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

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Abstract. Today, monitoring the evolution of sea level in coastal areas is of importance, since almost 11% of the world's population leaves in low-lying areas. Reducing uncertainties in sea level estimates requires a better understanding of both altimetry measurements and local sea level dynamics. In New-Caledonia, the Noumea lagoon is an example of this challenge, as altimetry, coastal tide gauge, and vertical land movements from Global Navigation Satellite Systems (GNSS) do not provide consistent information. The GEOCEAN-NC 2019 field campaign addresses this issue with deployments of *in situ* instruments in the lagoon (GNSS buoy, pressure gauge, etc.), with a particular focus on the crossover of one Jason-series track and two Sentinel-3a missions tracks. In this study, we propose a method to virtually transfer the Noumea tide gauge at the altimetry crossover point, using *in situ* data from the field campaign. Following the philosophy of Cal/Val studies, we derive absolute altimeter bias time series over the entire Jason and Sentinel-3a periods. 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. With our method, we are able to re-analyse about 20 years of altimetry observations and derive a linear trend of -0.2 ± 0.1 mm/y over the bias time series. Compared to previous studies, we do not find any significant uplift in the area, which is more consistent with the observations of inland permanent GNSS stations. These results support the idea of developing Cal/Val activities in the lagoon, which is already the subject of several experiments for the scientific calibration phase of the SWOT wide-swath altimetry mission.

Commenté [CC1]: Watson : 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.

Short summary. Reducing uncertainties in coastal sea level trends estimates requires to better understand altimeter measurements and local sea level dynamics. Using long-term sea level time series from Noumea tide gauge (New-Caledonia) and *in situ* data collected as part of the GEOCEAN-NC campaign, this study presents a method inspired from Cal/Val studies to re-analyse about twenty years of altimetry observations and re-address the question of sea level evolution in the lagoon.

1. Introduction

Coastal regions concentrate a large part of the world's population and economic activities, with nearly 11% of the population living in low-lying areas (i.e. < 10m above mean sea level) (Haasnoot et al., 2021). Therefore, in a context of global climate change, monitoring sea level and its evolution in coastal areas is particularly needed. At this scale, it is also a scientific challenge because many processes can affect sea level locally, such as small-scale ocean processes, change in sea level pressure, presence of fresh water coming from estuaries or anthropogenic subsidence (Oppenheimer et al., 2019).

Commenté [CC2]: Major comments on the introduction :

- More references are needed

- I get what you are saying but the uncertainty on GMSL rates in sub-mm/yr (e.g. ±0.4 mm/yr). You are also conflating ice altimetry with ocean altimetry - some revision here and inclusion of some big picture references might be useful.

- [altimetry provide invaluable information about ….] or propagating signals that are trapped to the coast (https://link.springer.com/article/10.1007/s10712-019-09535-x)

- [Willis ….] citing the Haines et al ASR paper or the Watson et al group presentation as the OSTST meeting in the Azores (which presented a history of calval from Corsica, Bass Strait, Harvest and Gavdos) might be useful.

- 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.

- The point of the cal/val sites is to provide in situ comparison against the latest GDR - the process of refining these is iterative - this iterative approach may be worth mentioned.

Commenté [CC3R2]:

Today, altimetry satellites have provided almost 30-year records of global sea level variation around the world, with instantaneous sea surface height (SSH) at the centimetric level (i.e. with SSH uncertainties ranges from 3.5-3.7 cm depending on the mission and time span considered; Escudier et al., 2017), leading to uncertainties about Global Mean Sea Level (GMSL) trends around ±0.4 mm/y [1] (Ablain et al., 2019). When it comes to local sea level trends, Prandi et al. (2021) estimates a mean uncertainties of ±0.83 mm/y over the [1993-2019] period, with regions where the trend uncertainty exceeds the trend estimate. In both cases, these uncertainties remain higher than the requirements of the Global Climate Observing System (GCOS, 2022) of ±0.3 mm/y with a 90% confident interval. Thus, there is a great interest in improving sea level estimates and better characterising their uncertainties at both global and local scales (Cazenave et al., 2018; Legeais et al., 2018).

This involves improving both the understanding of altimeter measurements and the evaluation of the correction parameters, which is the central purpose of calibration and validation operations (hereafter named Cal/Val activities) (Fu and Haines, 2013). Varying Cal/Val methods and geographically diverse area is important to have representative estimation of altimeter biases (Bonnefond et al., 2011). At global scale, studies based on worldwide tide gauge network (e.g. Mitchum, 2000; Ablain et al., 2009) and relative multi-mission calibration through crossover and along-track comparisons led to assess global performance of altimeter and the geographically correlated errors. Local experiments are also needed to characterise the performance of measurement systems and monitor their stability over time. For that, several dedicated sites around the world are used: Harvest in the USA (Haines et al., 2020), Bass-Strait in Australia (Watson et al., 2011), Corsica in France (Bonnefond et al., 2019) and more recently Gavdos in Greece (Mertikas et al., 2018). Since the launch of the first precise altimetry mission, these operations enabled, for example, the detection of significant drift in the TOPEX/Poseidon observations (Nerem et al., 1997) or problems in algorithms and instruments (e.g. the unaccounted-for bias for Jason 1 and 2 missions describe in Willis, 2011).

Commenté [CC4]: citing the Haines et al ASR paper or the Watson et al group presentation as the OSTST meeting in the Azores (which presented a history of calval from Corsica, Bass Strait, Harvest and Gavdos) might be useful.

To achieve the centimetric level, absolute Cal/Val involves overcoming the limits of *in situ* measurement systems, with the deployment over long periods of reliable and accurate instruments that can be linked to the same global reference frame as the satellite data. With the idea of taking advantage of the existing *in situ* systems (e.g. long-term tide gauge measurements,

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[1] Results over period [1993-2017] with 90% confident interval

permanent GNSS sites, weather stations, etc.), the location of these sites is important. Coastal areas then seem to be an ideal compromise, but with an altimeter comparison point in the open ocean to avoid – among other things – issues related to land contamination of the altimeter and radiometer signals (Gommenginger et al., 2011). Diversifying *in situ* instrumentation is also a key factor to reduce biases related to the technique used, and multiply the comparison sites help to avoid geographically correlated errors such as those due to local site configuration (e.g. some local hydrodynamic effects) or regionally correlated altimeter errors (e.g. orbit, SSB, etc.).

