



Sensitivity of Cloud Microphysics on the Simulation of a Monsoon Depression Over the Bay of Bengal

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Abstract—In this study, we have examined the role of implicit and explicit representation of cloud microphysics on the simulation of a monsoon depression formed over the Bay of Bengal and the associated rainfall from 0000 UTC of 13 August to 0000 UTC of 17 August 2018 using the Weather Research and Forecast model. Five different WRF model simulations are performed by changing the Cloud Micro Physics (CMP) schemes: WSM6, Goddard, Thompson, Morrison, and Thompson Scheme with Aerosol aware options in both explicit and implicit cloud models. WRF simulations are conducted by initializing the NCEP GFS analysis at 0000 UTC of 13 August 2018 and integrated up to 96-h. The boundary conditions are updated at 6-hourly intervals with the respective GFS forecasts. Our results of sensitivity simulations suggest that the Thompson Scheme with Aerosol aware scheme, followed by Goddard microphysics, captured the features of monsoon depression and associated rainfall. Microphysics schemes have an influence on the simulation of low level westerly jet, and upper level easterly jet. Implicit and explicit cloud microphysics options are able to reproduce the convection over the west-coast, but the implicit option failed in producing the prolonged convection over the east coast. The comparison of model rainfall with rain-gauge, and satellite merged rainfall estimates reveals that the large scale off-shore precipitation is better captured in CMP with the inclusion of explicit cumulus parameterization. The orographic rainfall over the wind-ward and lee-ward sides of the Eastern and Western Ghats is well predicted in the implicit CMP. The vertical distribution of the hydrometeors and rainfall analysis suggest that the Thompson Scheme with Aerosol aware scheme with the cloud-resolving explicit mode is suitable for simulating the monsoon depressions formed over the Bay of Bengal and the associated heavy rainfall over the east coast of India.

Keywords: Heavy rainfall, monsoon depression, cloud-microphysics, WRF model and Bay of Bengal.

1. Introduction

Numerical weather prediction (NWP) modelling is an important tool to understand the mechanisms that control the occurrence of heavy precipitation events (Hong et al. 2009). With the advent of high-performance computing, NWP has gained prominence and became one of the major tools for the prediction of severe weather events. Out of all the numerical models, the Weather Research and Forecasting (WRF) have gained attention for the short-range weather forecasting due to advanced numeric, sophisticated physics, and assimilation capability (Skamarock et al. 2008). The WRF Model is equipped with many parameterization modules and the accuracy of the model is highly dependent on the choice of parameterization that needs to be studied by carrying a suite of sensitivity experiments. Each parameterization process has a different level of complexity (Sobhani et al. 2017; Andraju et al. 2019) and the prediction of extremely heavy rainfall at shorter time scales is difficult (Das et al. 2008).

Several studies depict that the cloud microphysics plays a critical role in simulating the dynamical parameters such as sea level pressure, winds, rainfall, and vorticity/divergence at surface/upper levels (Mohan and Chawla 2018; Mohan et al. 2019). These studies showed that the choice of cloud microphysics (CMP) in weather models play a major role in simulating deep convective processes and associated rainfall at cloud-resolving and high resolution models

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(Srinivas et al. 2018; Mohan et al. 2019). Since the cumulus process at a very high-resolution scale are resolved by the microphysics, the calculation of precipitation by microphysics has a great impact (Waliser et al. 2009). CMP plays a crucial role in simulating the hydrometeors and in the precise spatial–temporal prediction of heavy rainfall (Wang et al. 2002). The primary species in the CMP schemes are water vapor, graupel, hail, cloud ice crystals, snow, and cloud and rain droplets.

Based on the size distribution of the hydrometers, the CMPs are divided into two groups such as bin and bulk. The bin type parameterization discretizes on the particle diameter size distribution into a large number of bins while the bulk type employs specific analytic functions for the size distribution. Though these two types (bin and bulk) predict the number and mixing ratios of cloud ice and rain and the mixing ratio of cloud droplets, but they differ significantly in their treatments of snow and graupel /hail in terms of double versus single moment and the shape of the particle size distributions (PSDs). These differences potentially alters the profiles of simulated hydrometeors which can impact the dynamics of the model through their phase transitions leading to produce changes in simulated winds (both horizontal and vertical wind) and low convergence of moisture (Rasmussen and Houze 2016; Morrison and Milbrandt 2011; Hazra et al. 2013). Several CMP sensitivity studies (Mohan et al. 2018, 2019) suggest that the utilization of more sophisticated and complex microphysical parameterization would certainly help to reduce the model errors, particularly in providing the precise location-specific rainfall forecasts. The availability of computational resources and improved cloud microphysics in the recent years, enables the research and weather community to use the meso-scale models very high resolutions grid resolutions ($\approx < 1$ km) and convection resolving capability for the short-range weather forecasting. Studies like Tao et al. (2012) highlighted that the use of high resolution and explicitly resolved model configurations helps in reducing precipitation biases in the summer season over USA.

The advantage of the explicit cloud resolving configuration in the numerical models is the CMP alone responsible for calculating the growth,

collection, glaciation, and melting of water and ice particles. Several CMP sensitivity studies (Srinivas et al. 2013, 2018; Halder et al. 2015; Halder and Mukhopadhyay, 2016; Ghosh et al. 2016; Mohan et al. 2019) are conducted over the Indian region which suggest that the choice of CMP schemes play a dominant role in the simulation of the timing, location, and intensity of precipitation over India. Most of these studies (Srinivas et al. 2013, 2018; Mohan et al. 2019) are on the analysis of tropical cyclones over Bay of Bengal, severe convective and heavy rainfall events over India. Ghosh et al. (2016) showed that the cloud-resolving simulations are capable of capturing a heavy rainfall location precisely associated with the severe convective rainfall event. Though Mohan et al. (2018) showed that the Thompson scheme works better for simulating heavy rainfall over Chennai, their study limited to the northeast monsoon season. However, the choice of micro-physics scheme with the WRF model at very-high resolution on the prediction of extreme rainfall events is not yet well understood and needs further research.

Implementation of cloud resolving and very high resolution (< 1 -km) model configuration over the Indian subcontinent demands huge computational resources. Considering these computational limitations, India Meteorological Department (IMD) implemented a high resolution WRF model domain (horizontal resolution of 3-km) for its short-range forecasts. However, the horizontal resolution of 3 km falls in the gray zone of resolving the cumulus convections and there are no studies over Indian region discussing on whether explicit convection scheme is required at 3-km horizontal resolution. Moreover, several studies (Vinoj et al. 2014; Sarangi et al. 2015, 2017) have already indicated the impact of natural and anthropogenic aerosols on monsoon depressions and associated rainfall. Recently, WRF is equipped with the cloud aerosol feedback through the Thomson scheme aerosol-aware scheme (Thompson et al. 2014). This scheme is an upgraded version to Thomson scheme (Thompson et al. 2008) to incorporate the cloud-aerosols effects explicitly and predict available number of aerosols. However, the performance of this aerosol aware scheme on the simulation of monsoon depressions has not been analysed out so far. This study attempts to analyse the

sensitivity of cloud microphysical process (CMP), particularly the impact of cloud-aerosol feedback and the role of implicit and explicit representation of CMP on the simulation of monsoon depression over Bay of Bengal for providing a feedback to operational predictions system in India.

The main aim of the present study is to identify the suitable CMP scheme on the prediction of monsoon depression and associated spatio-temporal variability of heavy rainfall events. For this exercise, we have considered a monsoon depression case between 13 and 17 August 2018 over the north-west BoB and analysed associated heavy rainfall features over the east coast (Visakhapatnam, Andhra Pradesh) and the west coast (Pookot, Kerala). As far as heavy rainfall is concerned, the IMD categorized three major rainfall events based on the daily accumulated rainfall data, namely, heavy rainfall (64.5–124.4 mm), very heavy rainfall (124.5–244.4 mm), and extremely heavy rainfall (above 244.5 mm). As per this classification, the east and west coasts rainfall events considered in this study comes under very heavy and extremely heavy rainfall categories respectively. The manuscript is organized as follows. Section 2 provides synoptic history of the extreme precipitation event and the details of the model and configuration described in Sect. 3. The results and discussion of the simulated extreme weather event detailed in Sect. 4 and finally, the summary and conclusions is provided in Sect. 5.

2. Synoptic Conditions of Monsoon Depression

The India Meteorological Department (IMD) reported a the monsoon depression with a low pressure circulation over the north-west Bay of Bengal on 13 August 2018 which becomes a well-organized low pressure system on 14 August (Fig. 1). It further developed as a depression on 15 August with a 993 hPa sea level pressure and 25 knots wind speed, with a 10–20 knots vertical wind shear. The depression over coastal Odisha moved in west-north-westwards and lay centred at over Odisha in the evening hours of 15 August. It further moved westwards and positioned over Vidarbha region of Maharashtra on 16 August 2018. Later, it moved in west to north-westward direction and weakens gradually into low pressure area

on 17 August 2018. Overall the depression travelled about 1145 km during the period 14–17 of August, 2018 and helped to activate of the southwest monsoon over the north-coastal Andhra Pradesh (AP), Kerala, Odisha, Telangana, and coastal Karnataka. Because of the monsoon depression's location and its passage, the north-coastal AP and Odisha experienced extreme rainfall, mainly over Visakhapatnam and its surroundings. The detailed discussion of the synoptic situation of this event is described by Viswanadhapalli et al. (2019). Based on the daily accumulated rainfall data over the Indian region the IMD categorized three rainfall events named heavy rainfall (64.5–124.4 mm), very heavy rainfall (124.5–244.4 mm), and extremely heavy rainfall (above 244.5 mm).

