Response to reviewer's comments on the manuscript

"A multi collocation method for coastal zone observations with applications to SENTINEL-3a altimeter wave height data"

by Johannes Schulz-Stellenfleth and Joanna Staneva

We thank Reviewer 1 for many helpful and constructive comments. We appreciate the time and effort you have obviously invested in this. In the following, You find point by point responses to all comments given in the review. The original comments are given in bold black and the respective responses in green italic. The page and line numbers refer to the original version and do naturally not exactly match with the revised manuscript.

Anonymous Referee #1

This paper describes a method to extend the established 'triple collocation' technique, used to quantify errors in measurement and forecast datasets, for use in the coastal zone and other regions where correlation length scales are short, and/or where observed data are sparse. This represents a significant addition to existing literature on triple collocation with some novel impacts. The paper is well written and clear and, as such, I would recommend it for publication subject to some minor corrections and additional clarifications/discussion points as outlined below.

Clarification / Discussion points:

The suggested additional discussion points are focused around the description of measured data in section 3 and the results in section 4.

Clarifications required in section 3 are as follows:

- **(with reference to previous studies, e.g. Janssen et al., 2007) a choice has been made to use satellite altimeter data in its 1Hz form, whereas these data have previously been super-observed in order to match a representation scale close to that of model or in-situ data. There is no particular issue in using the data this way, but possibly this impacts some of the later results regarding error variability. So could the authors please clarify the representation scales attributed to each of the data sources?**

  Thanks for the comment – we have added the following text at the end of Section 3.3.

  "Compared to previous studies (Janssen et al, 2008; Caires and Sterl, 2003), the spatial resolutions of the three analysed data sources are in quite close agreement. The effective resolutions of the altimeter and the insitu instruments both depend on the actual sea state. For the altimeter typical footprint sizes are between 1 km and 10 km as explained in Section 3.1. For the insitu data, the translation of the typical 20 min averages to spatial averages is determined by the group velocity. For example, the energy propagates with about 15 km/hour, if the dominant wave length is 50 m long and the water is deep (>50 m). A 20 min temporal average would therefore correspond to a 5 km spatial average in this case, which is in good correspondence to the spatial model resolution of about 3.5 km. We have therefore used the original data for the analysis and not generated super-observations by averaging, as done in Janssen et al. (2008) and Caires and Sterl (2003), who used wave model data with significantly coarser resolution."

- **(as part of the above) the dataset from the JCOMM verification project supplies two versions of in-situ observations; the raw values, and a QC'd value at synoptic hours but derived from a mean of the waves over several hours surrounding this time. It is not entirely clear which of these was used (my impression is the former?) and what QC/super-observing procedures were applied to these and the BSH data.**

The provided insitu data are hourly except for the BSH observations, which are every 30 min. These data are raw observations, which were run through basic sanity checks. We modified the last part of section 3.2 on page 12 according to:

"The GTS data have a temporal sampling of 1 hour, while the BSH buoys provide observations every 30 minutes.The insitu observations represent raw values and were checked for unrealistic wave heights. Looking at all the insitu stations for the analysed period in summary, the provided significant wave heights were in the range between 0.1 m to 7.8 m. These are realistic values for the North Sea (Semedo et al., 2015) and hence all observations were used in the analysis.

- **In addition to the offshore oil platforms (downward facing lasers/radars) and waveriders, one or two points in the JCOMM dataset are, I believe, measurements at lightvessels It is worth noting that a known low bias exists in the reports from these locations, due to the hull response of the platform (Anderson, G., Carse, F., Saulter A., and J. Turton, 2016: Quantification of Bias of Wave Measurements from Lightvessels. J Op Oceanography http://dx.doi.org/10.1080/1755876X.2016.1239242)**

We modified the text in Section 3.2. according to

"Due to the lack of respective metadata, it was in general not possible to distinguish between different types of instruments, e.g., waverider buoys, lightships, or platform mounted devices. One exception is the station "62170" near the east English Channel entrance, which is identical to the light ship "F3" mentioned in Anderson et al.,(2016)."

After eq. 42 we added the following text:

"It is interesting to note, that for the location of the lightvessel ``62170'' near the east entrance of the English Channel (see Fig.1) the satellite and the model show a positive bias of about 0.3 m and 0.2 m respectively. According to Anderson et al. (2016), one can expect a systematic low bias for wave height measurements from lightvessels of about 0.3 to 0.4 m. It is thus possible, that the estimated high bias for satellite and model is in this case an artefact caused by the violated assumption of bias free insitu observations."

In addition, we added a label for the lightvessel "62170" in Fig. 1 and Fig. 2b.

Discussion points in section 4 are:

- **the result that the buoys have the smallest errors is different to Janssen et al (2007)'s findings, in which buoy data were found to contain large errors. Caires and Sterl (2003) found something more in line with this study. This raises a question as to how much the results of triple collocation are influenced by the choice of in-situ data and use of super-observation. Janssen et al 'smoothed' their data significantly in attempting to use a unified representation scale (needed for data assimilation) and then explained the result for in-situ data as due to significant variations in the way in-situ data was processed (subsequent papers, e.g. Durrant et al 2009, seem to confirm this). In this paper the authors appear to have used the data in a more raw form and, although different platforms make up the in-situ dataset, behaviour within a regional observation network may well be more self-consistent than the global dataset used by Janssen et al. For the purposes of this paper, it would therefore be useful for the authors to contextualise the treatment of the study data and results relative to some of these past studies. This is in order that readers can correctly attribute some of the headline results about buoy/altimeter errors to the choice of data processing rather than the updated triple collocation method.**

