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Interactive comment on "Typhoon rainstorm simulation with radar data assimilation in southeast coast of China" *by* Jiyang Tian et al.

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We appreciate very much the referee's insightful comments and helpful suggestions for our manuscript. Efforts have been made to address every point of the referee's concerns. Gramma mistakes and spelling errors are carefully be checked before the revision is finally submitted. With the help of the referee, we hope the revised manuscript can be found rigorously and sufficiently improved.

Major comments:

Point 1: Please elaborate more to demonstrate the novelty of the current study. Why the assimilation time intervals are important? How they affect the performance of the data assimilation? Why previous studies (for instance those you refer in the introduction;

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Discussion paper

Page 2, L. 28-32 and Page 3, L. 1-2) follow different approaches (i.e., 1h, 3h, 6h)? How these time intervals have been set so far in the literature (more referenced are needed)? Based on experience? Is this the first study examining different assimilation time intervals?

Reply: The suggestion is very important for demonstrating the novelty of the study. For the rainfall forecasting in catchment scale, the assimilation time intervals are important. The operational forecast from meteorological department is guidance forecast with a large forecasting area. It is impossible to focus on the accuracy of the rainfall in small and medium catchment scale. Limited computing power makes that the number of restarting the forecasting system is only 2-4 times per day. The forecasting accuracy descends gradually as the run time goes on, because the data assimilation is not in real time. Due to the poor accuracy in small scale and low-resolution, the rainfall forecasting from the meteorological department cannot be used directly as the input for hydrological forecasting in small and medium catchment. The local meteorological observations are necessary to be assimilated to improve the high resolution rainfall forecast. The NWP model maybe not corrected timely with long time interval of data assimilation, while shortening the time interval need a lot of computational resources and the observation errors in local meteorological observations may be also amplified with high assimilation frequency in NWP model.

In previous studies, the time interval of data assimilation is set based on experience or computing resources. Most studies focus on the assimilated data selection and assimilation algorithm. Few studies pay attention on the time interval of data assimilation. That is why we design nine different modes to investigate the reasonable use of radar data assimilation. The following sentences are added in Line 30-32, Page 2:

"Most studies focus on the assimilation algorithm and data selection. However, consistent conclusions have not been obtained for the option of radar reflectivity and radial velocity, and few studies pay attention on the time interval setting of data assimilation."

The following sentences are added in Line 7-15, Page 3:

"In reality, the operational forecast from meteorological department is guidance forecast with a large forecasting area. It is impossible to focus on the accuracy of the rainfall in small and medium catchment scale. Limited computing power makes that the number of restarting the forecasting system is only 2-4 times per day (Xie et al., 2016). The forecasting accuracy descends gradually as the run time goes on, because the data assimilation is not in real time. Due to the poor accuracy in small scale and low-resolution, the rainfall forecasting from the meteorological department cannot be used directly as the input for hydrological forecasting in small and medium catchment (Tian et al., 2019). The local meteorological observations are necessary to be assimilated to improve the high resolution rainfall forecast. The NWP model maybe not corrected timely with long time interval of data assimilation, while shortening the time interval need a lot of computational resources and the observation errors in local meteorological observations may be also amplified with high assimilation frequency in NWP model."

References: Xie, Y., Xing, J., Shi, J., Dou, Y., Lei, Y. Impacts of radiance data assimilation on the Beijing 7.21 heavy rainfall, Atmos. Res., 169, 318-330, doi: 10.1016/j.atmosres.2015.10.016, 2016. Tian, J., Liu, J., Yan, D., Ding, L., Li, C. Ensemble flood forecasting based on a coupled atmospheric-hydrological modeling system with data assimilation, Atmos. Res., 224, 127-137, doi: 10.1016/j.atmosres.2019.03.029, 2019.

Point 2: The structure in Sections 1-3 is confusing for the reader. Firstly, in several parts of Sections 2-3 (e.g., Page 5, L. 12-14 and Page 6, L. 3-4), the motivation of conducting the study is mentioned. However, a comprehensive description of the background of the study (including the choice of the study area) should be given in Section 1 (Introduction). Secondly, the various information are mixed, as the model description (sub-sections 2.1, 2.2, 2.3) is presented with the evaluation process (sub-section 2.4) and then, the study area and storm events (sub-section 3.1), and numerical experiments (sub-sections 3.2. and 3.3) are presented. I strongly suggest, revising the above structure following a more appropriate set-up (for example: study area and case studies -> model description and numerical experiments -> evaluation process).