3. Data and Model Configuration

3.1. Data

The spatial distribution of WRF simulated rainfall is compared to the Global Precipitation Measurements (GPM) available at $0.25^\circ \times 0.25^\circ$ degree horizontal resolution and Automatic Weather Station (AWS) data. Low level moisture transport is computed for WRF model and ERA-5 ($0.25^\circ \times 0.25^\circ$ grid resolution) by making use of the spatial fields of specific humidity and winds. The model simulated sea level pressure (SLP) patterns are compared with Surface synoptic charts and SLP fields of ERA-5 ($0.25^\circ \times 0.25^\circ$ grid resolution) and the model reflectivity is validated against the Doppler Weather Radar (DWR) data available at IMD, Visakhapatnam.

3.2. Model Configuration

The Weather Research and Forecast (WRF) model (Skamarock et al. 2008) is configured with 2-way interactive nested domains of 9 and 3 km horizontal resolutions and with 72 vertical levels to predict this intense rainfall event (Figure. S1). The model physics as considered by the previous studies (Raju et al. 2011; Srinivas et al. 2013, 2018; Yesubabu et al. 2014; Ramakrishna et al. 2014, 2019; Hari Prasad et al. 2017; Rao et al. 2018; Kumari et al. 2019), includes Kain-Fritsch (Kain, 2004) scheme for

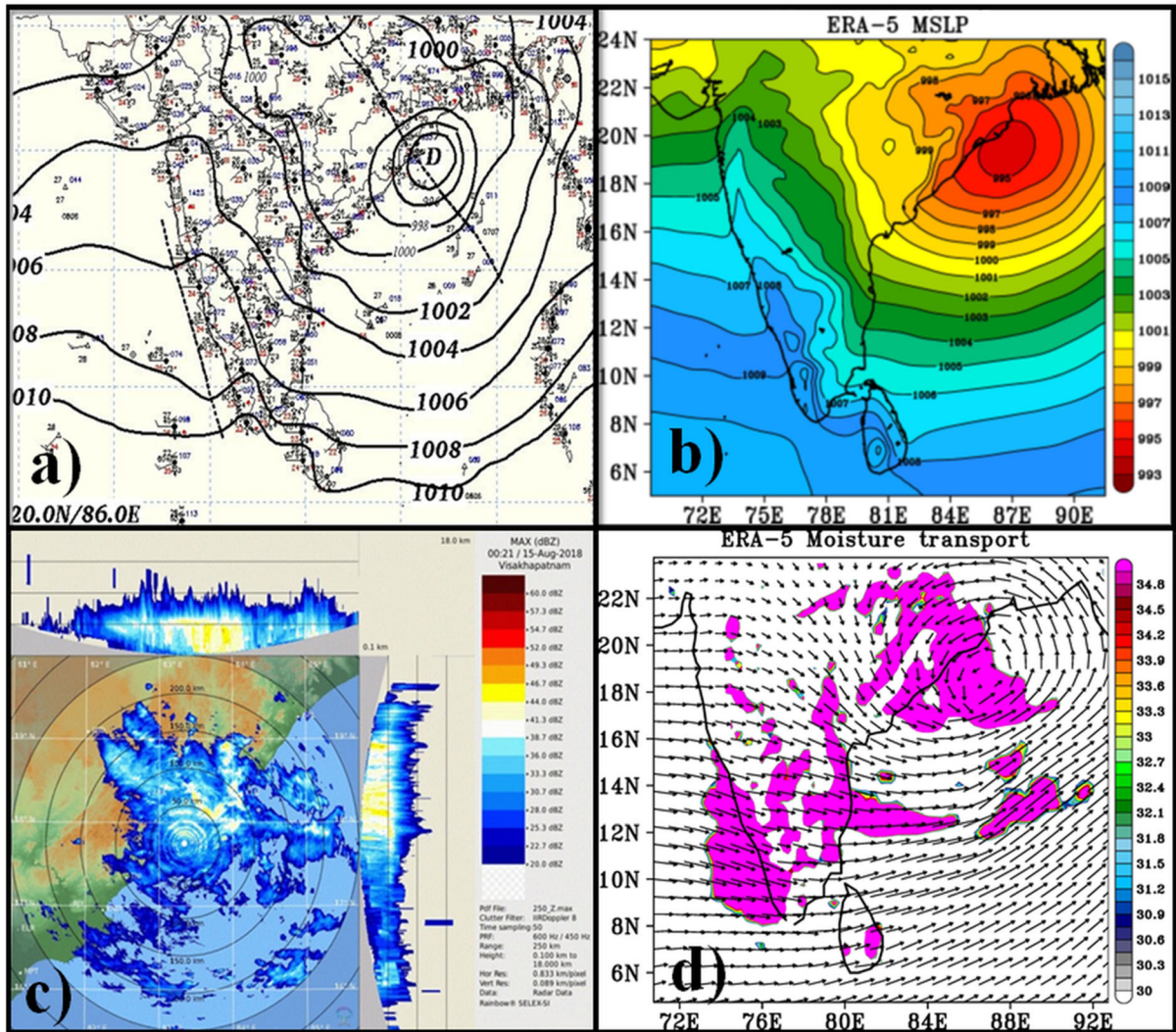


Figure 1

Snap shot of observations used in analysis; **a** Surface Synoptic chart from IMD, **b** Mean MSLP (in hPa) from ERA-5 reanalysis on 15 August, **c** Reflectivity imagery at 0021 UTC of 15 August from DWR, Visakhapatnam, **d** Mean moisture transport ($\text{kg m}^{-1} \text{s}^{-1}$) at 925 hPa derived from ERA-5 on 15 August 2018

cumulus convection, MYNN3.0 for PBL Scheme (YSU; Hong et al. 2006) for boundary layer processes, NOAHMP land surface scheme (Chen and Dudhia, 2001) for land surface exchange of energy processes, and a combination of different cloud microphysics (Table 1). Ten simulations are conducted by varying cloud microphysics namely WRF single moment 6 scheme (WSM6; Hong et al. 2006), Goddard scheme (Tao and Simpson, 1989), Thompson (Thompson et al. 2008), Morrison (Morrison

et al. 2009), and New Thompson Aerosol aware schemes (Thompson et al. 2014; here by we define as New Thompson scheme) to study the sensitivity of model. All the CMP sensitivity experiments are conducted by configuring with explicit (with convection) and implicit (without convection) option to study the effect of WRF skill on prediction of rainfall. The model is initialized at 0000 UTC of 13 August 2018 using NCEP Global Forecast System (GFS) analysis available at $0.25^\circ \times 0.25^\circ$ horizontal

resolution and is integrated for 96-h (up to 0000 UTC 17 August 2018). The boundary conditions are updated at every 6-h intervals using the GFS forecasts.

4. Results and Discussion

In this section, the analysis of dynamical and thermo dynamical features are performed for the model in the different observational platforms such as GPM, AWS and IMD. The role of cloud microphysics on the model dynamics in resolving the monsoon depression and associated rainfall is first discussed. Further, the dynamical changes which influenced the thermodynamics are then analysed which lead to the changes in simulating the hydrometers and rainfall.

4.1. Dynamical Features

4.1.1 Sea Level Pressure

The model simulated three-day averaged SLP (0000 UTC 14 August–0000 UTC 17 August 2018) distributions by different CMPs and ERA-5 shows (Fig. 2) clearly indicate the formation of a depression over south-coastal of Orissa with minimum SLP. The simulated SLP in implicit and explicit configurations suggests that the implicit configuration provides the maximum pressure drop over the Bay of Bengal compared to the explicit model (with convection in high resolution domain). This suggests that the WRF with the use of convection scheme in the high resolution domain (3-km; explicit) provides stronger depression due to the high pressure drop. Moreover, the CMP schemes of Goddard and New-Thompson schemes in implicit configuration are showing well organized surface trough over Visakhapatnam and surrounding regions. However, the all the CMP schemes in explicit mode using convection scheme produced maximum pressure drop and sharp features of offshore trough compared to the implicit cloud resolving configuration over Kerala and Tamil Nadu. Out of all the microphysical schemes, Goddard with implicit mode of convention, followed by New-Thompson schemes are produced closest features of

depression over Bay of Bengal as observed in the ERA-5 and IMD synoptic charts, while WSM6 produced weaker depression in all experiments.

4.1.2 Winds at 850 hPa and 150 hPa

The simulated surface winds during the depression shows (Fig. 3) a stronger low level jet in the west of India in the implicit mode compared to explicit mode. The 3-day averaged (during 0000 UTC 14 August–0000 UTC 17 August 2018) simulated surface winds at 850 hPa and upper level winds at 150 hPa shows (Fig. 3 and Figure S2) an enhancement of low level jets and the upper level TEJ in all experiments over the southern tip of Kerala though the implicit mode experiments predicted relatively stronger winds. Well-organized winds with a maximum speed of 40 ms^{-1} are noticed with Goddard and New-Thompson Aerosol schemes over Bay of Bengal, at the Visakhapatnam in neighboring places, whereas, all other simulations simulated a speed of 35 ms^{-1} . The strengthening of tropical easterly jet (TEJ) winds over the south-east coast (Nellore to Gudur) are seen in Goddard and New-Thompson schemes in the implicit configuration. Further, the WSM6 produces weaker wind at lower levels, and Morrison predicted weaker winds at upper levels compared to all other four experiments.

