Title: Technical note: Analysis of observation uncertainty for flood assimilation and forecasting
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We thank the editor and reviewers for their positive comments, which have helped improve the manuscript. Below we give each comment in bold (abridged where appropriate) and describe how we have altered the manuscript to address the reviewer's concern. We give changes to the manuscript in italic font. Following the suggestions from the Editor and reviewers we have altered the title of the manuscript (for details see response to Reviewer 1 comment 1). We note that several of the comments ask for clarification/additional details about the derivation of the water level observations and their associated uncertainties. To address these comments we have replaced Section 3 by a methodology section with the following subsections:

3.1 Derivation of water level observations.

3.2 Model and data assimilation.

3.3 Quality control and data thinning.

3.4 Potential observation error sources.

3.5 Experimental design.

The section contains material from the original Section 3, some of the material that was originally in the introduction and some additional new material that describes in more detail the observation derivation process and the possible sources of observation uncertainty.

For convenience all alterations in the revised submission appear in blue. For clarity we have altered the order of some material in the manuscript; these sections appear in green but otherwise remain unchanged. All line numbers in the response are for the revised manuscript unless otherwise stated.

1 Reviewer 1

1. **Title: I wonder whether flood assimilation is the most appropriate wording. The authors might consider a slight change in the title (assimilation in flood forecast models).**

   After considering this and other comments made by the reviewers we have altered the title to *Technical note: Assessment of observation quality for data assimilation in flood models*

2. **Page 1, Lines 7 - 8 The estimated correlations do not behave as expected: could you please be more explicit?.**

   We have altered the abstract (Pg 1, lines 7-9) as follows so that it is more explicit:

   'The average estimated correlation length scale of 7km is longer than the expected value of 250m. Furthermore, the correlations do not decrease monotonically; this unexpected behaviour is shown to be the result of assimilating some anomalous observations.'

3. **Page 2, line 13 unbiased: is bias the only error type in Remote Sensing-derived observations of floods?**

Bias is not the only type of error, but it is assumed that any systematic error is removed from an observation before assimilation. We clarify this in Section 2 (Pg 3, lines 14 - 16): *'The observation-minus-background residuals* $\mathbf{d}_b^o = \mathbf{y} - \mathcal{H}(\mathbf{x}^b)$*, also known as the innovations, are assumed to be unbiased. Hence any bias should be removed before assimilation [Dee, 2005].'*

To avoid confusion we remove *'if they are to be unbiased'* from Page 2, line 13 (line numbers for old manuscript version).

We note that a discussion of different error types is now included in section 3.4 (see response to comment 6 and Reviewer 2 comment 7).

4. **Page 2, line 18 as is standard in other assimilation applications: I suggest rephrasing this sentence. Could you please provide examples of the other assimilation applications?**

   To improve fluency and give examples we have reworded as follows (Pg 5, lines 28 - 30): *'Thus, to reduce the number of correlated observations and to avoid dealing with spatial correlation in the assimilation, the current approach is to further thin the data (as is standard in other assimilation applications such as numerical weather prediction and oceanography [Dando et al., 2007, Li et al., 2010]).'*

5. **Page 2, line 19 typically retaining approximately 1% of the pre-thinned observations: I suggest adding at least a reference.**

   This sentence now forms part of Section 3.3 (Pg 5, lines 33) which describes the quality control and data thinning of Mason et al. [2012] .

6. **Page 2, line 20 The authors might consider commenting on the algorithm presented Mason et al. [2012].**

   We have added additional information on the algorithm presented in Mason et al. [2012] in the new sections.

   In Section 3.1 we provide a brief description of water level observation derivation. This includes how:

   - flood extent can be extracted from SAR images by determining regions of low backscatter;
   - the initial flood extent estimate can be refined;
   - the flood extent is intersected with the DEM to provide the WLOs.

   In Section 3.2 we discuss the model and data assimilation. This section consists of some material that appeared in the previous version of the manuscript and some new material that describes how the model can be compared to the observations.

