historical observations into global estimates using the Integrated Forecasting System (IFS) and data assimilation systems. The Tropical Applications of Meteorology using SATellite (TAMSAT) data and ground-based observed rainfall estimates are also used in this study^{39,40}. TAMSAT provides daily rainfall estimates for the African continent at 4km resolution. The simulations are also compared against the 30 minute interval Global Precipitation Measurement (GPM) rainfall calibrated with ground observations⁴¹. Station data from the BDMS is also analysed and compared with the satellite based rainfall estimations and simulations.

Case study description

The influx of tropical moisture from the Congo Basin, and a surface trough coupled with a disturbance situated at medium levels triggered widespread thunderstorms. **Figure 2a** shows 500hPa level Geopotential heights and sea level pressure (**Figure 2b**) at 12Z on 18 February 2017 plotted from the ERA5 reanalysis. An upper air trough is visible south of the subcontinent. A low pressure centre which is associated with the remnants of the tropical cyclone Dineo is located on the boundary of South Africa, Zimbabwe and Botswana. The ERA5 simulated total rainfall is also plotted on **Figure 2a** (shaded) which shows that the synoptic circulation resulted in widespread rainfall across most of southern Africa. Torrential rains were experienced over most of Botswana from 17 to 27 February 2017. The 12th -17th February covers the lifespan of tropical cyclone Dineo and its remnant low, on 17 February

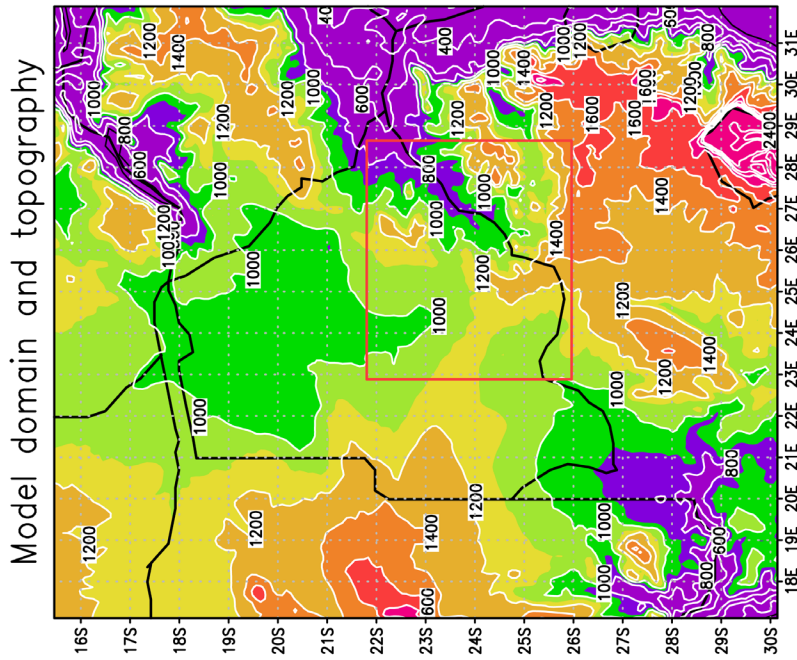


Figure 1. 9km model domain, and the 3km domain shown by the red rectangle. The shading and contours show the topography of the region.

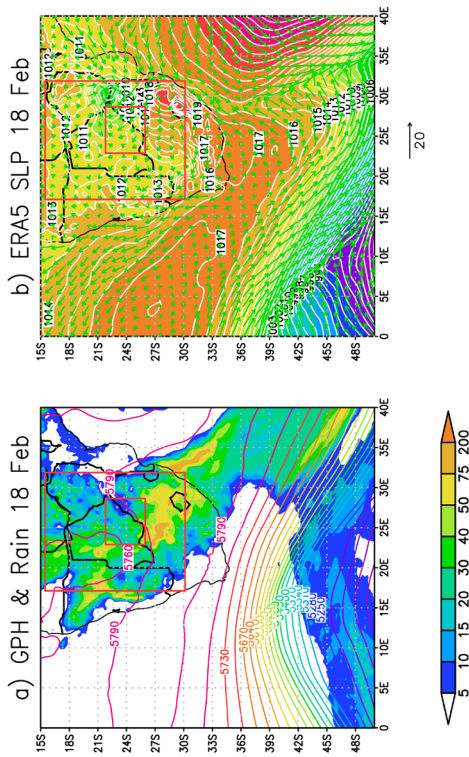


Figure 2. ECMWF Reanalysis Version 5 (ERA5) reanalysis a) Geopotential height at 500hPa level with total precipitation and b) Sea Level pressure and 10m winds on 18 February.

the tropical cyclone’s remnant low dissipated but the 24-hour accumulated rainfall associated with it was recorded on 18 February. Rainfall that occurred on 18 February, the first day after dissipation of the remnant low was recorded on 19 February¹.

The first column of **Figure 3** shows the observed rainfall as recorded by the BDMS ground stations across the whole of Botswana on a) 17, e) 18 and i) 19 February 2017. The colour dots shown on each station correspond with the observed rainfall amount as shown on the colour bar. Large amounts of rainfall were recorded over the north and north-eastern parts of the country on 17 February. The largest amount of rainfall of 270mm was recorded at Changate Primary school indicated by a red dot on the border of Zimbabwe and Botswana. Seven other stations reported over 100mm in 24 hours. Sixteen other stations recorded amounts ranging from 50 to 100 mm. A total of 50 stations recorded over 10mm of rain during a 24 hour period. The rainfall extended further south on 18 February, however, with smaller amounts compared to the previous day, with 55.5 mm as the highest amount reported on the second day. Rainfall continued over the whole of Botswana on 19 February with Manyelong Wildlife Camp and Baipidi Primary school recording 144.5 and 135 mm of rainfall in 24 hours respectively. More rainfall was recorded in general on the 19th compared to the 18th. Roads were affected with overflowing water and some homestead were submerged in water. The flooding prevented people traveling to other villages even across neighbouring countries because of collapsed

