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Interactive comment

Interactive comment on "Evaluation of Doppler radar and GTS Data Assimilation for NWP Rainfall Prediction of an Extreme Summer Storm in Northern China: from the Hydrological Perspective" *by* Jia Liu et al.

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Point 1: I agree with the authors that hydrologists are particularly concerned about the accuracy of the accumulative amount and the process of the predicted rainfall at the catchment scale. However, I did not observe any special configuration of WRF or data assimilation for this goal.

Reply: As the reviewer mentioned, the configuration of WRF or data assimilation may have effects on the rainfall prediction, not only the accumulative amount but also the

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rainfall process. Before we investigated the Doppler radar and GTS data assimilation, the configuration of WRF has been discussed in detail in our two other articles (Tian et al, 2017a and 2017b), especially for the selection of the WRF physical parameterizations in the same study area of this manuscript. The aim of this study is to explore the potential effects of assimilating different sources of observations from the Doppler weather radar and the Global Telecommunication System (GTS) in improving the mesoscale NWP rainfall products. That is why the eleven modes are specially set for data assimilation. The following sentences are added to address this issue and two references are also added:

“According to our previous investigations on the performances of the most important WRF physical parameterizations affecting the rainfall processes in Northern China (Tian et al, 2017a and 2017b), the most appropriate set of parameterizations for this extreme summer storm , including Kain-Fritsch (KF), WRF single-moment 6 (WSM6) and Mellor-Yamada-Janjic (MYJ), was adopted in this study when configuring the WRF model.”

Tian, J., Liu, J., Wang, J., Li, C., Yu, F., and Chu, Z.: A spatio-temporal evaluation of the WRF physical parameterisations for numerical rainfall simulation in semi-humid and semi-arid catchments of Northern China, Atmos. Res., 191: 141-155, doi: 10.1016/j.atmosres.2017.03.012, 2017a.

Tian, J., Liu, J., Yan, D., Li, C., and Yu, F.: Numerical rainfall simulation with different spatial and temporal evenness by using a WRF multiphysics ensemble. Nat. Hazards Earth Syst. Sci., 17: 563-579, doi: 10.5194/nhess-17-563-2017, 2017b.

Point 2: What factors drove your decision to have 40 vertical levels in WRF? Why not more?

Reply: In general, the vertical levels between 25 and 55 are acceptable for numerical weather prediction with the WRF model. The reviewer may think that the vertical levels can affect the performance of WRF model. Actually, the optimal number of the

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vertical levels has been deeply investigated by the meteorological society but no consistent conclusion is yet obtained. Aligo et al. (2009) found that the QPF forecasts cannot always be improved by adding the vertical levels with 4-km horizontal resolution in American Midwest. Done et al. (2004) forecasted the convective rainfall in North America with 4-km grid size and the vertical levels were only set at 35. Fierro et al. (2013) simulated a storm event in Oklahoma City, and the horizontal and vertical resolutions were set to be 3-km and 43 levels respectively. Qie et al. (2014) simulated the storm event occurred in Beijing, which is near the study area of this manuscript. The inner domain is 2-km and the vertical levels were set to be 27. Many studies had the horizontal resolution of the WRF inner domain around 3-km as the manuscript, while the vertical levels were less than 40 or close to 40. It is an interesting issue to investigate the relation between the number of the vertical layers and the horizontal resolutions of the WRF model. However, this is not the main concern of this study. We hope to obtain meaningful conclusions with adequate experiments in further studies. The aforementioned references are added in the manuscript to support the use of the 40 layers in this study.

"The two domains were comprised of 40 vertical pressure levels, with the top level set to 50 hPa (Done et al., 2004; Aligo et al, 2009; Fierro et al., 2013; Qie et al, 2014)."

Aligo, E.A., Gallus, W.A., and Segal, M.: On the impact of WRF model vertical grid resolution on Midwest summer rainfall forecasts, Weather Forecast., 24: 575-594, doi: 10.1175/2008WAF2007101.1, 2009.

Qie, X., Zhu, R., Yuan, T., Wu, X., Li, W., and Liu, D.: Application of total-lightning data assimilation in a mesoscale convective system based on the WRF model, Atmos. Res., 145–146: 255-266, doi: 10.1016/j.atmosres.2014.04.012, 2014.

