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Impacts of radiance data assimilation on the Beijing 7.21 heavy rainfall

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A B S T R A C T

Precipitation simulation during the Beijing heavy rainfall event on 21 July 2012 has been investigated in this study. A control run of the Weather Research and Forecasting (WRF) model can roughly simulate the mesoscale features and spatial heterogeneity of precipitation over North China, but it cannot capture the locations, intensity and timing of maximum rainfall over the Beijing area compared with ground observations. To gain better initial conditions in the performance of the mesoscale model, Advanced Microwave Sounding Unit (AMSU) radiance data assimilation was carried out. The spatial distribution and intensity of precipitation have been significantly improved. In particular, data assimilation of Advanced Microwave Sounding Unit-A only has similar impacts on heavy rainfall simulation as the AMSU data assimilation run. Data assimilation of Advanced Microwave Sounding Unit-B only has improved the spatial distribution of heavy rainfall, but it has little impact on the intensity of rainfall. However, the timing of heavy rainfall in all simulations is about 5 to 6 h later than observations. Further analysis shows that the center and strength of the low-pressure system was not well simulated during the early development of heavy rainfall in the model. Results from radiance data assimilation suggest that improvement of the initial conditions plays a positive impact on heavy rainfall in 24 h simulation. Operational forecast system including satellite radiance data assimilation may improve heavy rainfall forecasting.

1. Introduction

The heaviest daily rainfall in Beijing city since 1951 occurred on 21 July 2012 (Wang et al., 2013), often referred to as the “7.21” event. It caused huge losses and death, and drew wide attention in the scientific community. A number of studies (e.g., Chen et al., 2012; Sang et al., 2013; Zhang et al., 2013; Zhong et al., 2015) explored the precipitation pattern, the dynamic factors and causes of the storm. Sun et al. (2012) and Fang et al. (2012) investigated the synoptic conditions and the mechanism of the rainstorm system. Their studies showed that strong upward motion, high precipitation efficiency, long duration and southwesterly extreme abundant water vapor were brought together, leading to about a 16-h (from 0200 to 1800 UTC 21 July) severe precipitation process over the Beijing area. The latest Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) products captured the rainfall spatial pattern (Huang et al., 2014), but it presented a relatively large deviation from the temporal evolution of rainfall process and underestimated the intensity of the storm.

Extreme heavy rainfall events are of high concern among the scientific community due to large economic, social and ecological impacts (Nastos et al., 2013; Stocker et al., 2013; Yu et al., 2015). Prediction of local heavy precipitation is a challenging task because complex processes and interactions of many factors are involved (Litta et al., 2012). Grumm (2012) used the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) and Global Ensemble Forecast System (GEFS) models data to examine the forecasts of the pattern and the potential quantitative precipitation forecasts (QPFs) during the Beijing extreme event on 21 July 2012. The result showed that the larger scale pattern for this event was relatively well predicted by the NCEP models with about a 4-day leading time. Jiang et al. (2014) analyzed and verified the rainfall forecasts of different initial times using BJ-RUCv2.0 system based on the Weather Research and Forecasting (WRF) model and WRF data assimilation (WRFDA) system. The results showed significant timing and location errors of the rainfall forecasts.

The forecast accuracy of local heavy rainfall is influenced by many factors in a dynamical numerical model, in particular uncertainties of initial conditions. Biazeto and Dias (2012) pointed out that precipitation was the result of a convective parameterization and not a predictable variable of the model. The numerical model represents rainfall by means of triggering functions with criteria based on humidity and temperature profiles. Therefore, the thermodynamic environment plays a significant role in triggering convection parameterization in the model. William et al. (2006) compared the impacts of WRF dynamics core, physics package and initial conditions on warm season rainfall

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forecasts over the central United States. They found that the sensitivity to initial conditions was more substantial than the sensitivity to changes of dynamics core or physics in the first 6–12 h of the forecast, especially for heavy rainfall. Etherton and Santos (2008) also studied the sensitivity of WRF forecasts to initial conditions in South Florida. Their results highlighted that the improvement in initialization could offer more accurate precipitation forecasts. Xu and Powell (2012) investigated dynamical downscaling precipitation over Southwest Asia based on the WRF model, and the results showed that the accuracy of the precipitation forecasts was closely related to the initial condition uncertainties and the complex topography of the surrounding mountain areas. Davis et al. (2006) evaluated WRF forecasts over the continental United States based on precipitation objects. They found that WRF rain errors depended on the precipitation object size and synoptic system over different locations. In addition, the local environment such as topographic and land cover is likely to further impact the precipitation.

Considerable efforts have been made to improve the estimation of the model initial states. In particular, assimilating satellite data can improve the initial condition of numerical model with better representation of mesoscale features (e.g., Routray et al., 2010; Liu et al., 2011; Rakesh et al., 2011). Qi et al. (2005) conducted Advanced Television and Infrared Observation Satellite Operational Vertical Sounder (ATOVS) data assimilation experiments on the heavy rain over the Yangtze River Basin. Their results implied that the mesoscale convective system and the heavy rain could be improved with ATOVS assimilated directly. Xu and Powell (2012)) evaluated the impacts of radiance data assimilation on dynamical downscaling precipitation over Southwest Asia, and the results showed that the satellite data provided improvement of the initial conditions within 24-h hindcasts. Liu et al. (2012) studied the impact of assimilating radiance observations from Advanced Microwave Sounding Unit-A (AMSU-A) on forecasts of several tropical cyclones based on the WRF model and a limited-area ensemble Kalman filter. The result showed that assimilating AMSU-A radiances produced better depictions of the environmental fields compared to reanalyses and dropwindsonde observations.

