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Simulation of a heavy rainfall event over Chennai in Southeast India using WRF: Sensitivity to microphysics parameterization

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ABSTRACT

Chennai City on the southeast coast of India experienced record heavy rainfall on 1 Dec 2015 during the Northeast Monsoon. In this study, numerical simulations of this event are performed using the Advanced Research and Weather Research and Forecasting (WRF-ARW) model, with a cloud-resolving grid resolution of 1 km. Five simulations are performed to study the model sensitivity to cloud microphysics parameterizations on the heavy rainfall prediction. Model results are compared with the available surface and Doppler weather radar (DWR) observations. Results show that the microphysics significantly influenced the rainfall simulation due to variation in mixing ratios of different hydrometeors and the associated dynamic and thermodynamic parameters. The Thompson scheme, followed by the Morrison scheme captured the location of maximum rainfall, its spatial distribution, and its time of occurrence in close agreement with the observations. All the other schemes simulated the event with lesser intensity and at a later time. Results suggest that the Thomson scheme captured the time evolution of different hydrometeors that led to produce the observed pattern of rainfall both spatially and temporally. It is also found that the Thompson scheme correctly produced high vertical motions associated with high instability, strong mid-level convergence and upper air divergence associated with strong cyclonic vorticity, which led to the observed feature of the intense precipitation over Chennai.

1. Introduction

The Chennai flood of 2015 was the most catastrophic natural disaster of the century in the state of Tamil Nadu. The city experienced torrential rain during the Northeast Monsoon of 2015 due to low pressure weather systems which formed consecutively over the Bay of Bengal (IMD, 2015; Mishra, 2016). The city and its neighboring areas were affected by a record heavy rainfall event on 1 December 2015 that led to flooding, loss of life, and severe damage. Many studies have been conducted to investigate the causes as well as the consequences of the flood. Saravanan and Naveen Chander (2015) discussed about the causative factors for the 2015 Chennai flood with reference to the Urban Flood Management Strategies which have been implemented in various developed countries. The formation of a localized upper air circulation over Chennai city in association with a passing low pressure system was attributed as the contributing factors of the Chennai flood (Srinivas et al., 2017). High resolution mesoscale numerical models can be used to understand the complex physical and dynamical atmospheric processes leading to such events.

Rainfall prediction in NWP models is made by representing the clouds and precipitation processes using convective parameterization and microphysics schemes (Powers and Klemp, 2017). These parameterizations are critical in the prediction of precipitation and associated variables. At high resolution (1–3 km), microphysics can be used to explicitly resolve the convective precipitation without using convective schemes. The high resolution also enables to resolve the mesoscale features more realistically (Ghosh et al., 2016). In NWP models, bulk microphysics parameterization schemes are commonly employed due to computational limitations (Lin et al., 1983; Ferrier, 1994; Walko et al., 1995; Morrison et al., 2005, 2009). In these schemes, the hydrometeor size spectra are assumed to follow a prescribed exponential or gamma distribution (Walko et al., 1995). With the increase in horizontal resolution of the models, the cloud microphysical processes play an important role through direct influences on the cold pool strength due to evaporation of rainfall and latent heating due to condensation (Rajeevan et al., 2010). Halder and Mukhopadhyay (2016) reported that the Thompson microphysics scheme does not produce good rainfall predictions in India. However, their study was mostly focused on the convective thunderstorm events in northern India. Rajeevan et al. (2010) reported a better performance of the Thomson scheme than

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other microphysics schemes in WRF for the convective precipitation over southern India. Recent studies also showed that the Thompson scheme performs well for the prediction of heavy rainfall events (Hari Prasad and Salgado, 2015).

The primary microphysical species are water vapour, cloud droplets, rain droplets, cloud ice crystals, snow, rimed ice, graupel, and hail. Microphysics budgets depends on atmospheric dynamical and thermodynamical conditions which determine the partitioning of hydrometeors (Huang and Wang, 2017). Most of the schemes may have two or three ice categories; however, the degree of sophistication used to represent the microphysics processes varies considerably (McCumber et al., 1991). There has been a rapid progress in understanding of cloud microphysical processes in recent decades and many microphysical schemes have been developed for application in NWP and climate models. Many studies have highlighted the importance of ice microphysical processes in the prediction of rainfall from thunderstorms as well as synoptic scale convective systems (Guo et al., 2015, Singh et al., 2017, Maheskumar et al., 2018, De Meij et al., 2018). McCumber et al. (1991) reported that the inclusion of mixed-ice-phase cloud microphysics in the cloud model significantly produced better output in the convection simulations. Even in tropical areas, ice crystals play an important role in rain patterns and accumulation, heating rate profiles, and the organization of rain cells (Takahashi and Shimura, 2004). Lim and Hong (2005), examined the effect of bulk ice microphysical processes on the simulation of monsoonal precipitation over East Asia and found that the impact of ice microphysics itself is more likely limited to the area of heavy precipitation. They further inferred that ice sedimentation becomes more important for rainfall cases associated with a surface cyclone system and is crucial to the successful simulation of monsoonal precipitation. Recent simulation studies using WRF-ARW on severe weather phenomena such as thunderstorms and hurricanes have suggested large sensitivity of predicted rainfall and hurricane tracks to microphysics (Rajeevan et al., 2010; Fovell et al., 2010). It has been shown that microphysical parameterizations modulate temperature and pressure gradients which generate winds and ultimately influence the storm track prediction. Hari Prasad and Salgado (2015) simulated a heavy rainfall event over Red Sea region using WRF-ARW. It has been shown that the model-produced heavy rainfall is sensitive to different cloud microphysics schemes with the Lin and Thompson schemes producing a more realistic simulation of the heavy rainfall. Cassola et al. (2015) showed that single-moment schemes provide better precipitation estimates when compared to double moment schemes, except for the Thompson scheme, which is double moment for cloud ice. Huang et al. (2016) reported that the variation of precipitation intensity with cloud microphysics was closely related to the distribution of the large-scale vertical motion. This indicates that the combination of large-scale dynamics and cloud microphysics is very important when studying the rainfall events.