4.1.3 Simulated Moisture Convergence and the Transport

The stronger wind flow over the windward side of the Eastern Ghats leads to enhanced moisture convergence at the lower levels and divergence at upper tropospheric levels. Figure 4 is the 3-day averaged (15 August 2018) moisture convergence averaged between the surface to 700 hPa levels, and the corresponding moisture transport is presented in the Fig. 5. The results suggest that the simulated moisture convergence is stronger in implicit mode experiments near the windward side of Western Ghats (Kerala) and Eastern Ghats (Visakhapatnam). Accumulation of moisture along with the cyclonic circulation pattern is visible in all experiments due to the monsoon depression over Bay of Bengal, allowing winds to converge and carry moisture towards the

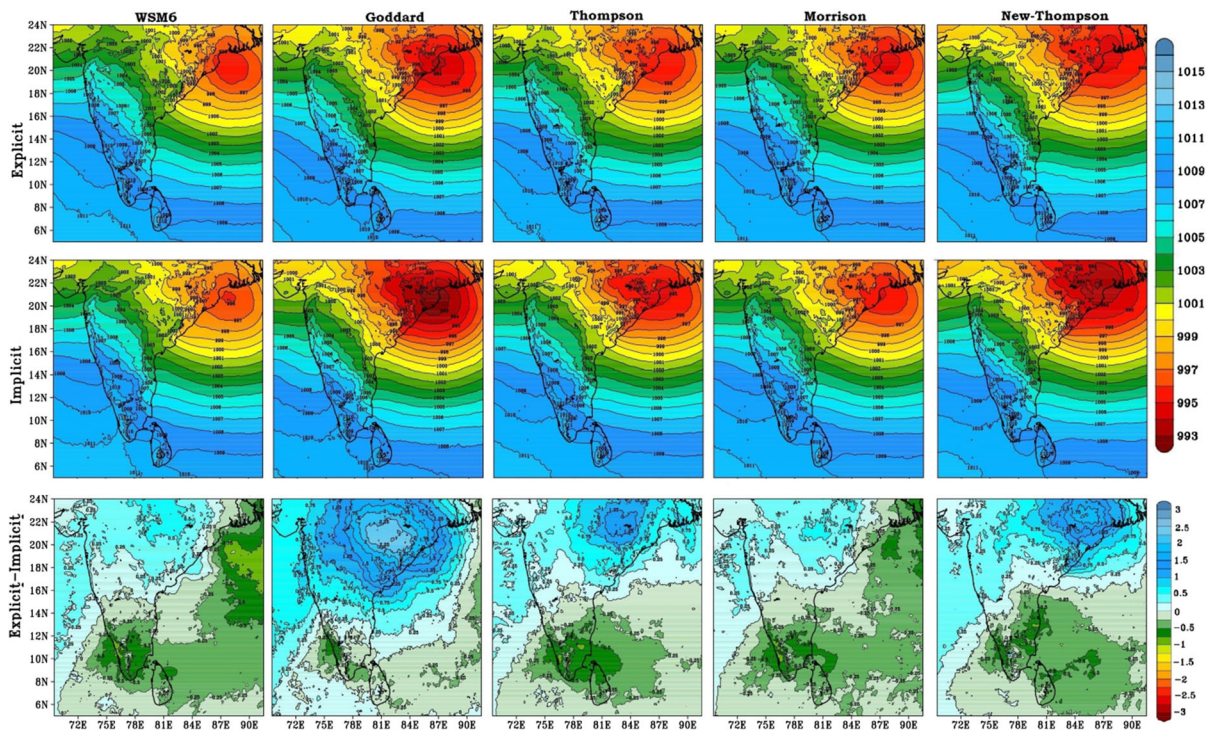


Figure 2

3-day mean simulated Mean Sea Level Pressure (hPa) from the explicit (top panels), the implicit (middle panels) and their differences (bottom panels) during 14–17 August 2018

region. The Goddard implicit scheme produced better convergence as well as the moisture transport over the Indian coast followed by the New-Thompson scheme.

The moisture transport and its convergence obtained from the ERA-5 and WRF model for the period 0000 UTC 15 to 0000 UTC 16 August 2018 indicate (Figs. 5 and 1d) the moisture transport confined to south west-coast of India, and over Bay of Bengal. The study of moisture convergence and transport variables are more important for the better estimation of monsoon rainfall (Ramakrishna et al. 2017; Viswandhapalli et al. 2019, 2020). WRF sensitivity experiments indicate that the transport of moisture from the Bay of Bengal is following the path of cyclonic circulation flow patterns in all experiments. However, the transport of moisture is stronger in the implicit mode (without convection) than explicit mode. Moreover, the Goddard scheme simulated strong moisture transport followed

by New-Thompson which is probably due to the simulation of stronger winds at lower level that enhanced the moisture advection. WSM6 scheme in both implicit and explicit modes exhibits weaker convergence and transport of moisture, followed by Morrison.

4.2. Convective Available Potential Energy (CAPE)

Several studies reported (Mohan et al. 2018; Viswanadhapalli et al. 2019) that the Thompson scheme has tendency to produce stronger warming which enhances the vertical velocity. This highlights that the changes in cloud microphysics formulation impacts the thermodynamic parameters of Convective Available Potential Energy (CAPE) and Convective Inhibition energy (CIN). The time series of simulated CAPE and CIN over Visakhapatnam (17.87°N, 82.35°E) suggests (Fig. 6) that the New-Thompson schemes in the implicit mode provides

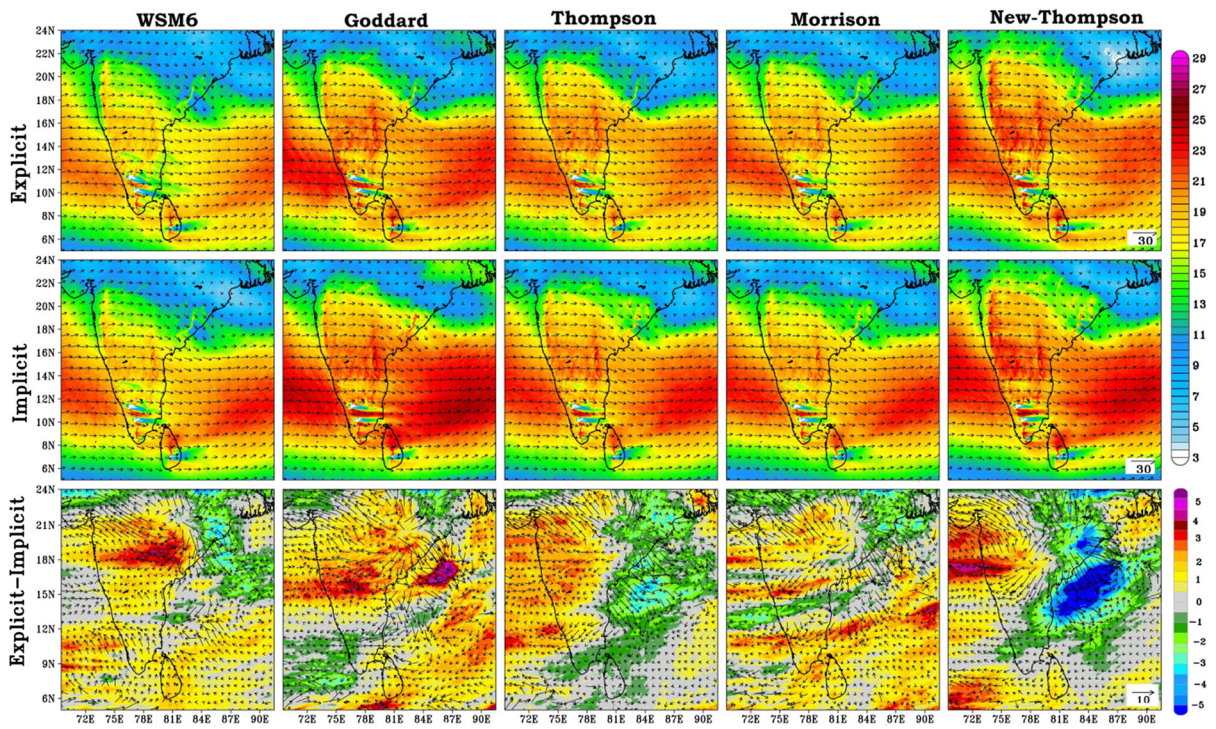


Figure 3

Spatial pattern of 3-day mean simulated 850 hPa winds (m s^{-1}) from the explicit (top panels), implicit (middle panels) and their differences (bottom panels) during 14–17 August 2018

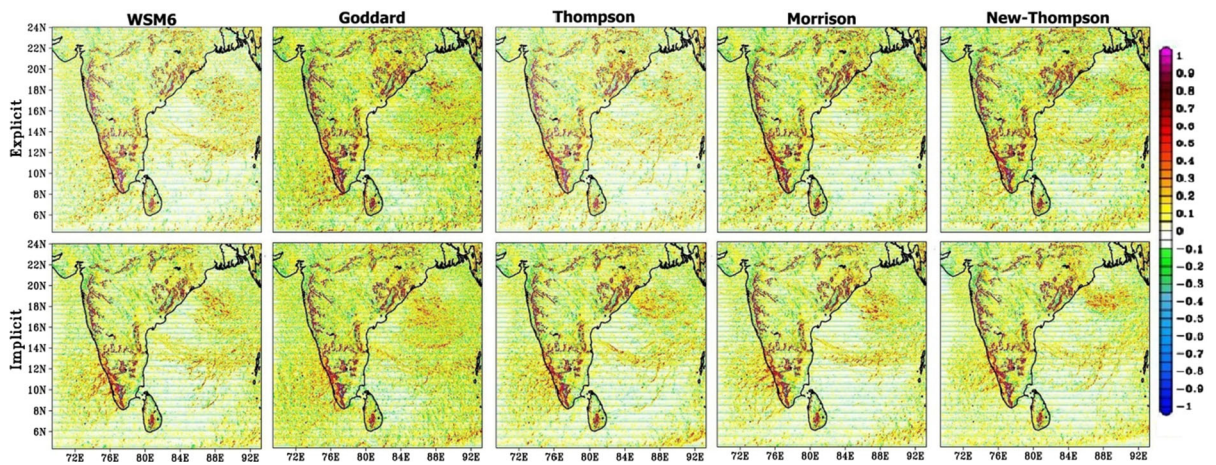


Figure 4

Mean moisture convergence ($\text{kg m}^{-1} \text{s}^{-1}$) at 700 hPa with different microphysics experiments during 14–17 August 2018

maximum CAPE and minimum CIN which is in close agreement with the observed value from radiosonde, Visakhapatnam. Among the five CMPs, the Goddard

and Morrison predicted the lowest values, and the WSM6, Thompson, and New-Thompson schemes predicted the highest value (about $1100 \text{ J}\cdot\text{kg}^{-1}$).