Commenté [CC5]: rephrase "keep reliable altimetry data". The history of these sites is that the comparison point was "open ocean"

Commenté [CC6]: important to separate the local site specific effects (such as local hydrodynamic effects, instrument specific systematics etc) from the regionally correlated altimeter errors (e.g. orbit, SSB etc).

This issue of better understanding altimeter measurement and local sea level dynamics was the motivation of our study in the Noumea lagoon in New Caledonia. In this area, the question of long-term sea level evolution is an unresolved issue: several studies have shown that altimetry measurements do not agree with observations from tide gauges and permanent GNSS stations (Aucan et al., 2017; Martínez-Asensio et al., 2019; Ballu et al., 2019). Following the philosophy of absolute Cal/Val studies, we therefore sought to use two major advantages of the lagoon: (1) the presence of a crossing point of three altimeter tracks from two different missions and (2) the presence of the Noumea tide gauge, which provides a long-term sea level time series. This particular configuration makes it also a relevant site to test and improve *in situ* measurements techniques in the specific environment of a lagoon: this was done during the dedicated GEOCEAN-NC cruise in October 2019. Thanks to the variety of observation collected as part of this field campaign, the present paper details a methodology to compare altimetry and *in situ* measurements. Our study site and the GEOCEAN-NC cruise and its objectives are described in Section 2. Then, Section 3 is dedicated to the processing of the *in situ* data to reconstruct a long sea level time series under the altimetry tracks. Finally, section 4 details the reprocessing of the altimeter data, and concludes with the comparison with *in situ* observations.

2. Noumea study site

2.1 The Noumea lagoon

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.

Commenté [CC7]: I'm immediately wondering if there are any lagoon specific effects previously studied - i.e. coastal trapped waves, seiche, other resonances etc. Being able to mention these (or lack of evidence for) would be useful here.

Commenté [CC8R7]: We add some details about the lagoon dynamics in Appendices G.

The lagoon is also the subject of numerous geological, environmental and societal studies supported by the presence of IRD (Institut de Recherche pour le Développement) in Noumea, that offers expertise and resources to organize observation campaigns and analyses. A network of in situ measurements has been developed, which includes tide gauges and permanent GNSS stations from the BANIAN network (Fig. 1a, resp. green and blue dots). 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.

The lagoon is also of particular interest for altimetry : it is covered by many altimetry tracks from past and current nadir altimetry missions (TP/Jason, Sentinel-3a…) and is already the target of dedicated Cal/Val campaigns planned during the fast-sampling phase of the future SWOT[2] large-swath mission (e.g. project "SWOT in the Tropics" - Gourdeau et al., 2020). Our study focused on the notable intersection of three altimetry tracks (Fig. 1b, black lines) at about 13 km from the main land coast and 28 km from Numbo tide gauge: the TP/Jason pass #162 and Sentinel-3a passes #359 and #458.

2.2 The GEOCEAN-NC 2019 field campaign

In October 2019, the GEOCEAN-NC oceanographic cruise was organised in Noumea lagoon on the R/V Alis (Ballu, 2019) to address the question of long-term sea level evolution (see section 2.1 and Appendix A). For that, one objective was to collect *in situ* data under satellite tracks. 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).

Commenté [CC9]: Are two panels really needed here? what about just one larger map of panel b with an offset locality map that shows the broader context?

cf comment above (115): cross ref the crossover on the map

Commenté [CC10R9]: We thought it is important to have a general map introducing the situation in the area for readers who are not familiar with New Caledonia. It also shows other tide gauges and permanent GNSS stations location, as well as the Cal/Val SWOT path where field campaigns will take place soon. To complete this figure, we highlight the location of the crossover point and complete the figure caption.

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[2] More information about the SWOT (Surface Water and Ocean Topography) mission are available on www.swot.jpl.nasa.gov

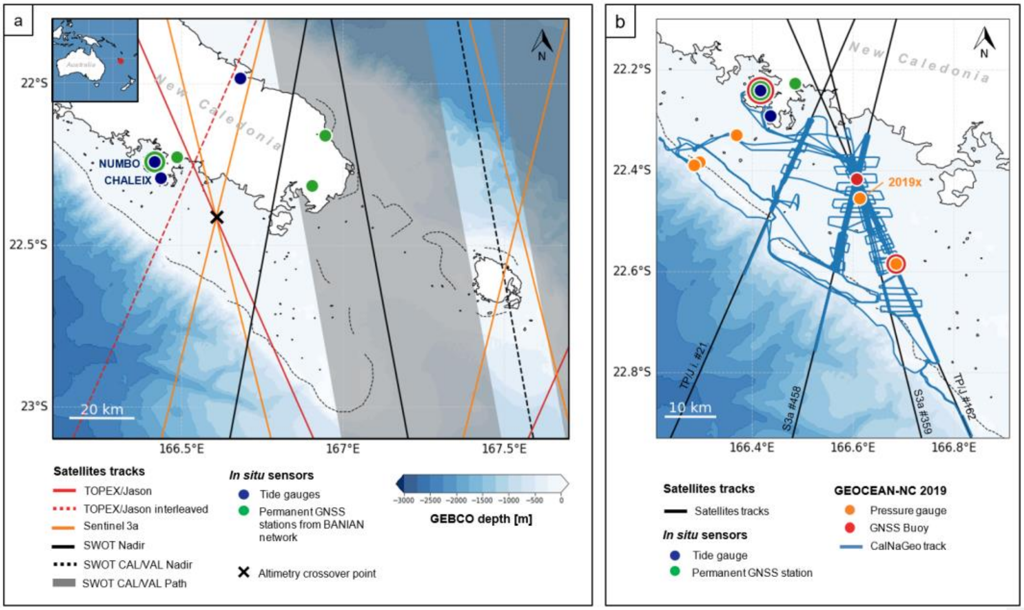
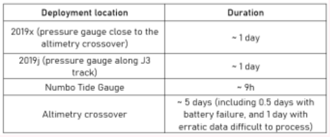


Figure 1. (a) Map of the Noumea lagoon in the South Pacific Ocean and localisation of the main altimetry tracks and *in situ* sensors. The bathymetry from the GEBCO global model (GEBCO Compilation Group 2020) is represented by a blue gradient and the dotted lines represent the coral reefs. The black cross highlights the altimetry crossover point used in this study. In-situ field campaigns will be conducted soon under the SWOT Cal/Val path. (b) Location of the sensors used (tide gauge, GNSS stations) and deployed (pressure gauge, GNSS buoy and CalNaGeo GNSS carpet) during the GEOCEAN-NC 2019 cruise. Note that some sensors were deployed at the same location: the coloured dots representing them therefore overlap.