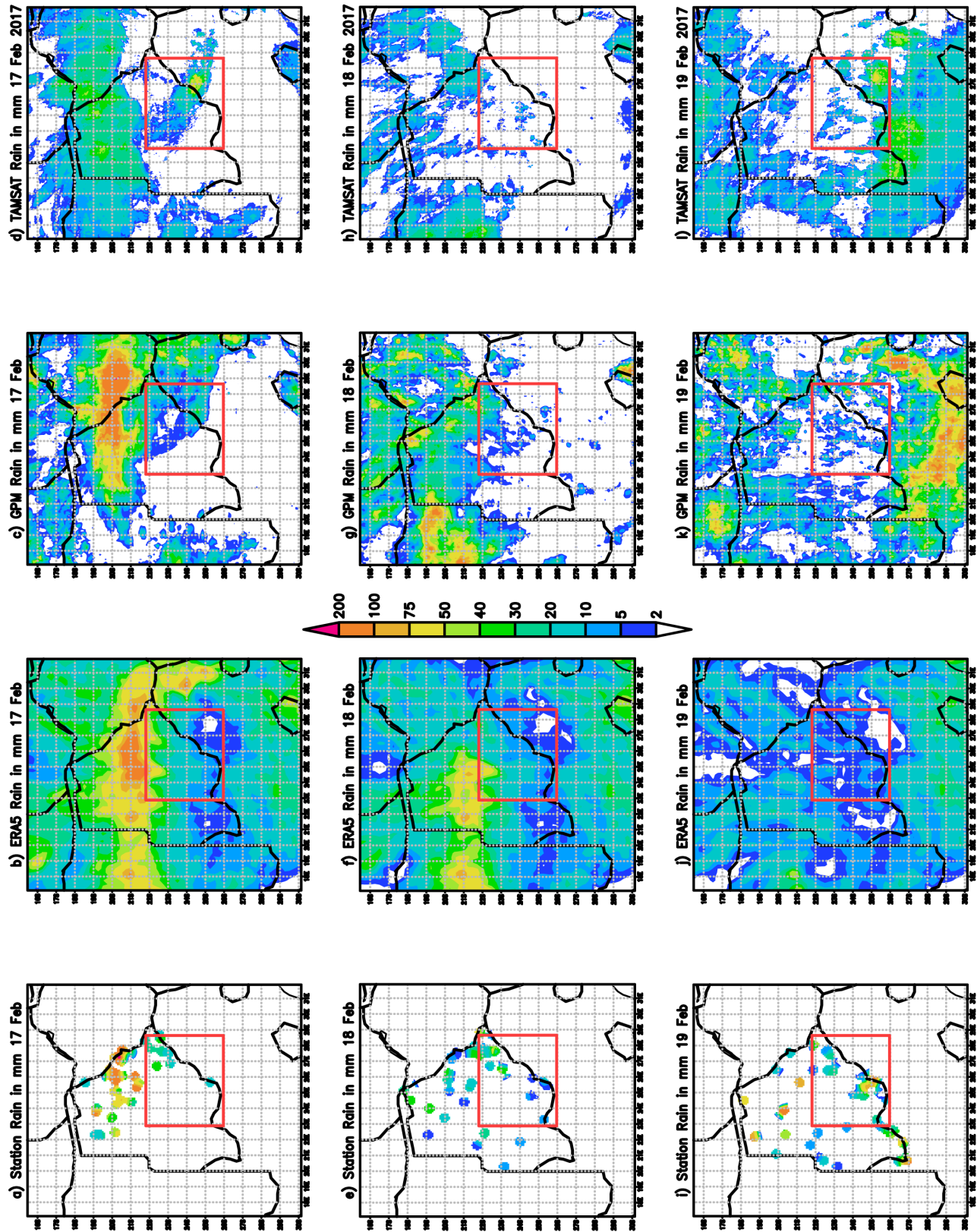


Figure 3. Station rainfall, ECMWF Reanalysis Version 5 (ERA5) reanalysis, Global Precipitation Measurements (GPM) and Tropical Applications of Meteorology using SATellite (TAMSAT) rainfall estimates for 17 Feb, 18 Feb and 19 Feb 2017.

bridges, derailed railway lines and submerged roads⁴². The Gaborone dam, which was at its lowest level in history before the event, was full to the brim to an extent of spilling over causing flooding and damage to properties in Gaborone city and other nearby villages such as Ramotswa, Metsimotlhabe and Molepolole. Observational data for the case study is provided as underlying data⁴³.

Results

In this section we first discuss different rainfall products, followed by a discussion of different rainfall simulations. A comparison between station data, reanalysis and satellite retrievals is made to also inform the hourly rainfall discussion.

Observations comparison

The second column of [Figure 3](#) shows ERA reanalysis, the third column is the GPM rainfall retrievals, while the TAMSAT retrievals are shown in column four over the three day period. The first row shows 17 February rainfall, the second row 18 February, and lastly 19 February in the third and last row. The GPM and TAMSAT datasets are considered as high resolution satellite based rainfall estimates, with TAMSAT developed specifically for the African continent. The large rainfall amounts recorded by the station data are captured by GPM, with the exception of rainfall exceeding 200mm. GPM captured a clear north-south rainfall occurrence difference with the south observed to be relatively dry on 17 February. TAMSAT also captured this distinction, but TAMSAT underestimated the rainfall over the northern parts of the country. While station data recorded over 100 mm in several locations, the TAMSAT rainfall estimate does not exceed 70mm. GPM compares better to observations on 17 February as compared to TAMSAT. The ERA5 reanalysis rainfall is found to simulate rainfall across the whole of Botswana on 17 February. It may be noted that ERA5 has the lowest resolution of these gridded products.

The station observations show that rainfall extended across the whole of Botswana on 18 February, but with smaller amounts compared to the 17th. GPM did not capture this southward extension of rainfall, and it maintained the north-south distinction with maximum rainfall being shifted further west into Namibia. TAMSAT underestimated the rainfall even further with a large part of the country not showing any rainfall. The ERA5 reanalysis produced a somewhat similar pattern to what it shown on 17 February with rainfall across most of the country. The rainfall continued over most of the country on 19 February but with larger amounts than observed on 18 February. The TAMSAT and GPM precipitation estimates did not capture the rainfall difference between 18 and 19 February, while ERA5 shows more rainfall on 18 February than 19 February in general.

The results shown in this section pose a challenge for modelling studies over the African continent whose ground observations are sparse. The three datasets (ERA5, TAMSAT and GPM) are all considered as observations, but they show different amounts of rainfall. Beck *et al.*⁴⁴ indicated that the reanalyses

are inferior to satellite retrievals where thunderstorms are dominant. Our study based on one case cannot provide a conclusion in this regard, but our results suggest that GPM performed better than the ERA5 reanalysis on 17 February. ERA5 compared better with station observations on 18 February because it shows rainfall across the whole of Botswana. There are efforts towards downscaling the reanalysis products to be used to formulate climate and hydrological record studies over the continent where observations are sparse. Moalafhi *et al.*⁴⁵ downscaled ERA-Interim reanalysis over the Limpopo basin using WRF version 3.6, and found that the downscaled temperature was underestimated during summer and autumn, while precipitation was overestimated during summer. This result shows a need for ground observations that can be used for modelling studies, as well as for studies in weather and climate sensitive sectors. For our purposes when investigating the timing of rainfall, both GPM estimates and ERA5 reanalysis were compared with the area averaged rainfall over Botswana and the 3km smaller domain over the three-day period.