Reply: Thanks for the reviewer's suggestion. The background of the choice of the study area is added in Line 24-26, Page 3:

"On July 9, 2016, heavy rainfall caused by typhoon Nepartak leads to severe flood, and attracted strong interest from the public, academics and government. Accurate rainfall simulation has a great practical significance in the study area."

Other description of the background of the study can be found in the reply of Point 1. The structure of the manuscript is revised accordingly. The section 2 is study area and case studies. The section 3 is model description and numerical experiments. The section 4 is rainfall evaluation statistics.

Point 3: The authors highlight the need of accurate rainfall forecasts in the study area. Thus, I would expect examining the radar data assimilation options under an operational forecasting model configuration. However, they use the global analysis FNL data, which are not maintained in real-time, to drive the model instead of an operational real-time global dataset (e.g., NCEP GFS). Also concerning the model set-up, what do you mean by "considering the application effect and frequency in southeast coast of China?" (Page 3. L. 29-30)? How does it affect the selection of physics options? Please provide a more clear and sufficient background for justifying the applied model configuration.

Reply: We appreciate the referee's deep insights. Firstly, FNL has higher applicability and accuracy than GFS for historical events simulation. GFS with no data assimilation is always used for weather forecasting. The aim of this study is to explore the reasonable use of Doppler radar data assimilation to improve the rainfall simulation rather than rainfall forecast in real-time. That is why we use FNL not GFS. Secondly, the selection of physics is investigated in our previous study, which has been published recently

(Tian et al., 2020). Thirty-six physical parameterization combinations are designed by three microphysics, three pairs of longwave/shortwave radiations and four cumulus parameterizations. The physical parameterizations in best performance are used in this study. The sentences in Line 29-31, Page 4 and Line 1-2, Page 5 are revised as:

"Considering the application effect in southeast coast of China and also according to our previous research, WRF Single-Moment 6 (WSM 6) for microphysics, Yonsei University (YSU) for PBL, Rapid Radiative Transfer Model for application to GCMs (RRTMG) for longwave and shortwave radiation, Noah for LSM and Kain-Fritsch (KF) for cumulus physics are adopted in this study (Srivastava et al., 2015; Hazra et al., 2017; Cai et al., 2018; Tian et al., 2020)."

References: Tian, J., Liu, R., Ding, L., Guo, L., Liu, Q. Evaluation of the WRF physical parameterisations for Typhoon rainstorm simulation in southeast coast of China, Atmos. Res., 247, 105130, doi: 10.1016/j.atmosres.2020.105130, 2020.

Point 4: Please justify the use of the Control Variable option 3 (CV3) of the WRF-3Dvar system for the model background errors covariance matrix (B matrix). As the authors acknowledge (e.g., Page 4, L. 10-11 and Page 10, L. 10-13), the B matrix has a strong impact on data assimilation process. Using domain-specific model background errors (i.e., CV5 option), instead of global (i.e., CV3 option), could lead to different results and conclusions. Since CV5 is a more appropriate option compared to CV3 option, and it is a common practice in data assimilation literature (e.g., radar data: Mazarella et al., 2019, conventional observations: Yang et al., 2014, and satellite and GNSS data: Giannaros et al., 2020; Lagasio et al., 2019), I strongly suggest conducting the study using the CV5 B matrix option.

Reply: I agree with the reviewer's point that different B matrix has a strong impact on rainfall simulation. The choice of the B matrix even constructing the B matrix are worth to be investigated, and B matrix is the key field of data assimilation. However, there is still no unified conclusion to make clear that which B matrix is better or how to construct the B matrix can make the simulation more close to the reality. The main reason is that none of them can accommodate all synoptic situation in different regions. CV5 B matrix is also need to be tested. Liu et al. (2013) explores the effect of data assimilation by WRF-3DVar with CV3 for different types of rainfall simulation in catchment scale in southwest England, and the results show that data assimilation with CV3 can also obtain accurate rainfall simulation. Wang et al. (2013) develops an indirect radar reflectivity assimilation scheme within WRF 3D-Var to improve the heavy rainfall simulations in Beijing, and CV5 is used. The results show that the assimilation scheme improves the subsequent prediction of the location and intensity of rainfall. In this study, assimilating radial velocity with time interval of 1 h has been able to obtain satisfactory rainfall simulations for three different storm events in the case of using CV3. Some studies also indicate that the simulation trend of various numerical experimentations will not change with different B matrixes (Blni et al., 2015). The main purpose of this study is to explore the reasonable use of Doppler radar data assimilation to correct the initial and lateral boundary conditions and chose the optimal data assimilation mode. We will investigate the optimal B matrix systematically in further study by using 3-DVar, 4-DVar, EnKF and ETKF-3DVAR.