   In section 3.3 we provide a brief discussion on the quality control and data thinning. This section consists mainly of material that appeared in the previous version of the manuscript, but has some additional information about the quality control and thinning procedures. For example we include (Pg 5, lines 23 - 25) that

   'An additional background check is performed where observations that result in anomalous observation-minus-background residuals are discarded.'

   and (Pg 5, lines 30 - 34)

   'The applied thinning, as described in Mason et al. [2012], uses a top down clustering approach in which principal component analysis is used to select observations that have the highest information

content. The spatial autocorrelation of the resulting observations is calculated, and if any significant correlation exists the thinning procedure is applied iteratively until no significant correlation remains.'

7. **Page 2, lines 21-24: is the discussion on DA of satellite-derived soil moisture strictly relevant here?**

   We have removed this sentence.

8. **Page 2, lines 24-30: I believe that moving this paragraph after line 11 could improve the readability of the manuscript. I suggest discussing error types, data thinning, and uncertainty estimation after this general introduction.**

   The discussion of error types and data thinning has been moved to Sections 3.4 and 3.3 respectively (see responses to comment 6 and Reviewer 2 comment 7). As a result the paragraph in lines 24-30 (original manuscript) has moved after line 11 (original manuscript).

9. **Page 2, line 31 directly: is this the most appropriate word? Do the authors mean computed in a systematic way?**

   We have rephrased the sentence as (Pg 1, lines 20 - 22): *'Since the true state of the system is not known, the exact observation errors and their statistics can not be calculated. Instead observation uncertainties must be estimated statistically [e.g. Hollingsworth and Lönnberg, 1986, Ueno and Nakamura, 2016].'*

10. **Page 2, line 34 with good results: would it be possible to clarify this statement?**

    Rather than 'with good results' we state (Pg 1/2, lines 24 - 3) *'The diagnostic has been applied to operational numerical weather prediction (NWP) settings to estimate observation uncertainties [Stewart et al., 2014, Waller et al., 2016a,b, Cordoba et al., 2017]. The use of these estimated statistics in NWP results in a more accurate analysis and improvements in objectively measured forecast skill [Weston et al., 2014, Bormann et al., 2016, Campbell et al., 2017].'*

11. **Page 3, line 4: is a new paragraph required?**

    We have joined the text to the previous paragraph.

12. **Page 3, line 5-6 Thus, we then consider: could you please rephrase this sentence?(e.g. Consequently, ...).**

    We have rephrased this sentence to state (Pg 2, lines 30 - 32) *'To determine the cause of these anomalous results we consider if observations in different sub-domains have different error characteristics. We also consider if the error statistics differ for different phases of the flood event.'*

13. **Page 3, line 7 is related not related: please correct this.**

    We have removed the first 'related'

14. **Page 3, lines 8-9 we show that ....: how is this result related to the papers cited in page 2 line 34? I would like to recommend adding a sentence to clarify the novelty of the study presented in the manuscript.**

    We make it clear in the introduction that (Pg 2, line 34) *'To the best of our knowledge this is the first time that the diagnostics have been applied to estimate error statistics for hydrological data assimilation.'*

15. **Page 3, lines 11-12: could you please improve the fluency of this sentence?**

    We rephrase as (Pg 3, lines 4 - 5) *'Data assimilation is a technique used to provide the best estimate, the analysis, of the current state of a dynamical system. The analysis is denoted* $\mathbf{x}^a \in \mathbb{R}^{N^m}$*.'*

16. **Page 3, line 15: are the superscripts correct?**

    We have swapped the superscripts so the manuscript reads (Pg 3, line 8) $\mathcal{H} : \mathbb{R}^{N^m} \rightarrow \mathbb{R}^{N^p}$.

17. **Page 3, line 21: could you please rephrase the last part of the sentence?**

    We have rephrased the last part of the sentence as (Pg 3, line 14) *'*$\mathbf{H}$ *is defined as the observation operator linearised about the background state.'*

18. **Page 4, line 30 error is repeated.**

    We have removed the repeated 'error'.