Done, J., Davis, C. A., and Weisman, M.: The next generation of NWP: explicit forecasts of convection using the weather research and forecasting (WRF) model, Atmos. Sci. Lett., 5:110–117, doi: 10.1002/asl.72, 2004.

Fierro, A. O., Mansell, E. R., Macgorman, D. R., and Ziegler, C. L.: The implementation of an explicit charging and discharge lightning scheme within the WRF-ARW model: benchmark simulations of a continental squall line, a tropical cyclone, and a winter storm, Mon. Weather Rev., 141: 2390-2415, doi: 10.1175/MWR-D-12-00278.1, 2013.

Point 3: The uncertainty of weather radar rainfall and GTS data, and their possible influences on the data assimilation process should be carefully specified.

Reply: The main uncertainty of the weather radar rainfall and GTS data comes from the observational and instrumental errors in the data. This can be eliminated through the data quality control procedure before the data assimilated (Rubel and Brugger, 2009). Sokol and Zacharov (2012) also indicated that data with large errors may fail to be assimilated by the NWP model and even make the model crash. In this study, before the data are assimilated by the WRF model, the radar and GTS data were thoroughly checked and strict quality controls were carried out. Descriptions of the data quality control can be found in Line 8-10 and 18-22, Page 6, respectively for the GTS and the radar data.

“The quality control of the GTS data is implemented in WRF-3DVar by defining the observation error covariance. The default US Air Force (AFWA) OBS error file is used in this study, which defines the instrumental and sensor errors for various air, water and surface observation types as well as satellite retrievals.”

“The S-band radar belongs to the newest generation weather radar network of China (CINRAD/SC), the quality control of which is supported by China Integrated Meteorological Information Service System (CIMISS) of China Meteorological Administration. The potential error sources, such as ground clutter, radial interference echo, speckles and other artefacts, were removed through the quality control procedure (Tong and Xue, 2005). The rainfall observations from rain gauges and weather radar were also compared to check the quality of the radar data.”

Rubel, F., and Brugger, K.: 3-hourly quantitative precipitation estimation over Central and Northern Europe from rain gauge and radar data, Atmos. Res., 94: 544-554, doi:10.1016/j.atmosres.2009.05.005, 2009.

Sokol, Z., and Zacharov, P.: Nowcasting of precipitation by an NWP model using assimilation of extrapolated radar reflectivity, Q. J. Roy. Meteor. Soc., 138: 1072–1082, doi: 10.1002/qj.970, 2012.

Point 4: The spin-up period may have influences on the rainfall simulation of the NWP. A 6 hour is used in this study, why not 12 h or other times? In fact, the authors should specify or at least discuss all the sense parameterizations, such as the domain design, downscaling ratios ect.

Reply: As for the spin-up period, 6 hour (Givati et al, 2012), 12 hour (Pan et al, 2017) and 24 hour (Jr et al, 2016) are common choices for the WRF model. In this study, all the three periods were tested before the 6 hour was used. The testing results showed that the spin-up periods had little influence on rainfall prediction of the extreme storm event in this study. In order to improve the calculation efficiency, the 6 hour spin-up period was finally adopted. The following sentences are added in the manuscript:

"According to the tests of different spin-up periods (6 h, 12 h and 24 h), which are commonly used in the WRF model (Givati et al, 2012; Pan et al, 2017; Jr et al, 2016), the spin-up periods have little influence on rainfall prediction of the extreme storm event in this study. Considering the calculation efficiency, the 6 hour spin-up period was chosen."

Givati A, Lynn B, Liu Y, and Rimmer A. Using the WRF model in an operational streamflow forecast system for the Jordan River, J. Appl. Meteorol. Clim., 51: 285-299, doi: 10.1175/JAMC-D-11-082.1, 2012.

Pan, X., Li, X., Cheng, G., and Hong, Y.: Effects of 4D-Var data assimilation using remote sensing precipitation products in a WRF model over the complex terrain of an arid region river basin, Remote Sensing, 9: 963, doi: 10.3390/rs9090963, 2017.