Microphysics comparison

A discussion on the microphysics is based on [Figure 4](#) to [Figure 9](#), as well as [Table 1](#). [Table 1](#) shows the spatial correlation between each model and GPM rainfall estimates, as well as spatial correlations between different simulations. This measure provides information on the similarity of spatial patterns between two datasets. [Figure 4](#) shows accumulated rainfall over the whole of Botswana, and the Inner domain, and hourly rainfall with GPM, ERA5 and the four microphysics schemes. [Figure 5](#) shows the Fraction Skill Score (FSS) for all four schemes calculated against GPM rainfall estimations for all three days calculated separately. The FSS was introduced by Roberts and Lean⁴⁶ to test the fractional coverage of rainfall forecasts over different sized areas. The score has been applied in a number of other studies including on the African continent⁴⁷. The 9km model simulations were interpolated to a 0.1° to provide a similar resolution to GPM and the scores were calculated using this dataset. A score of zero shows no skill, while a score of 1 indicates a perfect match between the forecast and observations.

The first column of [Figure 6](#) to [Figure 9](#) shows the total rainfall, the second column the rainfall from the convective scheme, and the third column shows resolved rainfall over the 9km domain. The last column shows the resolved rainfall over the 3km grid spacing. No rainfall is shown in the 3km domain box of column 2 in all the figures because the convection scheme was switched off when a grid spacing of 3km was used.

WSM6 scheme. The WSM6 is the microphysics scheme used in the tropical suite. The scheme includes water vapour, cloud water, cloud ice, rain, snow and graupel as predictive variables (Hong and Lim, 2006). The scheme scores and simulations are indicated by a dark blue line in [Figure 4](#) and [Figure 5](#), and the spatial distribution of the rainfall is shown in [Figure 6](#). WRF simulation with WSM6 captured the high

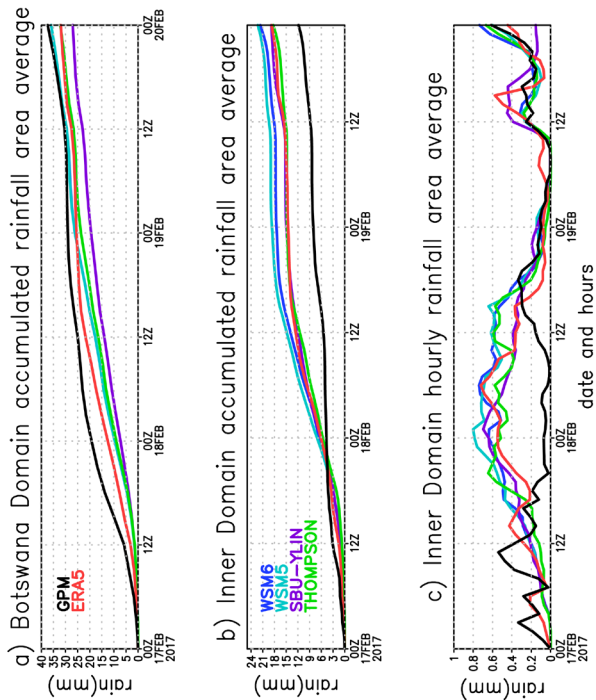


Figure 4. Accumulated rainfall over the **a)** parent **a)** and **b)** inner domain, as well as **c)** hourly rainfall with different microphysics schemes, Global Precipitation Measurements (GPM) and ECMWF Reanalysis Version 5 (ERA5).

Table 1. Spatial correlation between **a)** Global Precipitation Measurements (GPM) and Weather Research and Forecasting (WRF) 24-hour rainfall simulations with/ between different microphysics schemes namely WRF Single Momentum 6-class scheme (WSM6); 2) WRF Single Momentum 5-class scheme (WSM5); 3) Stone Brook University (SBU); and 4) Thompson (THOM).

Model-Obs	17-02-01	18-02-01	19-02-01
WMS6-GPM	0.459598	0.134505	0.208878
WMS5-GPM	0.459597	0.135421	0.213712
SBU-GPM	0.395706	0.134373	0.214992
THOM-GPM	0.453878	0.134373	0.269269
Model-Model	17-02-01	18-02-01	19-02-01
WSM6-WSM5	0.970667	0.905459	0.903018
WSM6-THOM	0.893388	0.811936	0.837476
WSM6-SBU	0.874309	0.755849	0.737954
WSM5-THOM	0.880328	0.789449	0.808934
WSM5-SBU	0.867912	0.738031	0.734269
THOM-SBU	0.846206	0.745232	0.711872

rainfall amount observed over the north-eastern parts of Botswana on 17 February. However, the rainfall is simulated slightly south of where it is observed by the ground stations and GPM (Figure 3). The spatial correlation between WSM6 9km simulation total rainfall and GPM on 17 February is 0.46 (Table 1). A perfect spatial correlation is given by a value of 1. The positioning of maximum rainfall aligns slightly more with the ERA5 reanalysis. The high amount of rainfall is not observed within the inner small domain, but WRF simulated a large amount of rainfall on the top right corner of the 3km domain. Figure 4 shows most of the rainfall to have been simulated to occur towards the end of the day, after 12h00Z, and the simulations agree with the ERA5 reanalysis. GPM rainfall estimates, however, show the highest amount of rainfall at 11h00Z. This then results in the GPM rainfall estimates area average being more than the simulations and the ERA5 reanalysis over both the inner domain and the whole of Botswana. Figure 5 shows that the skill in capturing the smaller scales is low and the skill increases similar to what is found in other models as the scale is increased⁴⁶.

The model extended the simulated rainfall across a large part of Botswana on the 18th, which agrees with station observations. The simulated rainfall is, however, much higher over the central parts of Botswana, and this is not found in either the station observations or GPM estimates. The area of higher rainfall is, however, found in the ERA5 reanalysis. This rainfall is shown to have been a continuation of the rainfall that started on 17 February, and the ERA5 line follows a similar diurnal cycle as all the simulations. The GPM rainfall remains low and increases to a peak around 18h00Z. In the inner domain, the increase in rainfall associated with GPM is, however, much smaller, resulting in the GPM line being smaller on the inner domain accumulated rainfall plot. By the end of 18 February, WSM6 is one of the two schemes having produced the most rainfall over the inner domain. The rainfall is also greater than, that simulated by ERA5. The spatial correlation between the GPM rainfall estimate and the WSM6 9km simulation is 0.13 showing the bid dissimilarity, which is also visible in the hourly plots.

The area associated with a large amount of rainfall is simulated to move towards the west, and is found in Namibia on 19 February. The station observations are only available in Botswana and so this feature can't be confirmed with *in-situ* data, but it is also not found in either the GPM or TAMSAT rainfall estimations. The ERA5 reanalysis also shows some rainfall over the neighbouring country of Namibia, but the amount is smaller than that simulated by WRF. At the end of the 72 hour period, GPM estimated the most amount of rainfall over the whole of Botswana, and the least amount over the inner domain. The WSM6 simulated area average matches the GPM, and is more than ERA5 over the whole of Botswana. Over the inner domain, WSM6 simulated more rainfall than both GPM and ERA5.

