Response to referee #2 comments

Major comments

Abstract, L1 >> I guess it's the first assessment in Italy, not in general

- *We agree with the reviewer. The first line of the abstract has been replaced as follows: "This work is a first assessment in Italy…"*

P7317, L15 >> Are you sure that radial velocities contain information on vertical motion? I think this can be misinterpreted.

- *We agree with the reviewer. We modified the sentence as follows: "… whereas the vertical component of the radial velocity contains information on vertical atmospheric motions which are both important for the onset and development of convection. However, the contribution of the radial velocity to its vertical component is variable and it depends by the elevation of the radar antenna and the variations of the refractive index. The latter might produce variations in the radar ray paths with respect to those expected in standard atmosphere conditions. In this work a standard atmosphere is assumed and this means that radar ray paths propagates in a straight line."*

P7320, L12 >> Please explain more about the filtering procedure as this can highly influence the results. Some numbers would be nice here

- *Please find enclosed some example of how filtering procedure works both for clean and rainy day.*
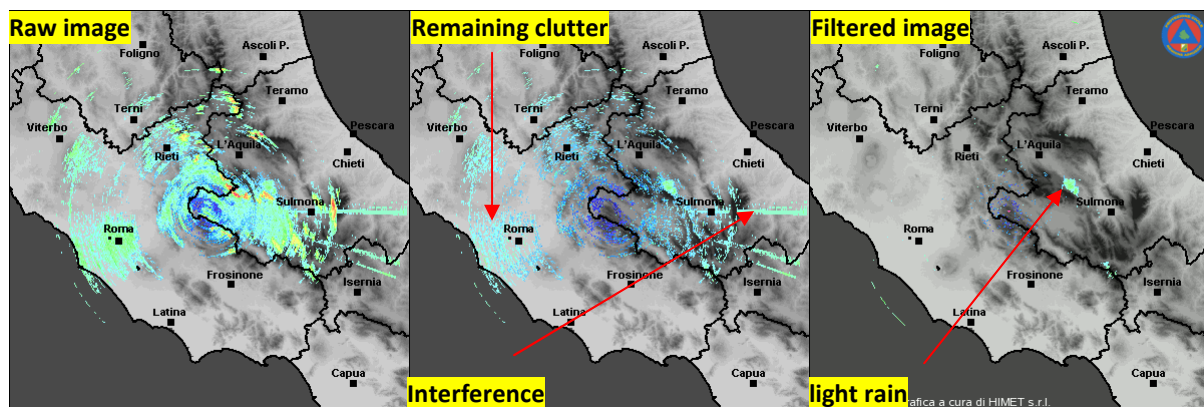

Fig 1. Example of filtering procedure in clear air condition: raw image (left), image after Doppler filter application (centre) and image after texture filter application (right). May 22, 2008 at 1400 UTC.

Fig 2. Example of filtering procedure in rainy condition: raw image (left), image after Doppler filter application (centre) and image after texture filter application (right). May 22, 2008 at 1400 UTC.
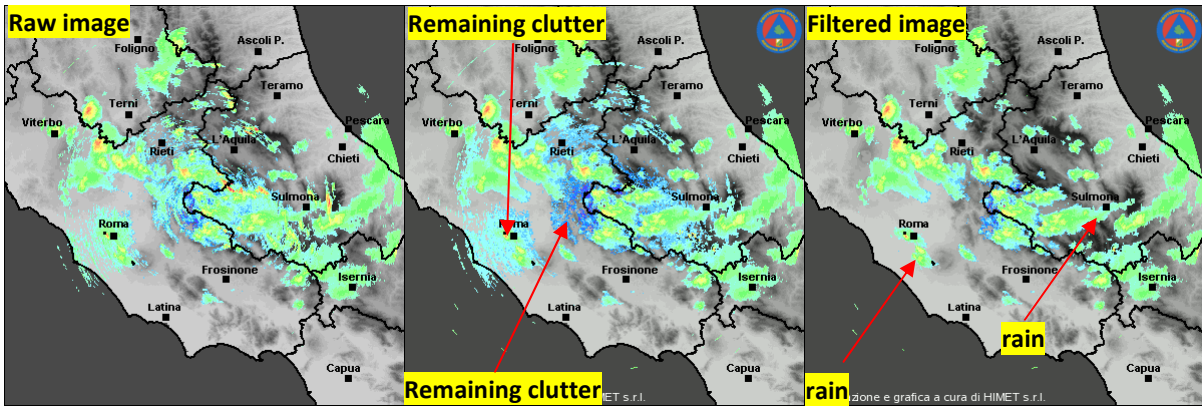
- Some numbers:

