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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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We appreciate the referee's high evaluation of the paper. We hope it can inspire more and wider studies seeking for the efficient way of data assimilation by making use of various sources of observations. We also hope it can promote involving easy data assimilation in the hydrological applications of the numerical weather prediction models. We would like to further improve the rigorousness and the depth of the paper according to the referee's helpful suggestions. Below are the point-to-point replies to the comments.

Comments:

Point 1: I understand the paper is very much a case study on an extreme event which certainly very useful in its own right. I do however think that paper like this should offer certain in-depth findings that will help model development community. I feel that the paper limits itself to present what has come out of the analysis without giving further reasoning on why. For example, the way of using the GTS data is vague and I don't think the author/or the reader have been able to answer why GTS has contributed to the improvement. For example, the location of the observations that have been assimilated, and what kind of variables are used etc. This will help explain the result with deeper understanding.

Reply: Thanks for the reviewer's suggestion, which is very helpful in explaining the contribution of the GTS data to the rainfall improvement. The following paragraph will be added in the manuscript and the Figure 2 is updated by adding the locations of the GTS data:

"In this study, five GTS datasets, including SOUND, SYNOP, PILOT, AIREP and METAR, were assimilated in the WRF model. Detailed descriptions of the datasets are shown in a new table. According to Figure 2, the observations covered by the outer domain were mostly located on land and only a few were on the ocean. The data located on land were distributed evenly, which is very helpful for the stability of the WRF model during data assimilation (Carrassi et al, 2008). The SOUND and SYNOP data took the majority of the GTS data, which means that the observations from surface-based observing station and upper-air observatory have the most contribution to the improvement of rainfall prediction. Pressure, temperature, humidity and wind from the surface and upper air are contained in SOUND and SYNOP datasets. The assimilation of these meteorological elements can directly correct the initial and lateral boundary conditions through the wide horizontal coverage and high vertical levels (Tu et al, 2017)."

References:

Carrassi, A., Ghil, M., Trevisan, A. and Uboldi, F.: Data assimilation as a nonlinear dynamical systems problem: stability and convergence of the prediction-assimilation system. Chaos, 18: 023112, doi: 10.1063/1.2909862, 2008.

Tu, C.C., Chen, Y.L., Chen, S.Y., Kuo, Y.H., and Lin, P.L.: Impacts of Including Rain-Evaporative Cooling in the Initial Conditions on the Prediction of a Coastal Heavy Rainfall Event during TiMREX, Mon. Weather Rev., 145: 253-277, doi: doi:10.1175/MWR-D-16-0224.1, 2017.

Point 2: There are many combinations in WRF settings that can affect rainfall prediction. A new scheme would have changed the overall conclusion. It would be helpful to discuss this in more details as to why certain schemes are chosen and whether that would affect the final conclusions. Being set as a limited area model, WRF is prone to the impact from the boundary condition. NCEP might be a good and reliable choice, but again, would using data from other centres like CMA and/or ECMWF change your final conclusion? Further, please make it clear whether the NCEP data has also involved assimilating GTS data in its operational cycle – i.e., whether it an analysis or a forecast initialised at 00hUTC on the day?

Reply: As the reviewer mentioned, the combinations in WRF settings can affect the rainfall prediction. Before we investigated the assimilating of Doppler radar and GTS data, the WRF settings have 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 WRF model settings are adjusted to the best for the rainfall prediction. This study is aimed 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. The following sentences will be added in the manuscript:

"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."

References:

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.

The initial and lateral boundary conditions provided by different centres like NCEP, CMA and ECMWF may make some difference of the rainfall forecasts. Some studies have specialized the different performance of the WRF model based on the initial and lateral boundary conditions from the different centres (Srivastava et al, 2013; Islam et al, 2015). Before the NCEP data was used in this study, we also tests ECMWF for data assimilation with storm events in the same region. Although the rainfall forecasts showed a little different based on the boundary conditions from the two centres, the patterns of improvements from different data assimilation modes are quite similar and the same conclusions can be obtained. Some study also found that the boundary conditions from different centres could even lead to similar rainfall forecasts through an optimal control (Zou, 1996). In order to highlight the main purpose of this study, we only present the assimilation results using the NCEP data. We appreciate the referee's deep insights and we also hope our work can inspire further studies on testing the data assimilation effects using other boundary data, such as CMA. The following sentences will be added in the Discussion section of the manuscript:

"Before the NCEP driven data was used in this study, ECMWF was also tested for the data assimilation with the same storm event. Although the rainfall forecasts showed some differences based on the boundary conditions from the two centres, the improvement patterns from different data assimilation modes were quite similar. The initial and lateral boundary conditions do have some potential impact on the rainfall forecasts results. More studies should be carried out to verify the effects of data assimilations using different driven data."