A GNSS buoy was also successively moored at multiple locations in the lagoon (Fig. 1b, red dots), for periods of a few hours (e.g. at Numbo tide gauge) to a few days (e.g. at the crossover location). Developed by DT-INSU (*Division Technique de l'Institut National des Sciences de l'Univers*), it consists of a GNSS antenna (Trimble Zephyr 3) supported by a floating structure, with a metal cylinder containing the receiver (Trimble NetR9) and batteries (see picture in Fig. 3). GNSS buoys are commonly used for Cal/Val activities (Born et al., 1994; Watson et al., 2011; Bonnefond et al., 2013; Zhou et al., 2023) and many studies have demonstrated their capability to provide sea level records with centimetric accuracy (André et al., 2013; Gobron et al., 2019). During the campaign, a calibration session was performed at the Noumea Numbo tide gauge to assess the performance of these GNSS instruments. Our results show that, despite vertical biases (−1.7 ± 0.5 cm for the buoy and -0.6 ± 0.4 cm for CalNaGeo) that could result from terrestrial geodesy measurements uncertainties and GNSS processes, these two instruments are consistent with the radar gauge observations (more details in Chupin et al., 2020).

Commenté [CC11]: just to confirm, you mean a single buoy was deployed multiple times at different locations? durations of deployments are important - could this be added here?

Commenté [CC12R11]: Yes, during the campaign, we deployed 1 single buoy at different location in the lagoon. We complete the sentence with an idea of duration of these deployments, but here is a most complete list :



Deployment location	Duration
2019x (pressure gauge close to the altimetry crossover)	~ 1 day
2019j (pressure gauge along J3 track)	~ 1 day
Numbo Tide Gauge	~ 9h
Altimetry crossover	~ 5 days (including 0.5 days with battery failure, and 1 day with erratic data difficult to process)

Commenté [CC13]: What's DT-INSU?

Commenté [CC14R13]: It is the French technical division that develops and deploys scientific sensors for INSU laboratories (Division Technique de l'Institut National des Sciences de l'Univers).

Commenté [CC15]: e.g. refs. Zhou et al is a recent example but completely your call.

Commenté [CC16R15]: We add the citation of Zhou et al. 2023 in the list.

Commenté [CC17]: This is a pretty large number which is concerning...

Commenté [CC18R17]: The details of our sensors calibration are available in chupin et al 2020 : however, we are aware of this important factor and have added several sentences throughout the paper to remind the reader of it.

During the campaign, five pressure sensors (Seabird SBE26plus) were moored in the lagoon at depths ranging from 12 to 20 m (Fig. 1b, orange dots). All sensors recorded pressure variations at the seafloor between October 2019 and November 2020. Three of them were installed along a profile linking the Noumea tide gauge and the outside border of the coral reef, with the aim of quantifying the setup induced by wind and waves. Two other gauges were deployed along the TP/Jason altimetry track #162 for the purpose of aiding analysis of altimeter data. Before and after their deployment, a calibration phase in a hyperbaric chamber was undertaken to check the proper functioning and overall drift of the gauges (detailed results are available in Appendix B).

Taking advantage of all observations acquired as part of the GEOCEAN-NC cruise, we thus develop a method to reconstruct a long term virtual *in situ* sea level time series at the altimetry crossover point (see the black cross on Fig. 1.a).

3. Reconstruction of a long term virtual *in situ* sea level time series under the altimetry tracks

3.1 Method

The objective of our analysis is to compare the offshore altimetry measurements at the Jason/Sentinel-3a crossover with *in situ* observations. For that, two methods can be adopted (Bonnefond et al., 2011): an indirect comparison, where the *in situ* measurement is distant from the altimetry pass (typically a coastal tide gauge), and a direct comparison where *in situ* sea surface height (SSH) is directly observed at the comparison point with instrumented platforms (as in Harvest Cal/Val site) or precise GNSS buoys. Following the method of Watson et al. 2011, we developed a mixed approach using both *in situ* measurements from the GEOCEAN-NC campaign and the Noumea tide gauge records.

Figure 2 summarises the three steps of this method, that are detailed in the following sections:

Step 1. The GNSS buoy deployed at the altimetry crossover point during the GEOCEAN-NC cruise provides SSH in the same reference system as the altimetry measurements (see Section 3.2 for more details).

Step 2. To extend the comparison, we use measurements from the pressure sensor closest to the altimetry crossover (hereafter named the *2019x* pressure sensor). By computing the mean offset between the GNSS buoy and this pressure gauge over common observation periods, the 2019x pressure sensor observations are linked to a global reference frame and virtually transferred to the altimeter comparison point (see Section 3.3 for more details).

Step 3. Finally, the SSH time series from the Noumea tide gauge site is used to increase the comparison duration. Using its common year of observation with the 2019x pressure gauge, the tide gauge is virtually transferred to the crossover location by computing a tidal and datum correction (see Section 3.4 for more details).

Commenté [CC19]: would be good to cross ref this specific point on the map figure

Commenté [CC20R19]: We add a black cross on Fig.1a.

Commenté [CC21]: how close? from the map, it looks to be about 5 km - this would/could be sufficient in induce some tidal differences?

Commenté [CC22R21]: The pressure gauge is located at about 4 km south of the Sentinel-3a and Jason-series cross over (Fig. 1b, orange dot) (see section 3.3 for more details about tide differences).

Commenté [CC23]: so the assumption here is that delta(tide) between 2919x and the crossover is negligible. you may wish to flag this as an assumption and then address it later in the discussion.

Commenté [CC24R23]: We analyse this assumption using SCHISM hydrodynamic model outputs providing by J.Lefevre, : the complete results are available in Appendix D. In the following, we add this tide contribution to correct the pressure gauge observations. We also update the Figure 2 to explain this process.

