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Hydrology and Earth System Sciences Discussions

Interactive comment on "Correcting the radar rainfall forcing of a hydrological model with data assimilation: application to flood forecasting in the Lez Catchment in Southern France" *by* E. Harader et al.

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The authors would like to thank reviewer #2 for his or her careful review of the paper. The questions are re-copied below followed by our responses.

Major comments:

1. My first concern is about the definition of R matrix (Eq. 27) using _obs. Can you please justify your approach and add some references to your method? It seems to

me that by doing this you completely eliminate discharge observation error. Because if I understand it well, the observation error will become smaller for higher discharges. However, it is common in many hydrological DA applications to assume heteroscedastic property of discharge observation error. Please, can you comment on this?

The error is not completely eliminated. It is given a small minimum value for all discharges above 2.5 m3s-1 in reanalysis mode. This choice is based on the use of the Nash-Sutcliffe criterion for measuring model efficiency. The Nash-Sutcliffe criterion measures model outputs against observed data, assuming that observed data is the 'truth'. In order to improve this criterion, the algorithm was used to match observations as closely as possible in the reanalysis mode. In pseudo-forecast mode and for very small discharges in reanalysis mode, the observation error becomes heteroscedastic (variance changing). This variance is proportional to the discharge measurement as done in Moradkhani et al., 2005, though an inverse proportionality scheme was selected in this case in order to place more weight on high discharges. Because we would like to improve representation of the event peak, higher discharges are favored.

The following explanations were added to Sect.3:

In reanalysis mode, βobs is selected such that all discharges above 2.5 m3s-1 have the minimum error covariance of 0.01 m6s-2. This choice is based on the use of the Nash-Sutcliffe criterion for measuring model efficiency. The Nash-Sutcliffe criterion measures model outputs against observed data, placing absolute confidence in the observed data. In order to improve this criterion, the algorithm was used to match observations as closely as possible in the reanalysis mode. In pseudo-forecast mode and for very small discharges in reanalysis mode, the observation error becomes heteroscedastic (variance changing). This variance is proportional to the discharge measurement as done so in Moradkhani et al. 2005, though an inverse proportionality scheme was selected in this case in order to place more weight on high flow conditions.

2. P.3545 L.19–22 Can you better justify your approach to define B matrix. It is not

completely clear to me. Furthermore, I would appreciate citing some literature you used for deriving your DA method.

The B matrix represents the background error covariance, which is the variance of the rainfall multiplier. This variance is difficult to define, as it is the uncertainty in a correction applied to the radar rainfall and not the uncertainty of the measure itself. In order to define B, α was assumed to have an error near that of the MFB, which has a standard deviation of 30% and an average deviation of 40%. The standard deviation of α was selected as the higher of these two error estimates as a precaution. This explanation has been added to Sect.3.

Thirel et al., 2011 which uses the same DA technique and Bouttier & Courtier have been added to the references of Sect.3.

3.a) Do you think that the residuals between observed and background discharges in Fig. 8 are caused only by the uncertain precipitation? Can you actually apply DA to correct for input uncertainty when your model is not able to represent the hydrological response of your catchment properly?

The residuals between the observed and background discharges are caused by a combination of structural errors in the model, parameterization errors and radar rainfall errors, not simply uncertain rainfall. This does not preclude the use of data assimilation, which is an important tool for updating uncertain models during flood events. In the case of multiple sources of error, the rainfall multiplier calculated by data assimilation may compensate for some of the other sources. However, not all of the errors resulting from the parameterization can be corrected by data assimilation, as discussed in the new version of Sect.6. Ongoing work on the Lez catchment aims at applying data assimilation to parameter correction.

3.b) How confident are you in your hydrological model when it is unable to simulate consecutive peaks (P.3549)?

The SCS equations have been well-tested and many examples exist in current literature (Abon et al.2011; Han et al., 2012). Given the complexity of the Karstic system underlying the Lez catchment, physics-based models were not well-adapted to this study, since subsurface properties are poorly known. To make up for some of the short-comings of the SCS method, the classical SCS equations have been adapted to better reproduce multiple peaks in succession through the introduction of the drainage coefficient, ds. However, this parameter may not be sufficient to account for the effects of intermittent rainfall. The karst is also thought to have a role in sustaining the discharge during the recession limb (Coustau et al., 2012). In addition to model errors, the radar rainfall error may differ between peaks (e.g. modifications in the raindrop granulometry). The combination of these factors leads to an unsuccessful model representation of multiple peaks. Yet, by taking into account the uncertainties associated with this model, data assimilation may be capable of improving flood forecasting.