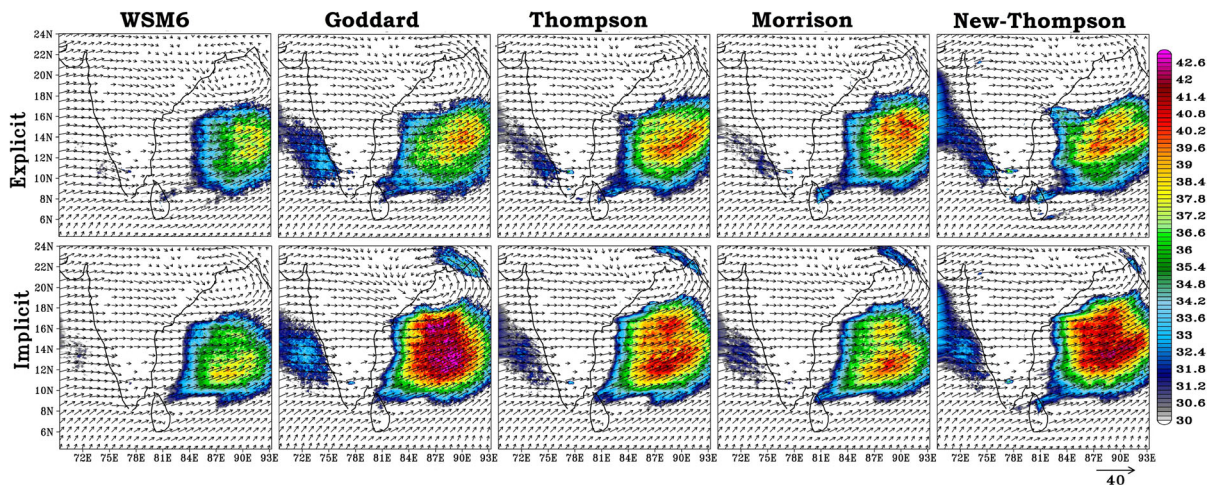


Figure 5

Mean simulated moisture transport ($\text{kg m}^{-1} \text{s}^{-1}$) at 925 hPa with different microphysics experiments during 14–17 August 2018

4.3. Analysis of Zonal, Meridional Winds and Vertical Velocity

4.3.1 Study of Zonal and Meridional Winds

The sensitivity of simulated winds with explicit and implicit modes at heavy rainfall location chinathapalle as shown in Fig. 7 suggests that the CMP schemes exhibit different characteristics from east coast to west coast during the heavy rainfall episode. The first and the second panels are the results of the explicit and implicit experiments over the east coast respectively. The third and fourth panels show the results of the explicit and implicit modes experiments respectively over the west coast. The stations considered for the study are Pookot (11.54°N , 76.02°E) in the west coast and Chinthapalle (17.87°N , 82.35°E) in the east coast.

The low level westerly jet and tropical easterly jets are noticed over Western Ghats region in all CMP experiments in explicit convection mode than the implicit mode. The results shows that the strong easterly low level jets move upward and down ward due to convection in Goddard and New-Thompson schemes in the west coast region. Over the west coast, Goddard and New-Thompson schemes in implicit mode produces stronger winds at the time of heavy rainfall. The Morrison, Thompson, and WSM6 schemes produce stronger winds irrespective

of the heavy rainfall events. Over the east coast of India, Goddard implicit mode produced better wind patterns followed by the New-Thompson schemes. The WSM6, Thompson and Morrison in the implicit modes results in feeble winds over the coast. Strong winds in the west coast than in the east coast enhances the intensity of the convection and resulting rainfall over the west coast.

4.3.2 Study of Vertical Velocity

The vertical velocity variations with different CMPs in both explicit and implicit modes (Fig. 8) indicate that the maximum updrafts (1.5 ms^{-1}) and downdrafts (1.5 ms^{-1}) are noticed over the west coast, producing stronger vertical winds compared to the east coast station. The intense vertical winds of 1.5 ms^{-1} extended up to 6 km ASL in the west coast and the vertical winds over east coast are weaker with values of about 0.4 ms^{-1} . The explicit experiments are producing strong vertical winds compare to the implicit experiments. New-Thompson explicit scheme illustrated the strong updrafts over the west coast followed by explicit modes of Morrison and Thompson schemes. The explicit mode of Thompson scheme produces stronger vertical winds over the east coast followed by explicit modes of New-Thompson and the Goddard scheme. In both coasts, the WSM6

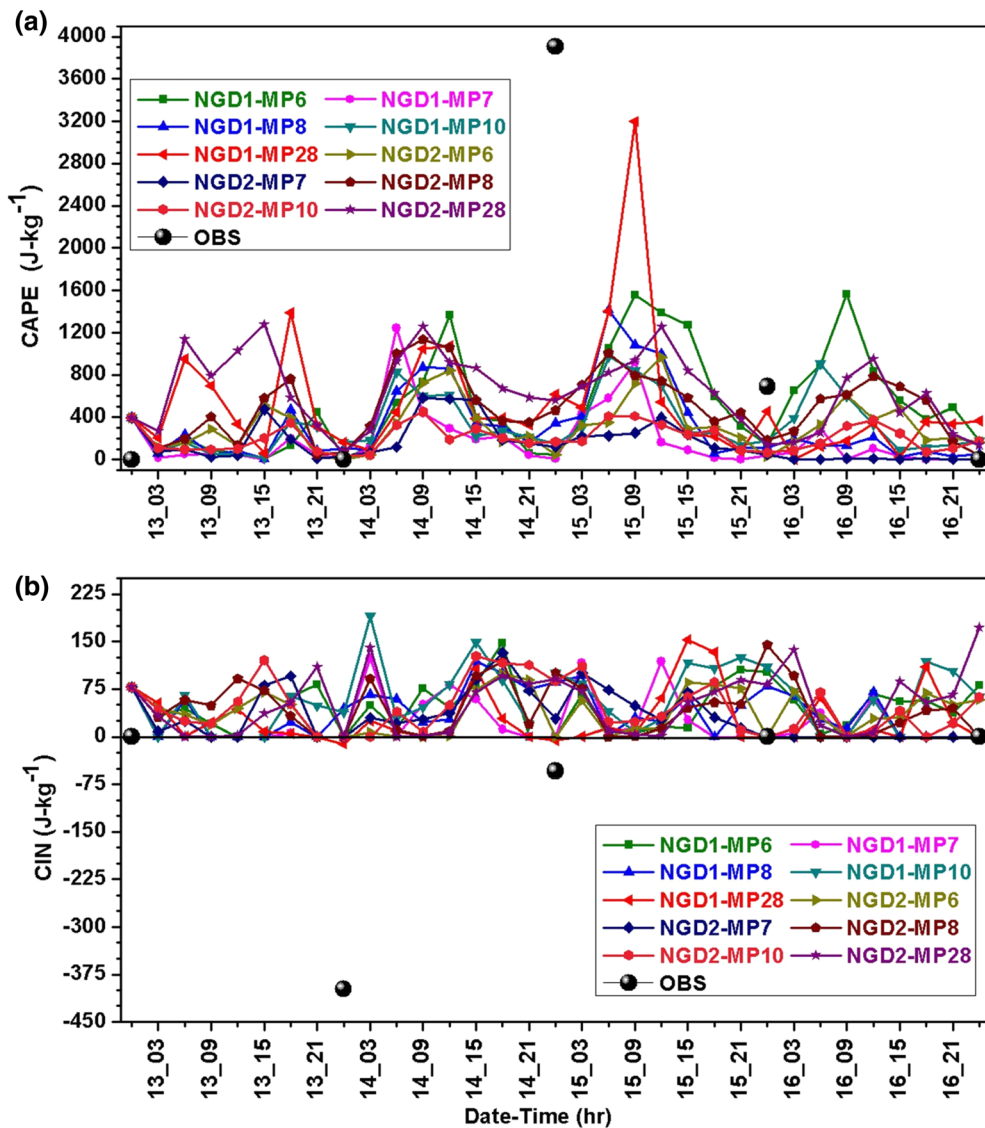


Figure 6

Time variation of **a** CAPE ($J\ kg^{-1}$) and **b** CIN ($J\ kg^{-1}$) at Visakhapatnam calculated from different CMP schemes and compared with radiosonde observations during 13–17 August 2018

implicit mode experiment produced weaker vertical winds.

4.3.3 Study of Reflectivity

The vertical extension of the reflectivity of different CMPs during heavy rainfall is presented in Fig. 9. The explicit mode experiments shows strong reflectivity than the implicit mode experiments with a maximum of 38 dbz over the east coast, while

implicit mode seems to produce enhanced reflectivity over the west coast compared to the explicit mode. The reflectivity and its vertical extension are strong (weak) in the west coast (east coast). The explicit mode of Thompson-New scheme produced the strong reflectivity and followed by Thompson-New implicit Morrison scheme. This vertical alignment of reflectivity from the surface reveals strong convection in the west coast during the heavy rainfall event.