Jr, J. H. R., and Johnson, R. H.: On the cumulus diurnal cycle over the tropical warm pool, J. Adv. Model Earth Sy., 8: 669-690, doi: 10.1002/2015MS000610, 2016.

Besides the spin-up period, the performance of the WRF model can also be influenced by the domain design and the downscaling ratios. In this study, the outer model domain covers Eastern China, Bohai Sea, Yellow Sea and parts of East China Sea, and the inner domain covers Beijing-Tianjin-Hebei region. The large scale topography and the main climate zone can be covered by the nested domains. That is to say, the main influence factors of the rainfall formation are considered in this study through the domain design. The inner domain is set as 3-km, which references to the study from Wang et al. (2012). Both studies focus on the Beijing-Tianjin-Hebei region and assimilate the radar data to improve the rainfall prediction. The downscaling ratio of 1:3 is fixed in the previous generation of the WRF model, MM5. With WRF the downscaling ratio can be flexible. Although some studies indicate that the commonly used downscaling ratio of 1:3 do not always perform the best for all kinds of rainfall events, it is still the best choice as a whole (Liu et al, 2012). The following sentences and two references are added in Line 21-22 and Line 23-24, Page 4:

"... the downscaling ratio was set to 1:3, which was commonly used and always performed well (Liu et al, 2012; Yang et al, 2012; Chambon et al, 2014)."

"The large scale topography and the main climate zone can be covered by the nested domains (Wang et al, 2012)."

Liu, J., Bray, M., and Han, D.: Sensitivity of the Weather Research and Forecasting (WRF) model to downscaling ratios and storm types in rainfall simulation, Hydrol. Process., 26, 3012-3031, doi: 10.1002/hyp.8247, 2012.

Wang, H., Sun, J., Fan, S., and Huang, X.: Indirect assimilation of radar reflectivity with WRF 3D-Var and its impact on prediction of four summertime convective events. J. Appl. Meteorol. Clim., 52: 889-902, doi: 10.1175/JAMC-D-12-0120.1, 2013.

Point 5: It is necessary to explain the causes of the heavy rainfall event in this study. The readers may be interested in the very convective system which affects the choices of the WRF parameterisation schemes.

Reply: Thanks for the reviewer's suggestion. The following paragraph is added to supplement the background information of the storm event in the manuscript:

"Many studies have investigated the causes and the properties of the storm (Sang et al, 2013; Zhong et al, 2015). Before the extreme storm event took place, an encounter between a northward-moving subtropical high vortex and an eastward-moving cold vortex in the mid-high troposphere provided a stable atmospheric circulation over the study area, which was conducive to heavy rain formation. Abundant water vapor transported from a low-level jet, strong upward motion caused by Taihang Mountain, together with a long duration of dense air humidity were the primary causes of the storm event. The extreme storm event contained two phases: 1) a strong convective rain that occurred in the warm sector ahead of the cold front and 2) a dominant frontal rain after the arrival of the cold front (Guo et al, 2015). Those showed the reasons why the parameterizations of KF, WSM6 and MYJ were chosen for WRF rainfall prediction. KF has strong ability in simulating the low-level jet and the upward transportation of vapour (Kain, 2003). WSM6 contains six water substance variables, which can realistically identify rainfall formation (Kim et al, 2013). MYJ is more suitable for the simulation of the convection system (Janjić, 1994)."

Sang, Y.F., Wang, Z., and Liu, C.: What factors are responsible for the Beijing storm, Nat. Hazards., 65: 2399-2400, doi: 10.1007/s11069-012-0426-8, 2013.

Zhong, L., Mu, R., Zhang, D., Zhao, P., Zhang, Z., and Wang, N.: An observational analysis of warm-sector rainfall characteristics associated with the 21 July 2012 Beijing extreme rainfall event, J. Geophys. Res., 120: 3274-3291. doi: 10.1002/2014JD022686, 2015.

Guo, C., Xiao, H., Yang, H., and Tang, Q.: Observation and modeling analyses of the macro-and microphysical characteristics of a heavy rain storm in Beijing, Atmos. Res., 156: 125-141, doi: 10.1016/j.atmosres.2015.01.007, 2015.

Kain, J.S.: The Kain-Fritsch convective parameterization: an update, J. Appl. Meteorol., 43: 170-181, doi: 10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2, 2004.