19. **Page 4, line 30 gross error measurement: could please the authors clarify this statement?**

    We have rephrased as follows (Pg 5, lines 21 - 22): *'Data assimilation techniques can lose accuracy if presented with an observation that is grossly inconsistent with the model state [Vanden-Eijnden and Weare, 2013].'*

20. **Page 5 line 2 typically: what do the authors mean here? Typically in this dataset or typically in the literature?**

    We clarify that (Pg 8, lines 1 - 2) *'When used in previous studies such as García-Pintado et al. [2015] the dataset has been thinned to a separation distance of 250m, at which the observation errors are assumed uncorrelated.'*

21. **Page 5, figure 1: the authors might consider adding the underlying map (or at least the river network).**

    We feel that the figure may be too cluttered if the observations are plotted over an underlying map. Therefore we have added an additional figure panel alongside the current figure (as Figure 1a) showing the digital elevation model over the domain.

22. **Page 6, lines 9-10: could the authors please clarify this statement?**

    We clarify this comment as follows (Pg 8, lines 10 - 12): *'As we use an LETKF we must use a modified form of the diagnostic (see Section 2). As a result we are not able to calculate observation error correlations for observation pairs with a separation distance greater than* $19km$*.'*

23. **Page 6, lines 17-18: please correct capital letters, full stop.**

    We have corrected the capital letters and full stop.

24. **Page 6, line 20 than those we estimate: I suggest rephrasing this sentence.**

    We rephrase to (Pg 8, lines 22 - 23) *'Therefore, we would expect the true standard deviations and length scales to be larger than those we estimate using the diagnostic.'*

25. **Page 6, line 31: the authors might consider replacing shoulder with something more formal.**

    We replace any occurrences of the word 'shoulder' with 'local maximum'.

26. **Page 7, line 6: is are resulting in the increase... correct? I wonder whether the authors mean that observations in different areas lead to the increase of...**

    We replace the sentence with (Pg 9, line 9) *'It is possible that the local maximum in the correlations is a result of observations on different tributaries of the river.'*

27. **Page 7, line 10 and therefore the results are subject to greater sampling error: could the authors please clarify this statement?**

    We clarify this statement as follows (Pg 9, lines 11 - 13): *'We note that there are fewer observations in the eastern domain. This results in fewer available samples for the calculation in equation (3) and hence the results are subject to greater sampling error.'*

28. **Page 8, line 6 we see: I suggest replacing this with something more formal.**

    We start the sentence with (Pg 9, line 20) *'At the beginning of the flood period'*.

29. **Page 8, line 12: please rephrase this sentence.**

    We rephrase as follows (Pg 10, line 7): *'Fig 7 shows the estimated error statistics for the recession stages of the flood. During this period a high proportion of the observations were in areas which remained flooded but were disconnected from the main river flow.'*

30. **Page 8, line 16 to keep the forecast on track: could the authors please clarify this statement?**

    We rephrase as follows (Pg 10, line 11): *'the assimilation increments were of a smaller magnitude in these last stages.'*

31. **Page 9, line 6: the authors might consider replacing end of the flood with receding limb or something more formal than end.**

    We replace 'end of the flood' with 'during the receding limb of the flood'.

32. **Page 9, line 9 More study is needed in this context: the authors might want to add details on future work/research needs.**

    We alter the sentence so it states (Pg 12, lines 2 - 4): *'However, due to the dependence of the observation error on the choice of observation operator and model resolution, results will differ for each individual user. Therefore, further study may be required to understand how the diagnostic results can best support QC protocols.'*

2 Reviewer 2

From the reviewer's comments we have identified the following points that need to be addressed.

1. **P 5 lines 4-6: As the standard deviation of the WLOs is estimated using rather strong hydraulic hypotheses, I would suggest to change the word measured by estimated for instance.**

    We state that (Pg 8, line 15) *'The assumed standard deviation for the WLOs is 59cm'*.

2. **The way the 59cm is estimated is not so clear to me.**

    In Section 3.3 we state that (Pg 6, lines 1 - 3) *'The measured standard deviation for the thinned data set is calculated by fitting a plane by linear regression to the WLOs. The variance of the*

difference between the WLO and planar surface can be used as an estimate of the observation error variance'.

