Revision 2 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 would like to thank the reviewer for his/her suggestions and comments. Please find below our answers to each comment.

Major Points

RC: *There is lack of the key figures to show the spatial results of 3DVar, 4DVar forecasting and control simulation in this paper.*
AC: Thanks for this insightful comment. In order to further investigate the impact of 3D/4D var methods and to provide a qualitative comparison of the rainfall forecasts from each experiment, we have calculated (also following the suggestions of referee number 1) the differences between the observed and forecast precipitation over the study area, considering the 3-hourly cumulated precipitation (Fig. 1). The results 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. 1c and 1d), improving the precipitation forecast accuracy also compared to the CTL (Fig. 1e). Conversely, the two simulations in cold mode overestimate the rainfall in the coastal region, even though they partially mitigate the error in the internal areas (Fig. 1a and 1b). This discussion will be added in the revised version of the manuscript.

RC: *Figures (1-3) in this paper are in poor quality. It seems that they are not made by authors, just copied from some applications, there is no longitude or latitude in these figures at all. There are 9 plots in Figures 5-7 in same form, it is better to display them in one panel.*
AC: Figure 2 and 3 (in the previous version) has been modified following the referee's suggestion. Unfortunately, Figure 1, has been downloaded by Eport portal – EUMeTrain and cannot be modified. However, we prefer to keep this figure because it provides a qualitative description of mesoscale precipitation system as well as the information about the cloud cover over the whole Europe. For what concerns the comment about the merging of the Figures 5-7, we are prone to keep this configuration to improve the readability of the statistical results.
The new figures (Fig. 2 and 3 in the present document) will be added in the revised version of the manuscript.

RC: *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.*
AC: We partially agree with the referee's comment. 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.
For what concerns the computational time, the three assimilation cycles with 4D-Var requires about 3 hours using the CRAY XC40 cluster at EMCWF. On the other hand, the cycling 3D-Var is significantly faster and takes less than 1 hour. However, despite the 4D-Var requires a large amount of computational resources, it may be used for operational purpose when using the assimilation window adopted for this work.

A wide literature on variational data assimilation with WRF model proves that the impact of data assimilation significantly decreases after the first hours of simulations (Maiello et al., 2017; 2014, Mazzarella et al., 2021; Choi et al., 2013, Xiao et al., 2007; Stanesic and Brewster, 2016). For this reason, we believe that performing a statistical analysis over a longer forecast lead time does not help us to better clarify the impact of hourly cycling assimilation.