no filtering >> 90740 pixels

after Doppler filter application >> 75229 pixels

after texture filter application >> 54890 pixels

P7320, L24 >> Do you think that setting a general error of 1m/s is appropriate? As the radar beam broadens with increasing distance, this error assumption is not valid at far distances. In my opinion an error of 1dBZ for reflectivity seems too small. I am not sure if the radar is that sensitive especially at far distances from the radar. Can you also say something about the measurement range?

- We partially agree with the reviewer. The number that we considered for the errors of the radar reflectivity and Doppler velocity refer to the calibration uncertainty. Internal calibration procedures are routinely performed during the maintenance of the M. Midia Radar that we used. This means that during calibration procedures, the radar-received signal is tested using a signal source, which is known, and it is locally generated. Thus, the procedure allows defining the radar constant "C" and the spectral width "sDV" with an accuracy of +/- 1 dB and +/-1 m/s, respectively.

- The possible degradation of radar accuracy with distance because of the beam broadening may be due to the non-uniform beam filling effects. These effects are especially evident in the melting layer or in the presence of mixed precipitation at far distances and they cannot be quantified using single polarization radars. Even though a rigorous approach should include the range dependence of the radar accuracy we preferred to maintain the treatment simple as much as possible to highlight the differences of the various assimilation experiments we tested.

- Mt. Midia Radar has a maximum range of 120 km with an antenna beam width of 1 deg which implies a maximum spacing interval in the horizontal direction of 1.74 km.

P7320, L25 >> Is the whole assimilation window set to ±5 minutes around analysis time? If so, you will miss a lot of information from the other observation types. Please comment on this and also include more information in the manuscript.

- The whole assimilation window has been set to ±5 minutes around analysis time only for radar data; for the other observation types the assimilation window is ±1 hour. The sentence "the assimilation window was chosen of 5min" has been replaced in the manuscript as follows: "The assimilation window has been set to ±5 minutes around analysis time for radar data, ±1 hour for conventional observations."

P7321, L6 >> Please explain the meaning of "control variables" in the manuscript.

- From L4: "The configuration of the WRF-3DVAR system is based on the multivariate incremental formulation (Courtier et al., 1994), where the preconditioned control variables are stream function ψ, velocity potential χ, unbalanced pressure p_u and total water mixing ratio q_t. The aim of the 3D-Variational approach is to produce the best compromise between an a priori estimation of the analysis field and observations, through the iterative solution that minimize a cost function J. Most leading assimilation schemes do not perform the minimization process in model space, but instead use a transformed or control variable space that is the space allowed for the corrections to the background. This new space is chosen to have a special and desirable property - when the background field is represented in this space, its errors are uncorrelated and variances are of unit size (the problem is said to be preconditioned). The cost function for 3DVAR is: …"

P7322, L15 >> Why is the Richardson Equation important here?

- Richardson equation is important because it avoids the difficulties in the implementation of the continuity equation in the 3DVAR system, which is not designed to take local time derivates into account and the analysis fields should be more balanced than using a simple incompressible continuity equation or anelastic continuity equation.

P7323, LL1-14 >> What is actually used in your study? The original formulation of Sun and Crook or the modified version from equation 3? I assume that you also adapted the tangent linear and adjoint code in the WRF 3DVAR system? If not, you will definitely run into trouble.

- The modified version of Sun and Crook from equation 3 is used in this study. The 3DVAR code has changed accordingly; following the evolution of WRF-3DVAR code during the years, we have careful adapted also the tangent linear and adjoint code.