References: Liu, J., Bray, M., Han, D. Exploring the effect of data assimilation by WRF-3DVar for numerical rainfall prediction with different types of storm events, Hydrol. Process., 27, 3627-3640, doi: 10.1002/hyp.9488, 2013. Wang, H., Sun, J., Fan, S., 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. Blni, G., Berre, L., Adamcsek, E. Comparison of static mesoscale background-error covariances estimated by three different ensemble data assimilation techniques, Q. J. Roy. Meteor. Soc., 141, 413-425. 2015.

Point 5: The description of the evaluation process is unclear and insufficient. No information (map illustration, data temporal analysis and coverage etc.) is presented concerning the rain gauges (Page 5, L. 6-7) used for evaluating the model results. No information is presented concerning the method for pairing the model output and observations (e.g., nearest neighbor?). What do you mean by "areal rainfall observation at each rain gauge i" (Page 5, L. 15), since, the areal rainfall is calculated at the catchment scale using the observations from all 8 stations (Page 5, L. 6-7)? In overall, the terms "spatial" and "temporal" for computing the statistics CSI and RMSE are confusing. For example, to my understanding, spatial RMSE refers to the evaluation of the modeled 24-h rainfall considering all 8 stations, while temporal RMSE refers the evaluation of the basin-averaged rainfall using 24 model-observations pairs. However, both metrics consider the spatial dimension. Most studies in the literature apply the standard approach of domain-wide statistics (spatial dimension), using model-observation pairs of the examined variable (e.g., 1h or 24h rainfall) over all available stations, aggregated for certain time periods (temporal dimension). Thus, please consider revising the application of the statistics. Also, please consider computing more statistic metrics (e.g., POD, FAR etc.) to enhance the evaluation process. In the same direction, please consider evaluating the model results under different time intervals (e.g., 6h; 0, 6, 12, 18) and rain thresholds (e.g., >0.1, > 0.2 etc.). Finally, please provide information in the description of evaluation process concerning the construction and usage of Figures 4-9. For instance, do Figures 4-6 refer to the 24-h modeled and observed rainfall? Do Figures 7-9 refer to areal rainfall?

Reply: Thanks for the reviewer's suggestion. The spatial distribution of rain gauges has been added in Fig.2. The evaluation process is revised concerning the rain gauges used for evaluating the model results and the method for pairing the model output and observations. The first paragraph in section 5.2.1 is revised as a whole:

"Table 6 indicates that although mode 8 with the highest CSI and lowest RMSE is the best choice in the nine data assimilation modes, rainfall simulations with data assimilation are always worse than without data assimilation for event I. Figure 4 shows that the observed rainfall center locates in the east of Meixi catchment and it rains more in the upstream side than the downstream side. However, the spatial distribution of the accumulated 24-h rainfall with no data assimilation is even. Mode 1 and 2 simulate the rainfall in the east side of Meixi catchment accurately, while the simulated rainfall in the west side is much smaller than the observation. The rainfall simulations of mode 3, 4, 5 and 6 are all even in spatial dimension and lower than the observation. The simulation of mode 7 shows that the rainfall in the downstream side is smaller than the upstream side, whereas the different distribution in east-west direction is not obvious and the simulated rainfall is smaller than the observation. For mode 9, the spatial distribution of rainfall is also inconsistent with the observation. Only the simulation of mode 8 is close to the observed rainfall.

All RMSEs of the simulations with radar data assimilation are lower than without data assimilation, while only the CSI of mode 8 is higher than the simulation without data assimilation for event II. According to the rainfall distribution shown in Fig.5, the falling areas of simulated rainfall without data assimilation are totally wrong. The observed rainfall center locates in the middle of upstream and downstream catchment. However, the rainfall centers of mode1, 4 and 7 are all located in middle and lower region. The rainfall center is in middle reaches for mode 2 while in western catchment for mode 3. For mode 5 and 6, the spatial distributions of rainfall are also inconsistent with the observation. The simulated rainfall in middle of upstream catchment is close to the observation for mode 8 and 9 but in the downstream catchment is poor. Although the spatial rainfall distributions have deviation compared with the observation, nine modes get better than the simulation without data assimilation as a whole. Based on the Table 6, not all data assimilation modes help improve the rainfall simulation for event III. Mode 4, 5 and 9 have just a little improvement on rainfall simulation in spatial distribution, and only the simulation of mode 8 is closed to the observation. The simulations of mode 1, 2, 3, 4 and 5 are much lower than the observation in whole catchment. Most observed rainfall falls in the east of the catchment, while the simulated rainfall concentrates in the west for mode 6 and 9 and in the downstream catchment for mode 7."

