Noumea: A new multi-mission Cal/Val site for past and future altimetry missions?

Clémence Chupin et al.

Response to reviewers

Dear Reviewers,

We thank you for your interest in our study and for your detailed and helpful comments which improved the coherence of the paper and its understanding. We have tried to consider your comments as much as possible. For any remarks regarding incorrect formulas, wrong spelling or minor suggestions in the text, please find the attached PDF with tracked changes. Below is a point by point response to the main comments.

Reviewer 1 – Christopher Watson

This paper presents an analysis of various types of in situ data from the Noumea lagoon in New-Caledonia in order to assess the utility of the site for ongoing altimetry validation purposes. The work replicates a method whereby a suite of in situ measurements are used involving a bottom pressure gauge, surface GNSS buoy and coastal tide gauge. In addition, a novel towed sea carpet is used to assess local geoid slope. The work is generally presented to a high standard, making a strong case for the suitability of the site for this purpose. A number of areas within the manuscript would benefit from some revision and clarification - I therefore consider that the manuscript warrants publication following consideration of the following comments. I have summarised my more substantive comments below and have attached an annotated PDF which contains many more minor comments/suggestions throughout the manuscript.

Thank you for summarizing the points requiring clarification. We hope that the additional information provided after will help to clarify our message.

1. One of the characteristics of existing validation facilities is a robust understanding of vertical land motion. In this paper, I felt that review of the land based GNSS sites and existing VLM time series was lacking - VLM was mentioned at various stages in the manuscript (including divergent estimates from ALT-TG records) but I felt this needed greater context and quantitative information presented to the reader. I was left feeling uncertain regarding the geophysical context (e.g. proximity to co-/post-seismic signals), and wanted more of a sense of what the current GNSS record shows in terms of linearity/noise etc. Some additional review of previous work, plus perhaps some plots of GNSS time series in the appendices/supp material would be of benefit.

Since the primary purpose of our article is to introduce the data acquired as part of the GEOCEAN-NC campaign, we did not focus on the geophysical context of the site and the GNSS-based ground movements. Considering the results obtained, it appears that this information is indeed missing. Following your suggestions, we thus work on 3 points:

- We add the Appendix A that summarizes the geophysical context of the Lagoon and the global and local hydrodynamic context. It also provides a review of previous results about sea level evolution and vertical land motions, and shows some permanent GNSS stations time series and tide gauge results.

- We update the Noumea site context (Section 2.1) with new information:

  [Lines 83 - 101] *In the Southwest Pacific, the lagoon surrounding New Caledonia (Fig. 1a) is the world largest lagoon with a surface of 24,000 square kilometres. Located in an active tectonic area on the Indo-Australian plate, occasional earthquakes inducing rapid vertical displacement could occur (Ballu et al., 2019). Contributions of non-tectonic processes (i.e. subsidence, post-glacial isostatic adjustments, etc.) to vertical displacements are estimated to be less than 1mm/y in the area (more details in Appendix A).*

In the present study, we particularly focused on the southern part of the lagoon, near Noumea city (hereafter named "Noumea lagoon", Fig. 1b). With an average depth of 15-20 m, its dynamics are mainly dominated by semi-diurnal tides, with a mean tidal range varying from about 1.4 m at spring tides to 0.6 m at neap tides (Douillet, 1998). A more detailed description of the lagoon hydrodynamics is available in Appendix A.

[...] Previous studies have shown the difficulty of reconciling long-term sea level evolution estimates in this area, because altimetry, tide gauge and GNSS land-based observations do not provide consistent information (Aucan et al., 2017; Martínez-Asensio et al., 2019; Ballu et al., 2019 and Appendix A for a detailed review of these studies and existing time series). For example, over the altimetry period (1993-2013), Aucan et al. (2017a) find an uplift of +1.4 ± 0.7 mm/y from tide gauges and altimetry measurements that could not be explained by VLM from inland GNSS stations.