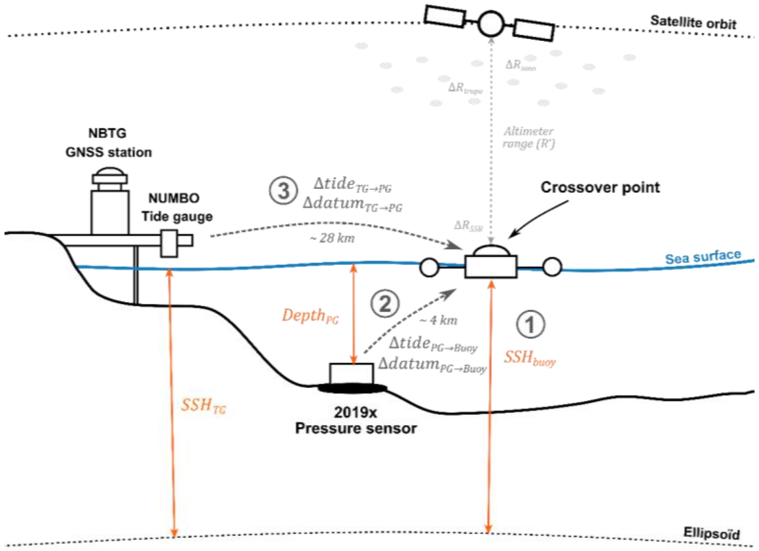


Figure 2. Configuration of the sensor's deployment. They are used to derive a long term *in situ* sea level time series under the altimetry tracks. The three steps of the methodology are represented by the circled numbers.

3.2 GNSS Buoy sea level measurements

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).

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

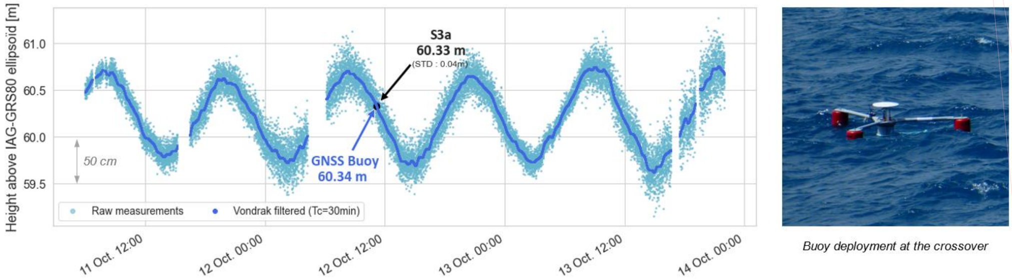
Commenté [CC25]: What's the GINS software? Please specify.

Commenté [CC26R25]: We add a short comment to define the GINS software and move the reference to the original paper closer to the GINS name.

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).

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. The distance from the GNSS Antenna Reference Point (ARP) to sea level was determined using buoy dimensions and ruler readings during static sessions in Nouméa harbour. By subtracting all these corrections from the initial time series, we obtain the water level relative to the IAG-GRS80 ellipsoid. After a first data selection to keep positions determined with more than 10 satellites and remove outliers, the resulting heights are filtered using a Vondrak filter with a 30 min cut-off frequency (Vondrak, 1977) (Fig. 3). This filtering lead to a SSH time series cleaned from high frequency signal (short waves, …) (Step 1 in Fig. 2), adequate for a comparison with a 20 m depth bottom pressure records (Step 2 in Fig. 2).

During the buoy deployment, the area was overflown by the Sentinel-3a satellite on its track #359, which allows a direct comparison with the buoy measurements. At the time of the overfly, the SSH difference between the filtered buoy time series and altimetry measurements is about 1.4 cm (Fig. 3). As this single comparison remains limited we then use the 1-year pressure sensor observations to extend the time series of *in situ* measurements.



Buoy deployment at the crossover

Figure 3. GNSS Buoy raw (light blue) and Vondrak filtered (dark blue) sea level heights above the IAG-GRS80 ellipsoid.

3.3 Pressure sensor observations

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

Commenté [CC27]: this is unclear - do you mean 10 Hz or 1 obs every 10 seconds? Also, the duration of the deployment is not known and should be mentioned. If the obs rate is 1 per 10 seconds, why so slow?

Commenté [CC28R27]: To complete our description, we add more details about the buoy deployments in Section 2.2 and at the beginning of section 3.2.

GNSS measurements were made at 1Hz (1 obs per second), but when processing the data with GINS software, errors occurs with 1Hz data. With a rate of 1 obs per 10 seconds, the computation worked and we finally chose this solution for the further processing.

Commenté [CC29]: this opening sentence is quite unclear. The reference frame of the orbits needs to be mentioned (ITRF2014), and the various tidal and loading corrections needs to be summarised. Also setting such as how the nominal troposphere delays are computed, and then how these are solved for needs to be included.

Commenté [CC30R29]: The GINS solution is in the IGSR3 reference system (the reference system that is used to make the REPRO3/MG3 orbital clock products). There is no translations/rotations vs ITRF2014, only a vertical scale that change over time and that could be approximate with : + 7.7 + 0.17 (t – 2010) mm. Over the period of the cruise [October 2019 - November 2019], the mean offset to ITRF14 is equal to 9.4 mm +/- 0.01mm. We add these details in the text.

Commenté [CC31]: What is “time-dependent vertical scale”?

Commenté [CC32R31]: We add some details to clarify the term of “time-dependant vertical scale’.

Commenté [CC33]: some further information on how this is determined would be wise.

Commenté [CC34R33]: For the calculation of the buoy's air draft, we used the buoy's dimensional drawings as well as readings on the buoy's lateral rulers during a static session in Noumea harbor. This allowed us to deduce the air draft of the buoy, a value that we used for the entire campaign. We complete the paragraph with some more details about that.

Commenté [CC35]: **Figure** : This picture made me think the series shown on the left was from this location - which it is not. Why not show this series and compare to the tide gauge to give the readers a sense of quality of the buoy solutions?

The smoothed line in Figure 3 looks quite variable - I'm left pondering if this is real (lagoon hydro effects) or if it is GPS related. I suggest you show the harbor solution and compare to the TG - thus give a sense for GPS quality before going to the next step.