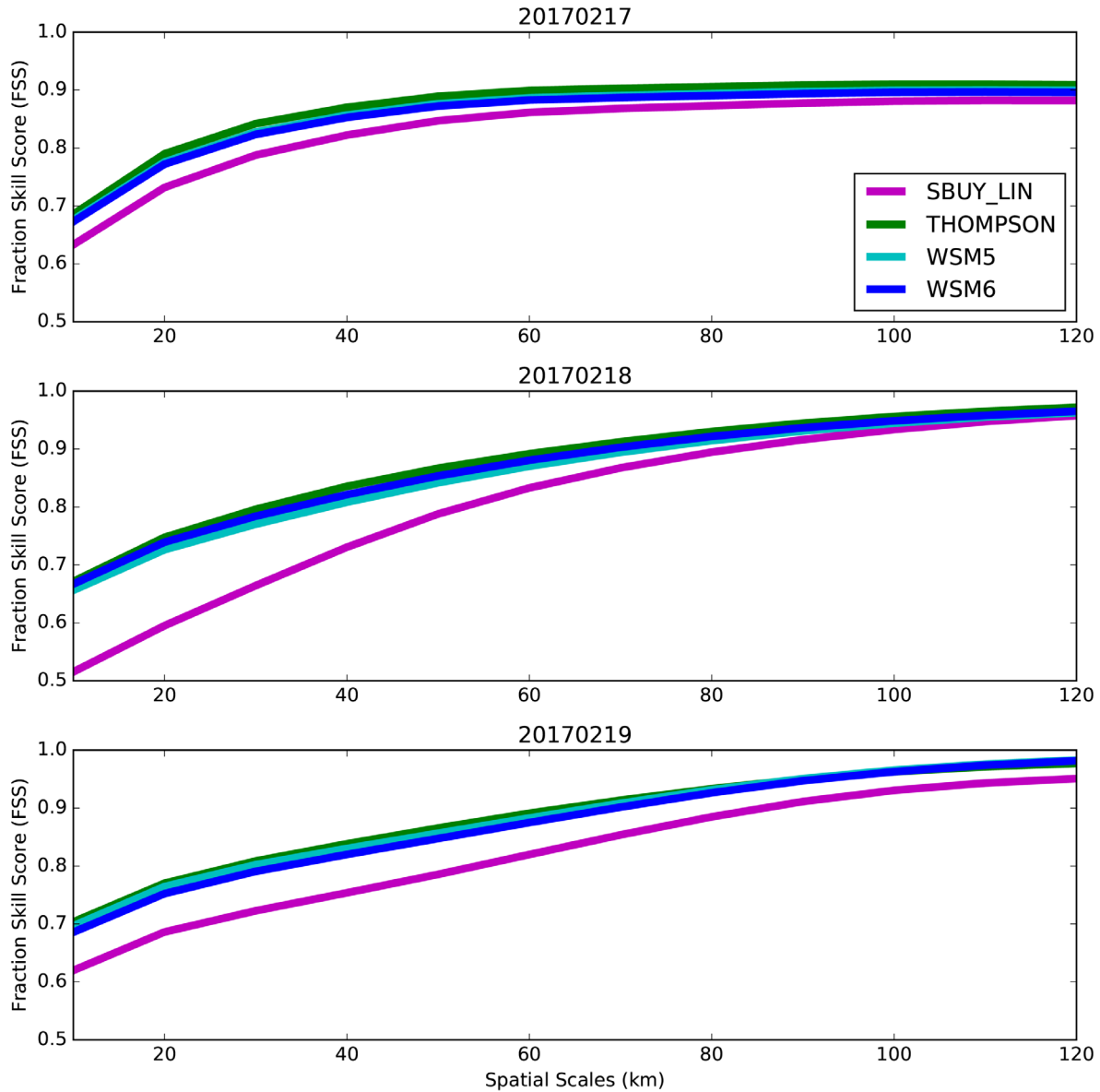


Figure 5. Fraction skill score on 17, 18 and 19 February between Global Precipitation Measurements (GPM) and different microphysics schemes namely WRF Single Momentum 6-class scheme (WSM6); 2) WRF Single Momentum 5-class scheme (WSM5); 3) Stone Brook University (SBU-YLIN); and 4) Thompson.

The second and third column show the rainfall produced by the convective scheme and the resolved rainfall, respectively. The convection scheme produced a large amount of rainfall over the north-eastern parts of Botswana on 17 February. The rainfall from the convection scheme extended south on 18 February and further south, including over South Africa, on the 19th. The resolved rainfall on the 9km domain is associated with regions with high rainfall amounts. These regions are on the north-eastern parts of Botswana into Zimbabwe on 17 February, the central parts on 18 February, and Namibia and part of South Africa on 19 February. The area

associated with a high amount of rainfall over Namibia on 19 February which is not observed, appears to have a circular shape. As already mentioned this phenomenon is not found in any of the observations used in this study. Over the inner 3km domain, the rainfall is overestimated over the north-eastern corner of the domain on 17 February, and the rainfall extends further south as seen in the station observations on 18 February. Some rainfall is simulated in the inner domain on 19 February, however, it is patchy. The model did not capture the larger rainfall over Botswana on 19 February as compared to 18 February.