Previous studies show that it is a challenge to catch the processes of heavy rainfall in model simulations. This study focuses on the impacts of radiance data assimilation on the Beijing 7.21 heavy rainfall in 2012 based on the WRF model. Firstly, the performance of the WRF model was evaluated in terms of spatial pattern, intensity and time of precipitation occurrence over North China during the Beijing heavy rainfall on 21 July 2012. Secondly, impacts of satellite radiance data assimilation on Beijing 7.21 heavy rainfall event were investigated. The model simulated results with and without satellite radiance data are compared with hourly observations of ground precipitation. Synoptic features are diagnosed in the simulations against the NCEP Climate Forecast System Reanalysis (CFSR).

2. Data and methodology

2.1. Observed precipitation

The observed precipitation data are taken from China Meteorological Data Sharing Service System. They are derived from Climate Prediction Center (CPC) Morphing technique of global precipitation estimates (CMORPH) satellite retrieved precipitation merged with hourly precipitation from ground automatic weather stations (AWS) in China. The merged dataset has been developed through algorithms of probability density function and optimal interpolation and quality assessment to increase the accuracy of rainfall estimates by reducing bias and random error compared to individual precipitation data sources (Xie and Arkin, 1996; Shen et al., 2013). The surface hourly precipitation data is obtained from about 30,000 AWS and finally interpolated into gridded data with $0.1° \times 0.1°$ horizontal resolution. CMORPH uses motion vectors derived from half-hourly interval geostationary satellite IR imagery to propagate the relatively high quality precipitation estimates derived from passive microwave data (Joyce et al., 2004). The shape and intensity of the precipitation features are morphed by performing a time-weighted linear interpolation and converted to a geographic grid with $0.1° \times 0.1°$ horizontal resolution. Shen et al. (2013) assessed the quality of the merged precipitation from the points of temporal-spatial characteristics of error, accuracy at different precipitation rates and cumulative times, merging effect at three-station network densities and monitoring capability of heavy rainfall. The results indicate that the merged precipitation product can effectively use the advantages of AWS observations and satellite product of CMORPH. It can capture the precipitation process very well, with more reasonable precipitation amount and spatial distribution.

The observed 24-h accumulated precipitation from 0000 UTC 21 July to 0000 UTC 22 July 2012 implies high spatial variability over the main domain (Fig. 1b). Heavy rainfall mainly concentrated in the Beijing area with more than 150 mm, while other regions received less than 60 mm. The spatial distribution of precipitation shows a southwest-to-northeast zonal distribution following the topography and heavy precipitation occurred in front of the Taihang and Yan mountains.

2.2. Satellite radiance data

The satellite radiance data used in this work are taken from the ATOVS datasets supplied by the National Environmental Satellite, Data, and Information Service (NESDIS). The ATOVS is composed of Advanced Microwave Sounding Unit (AMSU) and High-Resolution Infrared Sounder (HIRS/3), which are flying on the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites. Two separate radiometers, AMSU-A and AMSU-B, comprise the AMSU platform providing passive measurements of the radiation emitted from the earth's surface and throughout the atmosphere. The AMSU-A has an instantaneous field-of-view of 3.3° at the half-power points and the spatial resolution at nadir is nominally 48 km. It has 15 channels in total of which 4 (channels 1, 2, 3 and 15) measure in "window" spectral regions, and the remaining 11 channels are "temperature sounding" channels which can be used to derive atmospheric temperature profiles from the surface to an altitude of about 40 km (Amstrup, 2001). The window channels receive energy primarily from the surface, clouds and lower atmosphere water vapor which can be used to derive total precipitative water and cloud liquid water. The AMSU-B has an instantaneous field-of-view of 1.1° at the half-power points with a nominal spatial resolution at nadir of 16 km. Channels 1 and 2 of the total 5 instrument channels work in "window" spectral regions, which have strong contributions from the surface and the boundary layer. Channels 3, 4 and 5 are used to derive the vertical profile of atmospheric humidity.

The data used in this study are AMSU-A and AMSU-B radiance data, which have undergone substantial preprocessing by NESDIS before it becomes available for user. Statistical limb adjustment and surface emissivity corrections in the microwave channels have been performed for the dataset. Scan coverages of the two microwave sensors from NOAA-15, 16 and 17 used for data assimilation experiments are shown in Fig. 2.

2.3. Data assimilation system

Data assimilation is a technique combining observations with short-range numerical weather prediction (NWP) product and their respective error statistics (Barker et al., 2012). Its goal is to provide an improved analysis of the atmospheric state at a specified time. The result from NWP is called the first guess or background forecast for comparison against the improved estimation (the analysis) in data assimilation system (Skamarock et al., 2008). There are two basic approaches to assimilate satellite sounder radiances in a data assimilation system. The traditional method is to indirectly assimilate retrieved data from the satellite radiance or brightness temperatures. However, the retrieval