P7324, L20 >> Why does the NMC-method accounts for ECMWF data? The basic concept of the NMC method is to use forecast data to obtain a model related background matrix to have only a minor influence of the driving model!

- Yes, that's right, the NMC method is based on the difference between the two forecasts at t+24 and t+12, as we said later. When we write 'ECMWF data' we mean that those forecasts are initialized with ECMWF analysis. Anyway, the following sentence "which accounts for ECMWF data on Mediterranean basin" has been removed to avoid misunderstanding.

P7325, section 4.3 >> Please explain in more detail which types of observations (SYNOP, TEMP) are used for which experiment and at which time they are assimilated (please also adjust table 1).

- We have added more detail about types of observations used for each experiment and the time of assimilation.

P7326, LL8-16 >> What does this mean? Does this indicate a good analysis? Please explain the results in more detail.

- We tried to explain the results in more detail; LL8-16 have been modified as follows: "*The observed (Fig. 6) and the WRF-3DVAR radio sounding at Pratica Di Mare at 0600UTC 20 May 2008 clearly show (Fig. 7) no differences among Exp0, 1 and 2, whereas remarkable differences are found with respect to the observed one especially between 850hPa and 700hPa and up to 350hPa for the Exp3 (Fig. 7d). This last one shows higher moisture content below 700hPa than the other experiments (Fig. 7a, b, c), increasing the agreement with the observed one (Fig. 6). This higher moisture content justifies the higher K-index and it supports the more unstable atmosphere as indicated by the convective indexes. It's not surprising that the initial conditions of Exp1 does not succeed in improving the observed moisture profile above 600 hPa, because the PDM sounding is not assimilated in Exp1, whereas it is assimilated only for Exp2 and Exp3 both having ICs produced by WRF output. Finally, the wind does not show any difference among the experiments (Fig. 7) and a fair agreement for all of them with the observed one (Fig. 6).*

P7327 >> Are you sure that you can expect to reproduce a 4km event with a model resolution of 2.3km?

- Sorry but I do not understand what do you mean, could you clarify 'a 4km event'? However, it would be impossible to reproduce a 2km (or less) event using a 4km resolution, because it would be a sub-grid structure!

P7327, LL19-23 >> Do you have any ideas why this is the case?

- 3h-DA cycle could be the 'cause'. But, as we pointed out in the conclusions, Exp3 would need further investigation to assess this finding.

P7327, L25 >> I agree for the mountains, but I think one should distinguish between mountains and the environmental areas

- The sentence in line 25 has been modified as follows: "Therefore, the previous results would suggest that Exp3 as the only one able to reproduce this event above all closeness to the mountains."

P7328, L17 >> Why did you decide to choose a different period here? This gives a little break in the manuscript.

- We are sorry, it was a typing error! The statistical evaluation has been performed from 0600UTC 20 May 2008 until 0600UTC 21 May, that are the start_time and end_time of the simulations respectively.

P7328, L 17: I think here a bit more distinction is necessary. Dou you have any explanation, why the FAR is larger for Exp3?

- Large ETS does not give indication on overestimation/underestimation, if this is the case then high value for FAR are also found.

Lines 17-25 have been changed as follow: "Figure 13 shows the results for the previous indexes for the 12h accumulated rainfall as a function of different thresholds. ACC, FBIAS and ETS show improvements obtained for Exp2 (Fig. 13, green line) with respect to Exp1 (Fig. 13, red line), for thresholds higher than approximately 15 mm/12h. Accordingly, the FAR index for Exp2 shows values lower than for the others. Also Exp3 produces best values for ETS at thresholds below 15 mm/12h, but rapidly degrading for higher thresholds. These results support the previous finding that the experiment performed using the ICs produced by a warm start improve the forecast."

P7329, LL4-5 >> Also a single outer loop takes the nonlinearity into account. WRF uses the incremental method as described by Courtier et al.(1994). That means at the beginning the full non-linear operator is applied while during minimization, only the linear version of the operator is applied. So what is then the advantage of multiple outer loops?

- Using multiple outer loops is possible to control the influence of various types of data representing different scales of analysis by utilizing them in certain order of the outer loop. However, this technique would allow the ingestion of more observations progressively.