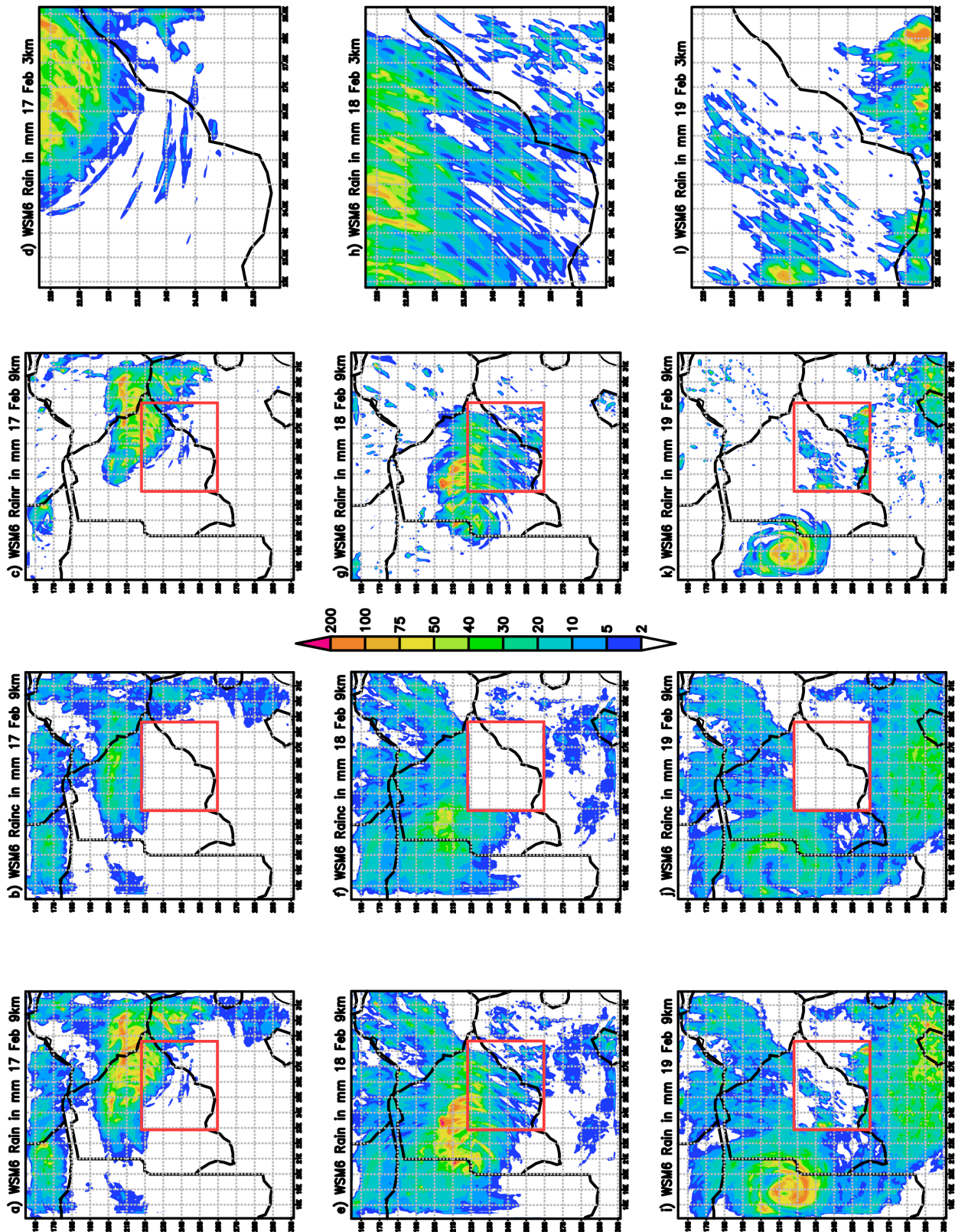


Figure 6. Total convective and resolved rainfall, convective rainfall, resolved rainfall and resolved rainfall over the full domain, and resolved rainfall over the inner domain for WRF Single Moment 6-class scheme (WSM6).

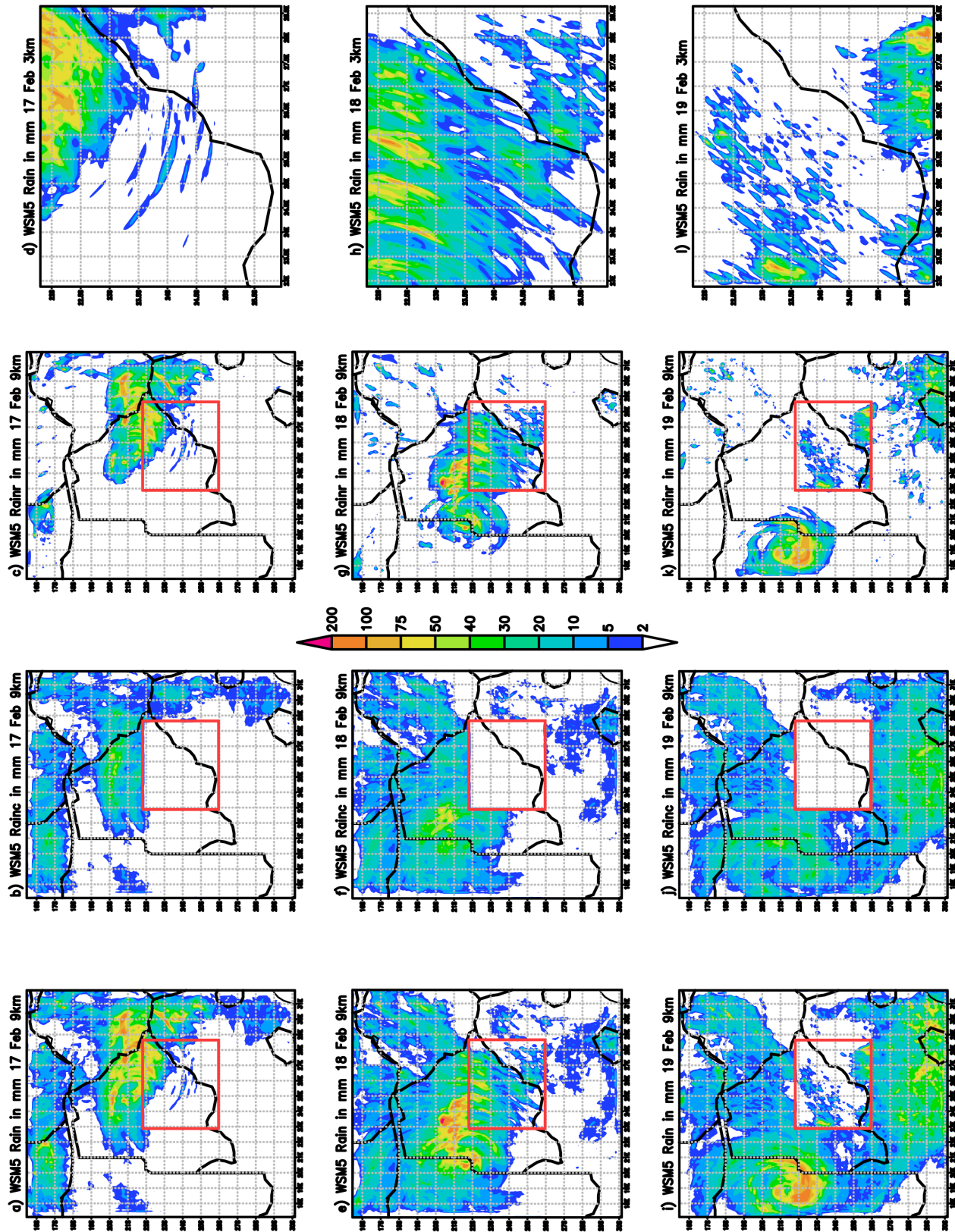


Figure 7. Total convective and resolved rainfall, convective rainfall, resolved rainfall and resolved rainfall over the full domain, and resolved rainfall over the inner domain for WRF Single Moment 5-class scheme (WSM5).

