Revision 1 of "Investigating 3D and 4D Variational Rapid-Update-Cycling Assimilation of Weather Radar Reflectivity for a Flash Flood 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.

Major Points

RC: *The introduction of the paper is poor and not representative of assimilation systems and weather forecasting models operating over Italy. A more complete review must be provided.*
AC: Following the reviewer's suggestion, a more complete review of the assimilation systems operating in Italy has been added in the introduction. More specifically, we have only mentioned the scientific papers focused on the radar data assimilation in Italy in line with the main topic of this work.
Federico et al. (2019) investigate the impact of radar reflectivity in combination with the lightning for two case studies in Italy with RAMS@ISAC model (Regional Atmospheric Modelling System at Institute for Atmospheric Sciences and Climate of the Italian National Research Council) using a 3D-Var method. The results show the benefit of lighting and reflectivity assimilation for forecasting the intense precipitation ($\geq$ 40 mm/3h). Gastaldo et al. (2018), instead, assimilated reflectivity volumes using a local ensemble transform Kalman filter (LETKF) implemented in the convection-permitting model of the COnsortium for Small-scale MOdelling (COSMO) operating at Hydro-Meteo-Climate Service of the Emilia-Romagna Region (Arpae-SIMC). The latter paper points out the positive impact of radar assimilation in the first hours of forecast and an improvement in quantitative precipitation forecast (QPF) accuracy both when a latent heat nudging (LHN) is applied or not. Finally, a new work made by Gastaldo et al. (2021) confirms the positive impact, up to 7 hours, of radar assimilation with LETKF in COSMO model, especially in convective cases, replacing the LHN scheme.
This discussion will be added in the new version of the manuscript.

RC: *Precipitation thresholds: The precipitation thresholds considered in sections 6.1.1 and 6.1.2 are small and not representative of heavy precipitation. The maximum intensity considered is 7 mm/1h, which is too small to be representative of a deep convective event.*
AC: For this work, we have selected a convective event, occurred on 3 May 2018, which cannot be considered as a severe weather event taking into account the absence of damage and the measured values of the rain gauges. From 0600 UTC to 1800 UTC, the rain-gauges in Vomano a Montorio and Tordino a Cordesco measured, respectively, 77 and 78 mm12 h^{-1}, while along the Abruzzo region coastline rain-gauges measured 64 mm12 h^{-1} at Pineto and 57 mm12 h^{-1} at Pescara Colli. However, following the reviewer's suggestion we have calculated the FSS for the 8 mm h^{-1} threshold, in accordance with World Meteorological Organisation (WMO-No. 544) that classifies the precipitation with a rain rate greater than 7.6 mm h^{-1} as heavy rain. The new results confirm the previous behaviour in terms of FSS and the positive impact of 4D-Var (Fig. 1).

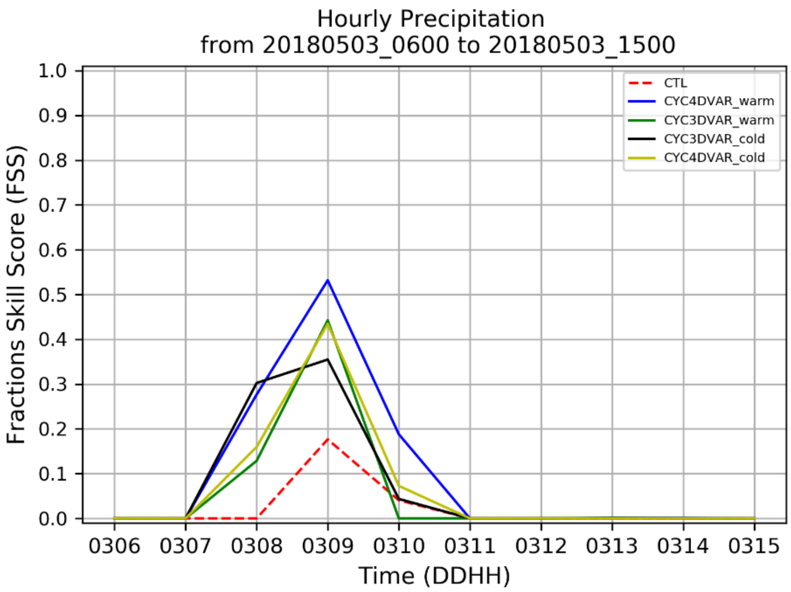

Figure 1: Evolution of FSS calculated in LA region considering the hourly accumulated precipitation for 8 mm h^{-1} threshold. Dashed red line represents the CTL, blue line CYC4DVAR_warm, green line CYC3DVAR_warm, black line the CYC3DVAR_cold and yellow line the CYC4DVAR_cold.