Kim, J.H., Shin, D.B., and Kummerow, C.: Impacts of a priori databases using six WRF microphysics schemes on passive microwave rainfall retrievals, J. Atmos. Ocean. Technol., 30: 2367–2381, doi: 10.1175/JTECH-D-12-00261.1, 2013.

Janjić, Z.I.: The step-mountain eta coordinate model: further developments of the convection, viscous sublayer, and turbulence closure schemes, Mon. Weather Rev., 122: 927–945, doi: 10.1175/1520-0493(1994)122<0927:TSMECM>2.0.CO;2, 1994.

Point 6: The description of assimilation mechanism for the radar data is too simple. Please complement the model-derived observation operators that are adopted in the 3DVar method. This may explain why the assimilation of the radar reflectivity performs better than the radial velocity.

Reply: The reviewer's point is very important and radar observation operators are added in the manuscript:

"2.3 Radar observation operators: radar reflectivity and radial velocity

The total water mixing ratio qt was chosen as the moisture control variable instead of the pseudo-relative humidity when assimilating the radar reflectivity and radial velocity. Dudhia (1989) provided a warm parameterization, which assists the partitioning of the rainwater mixing ratio qr, the cloud water mixing ratio qc, and the water vapor mixing ratio qv. Eq. (2) shows the observation operator used to calculate the model-derived radar reflectivity Z from the rainwater mixing ratio qr (Sun and Crook, 1997):

Equation (2)

where is the density of air. By assuming a Marshall-Palmer raindrop size distribution and that the ice phases have no effect on reflectivity, Eq. (2) can be derived.

For the assimilation of the radial velocity, the preconditioned wind control variables were also combined with the rainwater mixing ratio qr. Eq. (3)-(5) show how the model-derived radial velocity Vr was calculated:

Equation (3)

where u, v and w represent the three-dimensional wind field, x, y, and z represent the location of the observation point, and xi, yi, and zi represent the location of the radar station. ri is the distance between the data point and the radar, and vt is the hydrometer fall speed or terminal velocity.

According to Sun and Crook (1998), vt can be represented as follows:

Equation (4)

Equation (5)

where a is the correction factor, p is the base-state pressure, and p0 is the pressure at the ground."

Dudhia, J.: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model, J. Atmos. Sci., 46: 3077-3107, doi: 10.1175/1520-0469(1989)046<3077:NSOCOD>2.0.CO;2, 1989.

Sun, J., and Crook, N. A.: Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint. Part I: Model development and simulated data experiments, J. Atmos. Sci., 54: 1642-1661. doi: 10.1175/1520-0469(1997)054<1642:DAMRFD>2.0.CO;2, 1997.

Sun, J., and Crook, N. A.: Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint. Part II: Retrieval experiments of an observed Florida convective storm, J. Atmos. Sci., 55: 835-852, doi: 10.1175/1520-0469(1998)055<0835:DAMRFD>2.0.CO;2, 1998.

Point 7: In general, this study describes the results of different data assimilation experiments and explains the reasons why the assimilation of the radar velocity always leads to worse results. It is wondered why the GTS data and the radar reflectivity can perform better, and neither does the author give a plausible explanation why the assimilation of GTS data together with the radar data performs the best among the eleven assimilation modes. The revised manuscript needs to contain more deep analysis in the Discussion section.

Reply: The suggestion is very helpful for improving the manuscript and the readers may also have the same query while reading the paper. The following sentences are added in the manuscript:

“Assimilating radar reflectivity always had a positive effect on the forecasted rainfall, and the performance was relatively stable. The data assimilation modes which involved the radar reflectivity always performed better than the others. The main reason is that radar reflectivity data contain information related to the precipitation hydrometeors. According to the Eq. (2), the assimilation of radar reflectivity is a correction to the humidity field in essence, which directly influences the rainfall prediction. Additionally, Figure 3 shows that the radar reflectivity used in this study had good quality, which helped result in more effective assimilation results.”