4. To get better understanding of your DA method, I would suggest adding a short example, in which you carry out “synthetic experiment”. By doing this simplification you can verify the applicability of your DA method to identify some true precipitation multipliers.

Synthetic experiments were carried out prior during the development of the DA system. A dedicated section was not included because the visual representation provided information similar to Fig.8.

5. I am completely missing a section, where you would discuss and confront your results with other similar hydrological DA applications.

The ’Summary and conclusions’ section has now been changed to a ’Discussion and conclusions’ section. Comparisons of the reanalysis and pseudo-forecast modes have been added as recommended by reviewer #1. A discussion of parallels to previous work has also been added. Much of previous work has focused on using ground rainfall data to correct radar rainfall with data assimilation (Chumchean et al., 2006; Seo et al., 1999). This approach does not directly address the question of suitability for hydrological simulations. Kahl and Natchnebel, 2008 adopted an updating technique which relates the rainfall correction to a hydrological simulation through the minimisation of an objective function. The objective function has two drawbacks: i) it has no explicit solution and ii) does not take into account the observation error. Using a hydrological model along with a simplified Kalman filter, this study addresses the hydrological applications of corrected radar rainfall with the flexibility of sequential data assimilation.

6. Finally, I agree with Referee #1 that the overall wording including punctuation needs to be significantly improved. Some suggestions are listed below.

The paper will be reviewed and corrected.

Minor comments

1. P.3532 L.1–3: Please, rephrase the whole sentence to make really clear to the reader that you update only rainfall multipliers.

This has been changed to " In this case, the control vector contains only the constant rainfall corrective coefficient."

2. P.3532 L.7: How do you define “outer loop”?

The outer loop is an iterative process in which a new analysis is calculated using the previous analysis as the background of the next iteration. This is a commonly used technique in meteorological data assimilation. It accounts for some of the non-linearities present in the model. This is discussed on p.3545, L.7-10.

3. Results should not be in introduction, please remove sentences P.3532 L.11–14.

Changed.

4. Figs. 1 and 2 contain a lot of duplicated information. I suggest that you merge those 3 maps together and plot only the most relevant information. For example, you do not carry out any analyses with Mosson catchment so you do not need to plot it at all.

The information in Figs. 1, 2 and 3 has been merged together and the Mosson catchment removed. The downside of merging the figures together is that some of the titles and small-scale features of the catchment are now more difficult to read.

5. Furthermore, you mention two times “orographic precipitations or rainfall” in the manuscript but I did read anything about the altitude differences in the region.

The following sentence has been added to Sect.2.1.1:

"To the North of the Lez catchment, frontal systems are strengthened by relief changes in the Massif Central."

6. P.3533–3534: I am not sure whether the detailed information on the Karst system needs to have its own subsubsection. You do not carry out any analyses of the simulated model storages, therefore I would reduce it significantly to 1–2 sentences and place it directly after P.3533 L.17. Your main interest is in identifying the rainfall multipliers.

Section 2.1.1 has been reduced to a paragraph following section 2.1. However, it was important to retain some information on the Karst in order to explain errors in the model.

7. P.3534 L.14: Do you mean actual or potential evapotranspiration?

Potential. This has been added to the text.

8. I think that socio-economical aspects fit better into the introduction, so I suggest moving P.3534 L.21–25 on a suitable place there.

These lines were removed from the paper, while keeping the rainfall totals of the September 2002 event in order to illustrate the intensity of events in this region.

9. P.3536 L.7–8: Mention as well the very small magnitude of the observed peak as a possible reason for large MFB.

The May 2007 event also has a very small peak, but has a MFB in the normal range

(1.01). We have changed "were not" to "may not have been" to indicate that the cause of the anomalous MFB is not precisely known.

10. P.3536 L.19–20: Add references to 1) SCS-derived runoff production function and 2) Lag and 3) Route transfer functions.

References to Gaume et al., 2004 and Tramblay et al. 2011 were added.

11. P.3537 L.21: Please, specify the units of A. I guess this A is not in m2 as further written on P.3538 L.19, otherwise the dimensions would not fit in between equations (3) and (4).

This equation was removed in order to reduce section 2.2.1 as recommended in question 12.

12. I agree with Referee #1 and I would suggest reducing the content of the whole subsubsection 2.2.1.

Equations have been removed and the content summarized.

13. P.3541 L.1: Denominator in the Nash-Sutcliffe model efficiency is NOT the variance of the measured discharge, check e.g. Montanari et al. (2009). And please remove as well the multiplier of 100, because later on you do not express NS as [%] but as [-]. Correct corresponding Eq. 16 as well.