In addition, we have also calculated the FSS for the 3-hourly cumulated precipitation considering a higher threshold value of 10 mm $3h^{-1}$ (Fig. 2) as suggested by the referee. The FSS is consistent with the previous results for the 7 mm $3h^{-1}$ threshold. Finally, we have also considered a higher threshold value for the 6-hourly accumulated precipitation. The FSS for the 25 mm $6h^{-1}$ (Fig.3) proves the positive impact of radar data assimilation in cycling mode, highlighting the good performance of 4D-Var with a warm initialization compared to the other simulations.
A more detailed description will be presented in the new version of the manuscript.

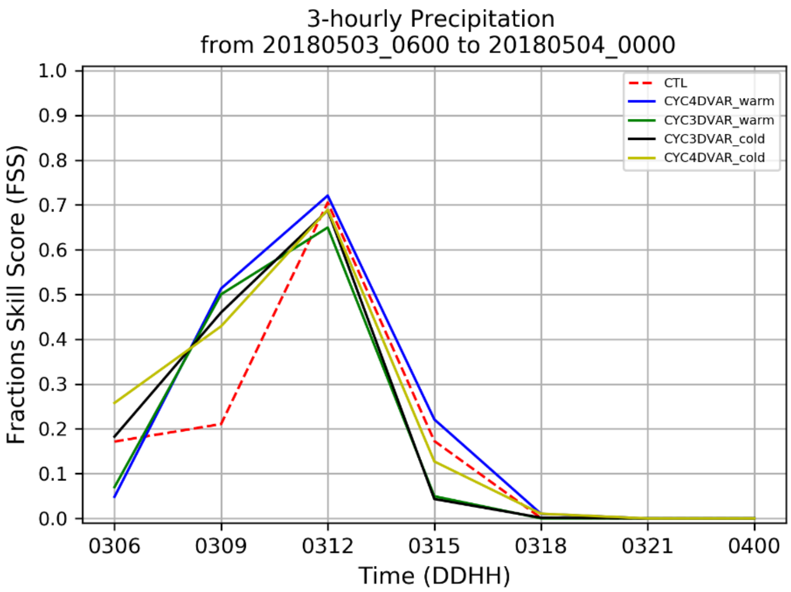

Figure 2: Evolution of FSS calculated in LA region considering the 3-hourly accumulated precipitation for 10 mm $3h^{-1}$ threshold. Dashed red line represents the CTL, blue line CYC4DVAR_warm, green line CYC3DVAR_warm, black line the CYC3DVAR_cold and yellow line the CYC4DVAR_cold.

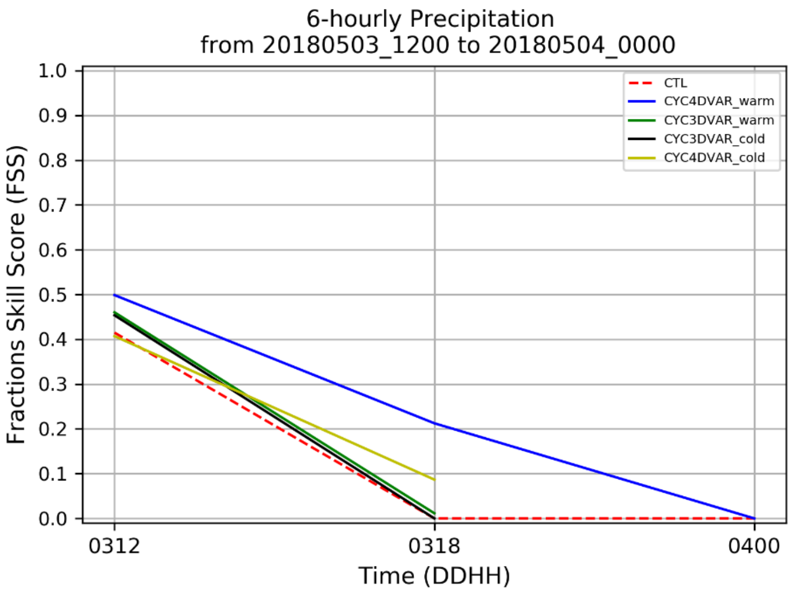

Figure 3: Evolution of FSS calculated in LA region considering the 6-hourly accumulated precipitation for 25 mm 6h^{-1}. Dashed red line represents the CTL, blue line CYC4DVAR_warm, green line CYC3DVAR_warm, black line the CYC3DVAR_cold and yellow line the CYC4DVAR_cold.

