Revision 1 of "Investigating 3D and 4D Variational Rapid-Update-Cycling Assimilation of Weather Radar Reflectivity for a Heavy Rain Event in Central Italy"

RC = Referee comment
AC = Authors' comment

AC: We thank the reviewer for the precious and insightful suggestions/comments, which will certainly enhance the quality of the manuscript. Please, find below our answers to all comments.

Main points

RC: The section of data assimilation needs to be improved. I put several sticky notes in the attached pdf that must be considered. Among the two are particularly important:
First: the variable analysed by 3D/4D-Var is hail, but WSM6 doesn't have hail. How is this issue handled?
AC: We thank the reviewer for this valuable comment. Indeed, the WSM6 microphysics scheme does not take into account the hail, but WRFDA code recognises this scheme and uses the q_h variable as a graupel species q_g (Lagasio et al., 2019). To further clarify this aspect, we have calculated the maximum and minimum values of AO (analysis minus observation) in terms of graupel mixing ratio from radar reflectivity (rqr), after the last assimilation cycle (0300 UTC) for the two simulations CYC3DVAR_warm and CYC4DVAR_warm (Table 1). The results confirm that both data assimilation schemes work properly even if the WSM6 scheme is used.
This clarification has been added in Section 4.2 (page 9) of the manuscript.

RC: Second: The point of in-cloud data assimilation is unclear. Is there assumed that the environment is saturated?
AC: The estimate of the saturated water vapor observation is produced considering the assumption that in cloud humidity is saturated.
The in-cloud relative humidity is assumed to be 100% where radar reflectivity is higher than a threshold above cloud base, so that the estimated water vapor equals to the saturation water vapor that is calculated based on the pressure and temperature of the background (Eq. 9 in the manuscript). In this paper the threshold is set to 25 dBZ (WRFDA – default value). A full description of the indirect assimilation method is provided in Wang et al. (2013).
It is worth noticing that the assimilation of the in-cloud humidity is used in combination with the indirect assimilation. Thus, the numerical experiments also include the assimilation of the in-cloud humidity in addition to the hydrometeor species retrieved with the indirect method alone. This discussion has been included in Section 4.2 (pages 9 and 10) of the manuscript.

Minor points

RC: There are several sticky notes in the pdf attached to this review. Go through them for minor corrections.
AC: Please, find below our answers to all notes.

RC: Case studies. Page 2 line 55.

AC: Fixed, thanks.

RC: ";" in place of ",". Page 2 line 69.

AC: Done, thanks.

RC: With the aim? Page 3, line 105.

AC: Fixed, thanks.

RC: For readability use: 3D/4D always. Page 3 line 109.

AC: Done, thanks.

RC: surface low-pressure.... Page 4, line 137.

AC: Fixed, thanks.

RC: Delete about. Page 5, line 167.

AC: Fixed, thanks.

RC: Bold. Page 8, line 260.

AC: Fixed, thanks.

RC: What is the BE matrix? Page 8, line 261.

AC: B or BE matrix. We have replaced BE with B matrix. Thanks

RC: I cannot understand why the reduction of 50% of the length scale should ensure that increments are comparable with the weather radar range. Page 8, line 263.

AC: In a previous work (Mazzarella et al., 2020) the analysis increments of water vapor (i.e., the difference between analysis and first guess) have been evaluated with three different len_scaling factors: 1, 0.75 and 0.5, respectively. The use of a len_scaling factor of 0.5 proved that horizontal influence extension of increments falls within the area covered by weather radars. Since, we have used the same WRF configurations as well as the case study, a factor of 0.5 is also applied for this study.

RC: I would say the rain contribution to the equivalent reflectivity. Page 9, line 283.

AC: "Rain contribution" has been replaced with "rain contribution to the equivalent reflectivity" as suggested by the referee. In addition, a short sentence has been added to the line 222 to further clarify this aspect.

RC: forward observation operator...Page 9, line 294.

AC: Fixed, thanks.

RC: This point is rather unclear. Which are the state variables of the variational method? Is a saturated cloud environment assumed? Page 9, line 297.

AC: In addition to the hydrometeor species retrieved with the indirect method we have added the assimilation of the in-cloud humidity estimated from reflectivity. Please, see the answer in the previous section (main comments).

RC: 100 hPa is a bit to low for this kind of events. Could you discuss about this point? Page 11, line 350.