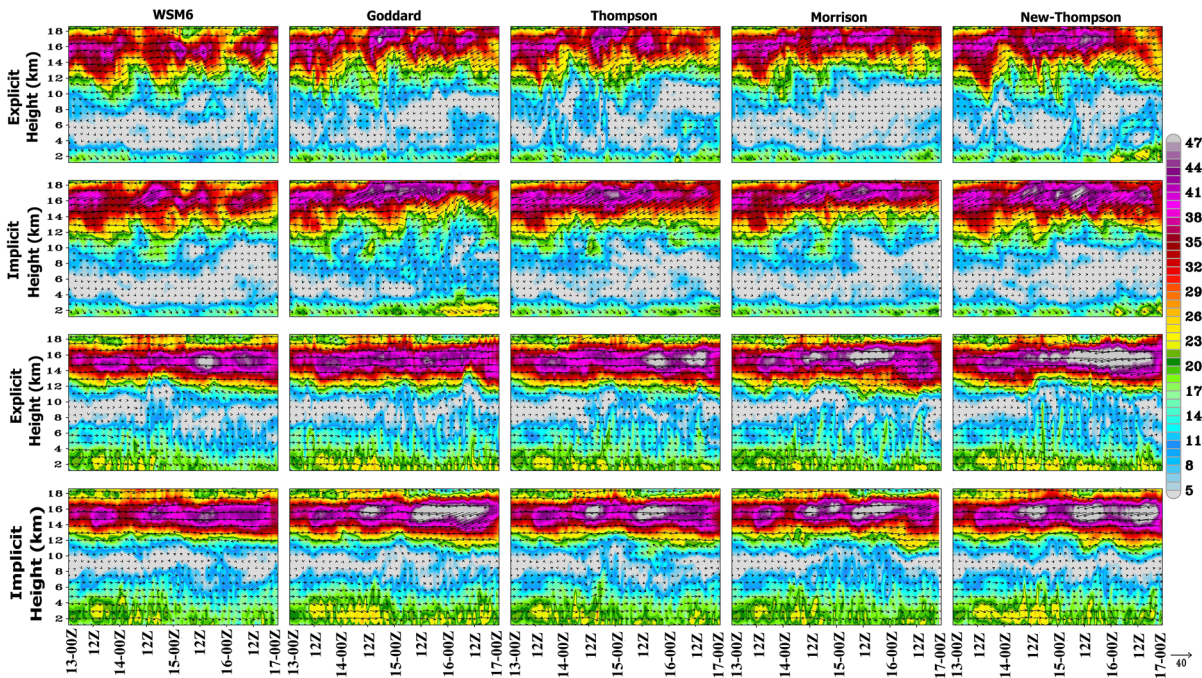


Figure 7

Simulated time-height profiles of zonal and meridional winds at Visakhapatnam (East coast; top two panels) and Pookot (West coast; bottom two panels) stations during 13–17 August 2018

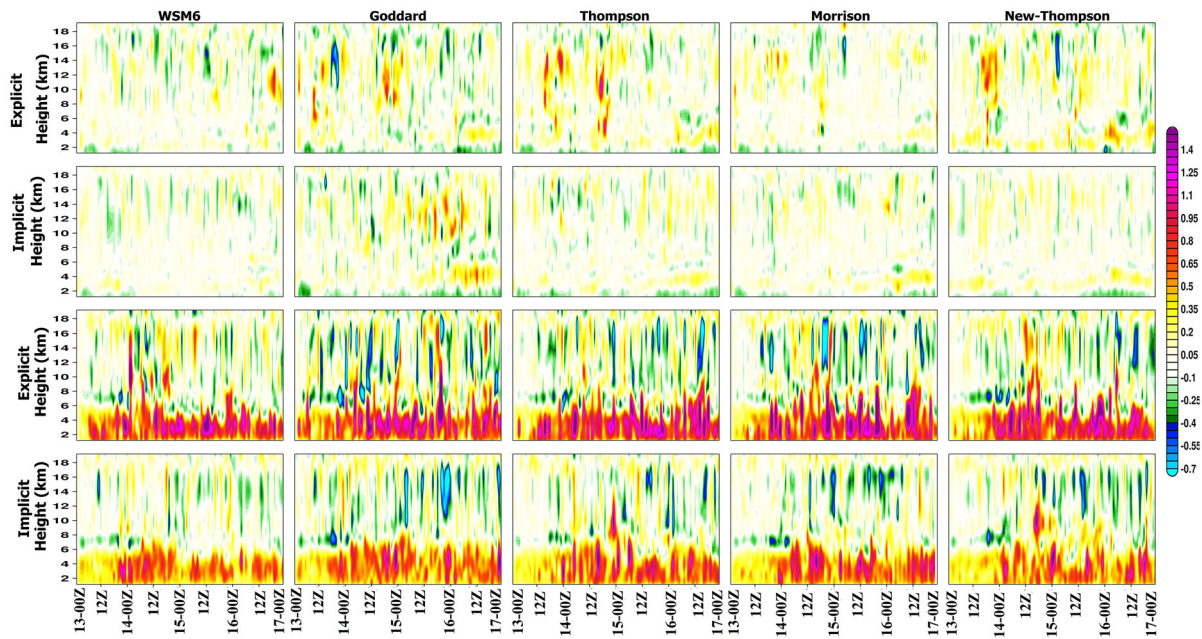


Figure 8

Simulated time-height sections of vertical velocity (ms^{-1}) at Visakhapatnam (East coast; top two panels) and Pookot (West coast; bottom two panels) stations during 13–17 August 2018

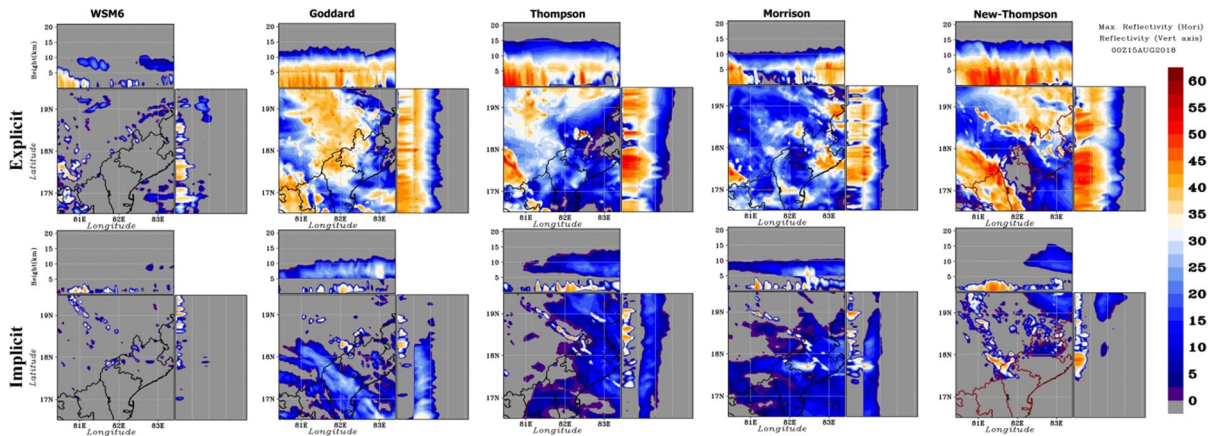


Figure 9

Spatial distribution of simulated maximum reflectivity (dBZ) from the explicit (top panels) and implicit experiments (bottom panels) plotted at 0000 UTC, 15 August 2018

Goddard and Thompson schemes produced better results over the west coast and the Thompson explicit scheme simulated strong reflectivity in east coast (Figure. S3). The reflectivity pattern over east coast with stronger bands up to 14 km suggests the presence of deep convective system. The time and intensity of the strong reflectivity in the explicit Thompson and Goddard schemes are in close agreement with the observed time of heavy rainfall. All the implicit experiments produced weak reflectivity except Goddard, Thomson and New-Thomson Aerosol aware schemes, where well organized deep reflectivity patterns are noticed.

4.4. Analysis of Hydrometeors

4.4.1 Study of Cloud Mixing Ratio

The time-height variation of cloud mixing ratio (q_c , Kg Kg^{-1}) for the five microphysics CMP schemes with explicit and implicit mode are shown in Fig. 10. Results indicate a clear distinction between the simulated cloud mixing ratio (q_c) between the locations over the east and west coast. Shallow and low level clouds seen in the east coast and deep convective systems over west coast with the maximum ($4 \times 10^{-4} \text{ kg kg}^{-1}$) are seen at 8–9 km ASL. Over the west coast, high concentrations are seen in the vertical distribution of cloud mixing ratio (q_c)

with the implicit mode indicating the presence of deep convective clouds compared to the explicit mode. These concentrations are found to be high in Goddard schemes followed by Thompson, Morrison schemes. Even in the east coast, Goddard schemes produced high values of q_c in the low and mid-tropospheric levels and the WSM6, New-Thompson schemes in both explicit and implicit modes simulated in feeble cloud mixing ratios.