RC: *Precipitation fields: there are no model output of the precipitation. The only precipitation shown is the observed one. Precipitation forecast is discussed only using a statistical approach, without any example of what is predicted and how the rainfall forecast is improved by radar data assimilation. A map comparison of forecasted precipitation and observed precipitation must be provided in order to understand which is the impact of data assimilation for the case study.*

AC: We thank the reviewer for this valuable suggestion. In order to provide a qualitatively comparison in addition to the statistical analysis, the differences between forecast and observed precipitation fields have been calculated for each simulation over the study area. The comparison is performed considering the 3-hourly cumulated precipitation from 0900UTC to 1200UTC, when the FSS shows the highest values and the gap between the different simulations is more meaningful. The results (Fig. 4) confirm the positive impact of cycling assimilation: both methods reduce the underestimation of the rainfall (blue area) over the mountain area at the border between Lazio and Abruzzo regions. In this context, the 4D-Var and 3D-Var experiments with a warm start initialization show the best performances in this area (Fig. 4c and 4d), improving the precipitation forecast accuracy also compared to the CTL (Fig. 4e). Conversely, the two simulations in cold mode overestimate the rainfall along the coastal area of the Abruzzo region, even though they partially mitigate the error in the internal areas (Fig. 4a and 4b).
This discussion will be added in the revised version of the manuscript.

RC: *Analysis fields: we know that the CAPPIs of radar reflectivity are assimilated in WRF but we don't know their effect. In general, when doing analyses, a comparison of the background and analysis fields must be shown to understand the impact of the data assimilation on the modelled fields. Nothing is shown.*

AC: In order to clarify the impact of CAPPI reflectivity at 2, 3 and 5 km in cycling 3D/4D-Var methods, we have calculated the analysis increments (analysis minus first guess) at the end of the last assimilation cycle (1200 UTC) for each experiment. The assimilation of radar reflectivity mainly impacts on water vapour and cloud hydrometeors variables other than on temperature and wind components. Therefore, we have considered the analysis increments for the two variables, mixing ratios for rain (Fig. 5) and water vapour (Fig. 6), which best represent the added value of the assimilation of radar reflectivity. For this purpose, we chose the vertical level 15 (about 2000 m asl) because the influence of radar data is more relevant. A qualitative comparison between the two

assimilation methods points out that the 4D-Var is more impactful in terms of q_{rain} and q_{vapor} both with warm and cold start compared to 3D-Var. Furthermore, the larger analysis increments of q_{rain} as well as q_{vapor} are along the Adriatic Sea near Abruzzo coastline in agreement with the assimilated CAPPI maps, which showed high reflectivity values in this area.
A more detailed description will be added in the new version of the manuscript.