“Although the spatial density of the GTS data is relatively low compared to the radar data, it contains observations of various atmospheric states, including temperature, humidity, pressure, wind speed, etc. Assimilating the GTS data can update the atmospheric background holistically. With the two-way nesting mechanism, data assimilation in the outer domain can help improve the atmospheric motion and water vapour transport in the inner domain. When the GTS data and the radar data are assimilated at the same time, the atmospheric motion in the large scale can be improved by the assimilation of GTS data, while the humidity field in the smaller scale can be corrected by the assimilation of radar data. That is why the assimilation of GTS data together with the radar data performs the best in this study.”

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Point 8: The ultimate goal of the WRF applications in this study is for flood forecasts. It would be helpful to add references to explain how much the flood forecasts in general can be improved by the improvement of the rainfall accuracy. I also look forward to the follow-up study for the improvement of flood forecasts with data assimilation.

Reply: Thanks for the reviewer's suggestion. The following paragraph is added in the manuscript:

"Ultimately, the main goal of rainfall prediction based on the WRF model is to make the flow forecasts. Errors in the forecasted rainfall process and amount can result in divergent flood peak time and peak stage of the flood (Shih et al, 2014). Therefore, data assimilation is an important tool in improving the forecasted rainfall as well as the flow. Yucel et al. (2015) assimilated conventional meteorological observations to improve the rainfall prediction, and the mean runoff error was reduced by 14.7% with data assimilation in the Black Sea Region. While in the work of Rossa et al. (2010), the error of simulated peak discharge can be reduced from 50% to 14% when the radar data were assimilated in the hydro-meteorological model in the Dese river catchment. In further study, the coupled atmospheric-hydrological model with data assimilation will be built and flood forecasts from the coupling system will be examined to evaluate the effect of data assimilation on flood forecasting."

Shih, D. S., Chen, C. H., Yeh, G. T.: Improving our understanding of flood forecasting using earlier hydro-meteorological intelligence, J. Hydrol., 512: 470-481, doi: 10.1016/j.jhydrol.2014.02.059, 2014.

Yucel, I., Onen, A., Yilmaz, K. K., Gochis, D. J.: Calibration and evaluation of a flood forecasting system: Utility of numerical weather prediction model, data assimilation and satellite-based rainfall, J. Hydrol., 523: 49-66, doi: 10.1016/j.jhydrol.2015.01.042, 2015.

Rossa, A. M., Guerra, F. L. D., Borga, M., Zanon, F., Settin, T., Leuenberger, D.: Radar-driven high-resolution hydro-meteorological forecasts of the 26 September 2007

Venice flash flood, J. Hydrol., 394: 230-244, doi: 10.1016/j.jhydrol.2010.08.035, 2010.

Point 9: There are several typos and some cases where the grammar is off. For example, '4.1 Evaluation of the storm process improvements', '. . . and the forecasts had negative errors in the accumulated areal rainfall (negative bias)', etc. Please check the whole paper carefully and improve the English language.

Reply: Grammar and spelling errors are corrected in the revised manuscript. We will make efforts to further improve the readability of the paper.

Point 10: The plot frame of the Figure 3(b) and Figure 3(c) is not clear.

Reply: The figures are revised as followed.

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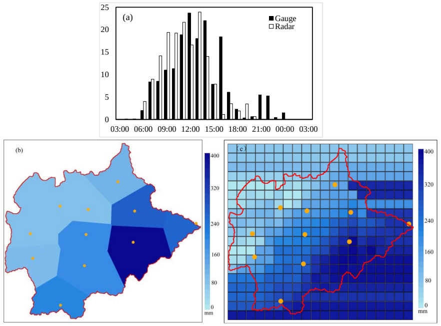

Figure 3. Comparison of the rainfalls from the rain gauges and radar: (a) time series bars of the hourly catchment areal rainfall; (b) 24 h rainfall accumulation from the rain gauges; (c) 24 h rainfall a 5 ccumulation from the radar.

Fig. 1.

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$$Z = 43.1 + 17.5\log(\rho q_r) \tag{2}$$

$$V_r = u\frac{x - x_i}{r_i} + v\frac{y - y_i}{r_i} + (w - v_t)\frac{z - z_i}{r_i} \tag{3}$$

$$v_t = 5.40a(\rho q_r)^{0.125} \tag{4}$$

$$a = \left(p_0 / \bar{p} \right)^{0.4} \tag{5}$$

Fig. 2.