- In the results, we now refer to Appendix A when discussing the [Alti-TG] variations observed (see Section 4.2.4)

2. The hydrodynamical characteristics of the lagoon were of interest to me given these would often generate a gradient in sea level observed at the coast, at the location of a bottom pressure gauge and then further offshore at an altimeter measurement location. Given the agreement between the tidally corrected tide gauge and BPR locations, this doesn't appear to be a major issue for this site. I feel more could be made of this point - further, more detail could be provided regarding the quality of the tide gauge record (e.g. RSL trend(s), description of dominant non-tidal variability etc).

The GEOCEAN-NC campaign was a real opportunity to study the hydrodynamic of the lagoon. This is encouraging by the deployment of 3 pressure gauge on a line linking the outside border of the coral reef to the Noumea tide gauge, with the idea of quantifying a potential setup in the lagoon. A first analysis of the resulting time series did not show any major clues of a setup in the lagoon. However, to have a better idea of the lagoon dynamics, we added some context in the site description section [Lines 83 - 101] and also some specific information in the new Appendix A (i.e. details about the hydrodynamic context of the lagoon, RSL tide gauge trends from previous studies, an overview of some tide gauge time series, ...).

A good point was made about considering the tidal gradients between the buoy and the pressure sensor, which are about 4km apart. We therefore used the output of the SCHISM hydrodynamic model, provided by Jérôme Lefevre from IRD in Noumea, to compute the tidal gradient between the two positions. Results shows that over the 3 days of the GNSS buoy deployment, we could have height differences up to ± 1 cm between the buoy and the pressure gauge location (see Appendix D for more details). When considering the differences [SSH_buoy – SSH_pressure], adding the gradient does not significantly change the mean value but improves the distribution of the residuals. We have subsequently considered this tidal gradient to correct the observations of our pressure sensor. We add this information in Section 3.3 and in the Figure 2.

[Lines 187-194] To extend the comparison, we used the 1-year length pressure gauge 2019x time series. The pressure gauge deployment site, located about 4 km south of the Sentinel-3a and Jason-series cross over (Fig. 1b, orange dot), was chosen as a compromise between distance to the tracks intersection and the depth limitation of the SBE26plus (20 m). An analysis of the Significant Wave Height (SWH) from both sensors shows that, despite the distance, they roughly monitor the same sea state (details of this analysis are shown in Appendix D). Thanks to the SCHISM hydrodynamic model output (Zhang et al., 2016), we also highlight a remaining tidal gradient between the two sensors that could reach ± 1cm in amplitude (see Appendix D for more details). When looking at the centimetric level, this must be considered: in the following, we then apply this tidal gradient to the pressure gauge observations to be in line with the crossover tidal regime.

3. Several aspects of the GNSS buoy solution appeared to lack explanation. Variability in the GNSS solution is perhaps higher than I expected - I also expected to see greater comparison of the buoy v tide gauge when deployed in the harbour. The buoy data appears to be 1 sample per 10 seconds (I initially thought 10 Hz but statements in the appendix confirm 2 epochs = 20 seconds). Given this is slower than the wave period, there is significant scope for aliasing here - this choice needs to be defended, or the likelihood of aliasing further explored. There are also some further clarifications required on the GNSS processing settings used (eg Kalman filter configuration, mapping function selection etc) - see the annotated PDF for further details.

Thanks to highlight this issue: choosing the best solution for positioning our GNSS buoy was a real question. The full comparison between the buoy and the tide gauge has been presented in another article (see Chupin et al. 2020) and we just cite this article here. There is no doubt that there is still room for improvement with our solution, especially as this is the only way to fix the absolute datum of our in-situ data.