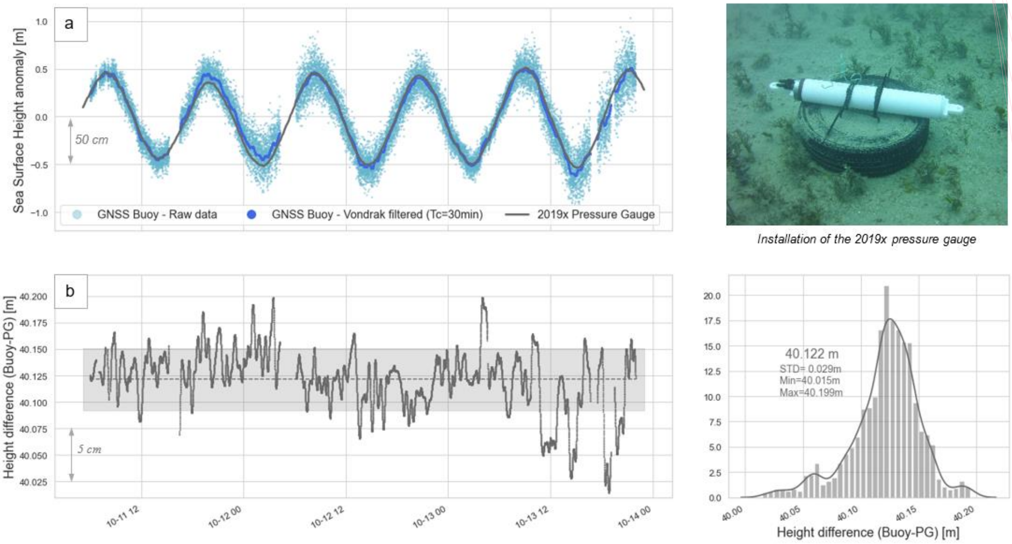
Figure 3: I guess S3a is Sentinel? If so, I would suggest just using “Sentinel”

Commenté [CC36R35]: The image presented here does not indeed correspond to the associated curve: however, it seems important for readers not familiar with these sensors to have an illustration of the equipment used. We have therefore modified the image to be more consistent.

...

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.

We then used the GNSS buoy observations to tie the pressure gauge measurements into the same reference frame as the altimetry data (Step 2 in Fig. 2). The 2019x seafloor pressure is converted to equivalent hydrostatic heights, using atmospheric pressure time series from ERA5, the latest climate reanalysis produced by ECMWF (Hersbach et al., 2018), at the pressure gauge location, and the water column density computed with the pressure gauge temperature and a mean salinity value of 35.5 psu. The calibration phase of the 2019x sensor shows a linear trend of about -70 mm/year (more details in Appendix B), which is removed to obtain the final sea level time series from the 2019x pressure sensor.



Installation of the 2019x pressure gauge

Figure 4. Comparison between GNSS buoy and 2019x pressure gauge observations / (a) Sea surface height anomaly from GNSS buoy raw data (light blue), GNSS buoy filtered data (dark blue) and 2019x pressure sensor (grey) / (b) Difference between filtered GNSS buoy and 2019x pressure gauge heights. The grey dotted line represents the mean difference (40.122 m), and the grey area represents the ± 1 standard deviation (3 cm). These differences are also showed on the lower right histogram.

Commenté [CC37]: SWH is one thing, but what about tide? Fig 3 shows a tidal range of ~1 m, so over ~4 km you could easily get > 1 cm of tidal difference (we see ~5 cm over 9 km in Bass Strait). This needs to be addressed.
Coming back to this comment after reading on, I see the tidal diff from the TG to the PG is not overly large, hence over 4 km, the difference is likely to be small - this does however need mentioning here.

Commenté [CC38R37]: This is an omission on our part: indeed, even 4km away, tidal gradients can exist. We used the outputs of the SCHISM hydrodynamic model (provided by J.Lefevre from IRD Nouméa) to compute the tidal gradient between these two locations. The detail of this analysis has been added in Appendix D. As this can impact the water level at the cm-level, we have chosen to include it in the rest of the study. We then update the main text to explain that.

Commenté [CC39]: similar isn't sufficient. Do you mean comparable? i.e. ITRF2014 to ITRF2014.

Commenté [CC40R39]: Indeed we meant that we wanted to compare data in the same absolute reference frame, i.e. ITRF14. To be more clear we have rephrased the sentence.

Commenté [CC41]: the duration of the pressure sensor obs isn't clear.

Commenté [CC42R41]: We change the first sentence of section 3.3 to make it more clear for the reader.

Commenté [CC43]: **Figure :** the bllue line is larger a dubplicate of the previous figure - see previous comment about showing buoy results from harbour in the previous figure .

Commenté [CC45]: **Figure :** Labelling with ± is potentially misleading as it could be interpreted as standard error about the mean (which it is not). Label as standard deviation.

Commenté [CC46R45]: We update the figure to change that.

The pressure gauge data are then tie to the ellipsoid by differencing the filtered GNSS buoy heights (Fig. 4a, dark blue) from the pressure sensor measurements (Fig. 4a, grey line). Over the 64 h of common observation period, the average difference is equal to 40.122 m (STD = 0.029 m - Fig. 3b). Added to the hydrostatic heights of the pressure sensor, this offset allows us to obtain a 1-year sea level record at the intersection of the altimeter tracks, thereafter named SSH_{PG} (Step 2 in Fig. 2). However, to have a longer *in situ* time series, we also considered the Noumea tide gauge dataset (Step 3 in Fig. 2).

Commenté [CC44R43]: The first curve represents the relative variations of the sea level seen by the buoy (blue) and by the pressure sensor (gray), information that is not represented in the previous figure. It seemed important for the reader to associate the two curves to better understand the methodology we used.

3.4 Noumea tide gauge long term measurements

The French Hydrographic Service (Shom) provides sea level observations at Noumea through the Chaleix (operating from 1957-2005) and Numbo (2005 to present) tide gauges (Fig. 1a, blue dots). Before 1967, measurements were paper records, and electronic observations began in 1967. Thanks to a 6 months overlap of data collection, the old Chaleix site has been linked to the new Numbo site, located about 6 km away (Fig. 1a, blue dots). Aucan et al., 2017 were thus able to reconstruct the whole time series by concatenating data from 1957 to 2018, making it one of the longest series available in the South Pacific. In this paper, we used the data available online (http://uhslc.soest.hawaii.edu/data/ - ID 019) and regularly updated with the latest measurements from Numbo tide gauge. This 1-hour sampling sea level time series will be referred to as SSH_{TG} in the following, and covers the entire altimetry period and our study ([1967-2021]).

The Noumea tide gauge site and the altimeter crossover point are separated by about 28 km. The last step of our methodology is to bring tide gauge observations at the comparison point (Step 3 in Fig.2). For that, we consider the height residuals between 2019x pressure sensor and Noumea tide gauge measurements and compute a tidal and datum correction, as made by Watson et al. (2011) at the Bass Strait Cal/Val site. After linearly interpolating the 10 min pressure gauge data on the 1-hour tide gauge time series over their common measurement period (Fig. 5a), we compute the difference [$SSH_{PG} – SSH_{TG}$] (Fig. 5b – black). We then computed an harmonic analysis on these residuals to get the tidal gradient correction in amplitude and phase ($\Delta tide_{TG\rightarrow PG}$) and the datum correction ($\Delta datum_{TG\rightarrow PG}$) to apply on the tide gauge record. Tidal residuals are mainly due to semi-diurnal waves, with a contribution from M2, S2 and N2 of about 4.5 cm, 1.7 cm and 1.1 cm respectively. The resulting datum correction is estimated to be -57.1 cm, which is coherent at the order of a few centimetres with gradients from two global gravity field models in the area (see Table F1 in Appendix F). After applying the tidal gradient and the datum offset, the difference [$SSH_{PG} – SSH_{TG}$] have a Root-Mean-Square Error (RMSE) of 1.3 cm (Fig. 5b – grey), to compare with the 3.7 cm without these corrections.