AC: The 100 hPa top is set because of operational constrain (computer limitation). This configuration is used at CETEMPS for the high resolution operational meteorological-hydrogeological chain. The results of this study are helpful to decide which cycling assimilation methods will be implemented operationally. This why, the WRF operational configuration used by CETEMPS (Ferretti et al., 2014; 2020) is adopted for this study. Moreover, the case study is not characterized by an intense deep convection for which using a higher model top does not provide further noticeable improvement.

RC: Here there is a significant issue: the variable analyzed by 3D/4D-Var is hail, but WSM6 doesn't have hail. How this issue is handled? Page 11, line 350.

AC: Please, see the answer in the previous section (main points).

RC: Put the time in the right order: 0000 UTC, 0010 UTC, 0100UTC , 0110 ... Page 11, line 364.

AC: Fixed, thanks.

RC: In the above section it is stated that the CAPPIs are assimilated until 0310 UTC. Why 1200 UTC? Page 13, line 408.

AC: We are sorry for the error. We have replaced 1200 UTC with 0300 UTC.

RC: previous analysis? Are you meaning the analysis of Figure 5? Page 13, line 416.

AC: The analysis increments of the water vapor mixing ratio (not shown in this manuscript) display a similar behavior to the rainwater mixing ratio in Figure 5. To avoid misunderstandings, the sentence has been modified in the revised version.

RC: Spelling. Page 15, line 489.

AC: Fixed, thanks.

RC: highest? Page 17, line 553.

AC: Fixed, thanks.

RC: The fact that the balance of the warm start simulations is worse that the cold balance is not convincing. Being the warm start background from a model output it should be well balanced. Likely, the forecast of the warm start run is worse that the cold start because the initial conditions of the simulation in warm start mode (6h before those of the cold start mode) are worse than those of the cold start. Page 17, line 564.

AC: We agree with the reviewer's comment. The initial and boundary conditions from ECMWF operational analysis (at 1800 UTC), are used to simulate the first 6 hours for the warm start simulations. Although they represent the best gridded estimate of the state of the atmosphere, the accuracy of the IC/BC is probably worse than these used for the cold start simulation. This comment has been added in the revised version of the manuscript.

RC: analysis in place of threshold. Page 20, line 715.

AC: Done, thanks.

RC: Likely initial conditions play a role. See also the comment at the end of section 6.1.2. Page 22, line 817.

AC: Please, see the answer to the previous comment.

RC: mm 6h-1. Page 22, line 820.

AC: Fixed, thanks.

RC: You should specify the number of cores used in the numerical exercise. Otherwise the time is meaningless. Page 22, line 844.

AC: Following the reviewer's suggestion, we have clarified this aspect. In addition, a more detailed discussion about the computation time has been added in the manuscript.

Table 1: Maximum and minimum of AO in terms of rqr for CYC4DVAR_warm and CYC3DVAR_warm experiments.

AO for radar	**CYC4DVAR_warm rgr (kg/kg)**	**CYC3DVAR_warm rgr (kg/kg)**
Minimum	-0.0051	-0.0018
Maximum	0.0002	0.0008

References

Ferretti, R., Lombardi, A., Tomassetti, B., Sangelantoni, L., Colaiuda, V., Mazzarella, V., Maiello, I., Verdecchia, M., and Redaelli, G.: A meteorological–hydrological regional ensemble forecast for an early-warning system over small Apennine catchments in Central Italy, Hydrol. Earth Syst. Sci., 24, 3135–3156, https://doi.org/10.5194/hess-24-3135-2020, 2020.

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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, Journal of Applied Meteorology and Climatology, 52(4), 889-902, 2013.

Revision 2 of "Investigating 3D and 4D Variational Rapid-Update-Cycling Assimilation of Weather Radar Reflectivity for a Heavy Rain Event in Central Italy"

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Major Points

RC: I mentioned that " The assimilation methods or evaluation methods are not novelty at all in this paper, it may be possible to show the efficient of forecasting. It is recommended to show the time cost and reasonable forecasting of 3DVar and 4DVar for 1day, 2days, 3days and even longer time, e.g. 7 days. " in last review, the reply is that " The application of an hourly cycling 4D-Var with WRF model represents a novelty in the framework of variational data assimilation. We would like to point out that Ballart et al., (2016) only attempt to apply the cycling 4D but using an NWP-based nowcast system. Moreover, this work also provides a comparison between the two variational assimilation methods 3D/4D-Var in cycling mode, evaluating their impact in terms of QPF. ". However, cycling 4D-Var method is not mentioned in the method section. It is strongly recommended to clarify the difference of efficiency between the normal 4D-Var and the cycling 4D-Var in method section.