References:

Zou, X.: Rainfall assimilation through an optimal control of initial and boundary conditions in a limited-area mesoscale model, Mon. Weather Rev., 124: 2859-2882, doi: 10.1175/1520-0493(1996)124<2859:RATAOC>2.0.CO;2, 1996.

Srivastava, P.K., Han, D., Ramirez, M.A.R., and Islam, T.: Comparative assessment of evapotranspiration derived from NCEP and ECMWF global datasets through Weather Research and Forecasting model, Atmos. Sci. Lett., 14: 118-125, doi: 10.1002/asl2.427, 2013.

Islam, T., Srivastava, P.K., Rico-Ramirez, M.A., Dai, Q., Gupta, M., and Singh, S.K.: Tracking a tropical cyclone through WRF-ARW simulation and sensitivity of model physics, Nat. Hazards, 76: 1473-1495, doi: 10.1007/s11069-014-1494-8, 2015.

The NCEP data (GFS) is the forecast data which is initialised at 00hUTC on the day and the GTS data are not assimilated in GFS, which can also be proven by the improvement of the rainfall forecasts with the assimilation of the GTS data in the outer domain. This will be further clarified in the revised manuscript.

Point 3: Data assimilation is routinely done at various levels in numerical weather prediction. The big problem to produce a hydrologically compatible rainfall forecast is that many of those forecasts fail to capture the two essential aspects: amount and distribution. With reference to the paper, Fig 5 shows a consistent time shift of all the runs

in all modes, i.e., the predicted storms started and stopped around 6-h earlier than the actual one. This might be linked to the setting of assimilation, and I suspect that more likely than not it is due to the constraint imposed by the background field from the lateral boundary conditions. This however, has not been properly explored.

Reply: We agree with the referee's opinion. The time shift of the storm was more likely caused by the background field from the lateral boundary conditions. From Fig 5 it can be seen that the 6h shift starts with run1, which is the original WRF run without data assimilation. Some studies also indicate that when data containing the information of water vapor are assimilated in the numerical weather prediction model, the predicted rainfall may start and stop earlier than the actual one (Georgakakos, 2000; Sun et al, 2016). The main reason is that the information of water vapor can make the rain in the initial fields form and fall to the earth more quickly in the case of no matched dynamic fields (Sun, 2005). In this study, both the radar reflectivity and the GTS data contain the information of water vapor. In addition, the radial velocity can neither improve the dynamic field through data assimilation. All the above reasons result in a consistent 6h time shift of all the runs with or without data assimilation in Fig 5. Considering the case, an error prediction model could be built to correct the consistent error. Some studies also suggest the assimilation of the latent heat might help improve the start and ending time of the forecasted rainfall process (Stephan et al, 2010; Schraff et al, 2016). The time shift issue will be addressed by adding the following paragraph in the Discussion section:

"It can be found in Figure 5 that the predicted storms always start and end around 6-h earlier than the observations. Besides the errors in the boundary conditions, it is found that the assimilation of the water vapor information (contained in the radar reflectivity and the GTS data) can make the rain in the initial fields form and fall to the earth more quickly (Georgakakos, 2000; Sun, 2005; Sun et al, 2016). Considering the error is consistent, an error prediction model could be built in further studies, and the assimilation of the latent heat may also be helpful in correcting the starting and ending time of the forecasted rainfall process (Stephan et al, 2010; Schraff et al, 2016)."

References:

Georgakakos, K.P.: Covariance propagation and updating in the context of real-time radar data assimilation by quantitative precipitation forecast models, J. Hydrol., 239: 115-129, doi: 10.1016/S0022-1694(00)00355-3, 2000.