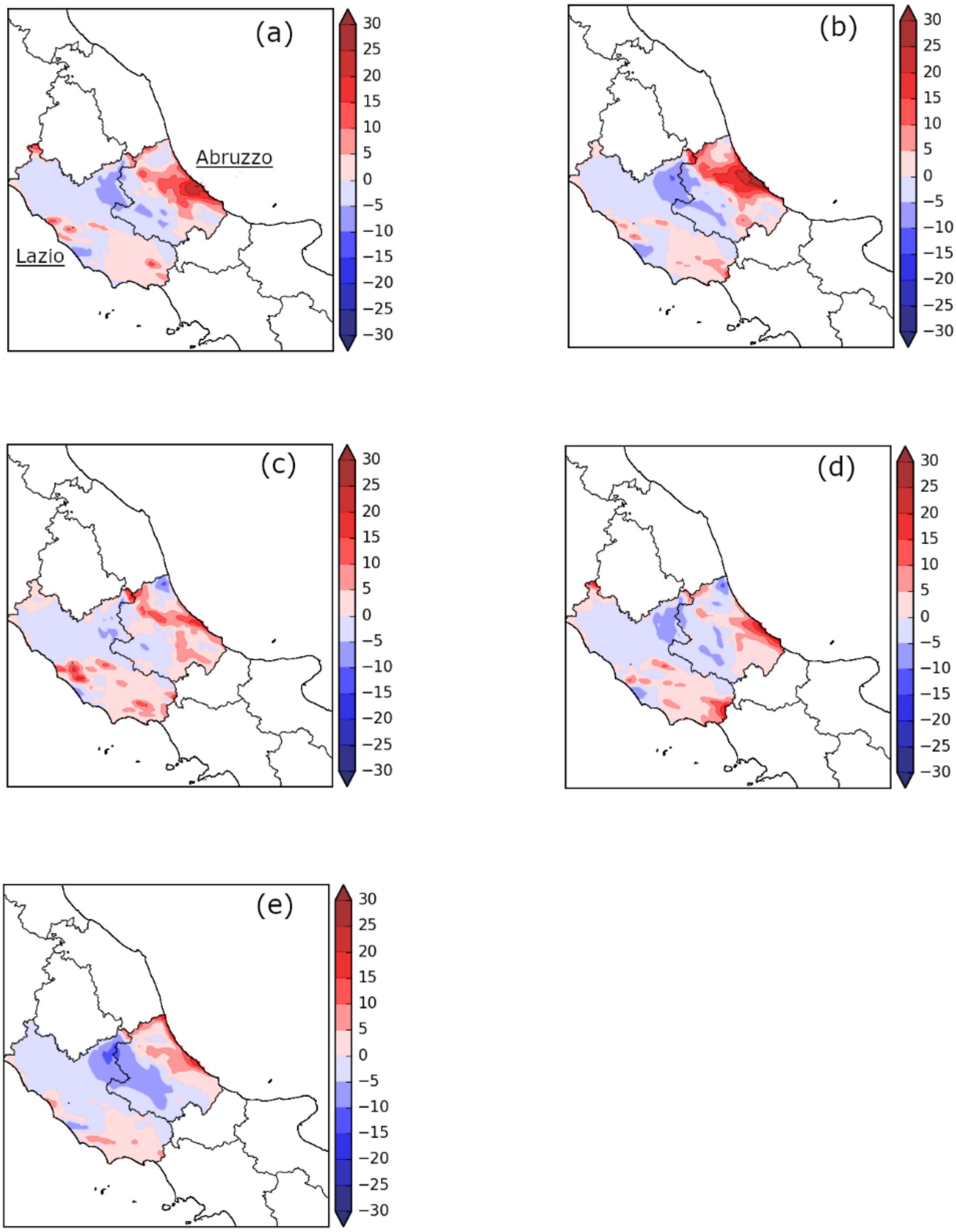

Figure 1: Differences between observed and predicted 3-hourly precipitation fields for CYC4DVAR_cold (a) and CYC3DVAR_cold (b) CYC4DVAR_warm (c), CYC3DVAR_warm (d) and CTL (e) simulations.

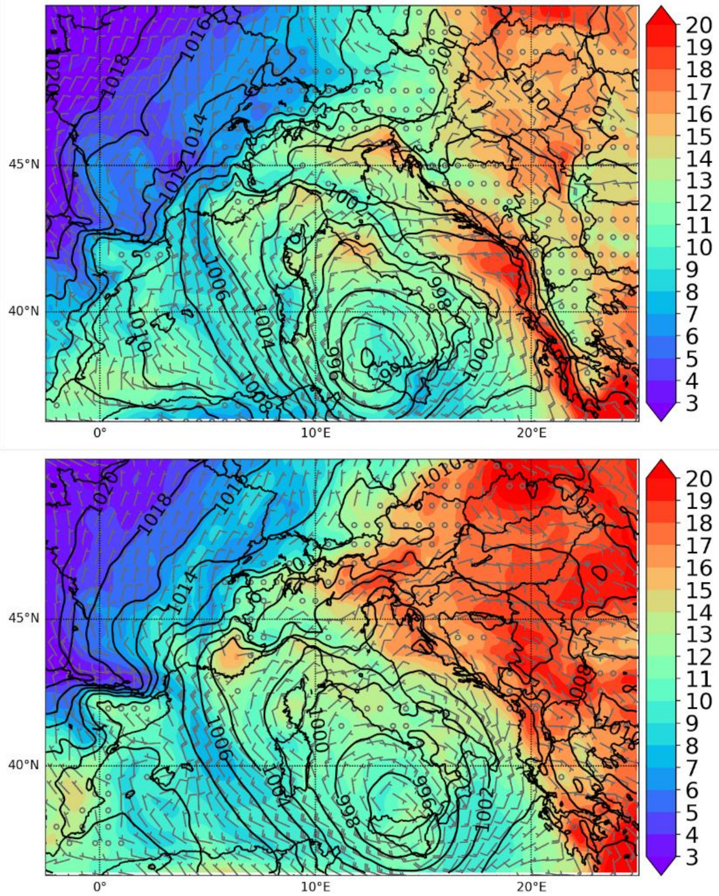

Figure 2: ECMWF analyses: 850 hPa temperature (°C), wind field (wind barbs) at 950 hPa and sea level pressure (black lines) on 3 May at 1200 UTC at 0600 UTC (upper panel) and 1200 UTC (lower panel).