Commenté [CC47]: is 2 dec places required?

Finally, we obtain an hourly *in situ* sea level time series at the altimeter comparison point (thereafter named $SSH_{in-situ}$) by virtually transferring the Noumea tide gauge observations (Step 3 in Fig.2) :

$$SSH_{in-situ} = SSH_{TG} + \Delta tide_{TG\rightarrow PG} + \Delta datum_{TG\rightarrow PG} \tag{1}$$

However, the altimeter fly over the area is for about 10 seconds between 1 and 3 times per month (resp. for Sentinel-3a and Jason missions). Doing a simple linear interpolation of the hourly $SSH_{in-situ}$ at the satellite overfly time (t_{sat}) does not well reproduce the tide evolution. Thanks to a harmonic analysis over the tide gauge time series, we expressed the SSH_{TG} as a tide reconstruction at the time of the satellite flyby (hereafter named $TGtide_{rec}(t_{sat})$) and add tide residuals linearly interpolated at the flyby time (i.e. $TGtide_{res}(t_{sat})$). Thus, for the final comparison with altimetry data, the $SSH_{in-situ}$ from Eq. (1) could be explained as:

$$SSH_{in-situ}\,(t_{sat}) = TGtide_{rec}(t_{sat}) + TGtide_{res}(t_{sat}) + \Delta tide_{TG\to PG}(t_{sat}) + \Delta datum_{TG\to PG} \tag{2}$$

With this method, there are still inaccuracies in the determination of the sea level due to weather and local conditions, but the tide evolution is well considered.

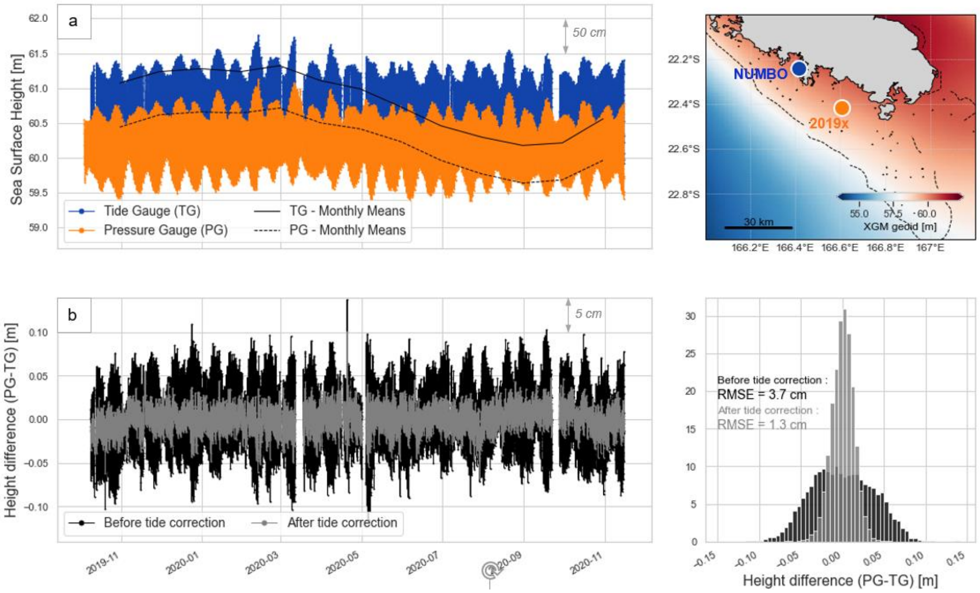
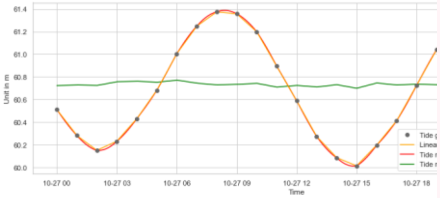


Figure 5. Tidal difference between the Noumea tide gauge (TG) and the 2019x pressure gauge (PG) / (a) Sea level record at 2019x pressure gauge (orange) and Numbo tide gauge (blue) during the common observation period (13 months). Monthly means are displayed in black (solid line for tide gauge, dotted line for pressure gauge). The two sensors are separated by about 28km. / (b) Height difference between PG and TG before (black) and after (grey) applying the tidal correction. These differences are also displayed on the histogram, with Root Mean Square Error (RMSE) values for both solutions.

Commenté [CC48]: This paragraph is a little unclear. Is TGtiderec the result of a harmonic analysis of the TG?
In this case, the statement about linear interp being not sufficent to reproduce oceanic variability is a little misleading. it isn't reproducing the tide - you linear interpolate the residual which contains other oceanic variability. Suggest revision to clarify this.

Commenté [CC49R48]: This is indeed the method we used. We have reworded the paragraph to explain this better:

Doing a simple linear interpolation of the hourly $SSH_{in-situ}$ at the satellite overfly time (t_{sat}) does not well reproduce the tide evolution. Thanks to an harmonic analysis over the tide gauge time series, we expressed the SSH_{TG} as a tide reconstruction at the time of the satellite flyby (hereafter named $TGtide_{rec}(t_{sat})$) and add tide residuals linearly interpolated at the flyby time (i.e. $TGtide_{res}(t_{sat})$).



Commenté [CC50]: this section does not address possible VLM at the TG (or the PG) for that matter. As far as the reader is concerned, both the TG and PG may have significant VLM that is common mode and doesn't show up in the difference. Suggest revision to comment about this.

Commenté [CC51R50]: This section only details the in situ datasets : there is already a lot of detail to be given and we do not want to lose a reader unfamiliar with this type of experience by discussing the VLMs now. However, this discussion is detailed in section 4.2.4, after the comparison with the altimeter data.

Commenté [CC52]: what is the scale for the monthly means? unclear
Add before correction/after correction to labels

4. Calibration/Validation of altimetry measurements

Commenté [CC53R52]: On the figure 5a, we simply show the monthly rolling average for both sensors, which is a requirement of previous reviewer of my work. We update the figure to add the before/after correction label.