The first paragraph in section 5.2.2 is also revised as a whole:

"As shown in Table 7, the similar results can be found that most data assimilation modes cannot help the simulation of WRF model get better for event I. Only mode 8 is outstanding with the highest CSI and lowest RMSE. Figure 7 shows that the rainfall is concentrated at 10:00-16:00 for the observation. However, the main rainfall processes occur at 3:00-5:00 for mode 3, 4, 6, 3:00-5:00 and 14:00-15:00 for mode 1, 3:00-5:00 and 17:00-19:00 for mode 2, 3:00-5:00 and 9:00-10:00 for mode7, 3:00-5:00 and 20:00-24:00 for mode 9. The rainfall processes of Mode 5 and 8 are similar with the observation, while the rainfall simulations at 12:00-13:00 and 15:00 for mode 5 are worse than for mode 8. According to the values of CSI and RMSE, only mode 8 and 9 are useful for the improvement of rainfall simulation and obvious improvement can be found in mode 8 for event II. The actual main rainfall process occurs at 15:00-18:00, while the time is advanced by 3 h for mode1, 4, 5, 6 and 7. There is a delay of 3 h for main rainfall process of mode 3. Although the times of heavy rainfall for mode 2 and 9 are consistent with the observation, the areal rainfall at 18:00 is much higher than the observation. For event III, although most CSIs of the simulation with radar data assimilation are lower than the simulation without data assimilation, the RMSEs show the opposite conclusions. From the Fig. 9, the observed rainfall is concentrated at 8:00-11:00. It can be easily found that mode 1, 2, 3, 4, 5, 6 cannot reproduce the heavy rainfall process in temporal dimension. The simulated rainfall is concentrated at 15:00-16:00 for mode 7. Only the simulation of mode 8 is basically consistent with the observation, while the simulation of mode 9 is worse than mode 8 at 8:00 and 10:00."

We check the sentence "...areal rainfall observation at each rain gauge i" carefully and the sentence is really wrong. In the revised manuscript, the expressions of two indices (CSI and m-RMSE) in section 4 are rewritten.

"The CSI is calculated based on the rain or no rain contingency table (Dai et al., 2019). Table 4 shows that rainfall<0.1 mm/h as the threshold is regarded as no rain. In order to evaluate the simulation of spatial rainfall distribution by CSI, NA, NB, NC at time i are calculated by comparing the rainfall observation with simulation extracted at rain gauge locations. The values of the NA, NB, NC at all times are averaged to obtain CSI based on Eq. (7). In this study, the time i is 1 h and the number of total times (N) is 24. Thus, CSI is the average value of the NA/(NA+NB+NC) for each hour of the 24-h rainfall duration. For temporal dimension evaluation, NA, NB, NC are calculated based on the time series data obtained for the simulated and observed rainfall at each rain gauge i. The values of the NA, NB, NC at all rain gauges are then averaged to obtain CSI according to Eq. (7). The total number of rain gauges (N) is 8. The perfect score of CSI is 1.

The m-RMSE is calculated using Eq. (8). For spatial dimension evaluation, P'j and Pj refer to the simulation and observation of 24-h accumulated rainfall at rain gauge j, respectively. M is the total number of rain gauges (M=8). For temporal dimension evaluation, P'j and Pj are the average areal rainfall simulation and observation at each time j. M represents the total number of time (M=24). The perfect score of RMSE is 0."

In addition, we really think carefully about the reviewer's suggestion that more statistic metrics (e.g., POD, FAR etc.) should be considered. However, according to our previous studies (Tian et al, 2017), the simulations high CSI always have high POD and low FAR. In terms of evaluating the rainfall simulations in spatial and temporal dimensions, the effects of the three indices are similar. More indices may make the manuscript complex and reader puzzled. The CSI can be considered as a comprehensive description of accuracy. That is why we use CSI. More information can be found in our previous studies.

References: Tian, J., Liu, J., Yan, D., Li, C., 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, 2017.