Sun, J., Wang, H., Tong, W., Zhang, Y., Lin, C.Y., and Xu, D.: Comparison of the impacts of momentum control variables on high-resolution variational data assimilation and precipitation forecasting, Mon. Weather Rev., 144: 149-169, doi: 10.1175/MWR-D-14-00205.1, 2016.

Sun, J.: Convective-scale assimilation of radar data: progress and challenges, Q. J. Roy. Meteor. Soc., 131: 3439–3463, doi: 10.1256/qj.05.149, 2005.

Stephan, K., Klink, S., and Schraff, C.: Assimilation of radar-derived rain rates into the convective-scale model COSMO-DE at DWD, Q. J. Roy. Meteor. Soc., 134: 1315-1326, doi: 10.1002/qj.269, 2010.

Schraff, C., Reich, H., Rhodin, A., Schomburg, A., Stephan, K., Perianez, A. and Potthast, R. Kilometre-scale ensemble data assimilation for the COSMO model (KENDA), Q. J. Roy. Meteor. Soc., 142: 1453-1472, doi: 10.1002/qj.2748, 2016.

Point 4: The choice of using cumulative (only) rainfall may be OK to compare the overall amount in general. Again, for hydrological use, we'd like to see how the prediction agrees with the distributions (both temporal and spatial) of the actual rainfall. So, I think it would be interesting to have a normal hyetograph and a spatial distribution would be more helpful. Some derivative indices like RMSE would make the discussion more convincing.

Reply: The referee's suggestion is thoughtful. Both the temporal and spatial distributions of the rainfall can have potential impacts on the formation of the flow, thus are paid equally important attention by the hydrologists. Actually when we initially organized the

paper, we intended to present the spatial distributions as well as the temporal variations of the forecasted rainfall from different data assimilation modes. However, that would involve too many figures (considering there are 11 assimilation modes), and we have also noticed that the lumped rainfall-runoff models are still widely used by the hydrological community and proven to be even better than the distributed ones in producing the forecasted flow. So in this paper we only paid special attention to the cumulative process of the areal rainfall across the catchment. However, if the number of figures is not limited by the journal, we would like to add the normal hyetographs and the spatial distributions of the forecasted rainfall, at least those from some representative assimilation modes.

Point 5: A few terminology and grammar issues: 1) we don't quite often use 'curve' in general, hyetograph is a better and more accurate choice when being used to describe the temporal distribution of rainfall. 2) P5 L26-28 'If more than . . . average value'. This sentence is confusing. 3) P11 L13-15 'The assimilation of radar velocity . . .' I think you meant 'radar radial velocity'. Also the sentence itself is self-contradicting: moisture transport does affect the rainfall 'physical' process. Please elaborate more. 4) P11 L18 '. . . are quite variably' should be 'are quite variable'.

Reply: The terminology and grammar errors will be carefully checked and corrected in the revised manuscript. We will also make efforts to further improve the readability of the paper. The four issues mentioned above are addressed as follows:

1) The terminology 'curve' will be replaced by 'hyetograph' throughout the manuscript.

2) The sentence is revised as: "The forecasted areal rainfall is calculated by averaging values of the grid cells those have more than 50% area located inside the Zijingguan catchment."

3) The sentence is revised as: "The assimilation of radar radial velocity cannot directly influence the physical process of rainfall formation, although the assimilation can change the wind field and affect the water vapor transport."

4) Revised accordingly.

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The descriptions of the five datasets

Name	*Meaning of the dataset*
SOUND	*Upper-level pressure, temperature, humidity and wind report*
SYNOP	*Report of surface observation from a fixed land station*
PILOT	*Upper-wind report from a fixed land station*
AIREP	*Aircraft weather report*
METAR	*Aerodrome routine meteorological report*

Fig. 1.

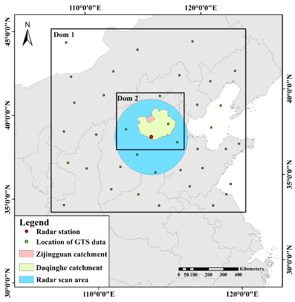

Figure 2. Locations of the radar scan area, the GTS data, the study catchments and the two nested domains.

Fig. 2.