The present study aims to estimate the relative sensitivities of various cloud microphysical parameterization schemes in the simulation of the 2015 heavy rainfall event in Chennai, using the WRF-ARW model. In a recent WRF simulation of the event, Srinivas et al. (2017) showed that the distribution and location of maximum rainfall was better predicted using a high resolution (1–3 km) with explicit convection due to better representation of the mesoscale upper air circulation and associated low-level moisture convergence. Hence in this study, we simulated the heavy rainfall event employing a high resolution of 1-km and studied the uncertainties associated with model microphysics. The paper is organized into six sections. The description of the heavy rainfall event is given in Section 2 and the simulation setup along with a brief description of different microphysics is given in Section 3, followed by the results and conclusions given in Section 4 and Section 5 respectively.

2. Heavy rainfall event

Each year from October to December, a very large area of South India, including Tamil Nadu, coastal regions of Andhra Pradesh, and the union territory of Puducherry receive the majority of its annual rainfall from the Northeast Monsoon. The 2015 Northeast Monsoon resulted in heavy flooding over the Coromandel coast, with Tamil Nadu and the city of Chennai particularly hard hit. In 2015, the city suffered the most catastrophic rainfall in over a century during the end of November and beginning of December. The city of Chennai and its suburb areas recorded multiple torrential rainfall events, resulting in heavy flooding that inundated the coastal districts of Chennai, Kancheepuram, and Tiruvallur. > 500 people were killed and over 1,800,000 people were displaced. With estimates of damages and losses ranging from nearly $3 billion to over $16 billion USD, the floods were the costliest to have occurred in 2015.

Three major weather systems during the Northeast Monsoon season were responsible for the intensive flooding over coastal and interior eastern Tamil Nadu (IMD, 2015; Mishra, 2016). On 8 November 2015, a low pressure area formed and consolidated into a depression in the southeastern Bay of Bengal and slowly intensified into a deep depression before crossing the coast of Tamil Nadu near Puducherry the following day. The system weakened into a well marked low pressure area over Northern Tamil Nadu on 10 November. The system brought very heavy rainfall over the coastal and the north interior districts of Tamil Nadu. On 15 November, a well-developed low pressure area formed and moved northward along the Tamil Nadu coast, dropping huge amounts of rainfall over coastal Tamil Nadu and Andhra Pradesh. On 28–29 November, another system developed and arrived over Tamil Nadu on 30 November, bringing additional rain and flooding. This system caused vigorous precipitation over north coastal Tamil Nadu. Very heavy rains led to flooding across the entire stretch of coast from Chennai to Cuddalore. The low pressure area moved off the south Tamil Nadu coast and gradually dissipated with the westward movement of the trough. According to daily rainfall records of IMD, total amounts received through 00 UTC 2 December in Tamil Nadu were 495 mm at Tambaram and 218 mm at Puducherry. The hourly rainfall records of IMD show that the heaviest precipitation in Chennai occurred between 05 UTC and 15 UTC 1 December.

3. Simulation setup

For the simulation of the heavy rainfall, WRF-ARW version 3.4 is used. ARW is a compressible, non-hydrostatic model designed for both research and operational applications. The detailed description of the model is given in Skamarock et al. (2008).

The model was configured with four interactive nested domains (Fig. 1) with 51 vertical levels. The outer domain was configured with 27 km resolution. The second, third, and fourth domains had a horizontal resolution of 9, 3, and 1 km respectively. The simulations were initialized at 00 UTC 30 November 2015 and the model was integrated up to 72 h. The initial and boundary conditions for the simulations were obtained from National Centre for Environmental Prediction (NCEP) Global Forecasting System (GFS) $0.25^{\circ} \times 0.25^{\circ}$ analysis and the boundary conditions were updated every 3 h with the GFS forecasts. The physics options included the Noah scheme for land surface processes (Chen and Dudhia, 2001; Tewari et al., 2004), RRTMG scheme for shortwave and longwave radiation transfer (Mlawer et al., 1997; Clough et al., 2005), MM5 similarity theory for calculating surface heat and moisture fluxes, Mellor-Yamada Nakanishi and Niino (MYNN) level 2.5 closure scheme for planetary boundary layer processes (Nakanishi and Niino, 2004). The Kain Fritsch scheme (Kain and Fritsch, 1993) was used for cumulus convection for the outer domains (27 and 9 km). In the inner domains 3 and 4, only microphysics was employed and no convective parameterization was used. Five numerical experiments with five different microphysics parameterization schemes were