Though the time window of the storm events is chosen as 24 h, the rainfall is concentrated mostly in only a few hours. If the time step is set as 6 h or more, the evaluation will be difficult. One hour may be the most suitable time step to evaluate the rainfall simulation finely. If the reviewer thinks that the results in different time intervals are necessary to add in the manuscript, we will supply the description in next round of modification. If possible, we suggest to evaluate the maximum 3-h, 6-h and 12-h rainfall simulations using RE rather than evaluate the model results under different time intervals with CSI or other indices.

Figure captions are revised to make the statements clear:

"Figure 4: Spatial distribution of the simulated 24 h rainfall accumulations with nine data assimilation modes for Event I. Figure 5. Spatial distribution of the simulated 24 h rainfall accumulations with nine data assimilation modes for Event II. Figure 6. Spatial distribution of the simulated 24 h rainfall accumulations with nine data assimilation modes for Event III. Figure 7: Time series bars of observed and simulated areal rainfall with nine data assimilation modes and the rainfall observation for Event I. Figure 8: Time series bars of observed and simulated areal rainfall with nine data assimilation modes and the rainfall observation for Event II. Figure 9: Time series bars of observed and simulated areal rainfall with nine data assimilation modes and the rainfall observation for Event III."

Point 6: 2/3 typhoon events affected the study area as tropical cyclones and had a limited impact in the study area. This fact does not support the aim of the study, which focus of typhoon rainfall simulations. I suggest including more high-impact typhoon rainfall events in the study. Also, please refer in more detail to the impacts on properties, people etc. in the study catchment, as well as to the flooding mechanisms (fluvial?) in the area. This will assist the results interpretation in terms of natural hazard analysis.

Reply: Much thanks for your suggestion that can make the manuscript closer to the aims and scope of the NHESS. In order to investigate the radar data assimilation effects on rainfall simulation, different kinds of rainfall processes caused by different stages of the typhoons. Rainfall storm event II occurs after the typhoon passes Meixi catchment and the effects of the Hagibis have weakened. The spatial and temporal distribution of the rainfall is uneven. Event I and III both occur when the typhoons are close to Meixi catchment. Event I has relatively even spatial-temporal distribution of the rainfall, while event III is extreme rainfall. The most destructive flood caused by storm event III leads to many casualties and huge economic losses. The supplementary of disaster situation is added in the revised manuscript. The section 2 is revised as shown in Line 2-15, Page 4:

"The Meixi catchment lies in east-central of Fujian province with subtropical monsoon climate (Fig.1). The drainage area is 956 km2 and the average annual rainfall is approximately 1560 mm. There are 8 rain gauges and hydrologic station (Fig.2). In order to investigate the radar data assimilation effects on rainfall simulation, different kinds of rainfall processes caused by different stages of the typhoons are chosen in Meixi catchment. Saola forms on July 28, 2012 while lands Fuding, Fujian until August 3. With moving inland slowly, Saola weakens into a tropical storm at Jiangxi. Although event I occurs during the movement of Saola to Meixi catchment, the accumulated 24-h rainfall is only 84 mm. Hagibis lands Shantou, Guangdong on June 15, 2014 and then moves toward north with a fast-moving speed. Fortunately, Hagibis weakens into a tropical depression quickly during moving to northeastern Fujian on June 17. Event II occurs after the typhoon passes Meixi catchment and the accumulated 24-h rainfall is only 66 mm. Nepartak reaches Fujian on July 9 and strengthens at Putian. Then Nepartak moves towards the northwest with a fast-moving speed and event III occurs when Nepartak is close to Meixi catchment. During the period, Nepartak reaches its peak intensity. The 24 h accumulated rainfall is 242 mm and peak flow reaches 4710 m3/s in Meixi catchment. The most destructive flood causes water and power cut-off in 11 villages and towns. Official figures stand at 74 dead and 15 missing from the flood, which also causes a direct economic loss of 5.234 billion yuan. Accurate rainfall forecasts appear to be particularly important for Meixi catchment. Three rainfall storms are shown in Table 1."

Point 7: Please provide evidence on how assimilating radial velocity and radar reflectivity affect the WRF model's initial and boundary conditions (ICBC), and performance during the conducted numerical experiments. For example, you could compare the ICBC wind field and water vapor transportation between the experiments. This is important to support the interpretation of the results.