To complete our description, we add more details about the buoy deployments in Section 2.2 [Lines 116-120] and at the beginning of section 3.2:

> [Lines 158-163] *During the campaign, a GNSS buoy was moored at multiple locations in the lagoon (see Section 2.2) and the first step of the data analysis concerns the measurement session during 3 days at the altimeter crossover point (Step 1 in Fig. 2). The processing of these data is essential as it constitutes the basis for the absolute attachment of our in-situ observations. In that sense, all errors related to GNSS processing or the application of sensor bias will directly affect the comparison with the altimeter measurements. In particular, it is important to keep in mind that during the calibration session with the Numbo tide gauge, we found a bias of 1.7cm with the tide gauge which is not yet fully understood (more details in Chupin et al., 2020).*

GNSS measurements were made at 1Hz (1 obs per second), but when processing the data with GINS software, errors occurs with 1Hz dataset. With a rate of 1 obs per 10 seconds, the computation worked and we finally chose this solution for the further processing. The settings for the GINS computation have been updated in Appendix C, with more information about atmospheric corrections and references to algorithms used.

4. The magnitude and subsequent removal of trends in BiasAlt time series (Figure 9) requires further explanation and defence. The trend for Jason-1 is ~-4 mm/yr which is noticeably different to Jason-2 and Jason-3. Is there an explanation for this? and coming back to point #1, could VLM be involved? Also relating to Figure 9, there appeared a number of outliers in the bias time series that warrant further investigation and possible discussion - e.g. three records for Jason-2 undoubtedly bias the standard deviation of this record and could be removed with justification. Are these symptomatic of erroneous altimeter data or do they provide insight to the lagoon dynamics? Comment on this would be insightful given the focus of the paper.

We update Figure 9 with our last results. It is important to note that in panel B, we do not apply any trends correction on the time series, only the vertical offset extract from our bias estimates. In Figure 9 panel A, while we do not have any significant trend for Jason 2 and Jason 3 periods, there is still a -4mm/y trend over Jason 1 dataset. We add a paragraph in Section 4.2.4 to highlight this:

> *[Line 400-405] While we do not obtain significant trends over Jason 2 and Jason 3 periods, our results show a subsidence of – 4 ± 1 mm/y for the Jason 1 period [2002-2008]. At this time, the VLM estimates at NOUM permanent GNSS station also show a subsidence (e.g. a trend estimates of -2.5 ± 0.5 mm/y over [2000-2007] with the SONEL-ULR7 solution). However, this value varies greatly depending on the time-span and the solutions considered (see Table A2 and Fig. A3), and further investigations are needed to explain this subsidence (remaining errors in the altimetry process, more robust trend estimates over this period, etc.).*

Before presenting our altimeter bias time series, we use the information on bias dispersion and mean MQE value to filter our data. In this reviewed version, we also apply a basic outlier algorithm method based on interquartile range to remove some outliers on the final bias time series. A paragraph detailed these steps in the introduction of section 4.2.

[Lines 320-330] At each pass, we therefore subtracted the $SSH_{in\ situ}$ from 20 Hz SSH_{alt}. All measurements within ± 1 km (about ± 0.17 s) from our comparison point are averaged to obtain a mean bias and an indicator of the altimeter bias dispersion. This method does not follow the standard approach used in Cal/Val sites, which consists in interpolating all corrections at the Point of Closest Approach (PCA) (Bonnefond et al., 2011; Watson et al., 2011). However, our method allows us to reject cycles where the standard deviation of the mean bias is greater than 10 cm. In the GDRs, we have also collected the range MQE parameter. In the altimetry process, the retracking step allows to determine the range by fitting a theorical model on the radar echo recorded by the altimeter. We thus have access to a metric to assess the quality of the radar echo retracking result: the closer the MQE is to zero, the better the chosen model reproduce the measured waveform. With our methodology, we thus have access to the mean MQE value over the ± 1km around the comparison point. After analysing MQE values on along-track data (more details in Appendix G), we decide to remove cycles where the MQE average exceeds the threshold value of 0.01. Finally, we apply a basic outlier detection algorithm based on the interquartile range method on the bias time series.

5. The absolute bias series presented are ~46 mm higher than other validation facilities. I wonder if the permanent component of the solid Earth tide has been appropriately considered in the analysis? This amounts to be ~34 mm at this latitude. The sign of this term would reduce the difference (assuming it has not already been applied). Without correcting for this bias, some of the statements made in the conclusions are not quite appropriately defended and require revision (see annotated copy). Regardless of the permanent component of the solid Earth tide, the conclusion needs to make it quite clear that the absolute datum for this work is obtained from just a single buoy deployment - some mention of the likely uncertainty associated with the absolute datum is therefore required.