4.1 Altimetry data processing

4.1.1 Jason and Sentinel-3a Geophysical Data Records (GDR)

There is a wide variety of altimetry products and sources, allowing both advanced analysis of raw altimeter data and corrections, and access to sea level databases that can be used directly without further processing. As our study focused on the absolute bias of the altimeter SSH, we thus consider the official latest release of along-track products to derive altimeter sea level with the up-to-date instrumental and geophysical corrections parameters.

Commenté [CC54]: This needs to come back to the question at the heart of altimeter validation - what is being validated? The basis of the large number of products/sources has to be the offical latest release GDR, hence this is the main focus of the validation sites. Then on top of this, a specific site may then test variants as they wish.

Commenté [CC55R54]: We have reworded this paragraph to include this essential distinction.

For the Jason track #162, we use the last Geophysical Data Records (GDR) delivered by AVISO+, that integrate precise orbits and up-to-date corrections for 20 Hz measurements (Table 1). For Sentinel-3a, we consider the SRAL Level 2 Marine data to ensure global coverage of the lagoon. 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). From 2016 to 2019, the Sentinel-3a data were reprocessed using the current standards of the Baseline Collection 004, used for Sentinel-3a products after 2019 (Table 1).

Commenté [CC56]: GDRE? I see these are mentioned in the table, perhaps indicate that in text

Commenté [CC57R56]: For Jason 1, we used GDR-E products, but it’s different for Jason 2 and Jason 3 so we choose to keep only GDR in the main text.

Table 1. Altimeter products used in the study

Mission	Jason			Sentinel-3a	
	Jason 1	Jason 2	Jason 3		
Cycles	1-259	1-303	1 - 219	3-52	53-81
Products	GDR-E	GDR-D	GDR-F	SR_2_WAT Baseline Collection 004	
				Reprocessed BP 2.61	Non-reprocessed BP 2.61/2.68
Source	AVISO+ FTP : https://www.aviso.altimetry.fr/en/home.html			EUMETSAT CODA : https://coda.eumetsat.int/#/home CODA REP : https://codarep.eumetsat.int/#/home	

4.1.2 Altimetric corrections considered in order to accurately estimate sea surface height

During its propagation, the radar signal is delayed by multiple phenomena that must be consider to estimate the altimetric sea surface height (SSH_{alt}) with a centimetric accuracy. Thus, the altimeter range must be corrected for instrumental errors (R'), sea state bias (ΔR_{SSB}) and atmospheric delays (ΔR_{iono} and ΔR_{tropo}). For the comparison with tide gauge measurements, it is also necessary to integrate geophysical corrections (ΔR_{geo}) to account for the effect of ocean tide loading, pole and solid earth tides.

Commenté [CC58]: what about geophysical range corrections e.g. solid earth tide, load tides etc. OK, I now see that below - I'd consider reordering that sentence and present it here.

Commenté [CC59R58]: We have simplified the paragraph to make the integration of the geophysical corrections more obvious.

In coastal areas, several factors can affect the quality of altimeter measurements. The proximity to the land can impact the echo received by the altimeter, which requires adapting the waveform retracking method (Gommenginger et al., 2011). The high variability of coastal processes, both in time and space, also limits the quality of atmospheric and geophysical corrections (Andersen and Scharroo, 2011). As this study is an opportunity to test different corrections in our area, we use GDR along-track products to select the most appropriate parameters or replace them by external products. In these files, the range is already corrected from instrumental errors (R'). For our study, we also consider the ΔR_{SSB} and the ΔR_{geo} parameters at 1 Hz, linearly interpolated at the time of each 20 Hz observations (see Table 2 for a summary).

Commenté [CC60]: it isn't just the corrections - the range determination from the waveform tracking can be limited, perhaps reword.

Commenté [CC61R60]: We have completed the paragraph by adding this phenomenon and some references.

Regarding the ionospheric delay (ΔR_{iono}), GDR files provide a correction based on observations from the dual frequency altimeter (*Jason-3 Products Handbook*, 2020) that could be very noisy. To improve this correction without degrading the altimeter measurements, one way is to smooth this ionospheric delay over a 150 km profile (Imel, 1994). Following methods developed on other historical Cal/Val sites (e.g. Watson et al., 2011), we use the mean ionospheric delay in the area between -23.85° and -22.5°, which covers part of the lagoon, the reef and the open ocean, and roughly corresponds to the recommended distance of 150 km.

Commenté [CC62]: ref user handbook ?

The tropospheric delay (ΔR_{tropo}) can be divided into a wet and a dry component. About 90% of this delay is related to the dry component, that can be estimated with atmospheric models (Chelton et al., 2001). We use the 1 Hz hydrostatic tropospheric correction provided in the GDR files, linearly interpolated to the time of the 20 Hz measurements. The wet component of the troposphere is related to the water vapor content in the atmosphere, that could be particularly variable in time and space when approaching the coast. 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). In the lagoon, the effect of the land contamination is visible when approaching the main island, but at our comparison point, the radiometer correction seems to be exploitable for both Jason and Sentinel-3a missions (more details in Appendix E). To confirm this hypothesis, we also test two other datasets: (1) a wet tropospheric delay provided by the European Center for Medium Range Weather Forecasting (ECMWF) and (2) a wet tropospheric correction computed from inland permanent GNSS stations (more details about this processing in Appendix E). When comparing with the *in situ* observations, we will be able to analyse the impact of these different solutions (see Section 4.2.1).

Commenté [CC63]: The sentence is unclear to me. What does “before the altimeter measurements” mean?

Commenté [CC64R63]: We rephrase this sentence to make our purpose clearer. This assumption is based on the following paper:

Andersen and Scharoo (2011) :

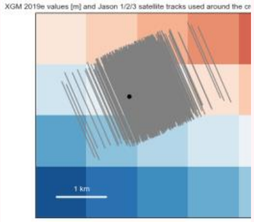
The footprint of the radiometer is dependent on the height of the spacecraft and the scanning frequency of the radiometer, but typical values of the footprint of the main beam range between 20 and 30 km. This is considerably larger than the 4–10 km footprint of the altimeter as illustrated in Fig. 5.6 for a pass across the Western Mediterranean Sea. Consequently, the radiometer is contaminated by the presence of land much earlier than the altimeter, as the spacecraft approaches the coast and generally the main beam is affected up to 30 km from the coast. The wet troposphere correction derived from the onboard radiometer is similarly affected, and a lot of research is put into improving the wet troposphere correction in coastal regions (i.e., Obligis et al. 2009).