Reply: We agree with the suggestion that can support the interpretation of the results. Each rainfall mainly concentrates in a short period, so the wind field and water vapor transportation increment for different modes at the rainfall concentrating time are used to show how assimilating radial velocity and radar reflectivity affect the WRF model's initial and boundary conditions (Fig. 11-13). The shadows in Fig. 11-13 mean that water vapor transportation in analysis field is more than in background field. The darker the shadow in the figures, the more water vapor transportation increment.

For event I, anticlockwise wind field has contributed to the water vapor transportation from ocean to inland at 12:00 on August 3, 2012. Mode 1, 2, 5, 7, 8 and 9 all obtain the shadow area with obvious water vapor transportation increment. However, according to the coverage area of the shadow, only mode 5 and 8 influence Meixi catchment directly, which is consistent with the result that rainfall simulations with mode 5 and 8 are higher than simulations with no data assimilation at 12:00, while the increment of simulated rainfall is quite obviously for Mode 8.

The differences of nine modes can be easily found in both wind field and water vapor transportation increment for event II. The water vapor transportation increases significantly in mode 2, 3, 8 and 9 at 18:00 on June 18, 2014, which has direct impact on the rainfall simulation in Meixi catchment. That is the main reason why rainfall simulations with mode 2, 3, 8 and 9 are higher than simulations with no data assimilation. However, the wind fields in these modes indicate a lack of warm and wet flow supply and the rainfall weakens is almost inevitable after 18:00. Considering wind field and the range of water vapor transportation increment, the rainfalls may continue for a period time after 18:00 in mode 3, 8 and 9, which can also be reflected by hourly simulated rainfall shown in Fig. 8.

For event III, the water vapor transportation increases significantly in mode 2, 3, 5, 6, 7, 8 and 9 at 6:00 on July 9, 2016, while only mode 8 and 9 affect Meixi catchment directly. The range of shadow in Fig. 13 is consistent with the result that rainfall simulations with mode 8 and 9 are higher than simulations with no data assimilation. Wind field indicates that water vapor transportation is sufficient for mode 8 in a later time, which leads to a significant increase of simulated rainfall.

The following paragraph is added in Line 19-33, Page 11 and Line 1-5, Page 12:

"Wind field and water vapor transportation increment for different modes at the rainfall concentrating time are used to show how assimilating radial velocity and radar reflectivity affect the WRF model's initial and boundary conditions (Fig, 11-13). The shadows in Fig. 11-13 mean that water vapor transportation in analysis field is more than in background field. The darker the shadow in the figures, the more water vapor transportation increment, which is one of the most important factors that affects the amount of rainfall. For event I, anticlockwise wind field has contributed to the water vapor transportation from ocean to inland at 12:00 on August 3, 2012. Mode 1, 2, 5, 7, 8 and 9 all obtain the shadow area with obvious water vapor transportation increment. However, according to the coverage area of the shadow, only mode 5 and 8 influence Meixi catchment directly, which is consistent with the result that rainfall simulations with mode 5 and 8 are higher than simulations with no data assimilation at 12:00, while the increment of simulated rainfall is quite obviously for Mode 8. The differences of nine modes can be easily found in both wind field and water vapor transportation increment for event II. The water vapor transportation increases significantly in mode 2, 3, 8 and 9 at 18:00 on June 18, 2014, which has direct impact on the rainfall simulation in Meixi catchment. That is the main reason why rainfall simulations with mode 2, 3, 8 and 9 are higher than simulations with no data assimilation. However, the wind fields in these modes indicate a lack of warm and wet flow supply and the rainfall weakens is almost inevitable after 18:00. Considering wind field and the range of water vapor transportation increment, the rainfalls may continue for a period time after 18:00 in mode 3, 8 and 9, which can also be reflected by hourly simulated rainfall shown in Fig. 8. For event III, the water vapor transportation increases significantly in mode 2, 3, 5, 6, 7, 8 and 9 at 6:00 on July 9, 2016, while only mode 8 and 9 affect Meixi catchment directly. The range of shadow in Fig. 13 is consistent with the result that rainfall simulations with mode 8 and 9 are higher than simulations with no data assimilation. Wind field indicates that water vapor transportation is sufficient for mode 8 in a later time, which leads to a significant increase of simulated rainfall."

Minor comments

Point 8: Page 2, L. 22-27, 29-31 and Page 3, L. 1-2: Please refer to models and data assimilation schemes used.