As in Rizvi et al. (2008) "Impact of outer loop for WRF data assimilation system (WRFDA)", the non-linear problem is solved iteratively as a sequence of linear problems by running more than one analysis outer loops, so the assimilation system is able to utilize more observations.

P7329 >> I think a more detailed discussion about Fig. 17 is required here.

- Discussion about Fig.17 has been changed as follows: "To better evaluate the impact of outer loops ACC, FAR, FBIAS and ETS are used. Only the results for Exp2 are shown here. If 2 outer loops are used during the assimilation process better scores (Fig. 17, red curve) are obtained especially for thresholds between 10-20 mm/12h once compared with blue curve (1 loop). On the contrary, for higher thresholds (30 mm/12h) positive results for the ETS and FAR are obtained if using 3 outer loops (green curve, Fig. 17 bottom). These results suggest that the increasing of the number of external outer loops could positively impact on the forecast of heavy rainfall."

P7331, L1 >> Usually, a domain specific B-matrix does not require any tuning. That's one of the main reasons why you create a separate matrix for each domain.

- The sentence at P7331, L1 is referred to the tuning of length scale and observation error parameters of a control variable and not to B-matrix. The sentence has been changed to clarify this point as follows: "Moreover, the technique of multiple outer loops will be further investigated by tuning length scale and observation error parameters as well as thinning of ….."

Minor comments

- Title of the paper has been changed: "Impact of radar data assimilation for the simulation of a heavy rainfall case in Central Italy using WRF-3DVAR"

1) P7316, L8: I think the main goal is to improve QPF..

- Yes, you are right, in fact we said in line 8 "thus improving the forecast of surface rainfall". Anyway, lines 7-8-9 of the abstract have been modified as follows: "The goal is to improve quantitative precipitation forecasts (QPF) by assimilating DWR data and using ECMWF analyses as First Guess."

2) P7317, L13: Reflectivity is not related to the amount of precipitation but to number density of the different hydrometeors.

- The following sentence "It is well known that the reflectivity is related to the amount of precipitation, size and water phase of the hydrometeors" is rewritten as follows: "It is well known that the reflectivity is related to the number of drops per unit volume and it depends on the number and size of hydrometeors, which includes rain, snow, graupel and hail, whereas…."

3) P7318, LL2-5: I suggest to delete this sentence as it is repeated later and is not that relevant in the introduction.

- We agree with reviewer, the following sentence has been deleted: "The total water mixing ratio was used as control variable for moisture and the warm rain process was incorporated into the system in order to partition the moisture and hydrometeor increments. Further, an observation operator for radar reflectivity was developed and incorporated into the 3DVAR system"

4) P7318, L18: What is ARW? Readers not familiar with WRF may be confused

- The word "ARW" has been deleted. Also from the caption of Fig. 4

5) P7318, LL25-27: I suggest to remove this sentence. If you are sure that this was never done before, you could "attenuate" this sentence a little bit

- We don't completely agree with the reviewer because it's important to highlight in the introduction where is the originality of the research. We tried to "attenuate" a little bit the sentence as follows: "In fact, the originality of this research lie in the fact of bringing together weather forecast and radar data both still challenge in complex orography."

6) I suggest to replace the heading of 2.1 with "Meteorological situation".

- ok, done

7) What is a cyclonic circulation? I guess you mean "low pressure system"

- Yes, a "low pressure system"; the sentence has been changed in "a deep low pressure system"

8) According to the heading of 2.2, this section should deal with radar data. Instead it starts with GTS data

- The beginning of section 2.2 has been modified. It now starts as follows: "Non conventional radar data and the GTS (Global Telecommunication System) conventional observations - SYNOP (Surface synoptic observations) and TEMP (upper level temperature, humidity and winds) - are used in this study."

9) P7321, LL20-26: Usually R is not a well known matrix, especially not for radar data or non-conventional observations. B is not flow-dependent in case of applying it for a 3DVAR but a climatological estimate of the model errors for a specific period.