When discussing the assumed observation error we state that (Pg 8, lines 15 - 16) *'The assumed standard deviation for the WLOs is 59cm; this is calculated as described in Section 3.3.'*

3. **P 4 equation 3: could you please elaborate a little more on the second term. It does not look so straightforward to me.**

   In data assimilation it is assumed that any systematic error is removed from an observation before assimilation. We clarify this in Section 2 (Pg 3, lines 14 - 16): *'The observation-minus-background residuals* $\mathbf{d}_b^o = \mathbf{y} - \mathcal{H}(\mathbf{x}^b)$*, also known as the innovations, are assumed to be unbiased. Hence any bias should be removed before assimilation [Dee, 2005].'*

   In Section 2 we elaborate on the second term of equation (3) by stating that (Pg 4, lines 1 - 3):

   'It is assumed that the observation-minus-background and observation-minus-analysis residuals are unbiased, but this is not guaranteed. Hence the second term of equation (3) .... '

4. **P4 lines 30-32: I found this sentence a little difficult to read. Could you please try to clarify it?**

   Please see response to Reviewer 1 comment 19 as they asked for the same clarification.

5. **P6 lines 7-10: Could you please try to clarify?**

   We rephrase as follows (Pg 8, lines 7 - 10): *'We first use all available data to calculate the average horizontal error variance and correlations. We then consider if the observations of the flood on the Severn have similar error characteristics to the observations of the flood on the Avon. Finally we consider if the error statistics vary for different periods of the flood. For all cases the observation error correlations are calculated at a 1km bin spacing.'*

6. **Could you please mention as well how you estimate the error spatial correlation from the covariance in the bin?**

   We include that (Pg 4, lines 4 - 5) *'To calculate the spatial correlation, the covariance in each bin,* $cov(\beta)$*, is divided by the estimated variance (the covariance at zero distance,* $cov(0)$*).'*

7. **P6 lines 13-15: What is meant by error of representation is not clear to me. Could you please clarify?**

   We include an improved description of representation error in the introduction (Pg 1, lines 14 - 16).

   'The observation error statistics are the sum of the instrument error and representation error [Janjić et al., 2017]. The error of representation arises due to the mismatch in the observation and its model equivalent and it is often correlated and state dependent [Waller et al., 2014, Hodyss and Nichols, 2015].'

   We have added Section 3.4 that discusses the potential sources of observation errors. We clarify (Pg 6, lines 7 - 13) , that *'The representation error arises due to the difference between an actual observation and the modeled representation of an observation; this difference can be a result of:*

   - *Pre-processing/QC error: Errors introduced during the observation pre-processing or quality control procedures.*

- *Observation operator error: Error that arises due to approximations in the mapping between model and observation space.*
- *The error due to unresolved scales and processes: Error that results from the mismatch between the scales represented in the model field and the observations.'*

We then discuss how the WLOs may be affected by each of these errors. This includes that:

- Correlated pre-processing error may exist due to errors in flood extent caused by, for example, high backscatter as a result of emergent vegetation or rough water surfaces. However the procedures in Mason et al. [2012] provide an estimated standard deviation for this error and thin the data to ensure that the errors are uncorrelated.
- The 'nearest wet pixel' observation operator, which is described in Section 3.2 (See response to Reviewer 1 comment 6), is a potential source of correlated error for WLOs. It is possible that in locating the nearest wet pixel and extrapolating information we introduce correlated error.
- The error due to unresolved scales and processes is also a possible source of observation error correlations. Although in this case the model is of relatively high resolution, there are still scales that are unresolved. Previous studies that have considered these scale mis-match errors have found that they are typically correlated [Janjć and Cohn, 2006, Waller et al., 2014].

In Section 3.5, we refer the reader back to the details in Sections 3.3 and 3.4. (Pg 8, lines 15 - 17):

'The assumed standard deviation for the WLOs is 59cm; this is calculated as described in Section 3.3. The value accounts only for the preprocessing error, and not for any error introduced by the approximations in the observation operator or scale mis-match errors and, therefore, may be an underestimate of the true error standard deviation.'

8. **The Authors should try to elaborate a little more on how the WLOs are obtained and what could be the sources of the error spatial correlation. Authors should in my opinion refer to some interesting remarks with that respect in Mason et al 2012.**

   We note that Reviewer 1 also asked for some elaboration on how the WLOs are derived. We include this information in Sections 3.1, 3.2 and 3.3 (see response to Reviewer 1 Comment 6). In section 3.4 we discuss the possible sources of the error spatial correlation (see response to comment 7).

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