Reply: The models and data assimilation schemes used in these studies are added in Line 22-32, Page 2 and Line 1-6, Page 3:

"Wang et al. (2013) tested the four-dimensional variational data assimilation (4-DVar) system by simulating a midlatitude squall-line case in the U.S. Great Plains, and the results indicated that radar data assimilation was able to improve rainfall forecasts from the WRF model at the convective scale. Liu et al. (2013) selected 4 storm events in a small catchment (135.2 km2) located in southwest England to explore the effect of data assimilation for rainfall forecasts based on WRF model, and assimilating radar reflectivity by 3-DVar model can significantly improve the forecasting accuracy for the events with one-dimensional evenness in either space or time. By using the WRF model and Advanced Regional Prediction System (ARPS) 3-Dvar, Hou et al. (2015) improved the short-term forecast skill up to 9 hours by assimilating radar data in southern China.

Most studies focus on the assimilation algorithm and data selection. However, consistent conclusions have not been obtained for the option of radar reflectivity and radial velocity, and few studies pay attention on the time interval setting of data assimilation. Based on the WRF and 3-DVar model, Tian et al. (2017b) found that radar reflectivity assimilation led to better rainfall simulation than radial velocity assimilation with the time interval of 6 h. Maiello et al. (2014) assimilated both radar reflectivity and radial velocity by 3-DVar model with 3 h assimilation cycle to improve the WRF high resolution initial condition, and the rainfall forecast became more accurate for several experiments in the urban area of Rome. Bauer et al. (2015) used the WRF model in combination with 3-DVar scheme to estimate the rainfall simulation, and the results showed that radar data assimilation significantly improved the rainfall simulation by a 1-hour Rapid-Update Cycle with the high resolution of 3 km in Germany."

Point 9: Page 4, Section 2.2: The description could be improved in terms of English and details provided.

Reply: The Section 2.2 (section 3.1.2 in the revised manuscript) are rewritten: "The fundamental of 3-DVar data assimilation is to produce an optimal estimate of the true atmospheric state by the iterative solution of a prescribed cost function (Ide et al., 1997): where x is the vector of the analysis, xb is the vector of first guess or background, y is the vector of the model-derived observation that is transformed from x by the observation operator H, i.e., y=H(x), and y0 is the vector of the observation. B is the background error covariance matrix, and R is the observational and representative error covariance matrix. Equation (1) shows that the 3-DVar is based on a multivariate incremental formulation. Velocity potential, total water mixing ratio, unbalanced pressure and stream function are all preconditioned control variables. Radial velocity has already been derived into component winds that are the same as the analysis variables, hence radial velocity can be assimilated directly by Eq. (1). However, radar reflectivity assimilation needs additional forward operator that associates the model hydrometeors with the radar reflectivity. Due to the wide applicability, the matrix of CV3 is adopted in this study to simplify the data assimilation procedure (Meng and Zhang, 2008)."

Point 10: Please refer to what is being shown in Figures 4-9 (24-h rainfall? Areal rainfall? See comment c) in Methodology above).

Reply: Figure captions are revised as follows:

Figure 4: Spatial distribution of the simulated 24 h rainfall accumulations with nine data assimilation modes for Event I. Figure 5. Spatial distribution of the simulated 24 h rainfall accumulations with nine data assimilation modes for Event II. Figure 6. Spatial distribution of the simulated 24 h rainfall accumulations with nine data assimilation modes for Event III. Figure 7: Time series bars of observed and simulated areal rainfall with nine data assimilation modes and the rainfall observation for Event I. Figure 8: Time series bars of observed and simulated areal rainfall with nine data assimilation modes and the rainfall observation for Event II. Figure 9: Time series bars of observed and simulated areal rainfall with nine data assimilation modes and the rainfall observation for Event III.

Point 11: Please enhance the resolution of Figures 7-9.

Reply: The resolution of Figures 7-9 is improved in the revised manuscript.

Point 12: Some examples where the English could be improved. Title: Please replace “simulation” by “simulations”. Page 2, L. 2 and 5: Please replace “system” by “systems”. Page 2, L. 10: Please replace “by” by “using the”. Page 2, L. 14: Please replace “WRF-LTNGA” by “the WRF-LTNGA scheme”. Page 2, L. 16-17: Please move “for hydrological applications” to the previous sentence (“...into the WRF model for hydrological applications”). Page 2, L. 19-20: Please rephrase. Page 2, L. 21: Please replace “the” by “their”. Page 2, L. 28: Please remove “the”. Page 3, L. 5: Please change to “caused by the interaction of typhoons and the complex terrain”. Page 3, L. 6-7: Please rephrase. Page 3, L. 11: Please rephrase “flood disasters have attacked...”. Page 3, L. 23: Please replace “can be” by “is”. Page 3, L. 28: Please add “a” (“...has a significant effect...”). Page 5, L. 13-14: Please rephrase “... and 24 for N is the ...”. Page 6, L. 1-2: Please use past tense.