- To avoid misunderstanding we changed the sentence as follows: "R is usually a diagonal matrix: well known for conventional observations, but not for radar data. B matrix accounts for the climatological model error and it has to be estimated using a statistical method, such as the National Meteorological Center (NMC) method (Parrish and Derber, 1992) or the ensemble one (Fisher et al., 1999). The first method is commonly used for the estimation of B in the WRF-3DVAR system. It is based on the statistical analysis of several couples of forecasts differences valid at the same time (e.g., month-long series of 24-h minus 12-h forecasts valid at the same time)."

10) P7322, LL5-6: Is vertical velocity poorly estimated in the model or the observations? If you mean the model, why?

- We mean poorly estimated not in the model. See also the answer at the major comment P7317, L15.

11) P7322, 17: What is "pseudo relative humidity"? What is the total water mixing ratio?

- Pseudo relative humidity and total water mixing ratio are both control variables for the analysis of moisture observations in a global atmospheric data assimilation system. In a variational framework, the choice of control variable is important because the notion of "distance" between model and observations depends on it. A pseudo-relative humidity can be defined by scaling the mixing ratio by the background saturation mixing ratio. A pseudo-relative humidity analysis is shown to be equivalent to a mixing ratio analysis with flow-dependent variance specifications.

12) P7323, L19: I guess it's the terminal velocity of raindrops.

-Yes, that's right.

13) Replace the heading of chapter 4 with "Experimental setup"

- ok, done

14) P7324: Which soil model was applied? The 5-layer model, the NOAH-LSM or the RUC model?

- The 5-layer thermal diffusion scheme has been applied.

15) I suggest to name chapter 5 only "Results"

- ok, done

16) P7326, L5: What is a "thundery atmosphere"?

- A thundery atmosphere is an unstable atmosphere with a high potential for thunderstorm development.

17) Should it be "K-Index" or KINX? Please check the whole manuscript.

- KINX is the acronym of K-index. The meaning is the same. We changed all in to K-index.

18) Section 5.2: Do you mean "Impact of IC's on precipitation forecast"?

- Section 5.2: Yes, we mean "Impact of IC's on precipitation forecast"

19) P7327, L3: Which boundaries?

- We meant the borders between Abruzzo and Lazio regions. We changed the text accordingly.

20) P7327, LL21-24: This paragraph is very difficult to understand.

- We rewrite the paragraph.

21) Please check the grammar here. This sentence is very difficult to understand

- Grammar has been checked.

22) Section 5.3 could be "Statistical evaluation"

- ok, done

23) Replace EQTS with ETS, I think this is more common.

- All the "EQTS" in the text have been replaced with "ETS", as well as in the caption of Fig. 13 and 17.

24) P7328, L20: In my opinion the threshold is 10mm not 20mm. Please check

- We think the threshold is between 10mm/12h and 20mm/12h. However, the sentence has been changed.

25) Chapter 6 can be named "Impact of multiple outer loops on precipitation"…

- ok, done

26) Discussion of "EXP1_OL" and "EXP1_OL3" are missing here.

- If you mean Exp1_OL=one loop this is Exp1 of the previous paragraphs and the analysis is performed having Exp1 as reference. Exp1_2OL is discussed in LL9-11, whereas for Exp1_3OL more details have been added.

27) P7329, L12: I still see some convection in Fig. 14

-You're right, the word 'completely' is not appropriate. Line 12 has been modified as follows: "If three outer loops are used the convection in the red circle is slightly reduced and its shape is changed (Fig. 14, right panel)."

28) Maybe one or two sentences can be added for the other experiments at the end of chapter 6.

- Two following sentences have been added for Exp1 and Exp2 at the end of chapter 6: "Same results are found for Exp1 and Exp2: FBIAS gives better response for thresholds between 30-40 mm/12h if 3 outer loops are used, whereas FAR shows good values for thresholds not higher than 10 mm/12h if 2 outer loops are applied."

29) P7330, first paragraph: I think you also used SYNOP and TEMP data?

-Yes that's right. SYNOP and TEMP data have been added in the paragraph.