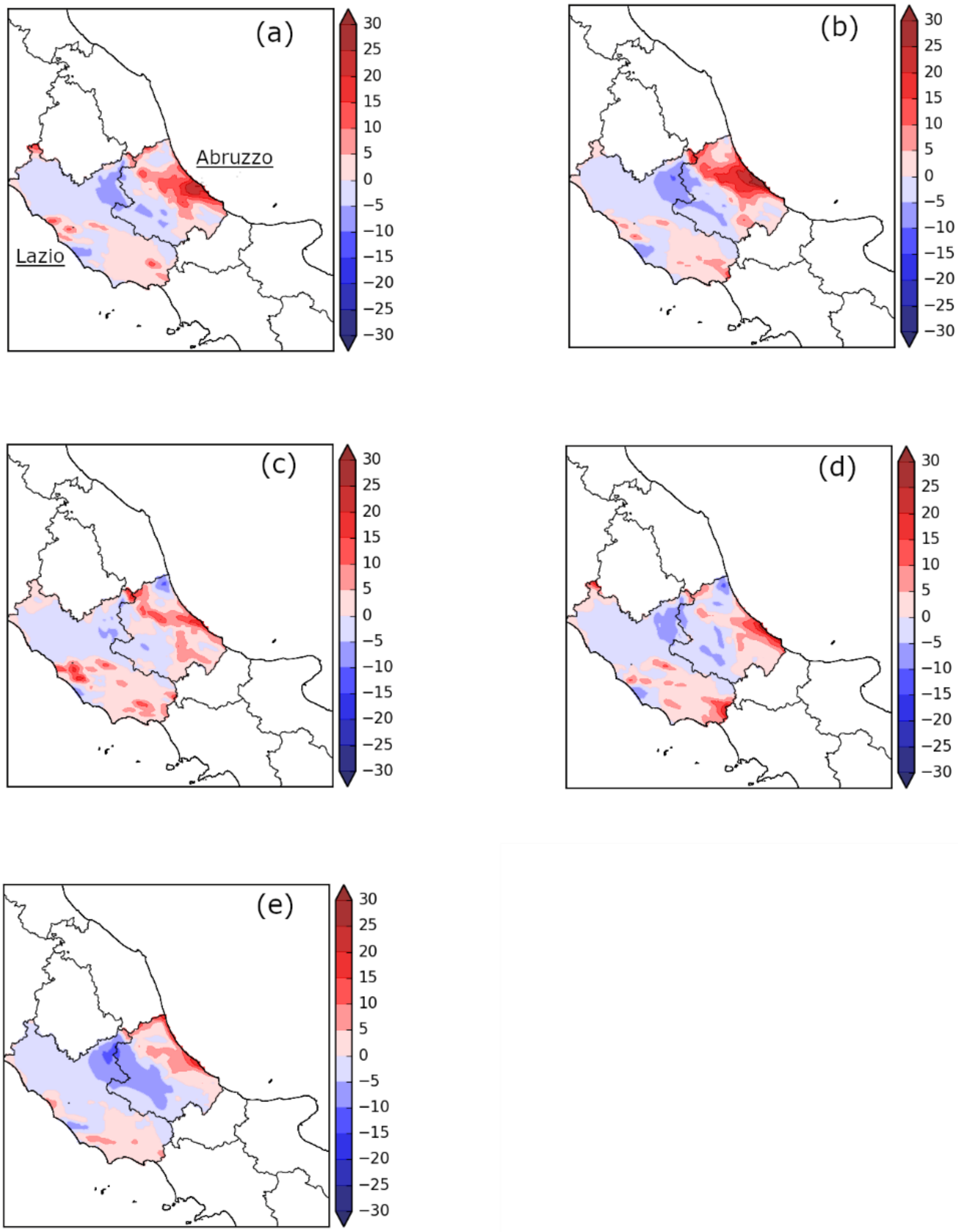

Figure 4: Differences between observed and predicted 3-hourly precipitation fields for CYC4DVAR_cold (a) and CYC3DVAR_cold (b) CYC4DVAR_warm (c), CYC3DVAR_warm (d) and CTL (e) simulations.