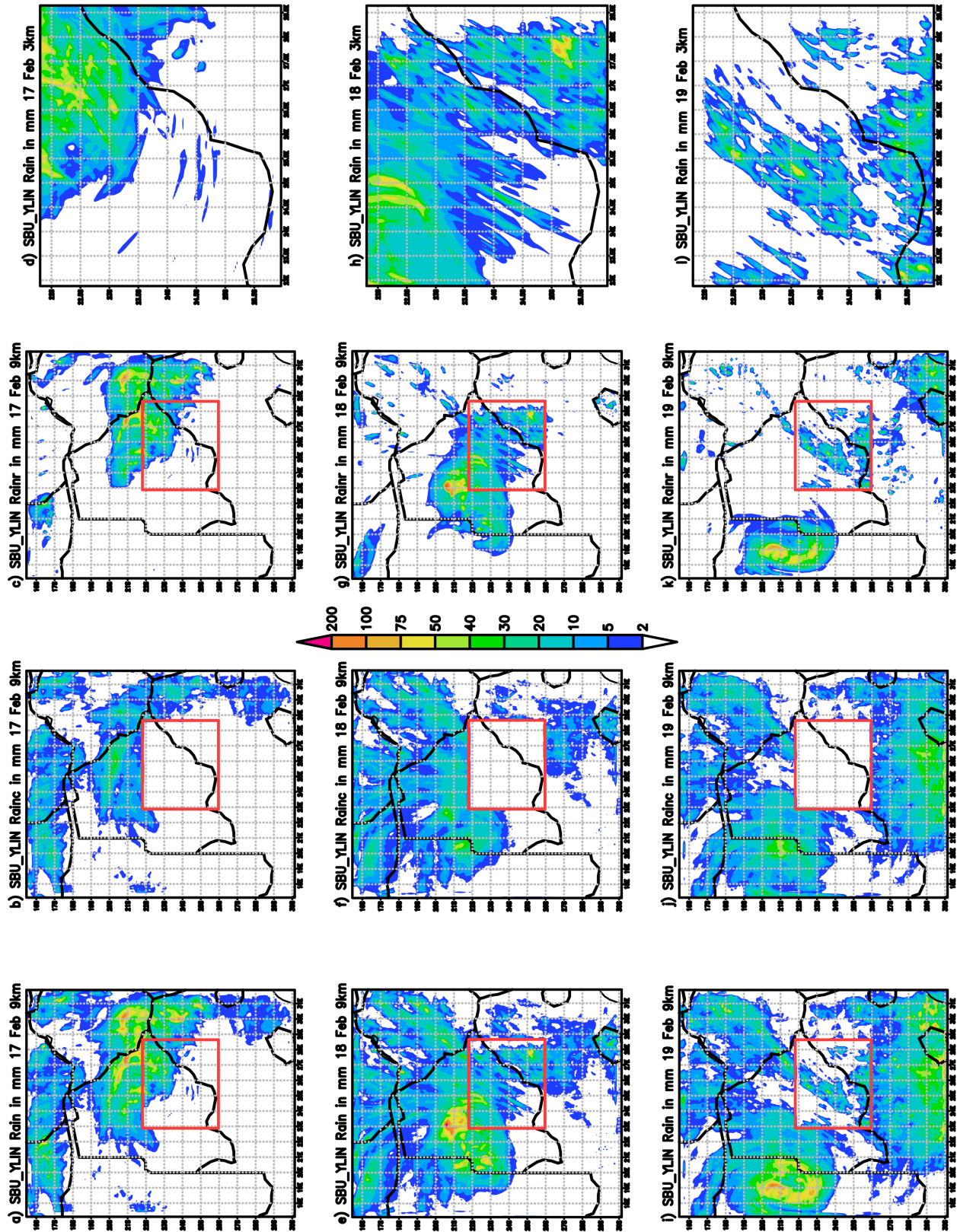


Figure 8. Total convective and resolved rainfall, convective rainfall, resolved rainfall and resolved rainfall over the full domain, and resolved rainfall over the inner domain for Stony Brook University scheme (SBU-YLIN) microphysics scheme.