30) P7330, L13: Both sentences in the third item have the same meaning for me

-You are right. The third item has been modified as follows: "the multiple outer loops technique allows assimilation of a larger number of observations progressively into WRF-3DVAR; this turns into a forecast improvement, especially for very localized cells as for Exp2"

31) P7330, LL20-23: Please discuss these two points a little bit more. Why can cycling be helpful and how can noise be introduced?

- Lines 20-23 have been a little bit modified as follows: "This is because the cycling benefits from the information transfer of the previous forecast as the background fields. Although the cycling mode serves to prevent the model error increasing rapidly with time, it should be used with caution because the analysis can include imbalances from the large-scale analysis."

- Noise can be introduced for example as high-frequency gravity waves.

32) P7330, L26: I think this is also very important here.

- It would have been very important and affecting having radar observations on the Tyrrhenian coastline.

33) P7331, L3: Does this mean that you haven't thinned the data before it went into the 3DVAR? I am not sure if the 3DVAR works properly when you have 5 observations of the same type in one model grid cell.

- Radar data were quality controlled before ingested into the 3DVAR. However, an observation thinning before the minimization to avoid as much as possible error correlations between adjacent pixels is not performed. Nevertheless, a dynamical thinning has been devised that selects, for every assimilation cycle, the most influential partition of a particular measurement, from information based on the previous cycle: this is the multiple outer loops technique! (Cardinali et al. 2004, "Influence matrix diagnostic of a data assimilation system", Q. J. R. Meteorol. Soc., 130, 2827-2849). Indeed, the experiments performed using different numbers of outer loops allowed to compare the impact of a small sub-group of very influential data (i.e. radar observations, experiments 2-3OL) on the forecast as the full amount of data (Exp1, 2, 3).

34) Table 2: I think it is not necessary to give CAPE with an accuracy of hundredth

- We agree with the reviewer.

35) Fig.1: Maybe you can cut the area at 33°N. Is 10m wind in kts or m/s?

- We prefer to keep it as it is. Wind is in m/s.

36) Fig.2: AQ and RM is hard to read. Also the color table is a little bit unfortunate. Is nearly impossible to distinguish between light and moderate precipitation

- We tried to improve the labels AQ and RM. Unfortunately the color table is automatically created by the Italian Civil Protection Department. Color bins are gradually implemented every 2mm for 'cold' colors, every 5mm, 10mm and so on for 'warm' ones.

37) Fig.3: I think you can remove Fig. "B" as this is not relevant for the manuscript

- ok, done.

38) Fig.7 is too small and the numbers in the left corner are unreadable

- The green numbers in the left corner have been removed as suggested by referee#1

39) Fig.9: You can think about giving letters to the subfigures. Then it is easier to cite them

- That's a good advice. We made the same for subfigures of Fig.11

40) Description of Fig. 10: "12h accumulated rainfall between 10UTC and 22UTC 20 May 2008 estimated by the Monte Midia radar".

- Description of Fig.10 has been changed as suggested by the reviewer.

41) Fig.11: think the wind barbs are not necessary when you show accumulated precipitation.

- We clean the figure by thinning the topography, but we prefer to keep the wind barbs. We believe the wind is adding useful information on the dynamics.

42) Fig.12 has a bad quality.

- Fig 12 has been improved.

43) Fig.13: Is it really "mm/h" or "mm/12h"? Also suggest something similar like "The blue line shows Exp0, the red line...." in the figure caption

- It's mm/12h. Fig.13 and 17 have been corrected. The caption has been changed as follows: "ACC (top left), FBIAS (top right), ETS (bottom left) and FAR (bottom right) used for the objective analysis of the four experiments as a function of threshold. The blue line shows Exp0, the red line Exp1, the green line Exp2, the pink line Exp3."

44) Fig. 14-16: Please add the ovals here

- The red ovals have been added to Fig.14-16

45) Fig.17 is too small and please check the grammar in the figure caption.

- Caption in the Fig.17 has been changed: "Outer loops sensitivity: ACC, FBIAS, ETS and FAR for Exp2 . Green line refers to 1 loop; red line to 2 loop; blue line 3 loop"