The question of absolute referencing of our *in situ* observations is an important issue in our study. Regarding the question of the permanent component of the Solid Earth Tide (SET), we have confirmed that our GNSS solution does include the SET cyclic and permanent component. However, it appears that in the altimeter GDR, the *solid_earth_tide* variable includes only the SET variable component, and that the permanent component is in the *geoid* parameter. As we did not used this *geoid* variable but our own geoid gradients, the altimeter observations were not corrected from permanent SET. We thus update our processing steps to add this permanent component in the altimeter measurements. We describe this issue in Section 4.1.2 and update the Table 2.

[Lines 298-306] Finally, altimetry satellites do not fly over the exact same point at each pass: it is therefore necessary to consider the height difference between the comparison point and the actual pass of the satellite track, which we approximate to be the geoid height difference ($\Delta R_{geoïd}$). Using CalNaGeo observations during the GEOCEAN-NC campaign (Fig. 1b, blue lines), we demonstrate that the geoid gradients from the XGM 2019e gravity field model are the most suitable in our area (details are available in Appendix E). At each pass, we therefore use this model to determine the geoid gradient to be applied. However, in the GDR used, the geoïd variable integrates the permanent component of the solid earth tide (ΔR_{set_perm}), while the cyclic component (ΔR_{set_cycl}) is including in the solid_earth_tide variable (see Jason-3 Products Handbook, 2020 and IERS Convention, 2010 for more details about this geophysical component). In our area, this permanent component reaches 3.2cm and must be corrected in the altimeter processing for a suitable comparison with the in-situ measurements.

Table 2. Altimetric corrections used to derive the SSH

Parameter		Correction used
Ionosphere (ΔR_{iono})		GDR Ionospheric mean delay between [-23.85°; -22.5°]
Troposphere (ΔR_{tropo})	Dry	1Hz GDR correction linearly interpolated at the 20 Hz measurements
	Wet	Radiometer / ECMWF model / GNSS Corrections linearly interpolated at the 20 Hz measurements
Sea State Bias (ΔR_{SSB})		1Hz GDR correction linearly interpolated at the 20 Hz measurements
Geophysical (ΔR_{geo})	Ocean tide loading	
	Solid earth tide (Cyclic component - $\Delta R_{set_{cycl}}$)	
	Pole tide	
Geoïd	Gradient ($\Delta R_{geoïd}$)	XGM 2019e gravity field model (Zingerle et al., 2020)
	Solid earth tide (Permanent component - $\Delta R_{set_{perm}}$)	Computed from equations from *IERS Convention* (2010)

We have tried to emphasise this question of the absolute referencing of our *in situ* observations along the paper:

- In Section 3.2 regarding the GNSS processing of the Buoy (Lines 158-163)
- In the discussion of our results (Section 4.2.3)

> *[Lines 376-386] The consistency of these results suggests that our methodology is suitable for estimating absolute biases. However, one must remember that it may remain uncertainties in the determination of the $SSH_{in\ situ}$. In this study, the absolute referencing of the in situ data is based on the 3 days of the GNSS buoy mooring, and many factors can influence these results at the centimetric level. These include the choice of the GNSS processing parameters, inaccuracies related to the integration of sensors biases or reference system changes, and the effect of the tether tension on the buoyancy as demonstrated at Bass Strait site (Zhou et al., 2020). One need to remember that during the buoy calibration session, we found a bias of 1.7cm with the tide gauge which is not yet fully understood (Chupin et al., 2020). Besides, although we show that our tide gauge data transfer method is relevant (see Section 4.2.2), there may remain some unaccounted-for dynamic processes between the tide gauge and the comparison point that may lead to inaccuracies. To consolidate the vertical datum, new geodesy measurements with a good calibration session should be conducted to reduce uncertainties in the $SSH_{in\ situ}$ estimation and better constrain the altimeter biases.*