The Nash-Sutcliffe criterion as defined in Nash & Sutcliffe 1970 was used in this study. We acknowledge, however, that many other variants of this popular criterion are possible. Eq.(16) will be corrected for units and the reference will be updated.

14. How did you generate Fig. 5? Which kind of data did you use?

This plot uses the ground rainfall for the September 2002 event. Using different values of the rainfall multiplier, the discharge at 3h before the peak was calculated.

15. Eq. (27): What is Qi? Should it be Qobs;i? And I am missing definition of tf

Qi has been changed to Qobs,i. This was added following the equation: "where ti is the initial time step and tf is the final time step of the assimilation period."

16. In general, I do not understand why you use “reanalysis” or “re-analysis”. Is not it better to use simply “analysis”? And what is the difference between “forecast” and “pseudoforecast”?

Reanalysis denotes the product of data assimilation using past data measurements. In this case, the corrected rainfall record using the rainfall multipliers calculated in Sect.5.2 would be the reanalysis rainfall. The analysis is the control vector calculated by data assimilation and it refers to control vectors calculated in both reanalysis and forecast mode. The term pseudo-forecast is used in this paper because data assimilation is applied to past events for which the rainfall is known. In real-time forecasting, modeled rainfall would be used. A modeled rainfall product of suitable quality and resolution for hydrological forecast is not yet available.

17. P.3546 L.17 What do you mean exactly by “batch parameters”? Why are they averaged over time? So are they time-dependent or time-independent? And are the those of V0, w, ds or K0 (P.3547 L.7–8)?

The notation of this section has been standardized. Instead of ’watershed constants’ or ’batch parameters’, ’batch-calibrated parameters’ is used (p.3546, L.11,14&17). These parameters are averaged over time to account for uncertainty in the calibration process due to measurement and model errors which leads to slightly different values for each episode. V0, w and K0 are batch parameters. ds is a mathematical property of the model, as noted on p.3547, L.2-3.

18. Please consider rephrasing the whole paragraph P.3546 L.11–19. For example “Watershed constants” into “watershed parameters”, etc.

See question #17.

19. P.3546 L.7 How did you define “valid” observations?

The range of assimilated discharges can be found on p.3549, L.8-13. The word "valid" was eliminated from p.3546 in order to avoid future concerns about this definition.

20. P.3547 L.7–8: How were those parameters calibrated?

This is explained in the first paragraph of Sect.4 (p.3546). The notation of this section has been improved so that the calibration procedure is clearer.

21. P.3549 L.11 Are the rating curves for discharge below 300 m3 s-1 reliable?

Below 300 m3s-1, the Lez is contained within the main river channel and has available discharge measurements. A rating curve was generated by the French regional environmental agency (DREAL) using a power-law relationship. This relationship has then been verified through studies of the river bed topology. For this range, known sources of error are the interpolation between measurements, instrumentation and the estimation of the river channel geometry. These errors are typically much smaller than those associated with extrapolation of the curve, which is necessary for discharges greater than 300 m3s-1. An in-depth analysis of the uncertainty associated with rating curves can be examined in Di Baldassarre and Montanari, 2009.

22. P.3550 L.10 Provide definition of “outer loop”. What is the difference with external loop (P.3573) and “open loop” (often used as a simulation without DA)?

The outer loop is defined on p.3545,L.7-10. The explanation will be improved to clarify this concept. The "external" loop is the notation for the outer loop used in Thirel et al., 2010. The "outer loop" notation commonly used in meteorology was adopted for this paper. p.3573 will be corrected. "open loop" is a notation unrelated to "outer loop". The open loop is analogous to the background simulation in this paper.

23. To conclusions: Repeat the full names of your shortcuts again (MFB, IE, PH), that people reading only your conclusions understand conclusions independently from the rest of your paper.

This has been added.

24. Table 1: Why is the first and last line in the figure in italics?

These two events had unexpectedly high or low MFB values, as mentioned in Sect.2.1.3. The italics were intended to bring attention to these two events. The italics will be removed since the two events are already discussed in the text.

25. Table 2: Provide explanation for all columns. What is R2, . . . ?

Added to text.

26. Table 4: Provide explanation for all columns, simply refer to Table 2.

Added to text.

Technical corrections:

1. P.3528 L.9: What do you mean exactly by “it”? Do you relate it to previous sentence or to the following?

The "it" refers to the radar rainfall in the same sentence. This has been changed to "Because the radar rainfall input to the model depends on geographical features and cloud structures, it is particularly uncertain and results in significant errors in the simulated discharges."