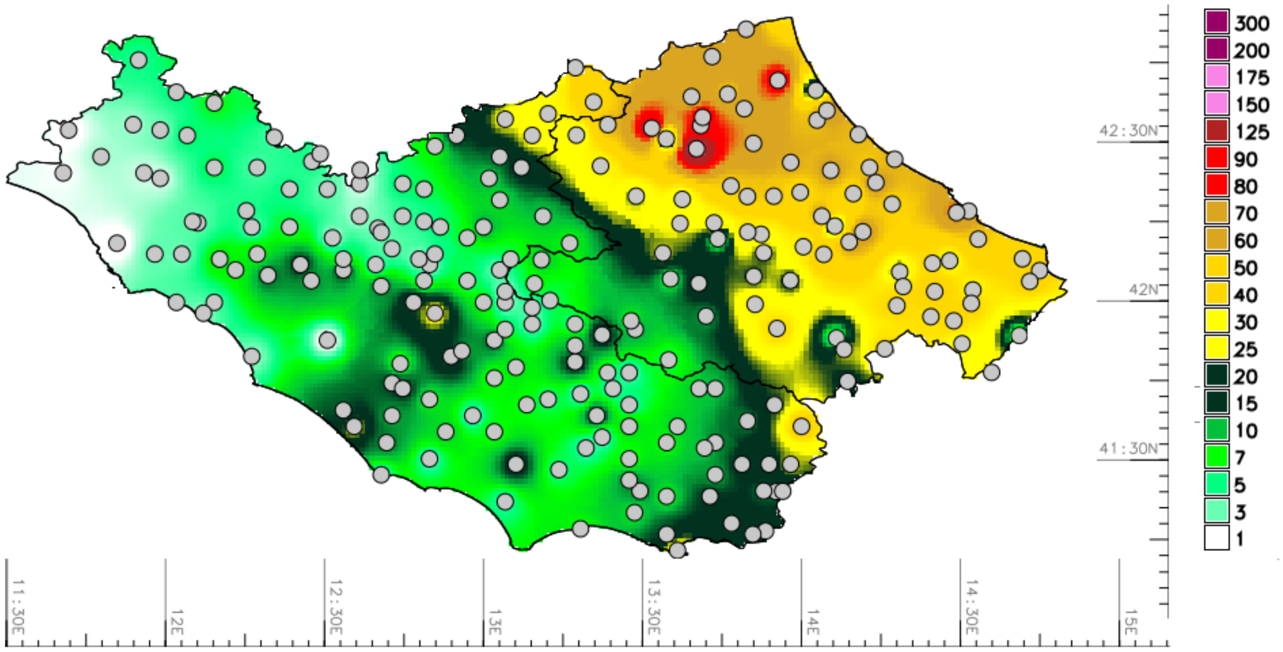

Figure 3: Observed daily precipitation (mm) on 3 May 2018 in Lazio Abruzzo regions. The points represent the locations of rain-gauges. Data courtesy of Italian Civil Protection Department.

RC: *This paper only shows the forecasting result of 1 day, it is far from the goal of forecasting for the Mediterranean basin, it is better to forecast for future 1 day, 2days, 3days and even longer time, e.g. 7 days.*
AC: This work aims to assess the performance of 1-hour cycling assimilation with 3D-Var and 4D-Var methods in terms of short-term quantitative precipitation forecasts for a heavy rainfall event in a complex orography region. As underlined in the previous answer, the impact of data assimilation is significantly reduced after few hours of simulation, so continue the experiment after the 24 hours is pointless and does not improve the quality of this work. In addition, it is known that the weather is a chaotic system: small errors in the initial conditions of a forecast grow rapidly. Furthermore, model errors linked to the approximate simulation of atmospheric processes can further reduce the predictability. This uncertainty limits the skill of single, deterministic forecasts in an unpredictable way. Nowadays the deterministic approach is largely adopted in meteorological–hydrological forecasting systems with lead times up to 2 days (McCullough, 1983; Georgakakos and Bras, 1984; Krzysztofowicz and Davis, 1984, Peppenberger et al., 2011). Over this period, a good skill for the precipitation forecast can only be achieved by using an ensemble prediction system (Gouweleeuw et al., 2005; Pappenberger et al., 2005)

RC: *The 2×2 contingency tables and indicators such as POD, TS, FAR and ETS are recommended to evaluate the discrete variable, e.g. precipitation.*
AC: Following the referee's suggestion, we have calculated the ETS for the hourly cumulated precipitation. The same threshold values have been used for this purpose. The ETS shows a similar behaviour to the FSS, confirming the positive impact of 4D-Var and the previous results (already discussed in this work). Therefore, the use of ETS, does not provide further added value to this work, so we prefer to keep the FSS analysis only.
The evolution of ETS for 1, 3 and 7 mm h^{-1} threshold values is presented in Figure 4.