- In the conclusion

> *[Lines 447-450] These results are very encouraging, despite the uncertainties about the vertical referencing of our in situ observations (see Section 4.2.3). Additional geodetic measurements with buoys and pressure sensors at the crossover location could help to control and consolidate this vertical datum.*

- In the abstract

> *Overall, our estimated altimeter mean biases are slightly larger by 1-2 cm compared to Corsica and Bass Strait results, with inter-mission biases in line with those of Bass Strait site. Uncertainties still remain regarding the determination of our vertical datum, only constrained by the three days of the GNSS buoy deployment.*

6. I feel the abstract lacks quantitative statements to best represent its claims - I at least expected statements around the level of variability observed in the absolute bias time series and stability of the vertical datum in order to make the case for the location. Uncertainty also requires some mention in the abstract (e.g. the buoy issue raised in the previous point). I also note that the final comment in the short summary about sea level evolution in the lagoon is not covered in the abstract - these should be revised to be more consistent.

Thank you for raising this issue : to better represent the content of the article and the issues addressed, the abstract and short summary have been rewritten to include quantitative information and to refer to the long-term comparison. It is now more in line with the content of the paper.

7. The paper could be strengthened by further elucidating the case for why further cal/val sites would be of benefit to the altimetry community. The rationale for altimetry validation is important - it is a fundamental component of mission design and takes many forms. I would like to see the authors address this point which would assist to build the justification behind the publication.

Originally, our study in the Noumea lagoon aimed to better understand the altimetry data (characterising the measurements, analysing the effect of land contamination, understanding the atmospheric corrections to be used, etc.) and to test new in situ acquisition methods. This turned out to be in line with the philosophy of absolute Cal/Val experiments. We have therefore reworded our introduction, emphasising the need to understand all these uncertainties to improve sea level measurement.

Reviewer 2 - Anonymous Referee

Chupin et al. assess a variety of different measurements (tide gauge, satellite along-track data, GNSS, etc.) in the Noumea lagoon. The area is of interest as a long-term validation site altimetry mission. The results reveal new insights into sea-level changes in the area. The methods are generally sound and the study should eventually be published. However, as a non-expert is some of the different measurement systems, I feel that the manuscript could benefit from a couple of clarifications. This can certainly be achieved by a few minor adjustments.

Thank you for your feedbacks. We have tried to be as complete as possible on the sensors used and the processing steps, which makes the article quite long and sometimes complex. We have tried to improve this with this review.

Main changes :

1. The analysis of vertical land motion could be done a little more thoroughly. First, the authors provide ideas why their estimate might differ from the conclusion reached in Aucan et al. (2017). However, this can easily be proved by comparing the rates (over their overlapping periods) derived from gridded and along-track data. Second, I think the comparison to GNSS could also be done over overlapping periods to see how time-dependent it is.

To have a more complete overview of the VLM in the area, we add Appendix A that describe the geophysical context of the area and review previous works about sea level trends in the area. We also add some more context in the site introduction (Section 2.1 - Lines 83 - 101). In the results, we now refer to Appendix A when discussing the [Alti-TG] variations observed (Section 4.2.4).

2. I feel that the paper is written very technically, which is ok for the topic, but I think it would be beneficial for the wider audience if the authors could significantly reduce the number abbreviation and explain all terminology (e.g., SWOT, DT-INSU, etc.) used. The latter might be obvious to experts, but certainly not to a wider audience that might be interested in this research.

We try to improve the readability of our paper by explaining some technical terminology. Please see the attached PDF file with tracked changes for more details.

Specific comments:

- Line 35: or propagating signals that are trapped to the coast (https://link.springer.com/article/10.1007/s10712-019-09535-x).

As we have reworded the introduction to highlight the need to better understand uncertainties in altimetry data, this sentence has been deleted. Therefore, we have not added this relevant reference.

- Line 92: Could you please specify in 1-2 sentences what a CALNAGeo GNSS carpet is?