2. P.3528 L.12: Please, replace “. . . a constant correction to each event hyetogram” with “. . . a constant hyetogram correction to each event”.

Changed.

3. P.3528 L.19: Mention “Nash-Sutcliffe efficiency” instead of “Nash” only

Changed.

4. P.3529 L.5: Rephrase to “neglecting spatial variability of rainfall”.

Changed.

5. P.3529 L.14: Replace “such as radar rainfall” with “such as provided by weather

radar”.

Changed.

6. P.3530 L.10: For clarity state “rain gauge”.

Changed.

7. P.3530 L.20: Correctly “developed”.

Changed.

8. P.3530 L.26: Write “e.g.” before Aubert et al.

Changed.

9. P.3531 L.7: Change “non-variational” to “sequential”.

Changed.

10. P.3532 L.10: Better “between approximately 10 and 400 . . . ”.

Changed.

11. P.3532 L.9: Correctly “occurring”.

Changed.

12. P.3532 L.8: Better move “The analysis was carried out for 19 heavy rainfall events occurring within the Lez catchment in Southern France between 1997 and 2008. The 10 events were of variable intensity and had measured peak flows between approximately 10 and 400 m3 s-1 at the watershed outlet.” to P.3531 L.28: after “. . . model.”.

Changed.

13. P.3532 L.26: Space in between “Lirou, Yorgues”.

Changed.

14. P.3532 L.26–P.3533 L.5: Remove three sentences “Other tributaries . . . in the South”, because it is not important to the reader when you do not take them into account.

Changed.

15. P.3533 L.6: Rephrase “before emptying”.

Changed to

"The Lez River runs for 26 km between its source and the Mediterranean Sea."

16. P.3534 L.18: Rephrase to “particularly in late summer and fall periods”.

Changed.

17. P.3535 L.1: Replace “either” with “both”.

Changed.

18. P.3535 L.2: Replace “or” with “and”.

Changed.

19. P.3535 L.4: Add a reference to the method used by Meteo-France.

This has been added.

20. For all the summation symbols (P) in the manuscript, please use the full form: e.g.PN i=1 that it is clear to the reader, where you start and where you stop summing up.

Changed.

21. P.3535 L.22: Remove comma between location and i.

Changed.

22. P.3536 L.3: Replace “along” with “together”.

Changed.

23. Furthermore, I would prefer “Lez catchment” with small “c”. Any reason for “C”?

This has been changed. The capital "C" was used in order to specify a proper name, such as the "Russian River".

24. P.3536 L.20: Remove the whole sentence “Discharges . . . ”.

Changed.

25. P.3536 L.21–23: Rephrase to “The model was calibrated at hourly time step by Coustau (2011) and Coustau et al (2012)”.

"Hourly time step" has been added to the previous sentence "It operates on independent grid cells..." in order to avoid possible confusion about the model calibration which was done on an event-by-event basis.

26. P.3541 L.21: Add reference to Nash and Sutcliffe (1970) as well. Additionally I would prefer changing your shortcut from IE to more commonly used NS or NSE. Where does your IE come from?

IE comes from "indice d’efficacité." This has been changed to NS.

27. P.3544 L.1: Add to the “control vector” that it is in other words the “posterior”, to be consistent what follows there (a priori).

The control vector is not the a posteriori value of the background control vector xb. The analysis control vector xa is the a posteriori value of the control vector x.

28. P.3547 L.6: Add reference to “equifinality”.

Beven and Freer, 2001 has been added.

29. P.3547 L.24 What does the “Hu2” stand for?

Hu2 stands for humidity of the second soil layer, which is the soil root horizon for the

Météo-France model. This is noted on p.3548,L.1.

30. P.3547 L.24–25: Refer to the location of indicators in Fig. 1.

This has been added.

31. P.3549 L.23 “renalysis” is misspelled.

Changed.

32. Eliminate detailed description of the used colors for individual lines in figures from the text (e.g. P.3549 L.26–27 & P.3550 L.1–2). Include the description in the figure, EITHER in the caption OR in the figure legend. Please, do not duplicate it as it is e.g. in Figs. 8 and 9.

The detailed description has been removed from the text.

33. P.3552 L.22 Better replace “efficacity” with “efficiency”.

Changed.

34. P.3555 L.22 I would be careful with the word “great”.

"Great" has been removed.

35. Table 1: Extend the caption of table.

More details have been included in the description.

36. Table 3: Change stars into dashes and extend the caption.

These changes have been adopted.

37. Figures: 10–15. Size of these figures needs to be INCREASED otherwise it is very difficult to read.

The size of the figures has been increased.

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