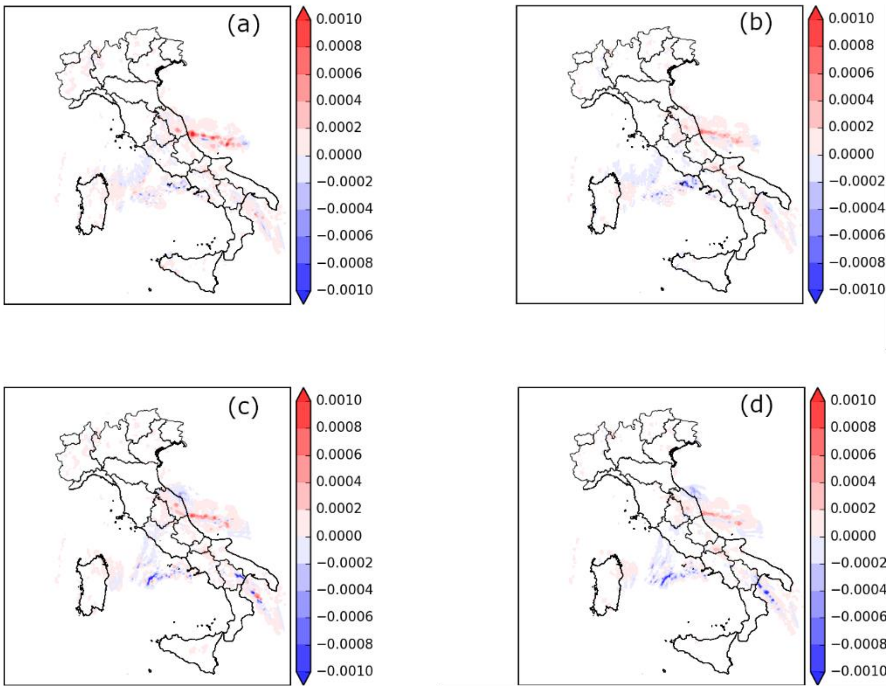

Figure 5: Rain water mixing ratio (kg kg^{-1}) analysis increments at vertical level 15 from CYC4DVAR_warm (a), CYC3DVAR_warm (b), CYC4DVAR_cold (c) and CYC3DVAR_cold (d) experiments.

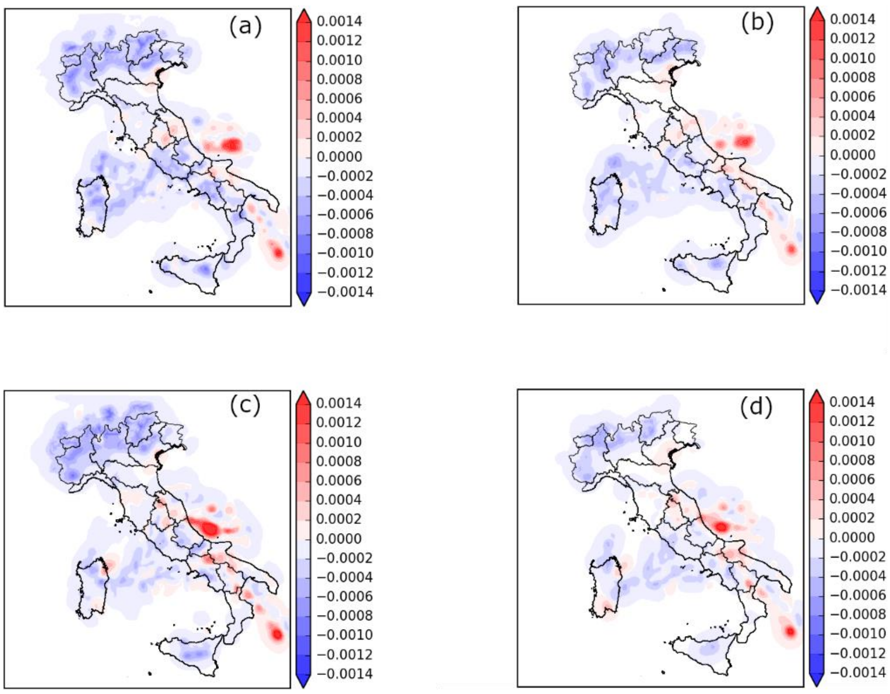

Figure 6: Water vapour mixing ratio (kg kg^{-1}) analysis increments at vertical level 15 from CYC4DVAR_warm (a), CYC3DVAR_warm (b), CYC4DVAR_cold (c) and CYC3DVAR_cold (d) experiments.

Minor Comments

RC: I think that the most important aspect of the precipitation forecast is the hydrological cycle and not the interest of Civil protection agencies. Line 21, page 1

AC: The sentence has been modified as follows: "Nowadays, the high-resolution rainfall forecast from Numerical Weather Prediction (NWP) models is essential for several applications. It is used by civil protection agencies to contrast the hydrological risks and safeguard people during severe weather event, by disaster management agencies to prepare emergency interventions as well as by public event managers, private enterprises and common people to plan their daily activities".

RC: Citations here. Page 1, line 25
AC: Some references has been added. "Recently, the development of more accurate parametrization of physical processes allowed a significant progress in NWP at high resolution but the prediction of exact location, timing and intensity of a convective event is still a challenge (Stensrud et al., 2009; Yano et al., 2018; Mass et al., 2002; Torcasio et al., 2021)

RC: Areas. Page 1, line 27
AC: It will be corrected in the revised version.

RC: Exposed. Page 1, line 29
AC: It will be corrected in the revised version.

RC: 19 billion. Page 2, line 31
AC: It will be corrected in the revised version.