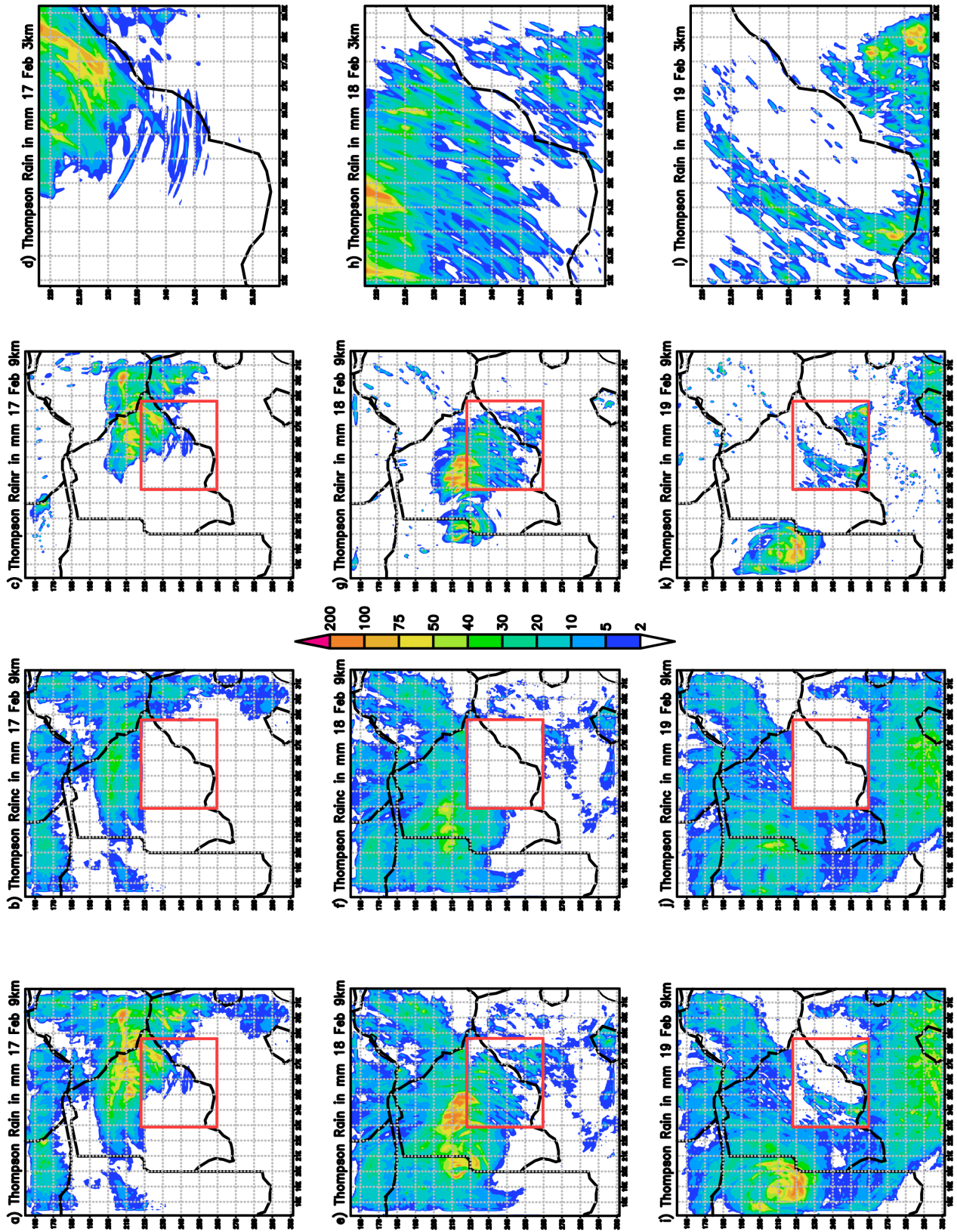


Figure 9. Total convective and resolved rainfall, convective rainfall, resolved rainfall and resolved rainfall over the full domain, and resolved rainfall over the inner domain for Thompson microphysics scheme.

WSM5 scheme. The WSM5 is a predecessor of WSM6, and so the expectation is that the WSM6 will outperform WSM5. The WSM5 includes five water continuity equations that are solved by WSM6 with the exception of graupel. The differences in the two simulations therefore mainly highlight the effect of graupel in the simulation of heavy rainfall over Botswana. The two simulations are found to be mostly similar with matching areas associated with a high amount of rainfall over both the larger and smaller domains. The simulation with WSM5 also starts with a large amount of rainfall over the northern parts of Botswana on 17 February, and the rainfall extends further south and west on 18 February. The rainfall continues on 19 February, however, areas associated with a large amount of rainfall in the smaller domain is missed, and is similar to the WSM6 simulation (Figure 7). The average rainfall simulated with WSM5 fall right on top of the WSM6 plot for the whole of Botswana. The accumulated rainfall area average for both WSM5 and WSM6 is just over 35mm, and this amount is matched by the GPM estimates. The spatial correlation between WSM5 and GPM is the same as that of WSM6, which is 0.46 on 17 February, 0.13 on 18 February and 0.21 on 19 February. The FFS is also similar with the two lines falling on top of one another. The large similarities between WSM5 and WSM6 simulations are also indicated by the spatial correlation between the two simulations which is over 0.9 during all the three days. The peak in rainfall over the central parts of Botswana on the 18th and over Namibia on the 19th, found in WSM6 simulations is also found in the WSM5 simulations. The rainfall amounts match in general; it is not obvious in our study that WSM6 produces more rainfall than WSM5 as was found by Hong and Lim³⁴ who compared simulation with a 5km grid spacing.

SBU-YLIN scheme. The SBU-YLIN also solves the same number of water continuity equations as WSM5, however, the precipitating ice of SBU-YLIN is thought to represent both snow and graupel. The level of sophistication of SBU-YLIN is thought to be similar to WSM6, with both being higher than WSM5. The scheme also reduces the number of parameterized processes by 50% as compared to one that solves 5 hydrometeor equations. The SBU-YLIN produces a smaller amount of rainfall in general as compared to both WSM5 and WSM6 schemes. The progression in rainfall is, however, found to be similar to the other two schemes with rainfall extending further south and west on 18 February, and progressing in the same direction on 19 February (Figure 8). The peak in rainfall is found over central Botswana on 18 February and over Namibia as was found with WSM5 and WSM6, but not shown in any of the observations used in the study.

The rainfall pattern in the SBU-YLIN is more different compared to WSM5 and WSM6. For example on the smaller domain a peak occurs on the southern border towards the east in both WSM5 and WSM6; however, this peak is not found in SBU-YLIN. The peak in rainfall over the neighbouring Namibia is also simulated to have a circular motion by SBU-YLIN. SBU-YLIN is shown by a purple line in Figure 4 and Figure 5. By the end of the simulation, SBU-YLIN simulated the least

amount of rainfall over the whole of Botswana. This amount is also less than the amount from the ERA5 reanalysis. The amount is, however, the same as the ERA5 reanalysis over the inner domain. The spatial correlation between SBU-YLIN simulations and GPM is 0.4 on 17 February, which is the lowest score of all the simulations. The correlation associated with SBU-YLIN is similar to other schemes on 18 and 19 February. The FFS shows the SBU-YLIN is the worst performing of the four schemes (Figure 5).

The Thompson scheme. The Thompson scheme is classed with the more sophisticated microphysics schemes which are double-moment. This scheme is used in the continental US physics suite of WRF. The Thompson scheme generally produced more rainfall than SBU-YLIN over areas associated with the largest amounts of rainfall. Both the WSM5 and WSM6, however, produced more rainfall than the Thompson scheme. The amount of rainfall simulated with Thompson is the same as that produced by the ERA5 reanalyses over the whole of Botswana, as well as over the inner domain. This result suggests that if ERA5 is taken as the best observation, the Thompson scheme would outperform all the other schemes based on the total amount of rainfall at the end of the simulation. The simulated rainfall is smaller than the GPM estimate over the bigger Botswana domain, and greater over the inner domain (Figure 4). The FFS shows the Thompson scheme as performing at a similar level to both WSM5 and WSM6. The simulated pattern again follows that found in other simulations with rainfall more being restricted towards the north of Botswana on 17 February and extending further south and west on 18 and 19 February. A high amount of rainfall is also simulated over the central part of Botswana on 18 February and over Namibia during 19 February. The spatial correlation between Thompson and GPM is similar to that found with other simulations, especially the WSM5 and WSM6. The Thompson scheme produced the largest spatial correlation on 19 February compared to all other schemes with GPM.

Summary, discussion and conclusions

The WRF model is used in this study to simulate a heavy rainfall event that took place over Botswana resulting in flooding over parts of the country, including Gaborone. The event occurred due to a mixture of synoptic systems including a dissipating tropical cyclone Dineo. The station observations indicate that the rainfall occurred over the northern parts of the country, with rainfall amounts exceeding 200mm reported by one station and over 100 mm in a few stations. The rainfall extended further south on the 18th, however, the total 24 hour rainfall was not as high as during the previous day. The rainfall continued during the next day, resulting in rainfall amounts exceeding 50mm over a number of stations on the 19th of February. The station observations were also compared with the TAMSAT and GPM satellite based rainfall estimations as well as with the ERA5 reanalysis. GPM compared best with station observations on 17 February, while TAMSAT underestimated the observed rainfall. Both rainfall estimates did not capture the rainfall observed on 18 and 19 February over most of the country. The ERA5 reanalysis show rainfall over

most of the country on both the 17th and 18th, and is possibly the best performing on 18 February. The results show a need for ground observations to help with model studies because “observations” are different.