Reply: The gramma mistakes and spelling errors are checked carefully. The errors mentioned by the reviewer are all revised accordingly.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2020-146, 2020.

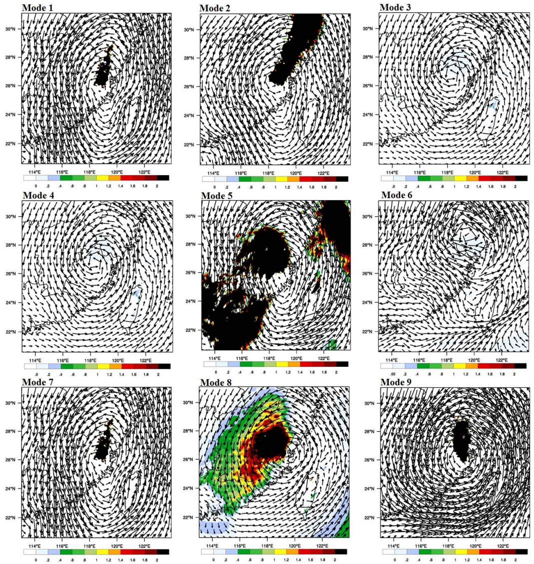

Figure 11. Wind field and water vapor transportation increment (850hPa) for Event I at 12:00 on August 3, 2012

1

Fig. 1. Figure 11

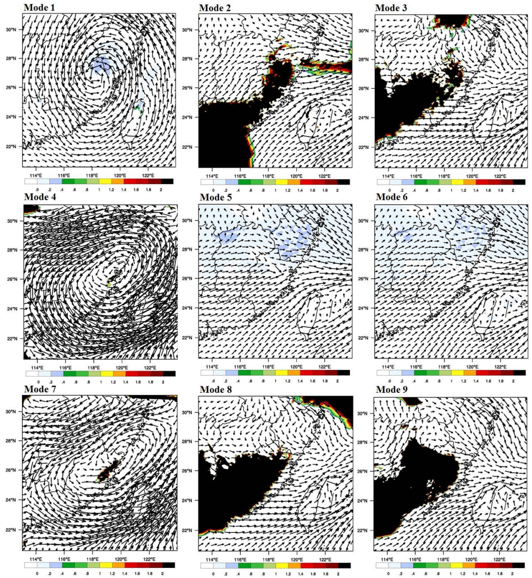

Figure 12. Wind field and water vapor transportation increment (850hPa) for Event II at 18:00 on June 18, 2014

1

Fig. 2. Figure 12

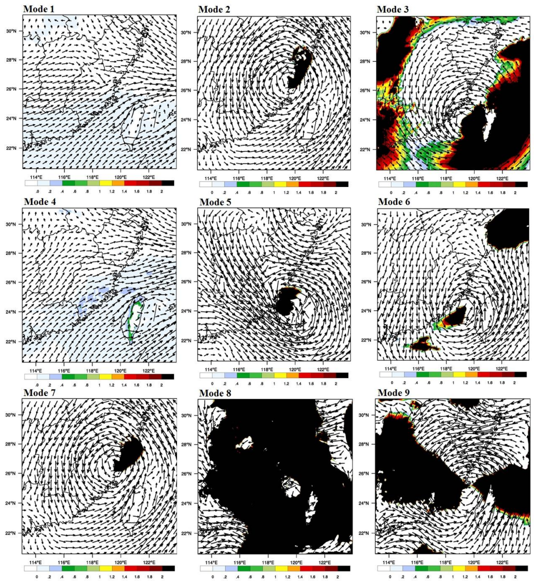

Figure 13.Wind field and water vapor transportation increment (850hPa) for Event III at 6:00 on July 9, 2016

1

Fig. 3. Figure 13

$$J(\mathbf{x}) = \frac{1}{2}\left(\mathbf{x} - \mathbf{x}^{b}\right)^{T} \mathbf{B}^{-1}\left(\mathbf{x} - \mathbf{x}^{b}\right) + \frac{1}{2}\left(\mathbf{y} - \mathbf{y}^{0}\right)^{T} \mathbf{R}^{-1}\left(\mathbf{y} - \mathbf{y}^{0}\right)$$

Fig. 4. Equation

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Discussion paper