RC: Are you referring to NWPs? Page 2, line 37
AC: The sentence has been modified as follows: "The precipitation forecast made by Numerical Weather Prediction (NWP) models is strongly dependent on the initial state…"

RC: There are also other experiences in Italy assimilating radar data together with other data and different models that should be cited here. Page 2, line 44
AC: Please, see the answer in the previous section.

RC: delete the comma. Page 3, line 74
AC: It will be corrected in the revised version.

RC: could you provide these maps on a larger area? Page 5, line 103
AC: Yes, the maps have been fixed. Please, see Figure 7.

RC: Are the CAPPI the only radar observations assimilated? Page 6, line 127
AC: Yes, only the CAPPI at 2, 3 and 5 km have been assimilated.

RC: Is there any reference about this quality control? Is it applied by the authors? Clarify. Page 6, line 136
AC: Quality control of rain gauges measurement data is the first step in the context of an operational use of the data.
Therefore, the rainfall data are preliminarily subjected to a quality control to identify and remove any inconsistencies. The quality control carried out includes the following actions:
1) control of rain gauges with the same name but different coordinates;
2) removal of data associated with rain gauges without valid coordinates;
3) removal of duplicate data;
4) identification of anomalous data (for example very different values respect to the surrounding rain gauges).
For more details see: Italian Civil Protection Department, CIMA Research Foundation (2014) The Dewetra Platform: A Multi-perspective Architecture for Risk Management during Emergencies. In: Hanachi C., Bénaben F., Charoy F. (eds) Information Systems for Crisis Response and Management in Mediterranean Countries. ISCRAM-med 2014. Lecture Notes in Business Information Processing, vol 196. Springer, Cham. https://doi.org/10.1007/978-3-319-11818-5_15

RC: cost. Page 7, line 146
AC: It will be corrected in revised version.

RC: the. Page 7, line 147
AC: It will be corrected in the revised version.

RC: x is not written in the same way as argument of H. Page 7, line 147
AC: It will be corrected in the revised version

RC: vector. Page 7, line 150
AC: It will be corrected in the revised version

RC: vector. Page 7, line 150
AC: It will be corrected in the revised version

RC: forward observation operator. Page 7, line 151.
AC: It will be corrected in the revised version

RC: start a new section here. Page 7, line 154
AC: It will be added in the revised version

RC: vector. Page 7, line 159
AC: It will be corrected in the revised version.

RC: B is a matrix. Page 7, line 167.
AC: It will be corrected in the revised version.

RC: what are these length scales? Could you interpret them from a physical point of view? Page 8, line 178.
AC: LEN_SCALING controls the spatial decorrelation for the following five variables: unbalanced velocity potential, unbalanced temperature, pseudo-relative humidity, unbalanced surface pressure and stream function**.** The use of a LEN_SCALING factor of 0.5 reduces the variable perturbation length scale by 50%, ensuring that the water vapour increments are comparable with the weather radar range; therefore, this value has been adopted for the simulations.

RC: As this is an important point, I believe that you should discuss it in more detail. Page 8, line 181.
AC: The no_echo option, developed by Min and Kim (2016), has been recently included in WRFDA (since its version 3.9). It allows the assimilation of null-echo within the radar observation range. This information reduces the excessive humidity and the contents of the following hydrometeors: snow, graupel, and rainwater based on radar reflectivity, improving the convective precipitation predictability. A new study (Lee et al., 2020) confirms the benefit of this option for the simulation of three summer convective events over the Seoul metropolitan area. The assimilation of null echo removes the erroneous model precipitation and improve the accuracy and reliability of convective precipitation forecast.

RC: Which kind of ECMWF data are used? Operational analysis/forecast cycle? Which cycle? Explain. Page 9, line 225
AC: The operational analysis/forecast cycle from the integrated forecast system (IFS) global model of the European Centre for Medium-Range Weather Forecasts (ECMWF) with a spatial resolution of 0.1° x 0.1° are used for this work and the boundary conditions are update every 3 hours.

RC: It is not clear why this should ensure the same number of data among the experiments. Page 10, line 235.
AC: We have used a 10 min assimilation window for each assimilation cycle. More specifically, we have assimilated the same number of observations in 3D-Var and 4D-Var simulations, namely the CAPPI radar acquired at 0000 UTC, 0010UTC for the first cycle, 0100 UTC, 0110 UTC for the second and 0300UTC, 0310 UTC for the last cycle.