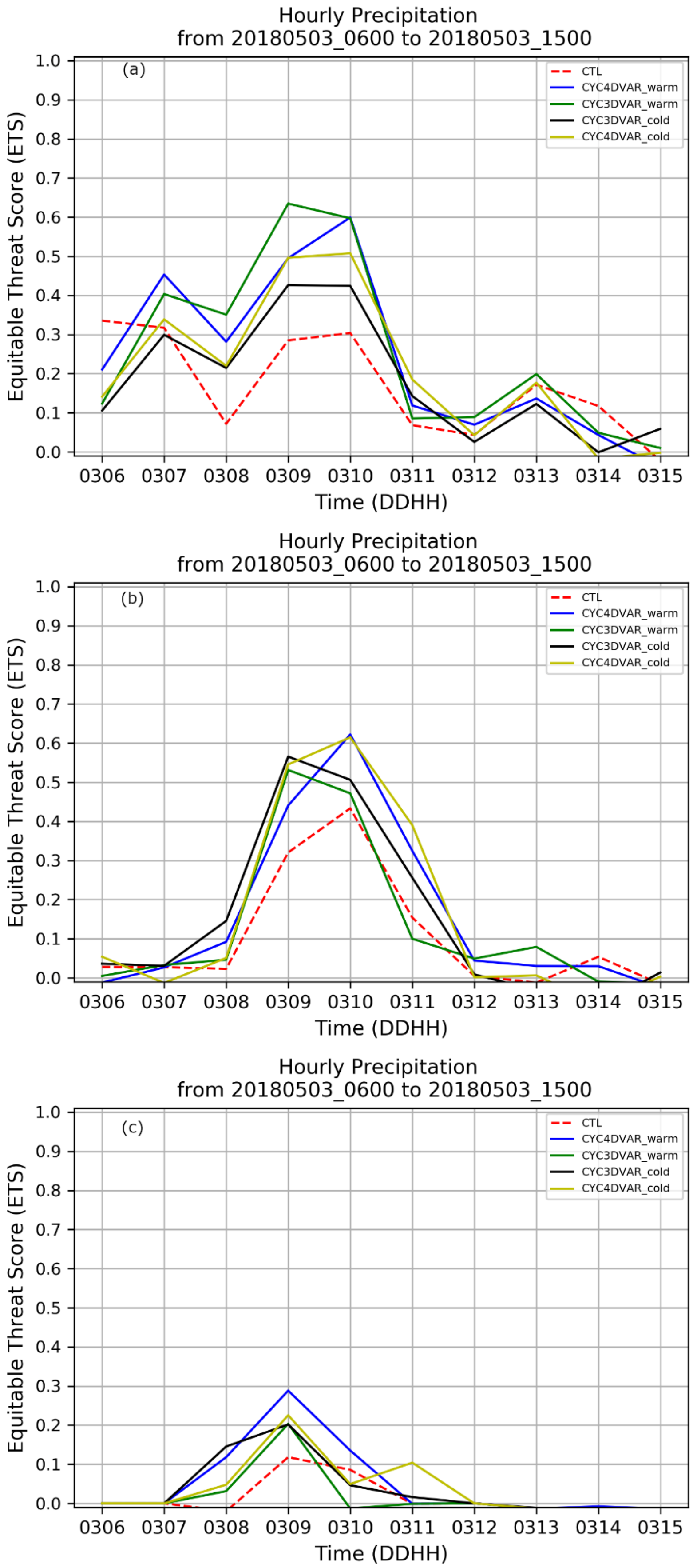

Figure 4: Evolution of ETS calculated in LA region considering the hourly accumulated precipitation for three threshold values: 1 mm h^{-1} (a), 3 mm h^{-1} (b) and 7 mm h^{-1} (c), respectively. Dashed red line represents the CTL, blue line CYC4DVAR_warm, green line CYC3DVAR_warm, black line the CYC3DVAR_cold and yellow line the CYC4DVAR_cold.

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