The WRF rainfall simulations of this event using four micro-physics schemes namely WSM5, WSM6, SBU-YLIN and Thompson are compared with observations. The general pattern simulated by the four schemes is the same, with the most rainfall over the northern parts but slightly south of where the pattern is observed on 17 February. All the schemes simulate a large amount of rainfall over the central parts of Botswana on 18 February, and over Namibia on 19 February, but this feature is not found in any of the observations used. SBU-YLIN simulates the least amount of rainfall, while WSM5 and WSM6 simulate the most rainfall and they are mostly similar. The large amount of rainfall observed on 19 February over Botswana is missed by all the schemes. The large rainfall amount area develops a circular motion as it enters the smaller domain, and this circular motion is maintained as the system progresses west into Namibia. This feature may be associated with the mother-child domain interactions. A study running in parallel for Namibia is investigating the effects of running multi-domains compared to a single domain nested within GFS.

The main conclusion from this study is that the schemes are mostly similar with associated shortcomings as compared to observations. This study was made possible by the HPC facilities available in southern Africa and shows that models should not be implemented for operational purposes without testing. The study further shows benefits of regional collaboration with simulations conducted on HPC systems based in two countries. Tests with WRF will be conducted going forward to identify the best configuration to use for BDMS operational forecasts.

Data availability

Source data

ERA5 (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview>), GPM (<https://storm.pps.eos-dis.nasa.gov/storm/>) and TAMSAT (<https://www.tamsat.org.uk/>) are all open data available for download in their respective websites.

Underlying data

Open Science Framework: Sensitivity of Botswana Ex-Tropical Cyclone Dineo rainfall simulations to cloud microphysics scheme. <https://doi.org/10.17605/OSF.IO/FPJBZ>⁴³

This project contains the following underlying data:

- Botswana rainfall observation valid 17 Feb 2017 06UTC.csv (Botswana observed ground station rainfall measurements from 17th February 2017 at 06UTC)
- Botswana rainfall observation valid 18 Feb 2017 06UTC.csv (Botswana observed ground station rainfall measurements from 18th February 2017 at 06UTC)
- Botswana rainfall observation valid 19 Feb 2017 06UTC.csv (Botswana observed ground station rainfall measurements from 19th February 2017 at 06UTC)
- Botswana rainfall observation valid 20 Feb 2017 06UTC.csv (Botswana observed ground station rainfall measurements from 20th February 2017 at 06UTC)
- drive-download-20200424T064422Z-001.zip (Zipped files containing microphysics schemes simulation data for postprocessing in GrADS.)

Data are available under the terms of the [Creative Commons Zero "No rights reserved" data waiver](#) (CC0 1.0 Public domain dedication).

Software availability

The analyses was made with GrADS (<http://cola.gmu.edu/grads/>), which is open source software. The model used is WRF (https://www2.mmm.ucar.edu/wrf/users/download/get_source.html) which is open source, and it was compiled with the GNU and Intel compilers and GFS data used to force the model is open.

Acknowledgement

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Xueliang Guo

State Key Laboratory of Severe Weather (LASW), Chinese Academy of Meteorological Sciences, Beijing, China

The manuscript is a sensitivity study of four microphysical schemes on a heavy rain process in Botswana by using WRF model. It is interesting since it is important to evaluate the model in different climate and geographic conditions. However, the manuscript needs to be further revised in the relevant parts. The detailed comments are as follows:

- Introduction: This part lacks the current status of the impacts of cloud microphysical schemes on precipitation forecasts or simulations. In fact, there are many relevant publications in terms of the sensitivities of cloud microphysical schemes on precipitation forecasts in meteorological communities. I suggest the authors to read these publications firstly, do more analyses and then compare your results with these publications.
- Methods: It can be simple for descriptions of microphysical schemes, such as “The schemes used were the Weather Research and Forecasting Single Moment 6-class scheme (WSM6); Weather Research and Forecasting Single Moment 5-class scheme (WSM5)”, instead of them, you can use “WRF-Single Moment 6-class scheme(WSM6)” etc., since all are microphysical schemes in WRF.
- Observations used: should be “Data used”, some are not observations such as ERA5.
- “Case study description” should be “Case description”.
- Figures: for convenience for readers, it is better to change the positions of figures.
- Microphysics comparisons: this part is too simple and needs major revision.
- The use of the Fraction Skill Score (FSS) is not enough for the evaluation of the four schemes in simulating heavy rain events. There are many TS scores used for rainfall intensity and accumulated rainfall in meteorological forecasting.

- The results analyses are not enough. Since the main differences in four schemes are the different treatments of cloud microphysical processes, more evaluations and comparisons are needed, such as atmospheric dynamic and thermodynamics, profiles of different hydrometeors from different schemes, in order to explain the different results from different schemes.

Is the work clearly and accurately presented and does it cite the current literature?

No

Is the study design appropriate and is the work technically sound?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Partly

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Atmospheric Physics, clouds and precipitation, numerical modeling.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 19 October 2020

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Shailendra Kumar

Geophysical Institute of Peru, Lima, Peru

The authors investigate the sensitivity of MP schemes to simulate the rainfall events. However the article is not ready for indexing yet and needs major revision. My comments are mentioned below:

Introduction:

- The introduction section must be re-written again. Please include a few studies which used MP schemes to see their sensitivity to simulate the rainfall across the world. For example, you can take help from the following articles (and many more):
 - Martínez-Castro *et al.* (2019¹).
 - Moya-Álvarez *et al.* (2018²).
 - Moya-Álvarez *et al.* (2018³).
 - Moya-Álvarez *et al.* (2020⁴).
 - Rajeevan *et al.* (2010⁵).
 - Nasrollahi *et al.* (2012⁶).
 - Mayor *et al.* (2015⁷).
- Make the table of WRF compilation.
- Figure 1: Do not use contour values but use colorer.
- Figure 3 quality is not good, although you need to improve the quality of all the figures.
- You need to do more analysis to compare the difference in MP simulations. For example:
 1. Spatial and temporal evolution of vertical velocity.
 2. Hydrometeors profiles (spatial, temporal and vertical) such as Graupel, ice, snow, cloud water and rain water.
 3. Biases in the rainfall.

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Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and is the work technically sound?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Partly

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Cloud microphysics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 20 Oct 2020

Charles Molongwane, Botswana Department Meteorological Services, Gaborone, Botswana

Dear Shailendra Kumar,

I acknowledge having read your comments. They will be very helpful in subsequent revised edition.

Thank you

Charles Molongwane (Co-Author)

Competing Interests: I am the Co-Author so no competing interest whatsoever