4.4.2 Study of Ice Mixing Ratio

The WSM6, Goddard and the Morrison schemes produces the strong ice mixing ratios (q_{ice}) concentrations (Fig. 11) and the Thompson and the New-Thompson schemes produce very weak q_{ice} values over both the locations. The concentrations in the explicit mode are stronger and spread across higher levels compared to the implicit mode. The WSM6 and Thomson scheme producing high/low concentrations of q_{ices} have been explained in the previous studies (Field et al. 2005; Galligani et al. 2017). The incorporated physics in WSM6 is ice oriented, whereas the cloud microphysics formulation in Thomson and New-Thomson Aerosol aware schemes are mainly snow dominated microphysical formulation. Out of the two stations, highest amount of ice mixing ratio at the time of heavy rainfall event are found in the west coast with explicit mode of

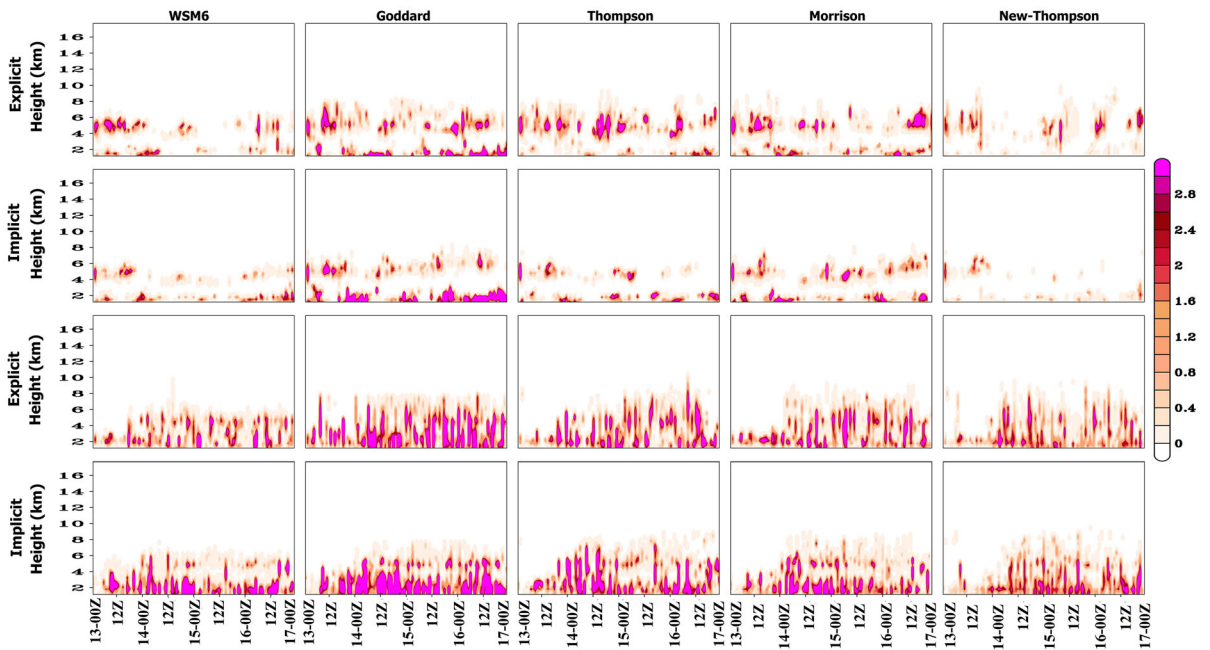


Figure 10

Time height sections of simulated cloud mixing ratio (kg kg^{-1}) at Visakhapatnam (East coast; top two panels) and Pookot (West coast; bottom two panels) stations during 13–17 August 2018

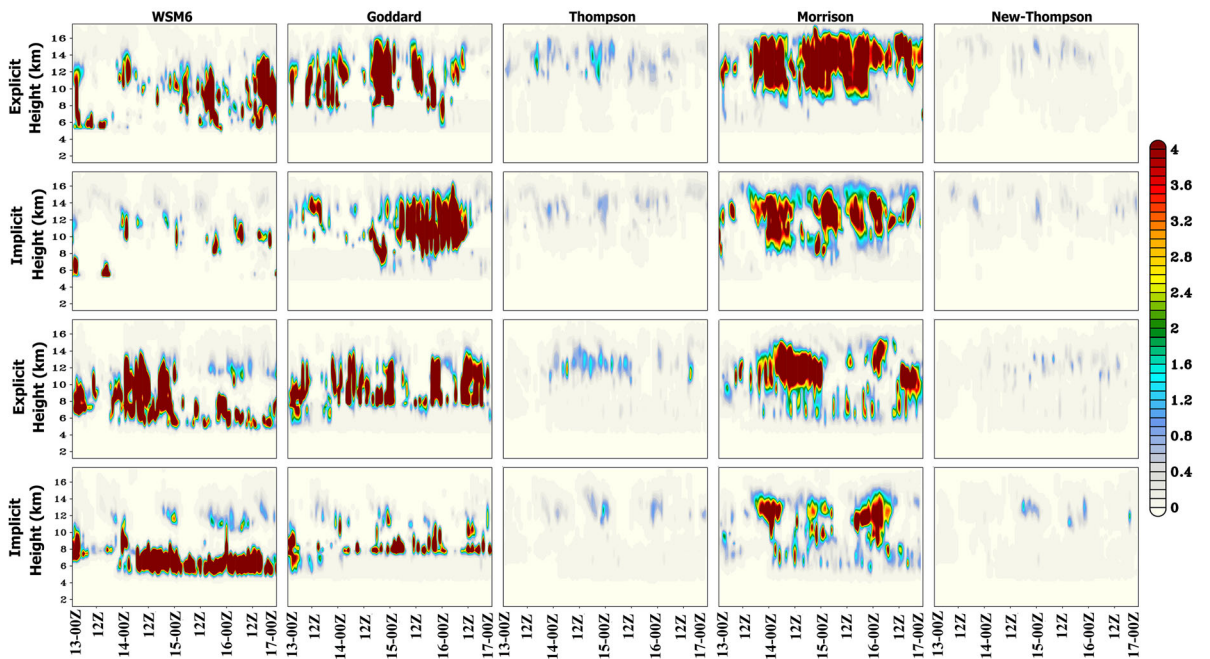


Figure 11

Time height sections of simulated ice mixing ratios (kg kg^{-1}) at Visakhapatnam (East coast; top two panels) and Pookot (West coast; bottom two panels) during 13–17 August 2018

Goddard schemes, followed by the WSM6, Morrison schemes, and Goddard scheme.

4.4.3 Study of Snow Mixing Ratio

The variations of different CMP schemes in producing the snow mixing ratio (q_{snow}) over the two coasts shows (Fig. 12) strongest concentration over the western coast with a maximum value of $4 \times 10^{-4} \text{ kg kg}^{-1}$ than in the east coast. The explicit mode experiments are producing strong concentrations extending to the higher elevations than in the implicit mode experiments. The Thompson scheme shows stronger concentrations followed by the explicit modes of Thompson-New scheme and Goddard scheme in the east coast. The Morrison explicit scheme produced strong q_{snow} over the west coast followed by explicit and implicit modes of Thompson and New-Thompson scheme. The WSM6 is illustrated very weak snow content in two modes as the microphysics formulation is mainly ice dominated. The Morrison scheme is producing weak results over east coast however stronger in the west coast.

4.4.4 Study of Graupel Mixing Ratio

The time-height variation of q_{graupel} mixing ratio (Kg Kg^{-1}) with different CMP schemes shows (Fig. 13) the Morrison explicit scheme simulated the maximum concentrations of q_{graupel} extending to higher elevations during the heavy rainfall time over the west coast. Goddard scheme in the explicit configuration produces high values of q_{graupel} ($3 \times 10^{-3} \text{ kg kg}^{-1}$) over the east coast, followed by the Thompson scheme. The WSM6 and New-Thompson scheme in the both modes simulates weak concentrations of q_{graupel} over the east coast.

4.4.5 Study of Rain Water Mixing Ratio

The time height cross-section of rain water mixing ratio (q_{rain} , Kg Kg^{-1}) over two locations in the east and west coast are presented in Fig. 14. The explicit experiments are producing strong values of q_{rain} than in the implicit mode and the rain water concentrations are noticed up to 6 km. Stronger values of q_{rain} are indicated in the west coast than the east coast. The

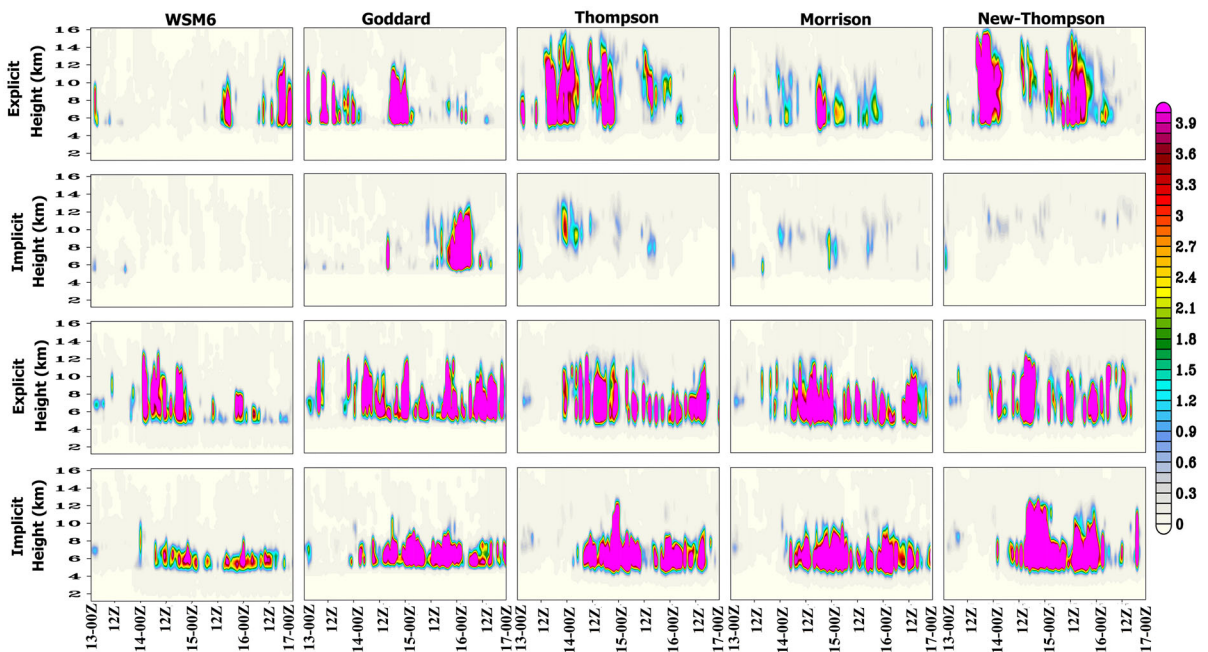


Figure 12

Time height sections of simulated snow mixing ratio (kg kg^{-1}) at Visakhapatnam (East coast; top two panels) and Pookot (West coast; bottom two panels) stations during 13–17 August (4 days mean)