AC: We would like to thank the reviewer for his/her insightful suggestions and comments. We tried our best to reply to your questions below.

This work is a first attempt of cycling assimilation with 4D-Var method using WRF model to reproduce a heavy rain event in central Italy as well as to provide a preliminary comparison with the largely used cycling 3D-Var. In an earlier work, Ballard et al. (2016) used the cycling 4D-Var with the Met Office operational model but in combination with a latent heating nudging technique. This work, instead, aims to investigate the impact of the cycling 3D/4D-Var methods implemented in WRF model, assimilating the radar reflectivity only.
In Mazzarella et al., (2020) we have already presented the results of a preliminary comparison between the 3D-Var and 4D-Var assimilation methods implemented in the WRF model. More specifically, the conventional 4D-Var (not in cycling mode) produces an increase of up to 22% in terms of the Fractions Skill Score compared to 3D-Var for the first case study, while an increase of about 5% is achieved for the second. Nevertheless, the paper pointed out the huge computational cost of 4D-Var method, in fact a 4D-Var simulation with 1h assimilation window required about 6 hours. As a result of this, we have developed the idea to apply the 4D-Var in cycling mode with an assimilation window of 10 minutes, the results of which are compared with the 3D-Var in cycling mode and presented in this work, without discussing again the impact of the conventional 4D-Var.
Following referee's suggestion, we have calculated the computation time need to perform the three cycles of assimilation for both assimilation methods. More in detail, the 3D-Var takes around 15-20 minutes whereas the 4D-Var, more computationally expensive, requires about 2h.
On the other hand, the use of 4D-Var with an assimilation window of 3 hours takes more than 12 hours. Therefore, the cycling approach adopting for this work, significatively reduces the computation time and allows the assimilation with 4D-Var also in the small forecast centres. To objectively compare the execution time, all numerical experiments are performed on the ECMWF's Cray HPC using 1080 computational cores. This discussion has been added in the revised version of the manuscript.

To clarify the last point raised by the reviewer about the efficiency of forecasting, we have carried out four new simulations increasing the simulation period (from 24 to 48h) to assess the performance

of 3D/4D cycling assimilation for the same event but starting the experiments 1 day before. To this purpose, the radar reflectivity has been assimilated on 2 May 2018 at 0000 UTC, 0010 UTC, 0100 UTC, 0110 UTC, 0200 UTC, 0210 UTC, 0300 UTC and 0310 UTC. To analyse the new simulations, we have recalculated the FSS for the same threshold values but considering the hourly cumulated precipitation only. The FSS for the 1 mmh^{-1} (Fig. 1, upper panel) still show a positive impact of cycling assimilation, although small, compared to the control run (initialized a day after). Conversely, the analysis over moderate and intense precipitation (Fig. 1, middle and lower panels), respectively 3 mmh^{-1} and 8 mmh^{-1}, proves that the performances of both cycling assimilation methods in the forecast of the rainfall peak are significatively reduced. These results confirm that the impact of the assimilation methods is limited to the first hours of the simulation, later the accuracy of the initial and boundary conditions still play a key role in the precipitation forecast.
It is worth noticing that the use of a two-way nesting for the high resolution numerical simulations, may generate noise when exchanging the high-resolution information in the coarser resolution regions, producing a worsening of the results, especially at longer timescales, (Kalnay, 2003), generally longer than 48h. Therefore, make additional simulations, starting two or three days before, is not worthy for evaluating the efficiency of the forecast.
Finally, the next steps will be to implement a nowcasting algorithm based on cycling WRF 4D-Var assimilating the radar reflectivity in combination with the conventional observations (e.g., SYNOP, and TEMP data) and to strengthen the statistical analysis taking into account a longer period, such as two weeks or one month.
This last comment has been added in the Conclusions section.

For what concerns the last reviewer's comment: "cycling 4D-Var method is not mentioned in the method section.", we have added a sentence (page 7, lines 157-158) on the cycling 4D-Var in Section 4 following the suggestion. Moreover, a more detailed description of cycling 4D-Var, which consists in applying the 4D-Var every hour, is provided in Section 5.2.