We complete the description of CalNaGeo system in Section 2.2, and link to the study of Chupin et al. 2020 that describe the CalNaGeo carpet.

> *[Lines 111-115] For the 3 weeks of the campaign, a GNSS floating carpet (i.e. CalNaGeo) was towed by R/V Alis along and across altimetry tracks, and inside and outside the lagoon (Fig. 1b, blue lines). This system consists of an inflatable boat connected to a floating soft shell, on which a geodetic GNSS antenna is installed (see Chupin et al., 2020 for a detailed description). Several studies have demonstrated the capability of CalNaGeo to accurately the map sea surface in motion in various sea and weather conditions (Chupin et al., 2020; Bonnefond et al., 2022b).*

- Line 95: What's DT-INSU? The DT-INSU is the French *Division Technique de l'Institut National des Sciences de l'Univers*. We add this description in the text.

- Line 135: What's the GINS software? Please specify.

We update the paragraph about GNSS processing (Section 3.2) to give more details about the software and method used. We also add more information about GNSS processing options in Appendix C.

> *[Lines 165-170] The kinematic processing of the GNSS data was carried out with the GINS software, a scientific GNSS software (Marty et al., 2011), using the Precise Point Positioning (PPP) mode. Developed in the 90s, this method makes it possible to determine a point position without using a reference GNSS base (Zumberge et al., 1997), and recent improvements of GNSS processing allows to compute the height of a GNSS buoy with a centimetric accuracy (Fund et al., 2013). The 10s buoy observations (i.e. 1 observation every 10 seconds) are processed with GINS PPP mode with the integer ambiguity resolution option (details of the processing option in Appendix C, Table C1).*

- Line 142: What is "time-dependent vertical scale"?

Thanks to mention this point that indeed lacked precision: we have therefore completed our statement.

> *[Lines 171-174] The resulting sea level time series is expressed with respect to the IGSR3 reference system, that is used to make the REPRO3/MG3 orbital clock products. There is no translations/rotations vs ITRF2014, only a time-dependant vertical scale and that could be approximate with : + 7.9 + 0.19 (t – 2010) mm.*

- Figure 3: I guess S3a is Sentinel? If so, I would suggest just using "Sentinel"

In our study, we use observations from the Sentinel 3 altimeter. Two Sentinel 3 satellites are in orbit, but we only use data from the Sentinel-3a mission. We have therefore kept this notation ("S3a") so as not to confuse readers who might use other dataset.

- Line 198: fly over the area (is) for about 10 seconds - This error has been corrected.
- Line 215: What are the EUMETSAT portals; please add link

We add the description of the EUMETSAT portal in the text, and add a link to the website.

> *[Lines 256-259] These data are disseminated by EUMETSAT, the European Organisation for the Exploitation of Meteorological Satellites, previously on their CODA portal (Copernicus Online Data Access, until September 2022) and now on their Data Store (https://data.eumetsat.int).*

- Line 224: remove s from integrates - This error has been corrected.
- Line 244: The sentence is unclear to me. What does "before the altimeter measurements" mean?

We rephrase this sentence to make our purpose clearer.

> *[Lines 288-290] Onboard radiometers can estimate these variations along the track. However, radiometer footprint is larger than the altimeter one (resp. ~20/30 km for the radiometer, and ~4/10 km for the altimeter): when approaching the coast, the radiometer is thus contaminated by land earlier than the altimeter measurements (Andersen and Scharroo, 2011).*

- Line 273: Is the abbreviation for Mean Quadratic Error really needed? – We removed this abbreviation.
- Line 354: What's the time span over which Ballu et al. (2019) estimated this trend, and how does it compare to the trend from your series over the same time span?

We do not have the final time span from Ballu et al estimates as it is a combination of multiple analysis centres, which could have different time span. However, authors select datasets with at least 7 continuous years and prior 2017. However, their estimates of -1.3mm/y is not inconsistent when comparing to other VLM estimates over various time periods as detailed in Appendix A.