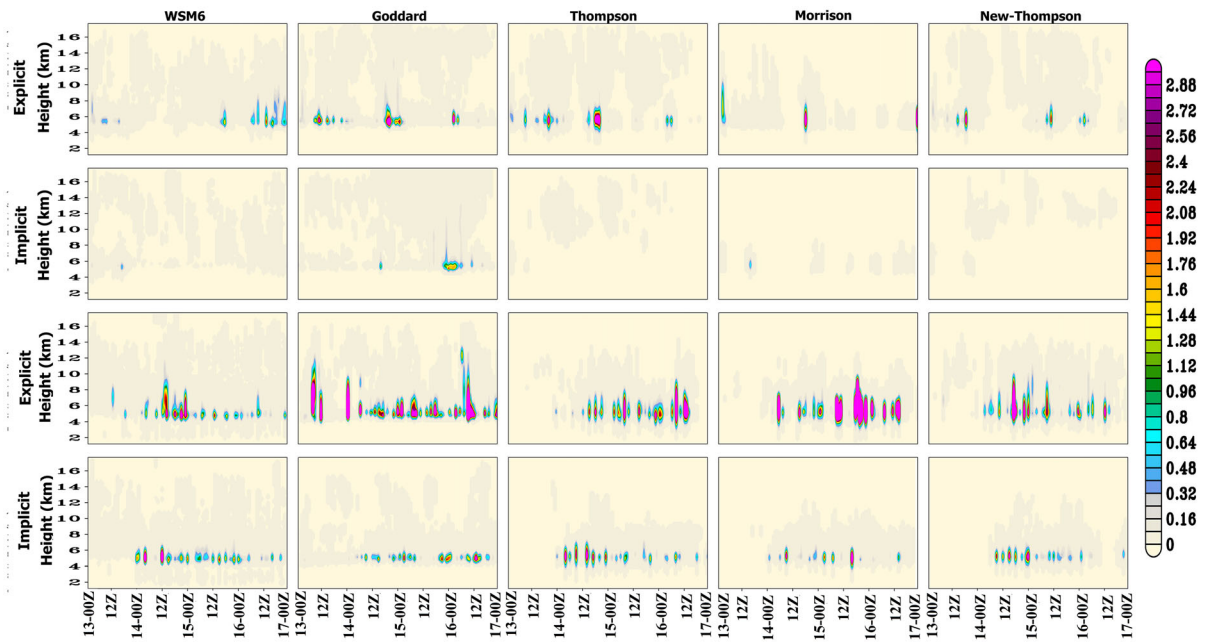


Figure 13

Time height sections of simulated graupel mixing ratios (kg kg^{-1}) at Visakhapatnam (East coast; top two panels) and Pookot (West coast; bottom two panels) during 13–17 August 2018

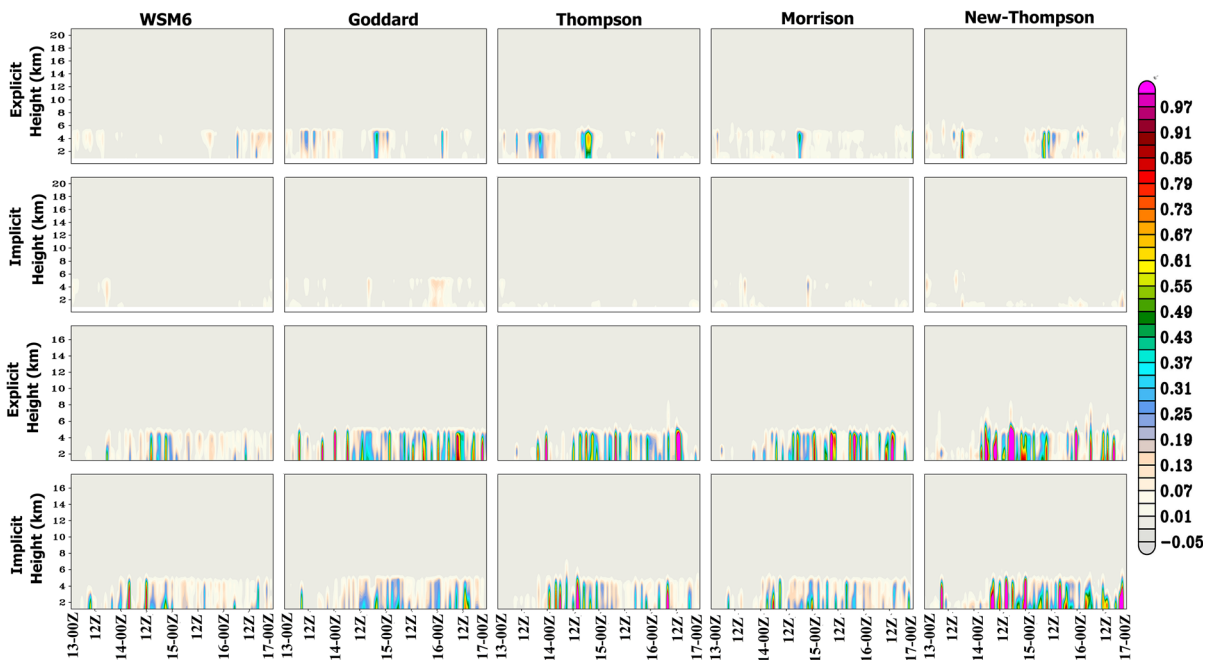


Figure 14

Time height sections of simulated rain water mixing ratios (kg kg^{-1}) at Visakhapatnam (East coast; top two panels) and Pookot (West coast; bottom two panels) during 13–17 August 2018

explicit mode of New-Thompson scheme produces stronger grain in both the coasts while relatively weak concentrations found in the implicit modes of WSM6 scheme. The study by Thompson et al. (2014) highlighted that the New-Thompson scheme is capable of producing the intense precipitation over the windward side of mountains due to the accretion of the cloud droplets as rain. However, this scheme is less efficient in producing the snow process. Also their study suggests that the inclusion of explicit aerosol-cloud feedback essentially enhances the formation of number of minute liquid water and rain droplets which increase the precipitation. Though, the Thompson scheme in explicit model produces mild concentrations of grain, only New-Thompson Aerosol aware scheme provides strong signal of grain concentrations close to the time of observed rainfall.

4.5. Analysis of Rainfall

4.5.1 Study of Rainfall Prediction with Different Microphysics Schemes

The 3-day mean daily accumulated rainfall during 13 and 16 August 2018 from different CMP schemes in explicit and implicit modes are compared to the GPM

estimates (Fig. 15). The GPM observed rainfall estimates depict the maximum rainfall distributed in three pockets, the first rainfall band (270 to 300 mm/day) seen along the southwest coast of India due to intensification of Monsoon Low Level Jet (MLLJ), the second peak observed in the bay of Bengal associated with the depression, and the third peak concentrated over the eastern Ghats i.e. southern parts of Orissa, north-coastal Andhra Pradesh (Visakhapatnam), and north-central Maharashtra due to the passage of the depression. The results of simulated spatial rainfall pattern suggest that the WRF with the parameterized convection (implicit) produces higher rainfall over the west coast and west central Bay of Bengal regions, whereas the cloud resolving simulations (implicit) captured the observed heavy rainfall features over the Eastern Ghats region. All model experiments failed in capturing the peak rainfall over east-central Maharashtra region. Further, our results suggest that New-Thomson Aerosol scheme followed by Goddard scheme and Thomson scheme produces better spatial pattern of rainfall amounts (range between 100 and 300 mm) compared to the GPM observed patterns. Nevertheless, WSM6 and Morrison Schemes