References

Ballard, S.P., Li, Z., Simonin, D. and Caron, J.-F.: Performance of 4D-Var NWP-based nowcasting of precipitation at the Met Office for summer 2012. Q.J.R. Meteorol. Soc., 142: 472-487. doi:10.1002/qj.2665, 2016.

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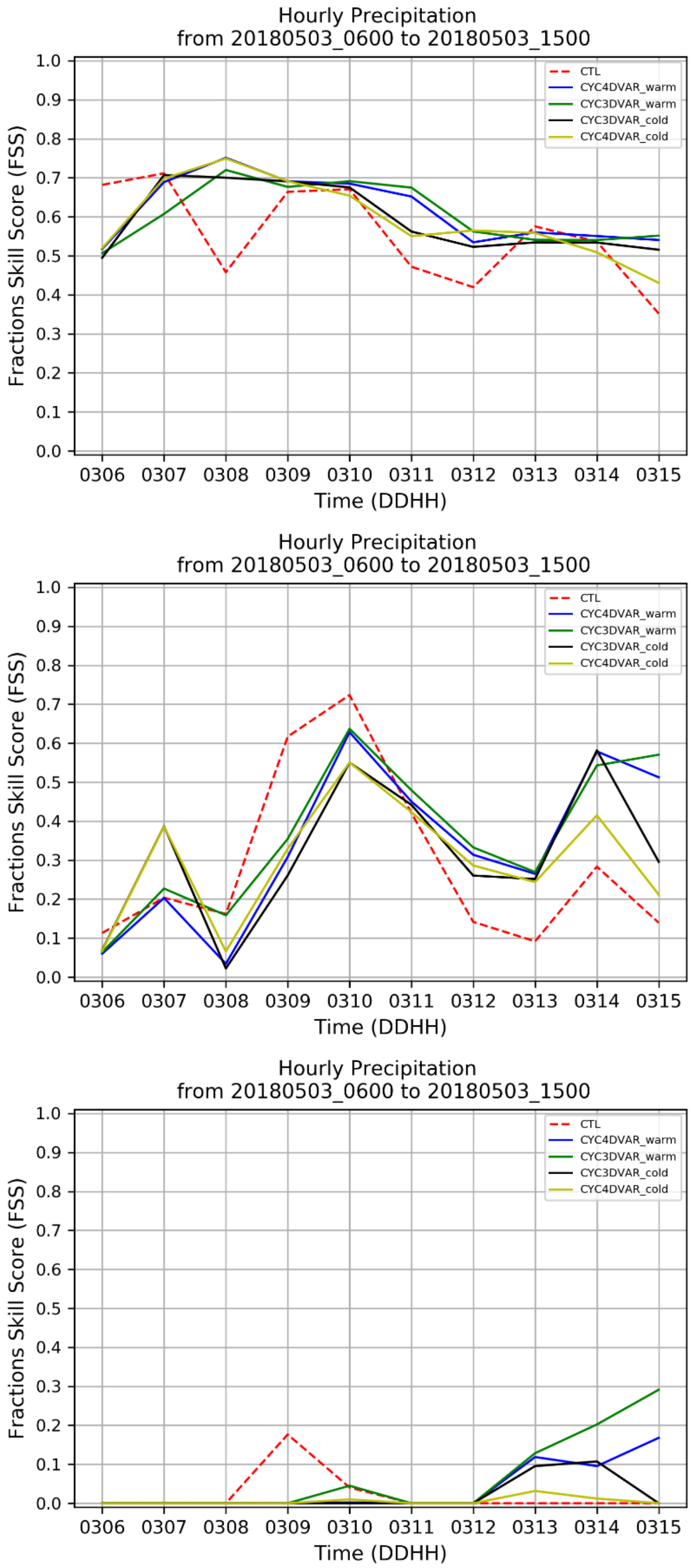

Figure 1: Evolution of FSS calculated in LA region considering the hourly accumulated precipitation for three threshold values: 1 mm h^{-1} (upper), 3 mm h^{-1} (middle) and 8 mm h^{-1} (lower), respectively. Dashed red line represents the CTL (initialized 1 day after), blue line CYC4DVAR_warm, green line CYC3DVAR_warm, black line the CYC3DVAR_cold and yellow line the CYC4DVAR_cold.