RC: The main problem with the results is that thresholds are too low. A severe convective event can give a rainfall larger than 50 mm/h. Here 7 mm/1h is considered, which is too low. Larger thresholds must be considered, otherwise the paper is not assessing the impact of radar DA for heavy precipitation thresholds. Page 12, page 267.
AC: Please, see the answer in the previous section (Major Points).

RC: The information about the time is missing. Page 12, line 270
AC: It will be corrected in the revised version.

RC: Is that behavior caused by the spin-up? Page 12, line 278
AC: No there is not caused by the spin up. We have chosen to calculate the statistical index from 06UTC because the precipitation occurred between the 06 UTC and 12/15 UTC.

RC: The thresholds considered are low also in this section. Severe weather is characterized by much larger precipitation thresholds that are missed in this analysis. Page 15, line 320
AC: Please, see the answer in the previous section (Major Points).

RC: Even if the thresholds are increased in this section, their values is too low and do not represent heavy convetcive events. Page 17, line 351.
AC: Please, see the answer in the previous section (Major Points).

RC: heavy precipitation are not considered. Page 20, line 381.
AC: Please, see the answer in the previous section (Major Points).

RC: I cannot understand this sentence: explain better. Page 20, line 387
AC: The sentence has been rearranged as follows: "Conversely, the poor amount of precipitation at the start time, reduce the impact of both assimilation methods at the start time for 1mm/h threshold."

RC: It is important to stress that these results and considerations are limited to a case study. The conclusions cannot be general. Page 21, line 407.
AC: The sentence has been modified as follows: "In conclusion, the cycling assimilation with 3D-VAR and 4D-Var methods for this flash flood event, improves the reliability of the precipitation forecast, even if the positive impact reduces in time. "
In addition, a new sentence has been added following the referee's suggestion. "Therefore, to further investigate the impact of cycling assimilation with 3D/4D methods and to generalize the achieved results, a dataset of flash flood events will be considered."

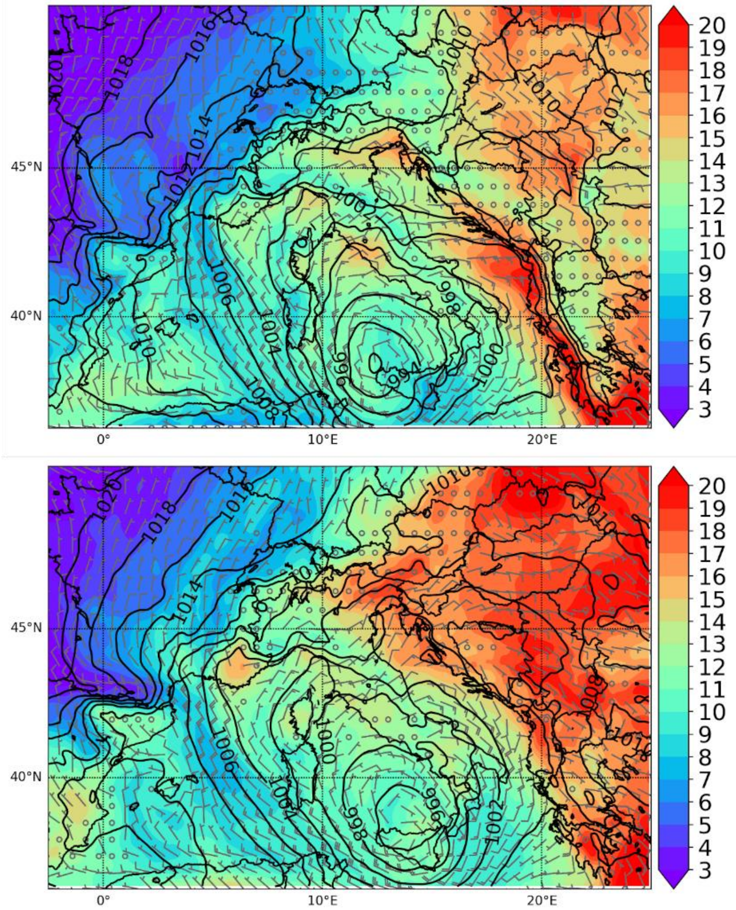

Figure 7: ECMWF analyses: 850 hPa temperature (°C), wind field (wind barbs) at 950 hPa and sea level pressure (black lines) on 3 May at 1200 UTC at 0600 UTC (upper panel) and 1200 UTC (lower panel).

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