  Thanks for this comment. We have added the following text as a final paragraph in Section 4 on page 15:

  "The finding that, on average, the insitu stations have the smallest stochastic errors is at first sight in disagreement with results presented in Janssen et al. (2007). One has to take into account however, that there are a number of significant differences in the analysis. First of all, a global wave model with 55 km resolution was used in the former study, whereas the computational model grid used in our analysis has a resolution more than 10 times higher. It is unlikely however, that the coarser model resolution is the only factor, because Caires and Sterl (2003) also concluded, that the insitu stations have the smallest stochastic errors using wave model output with even coarser resolution (1.5^o) than used by Janssen et al. (2007). Both studies introduced altimeter super-observations (averages over subsequent measurements) to make the altimeter observations more consistent with the model estimates. In the present study this was not considered necessary, because the altimeter and model resolutions are in much closer agreement. The second major difference with respect to previous studies is the geographic locations and the type of altimeter data considered in the analysis. Janssen et al. (2007) investigated global ERS-2 and ENVISAT altimeter data sets, while Caires and Sterl (2003) concentrated on TOPEX and ERS-1 altimeter data acquired over the Pacific and the US east coast. This means that there are certainly differences both with regard to the background wave statistics and the satellite and insitu observation errors. A third important difference between the studies is the applied collocation criteria. Janssen et al. (2007) required the model, insitu and satellite estimates to be within 200 km distance and Caires and Sterl (2003) used a smaller collocation distance of 0.75^o The allowed distance of 10 km used in the present study is still significantly smaller than that, and the collocation errors are therefore also likely to be smaller. For the above reasons one cannot conclude that the present study contradicts the results in Janssen et al. (2007). The conclusion is rather, that a common set of reference insitu data and collocation criteria are desirable to make different studies more comparable."

- **some expansion on the comments in the paragraph starting at P15-Line7 are, perhaps, warranted. For example, there is significant location to location variability in bias within buoy clusters in open waters (Figure 6), a number of buoys have high relative uncertainties (Figure 7), and one location in the southern North Sea shows similarly high stochastic errors to the two outliers identified in the northern North Sea. Combined with the known bias issues for**

lightvessels (some of which I think are included in this dataset) I think these results present an opportunity to ask whether in-situ networks, whilst a desirable reference, truly provide the consistency needed in this context?

We fully agree, that the heterogeneity of the insitu observations is a problem in the analysis. We have added the following text at the end of Section 4 to emphasize this point more: .

"It is evident that the observed heterogeneity of insitu measurements is a big complicating factor in the analysis. Wave model computations and satellite altimeter observations have reached a level of accuracy, where further improvements require a very careful selection and treatment of validation data sets. This in particular requires more knowledge about the type of insitu instruments and applied data processing techniques (e.g., averaging intervals). This could also be an argument for investments into dedicated validation instruments with more transparent and better documented error characteristics and quality control. The deployment of such instruments should take into account both research aspects and requirements for operational use."

Suggested minor corrections to text:

P1-Line10: 'presented method allows use of a large variety'

This was changed as suggested

P1-Line12: 'sources is too big to assume that they'

This was changed as suggested

P2-Line12: 'room for improvement, in particular'

This was corrected.

P3-Line22: 'an estimation of cross covariance' (delete leading 'to')

This was modified as suggested

P4-Line3: 'the track to assume that all three instruments'

Comma was removed

P4-Line9: 'the spatial variation of the "truth" are required'

Replaced "is" by "are"

P4-Line16: 'with a small number of samples'

Added "a"

P4-Line21: 'This includes a new step in the analysis, in which estimation errors are quantified.'

This was modified as suggested

P4-Line22: 'Section 5 describes the combination'

This was modified as suggested

P5-Line6: 'the "truth" cannot, in general, be represented by'

This was modified as suggested

P5-Line9: 'the approach in eq. 4 allows the addition of higher order terms'

This was modified as suggested

Figure 5: 'Bias and calibration errors were corrected for the model and satellite'; I'm not sure I understand this statement in the context of the figure, please clarify or remove.

We replaced this formulation by the following, which we hope is more clear:

"The model and satellite data sets were corrected according to the slope and bias parameters estimated in the collocation procedure.

P15-Line28: 'allows estimation of the errors of all'

This was corrected

P17-Line1: 'allow an estimation of the uncertainties'

This was modified as suggested

P17-Line10: 'allows an estimation of the errors'

This was adjusted accordingly

P19-Line2: 'In this study we considered only linear models, but this is not a restriction of the method, since more sophisticated functional forms (e.g., bilinear functions) can be easily integrated.'; Is it worth commenting that such forms are likely to be required in near coastal zones, where nonlinear processes are more likely to drive the spatial variations than in the offshore?

We agree and have added the following sentence at the end of the first paragraph of the conclusions on page 19:

"Such higher order approaches are certainly desirable for coastal areas with strong spatial variations, however they require a larger number of data sources (compare eq. 9)."

P19-Line13: 'allowed a demonstration of the usefulness'

Considering a comment from Reviewer 2, this part was reformulated as follows:

"The number of available samples was relatively small and estimation errors had therefore to be taken into account. The usefulness of the derived error bars for the interpretation of the data could be demonstrated."

P19-Line16: 'biased high, in particular at higher sea states'

This sentence was replaced following a comment by reviewer 2. .

Additional Changes

- *Corrected the n_o value for the 1D case in table 1 (from 6 to 5)*

- *Updated reference for Wiese et al, 2018*

- *Completed bibliography information (e.g., doi) for several references.*

P19-Line16: 'biased high, in particular at higher sea states'

This sentence was replaced following a comment by reviewer 2. .