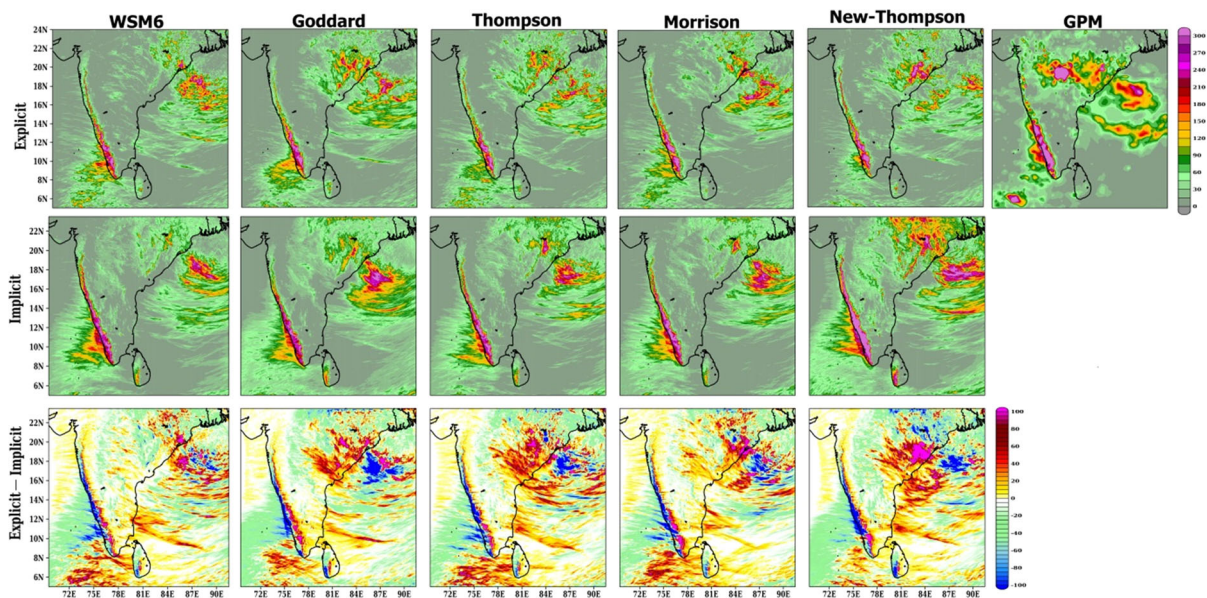


Figure 15
Comparison of 3-day mean simulated rainfall (mm/day) with GPM IMERG rainfall estimates during 14–16 August 2018

produced minimum amount of precipitation. Thus the model performs well in the east (west) coast with explicit (implicit) mode. The model performance over the west or east coast of India is probably due to the distinct characteristics of orography between the East and West coast, where the Eastern Ghats are associated with shallow mountain stretch and a sharp and complex orography of the Western Ghats.

4.5.2 Study of Simulation Rainfall with AWS Data

The time series analysis of daily accumulated rainfall from model and AWS data at four different stations Anandapuram (17.68°N and Lon 83.00°E), Chinthapalle (Lat 17.87°N and Lon 82.35°E), Anakapalle (Lat 17.68°N and Lon 83.00°E) in Visakhapatnam is performed to evaluate the temporal skill of the CMP schemes in capturing the localized station rainfall (Fig. 16 and Figure. S4). Over the east and west coasts, the New-Thompson schemes implicit mode is agreeing well with the observations. Out of four stations, highest rainfall is recorded at Anandapuram with peak of 142 mm/day on 15 August 2018 and the second peak on 15 August at Anakapalle. The time

series of 3-hourly rainfall patterns shows that the maximum rainfall occurred between 2100 UTC 14 August to 1200 UTC 15 August 2018 where the depression lay centred near Visakhapatnam. The third and fourth peak observed over Chinthapalle and Anandapuram is maintained during this period.

5. Summary and Conclusions

This study examined the sensitivity of cloud resolving microphysical parameterization to the prediction of monsoon depression formed over the Bay of Bengal and its associated rainfall. Further, we have also studied the role of the explicit and implicit configurations of the WRF model, at a high horizontal resolution of 3 km, using different CMPs on predicting the heavy rainfall associated with monsoon depression. We have evaluated five different cloud resolving microphysics schemes (WSM6, Goddard, Thompson, Morrison and New-Thompson Aerosol schemes) by comparing the analysis of dynamical and thermodynamical and hydrometeors with various

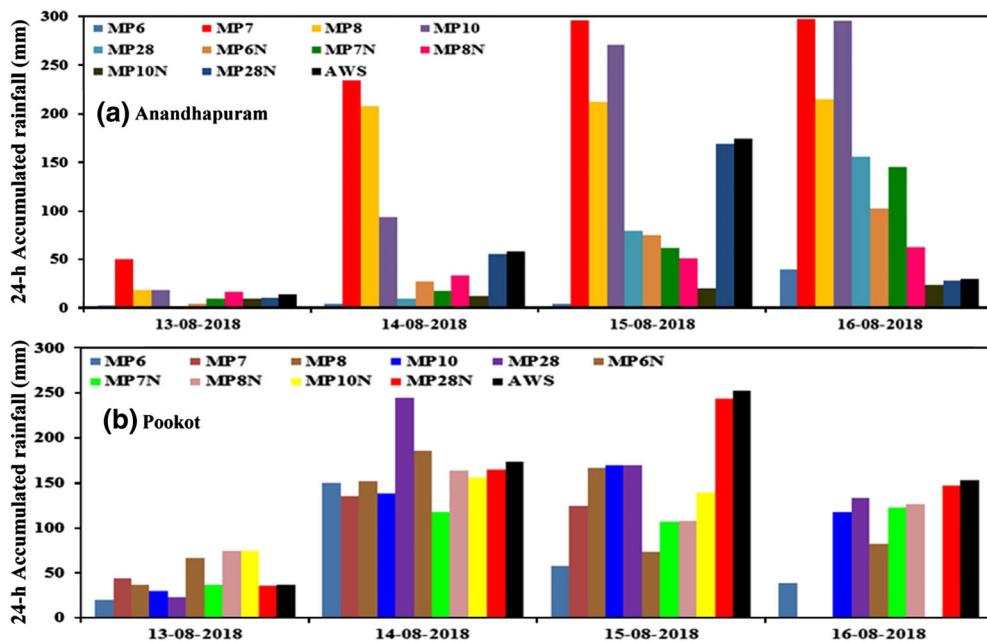


Figure 16

Daily accumulated rainfall (mm) from Explicit and Implicit experiments and compared with AWS observations at Anandapuram (located in Visakhapatnam) and Pookot

observational data. Our results indicated that the monsoon depression is simulated with WRF model in both explicit with convection and implicit without convection mode.

The following conclusions are obtained from this sensitivity study of microphysics.

1. The synoptic features seen in IMD synoptic chart and ERA-5 of the monsoon depression over the Bay of Bengal and offshore trough over west coast of India is captured by the Goddard scheme followed by New-Thompson Aerosol with implicit mode of convection. WSM6 produced least weak depression and feeble offshore trough over west coast. Increased pressure drop in Goddard and Thompson aerosol aware in implicit might led to enhanced lower tropospheric moisture convergence over west coasts (Kerala). All the experiments produced the convergence as well as the moisture transport over the Eastern Ghats (Visakhapatnam).
2. A strengthened tropical easterly jet is seen over the south-east coast nearer from Nellore to Gudur in the implicit configuration with the Goddard and New-Thompson Aerosol schemes. WSM6 at lower levels and Morrison at the upper levels produced weaker winds than other four schemes.
3. Simulated 3-day mean transport of moisture is stronger in the implicit mode (without convection) than in the explicit mode; moreover Goddard scheme simulated stronger moisture transport followed by New-Thompson Aerosol aware which is probably due to the presence of stronger winds at lower level.
4. The analysis of CAPE and CIN over Visakhapatnam suggests that the New-Thompson Aerosol schemes in the implicit mode provides maximum CAPE (1100 J-kg^{-1}) and minimum CIN as seen in the radiosonde observations. Goddard and New-Thompson schemes in implicit mode produced stronger horizontal winds at the time of heavy rainfall over the west coast than other schemes, whereas the explicit experiments with New-Thompson, Morrison, and Thompson schemes produced strong vertical winds over the east coast.
5. The vertical structure of reflectivity from different experiments reveals that stronger convection

along the west and east coast during the heavy rainfall event seen in Goddard and Thompson-New schemes. The vertical distribution of cloud mixing ratio (q_c) with the implicit mode indicates the presence of deep convective clouds compared to explicit mode. These concentrations are high in Goddard schemes followed by Thompson, Morrison schemes over the west and east coasts of India. Explicit mode of Morrison explicit scheme showed the highest amount of q_{graupel} mixing ratio at the time of heavy rainfall event over the west coast followed by the Goddard scheme. The WSM6 and New-Thompson Aerosol aware schemes in both implicit and explicit modes revealed the feeble q_{graupel} mixing ratio over the east coast. Further, the explicit mode of Goddard scheme produced highest ice mixing ratios during the heavy rainfall event, followed by the WSM6 and Morrison schemes over the east coast. However, it is found that the snow mixing ratio is highest with implicit mode of New-Thompson Aerosol aware scheme followed by the Goddard and Morrison schemes at the time of heavy rainfall event over the west coast. Similar results are also noticed in simulating rain water mixing ratios with strong concentrations found over the west coast with the implicit mode of New-Thompson Aerosol aware, and Goddard and Thompson schemes, while the same schemes with explicit mode showed weak concentrations over the east coast.

6. The 3-day mean 24-h accumulated rainfall (during 14 and 16 August 2018) analysis suggested that the maximum rainfall is distributed in three pockets, namely the first rainfall band (270 to 300 mm/day) along the southwest coast of India due to intensification of MLLJ, the second peak observed in the Bay of Bengal region associated with the monsoon depression, and the third peak concentrated over the Eastern Ghats regions. The WRF simulated spatial rainfall pattern suggest that the parameterized convection (implicit) produces better rainfall pattern over the west coast and west central Bay of Bengal regions, while the cloud resolving simulations (explicit) capture the observed heavy rainfall over the Eastern Ghats region.

Our study demonstrate that the New-Thompson-Aerosol aware scheme in cloud resolving mode is suitable for the simulation of monsoon depression over east coast and the new-Thompson scheme with convection parameterizations is suitable for the simulation of the off-shore trough over the west coast of India. Though the results are based only on a single monsoon depression case and are encouraging for the simulation of monsoon depressions over Bay of Bengal, to prove the statistical significance, large sample of monsoon depression case studies need to be performed which will be addressed in our future studies.

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