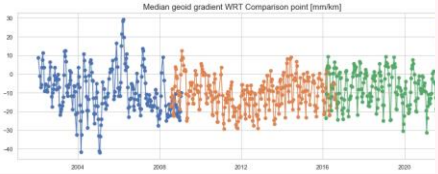
Finally, altimetry satellites do not fly over the exact same point at each pass: it is therefore necessary to consider the height difference between the comparison point and the actual pass of the satellite track, which we approximate to be the geoid height difference ($\Delta R_{geo\ddot{\imath}d}$). 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, the *geoïd* variable integrates the permanent component of the solid earth tide ($\Delta R_{set_{perm}}$), while the cyclic component ($\Delta R_{set_{cycl}}$) 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.

Commenté [CC65]: perhaps stating the gradient mm/km would be insightful.

Commenté [CC66R65]:


XGM 2019e values [m] and Jason 1/2/3 satellite tracks used around the cr


Median geoid gradient WRT Comparison point [mm/km]

In the end, the altimetric sea level time series at our comparison point is given by:

$$SSH_{alt} = H - R' - \Delta R_{iono} - \Delta R_{tropo} - \Delta R_{SSB} - \Delta R_{geo} + (\Delta R_{geoïd} - \Delta R_{set_{perm}}) \tag{3}$$

The corrections used to derive the SSH_{alt} are summarised in Table 2.

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)

4.2 Altimetric bias computation

The determination of the altimeter bias ($\Delta Bias_{alt}$) consists of comparing the satellite observations (SSH_{alt} from Eq. (3)) with the *in situ* measurements ($SSH_{in\,situ}$ from Eq. (1)) at the time of the overfly (Bonnefond et al., 2011) :

$$Bias_{alt} = SSH_{alt} - SSH_{in\,situ} \tag{4}$$

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

Commenté [CC67]: So you have multiple 20 hz obs per cycle that are averaged to generate the cycle-by-cycle series. How is the +- 1 km tolerance chosen? Why isn't 1 hz GDR data interpolated to the comparison point as per the standard approach - then present the 20 Hz approach as comparison?

Commenté [CC68R67]: At the beginning of the study, we were more focused on characterising the quality of the altimeter data than on the Cal/Val aspect. Thus, we developed our algorithm using this point averaging to have access to different indicators (SSH STD, MQE, ...) to justify the filtering of some data.

Our algorithms are therefore not designed to calculate the biases with respect to the PCA as on the other Cal/Val sites. To compare, we still coded the process for Jason 3: the difference on the mean bias estimate is millimetric, even if the PCA method seems to improve the standard deviation (see figure below). Seeing this, we decided to keep our method by specifying in the text this processing difference.

...

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.

Commenté [CC69]: Is the abbreviation for Mean Quadratic Error really needed?
(removed)

Commenté [CC70]: is this provided with the data? unclear

Commenté [CC71R70]: We considered GDR with this MQE parameter inside : in our processing, we thus keep this parameter to have access to a metric on the quality of altimetry data. We rephrase the paragraph to try to be more clear.

4.2.1 Impact of the wet tropospheric correction

To determine the most appropriate solution for the wet tropospheric correction, we compute variants of the altimeter absolute bias for the Jason 3 track #162 and the 2 Sentinel-3a tracks over the [2016-2021] period, only changing the wet tropospheric parameter (see section 4.1.2 for more details). Figure 6 represents the altimetric bias at the comparison point by using the wet tropospheric correction from the radiometer (black), the ECMWF model (grey) and the GNSS based solution (coloured). It is important to note that the GNSS correction is not available for all cycles, unlike the radiometer and model ones that are directly taken from the GDR files.

For all missions, the resulting mean bias estimates could vary at the centimetric level depending the correction used, and the GNSS-based corrections seems to slightly decrease the value of the mean altimeter bias. The radiometer and the model agree well for Jason 3 mission (mean difference of 0.3 cm), whereas for the S3-a track #359, the radiometer seems closer to the GNSS estimates (mean difference of 0.4 cm). For both Jason and Sentinel-3a missions, none of these three corrections significantly improves the mean bias dispersion. When analysing the along track values of the three wet tropospheric corrections (see Appendix E), we can see that they all can be very variable according to the cycles.

Commenté [CC72]: can you be a bit more quantitative here?

In any case, there is no evidence that the radiometer correction may be wrong within our study area. These results confirm that the latest improvements in radiometer corrections now included in the GDR files can be used to derive a consistent altimeter bias. A similar conclusion was made by Bonnefond et al. (2019) at the Corsica historical Cal/Val site for Jason missions. Since GNSS data are not available for all cycles, we chose to keep the wet tropospheric radiometer correction in the following analyses.

Commenté [CC73]: Why I agree in the outcome, I'm not convinced by the wording here. Smallest dispersion doesn't necessarily mean zero bias. I'd like to see some mention of analysis of along track wet delays from the radiometer to check you don't have a common mode land interference signal. Appendix D needs to be cross referenced here

Commenté [CC74]: Also, you haven't really shown any info from the land based GNSS sites to get a sense for their quality.

Commenté [CC75R74]: We have not done a thorough analysis of the corrections provided by the GNSS data. Nevertheless, the new Appendix A presents additional information on the permanent stations operating in New Caledonia.

4.2.2 Evaluation of the *in situ* SSH determination method

To evaluate our methodology for the $SSH_{in\ situ}$ reconstruction, we compared the mean bias estimated using the 2019x pressure sensor measurements with the one computed using our method (i.e. Eq. 1) over their common observation period (from October 2019 to November 2020). Figure 7 shows the evolution of the altimeter bias for the Jason and Sentinel tracks according to the *in situ* data considered. For the 3 tracks, the difference between the mean biases is a few millimetres (respectively +1/+2/+5 mm for the tracks #162/#359/#458). However, we could observe centimetre level variations in the time series of differences (lower right panels, coloured curve). Despite the use of tidal gradients to integrate differences due to hydrodynamic effects in the lagoon, some variability may still exist between the location of the tide gauge and the pressure sensor. Although it is important to take this effect into account for long-term comparisons, we can still assume that the use of the tide gauge series does not affect the estimate of the mean altimeter bias. Our tide gauge data transfer method seems to be relevant for estimating the altimeter bias at the cm-level.

Commenté [CC76]: reword - differences due to hydrodynamic effects associate with the shallow lagoon...?

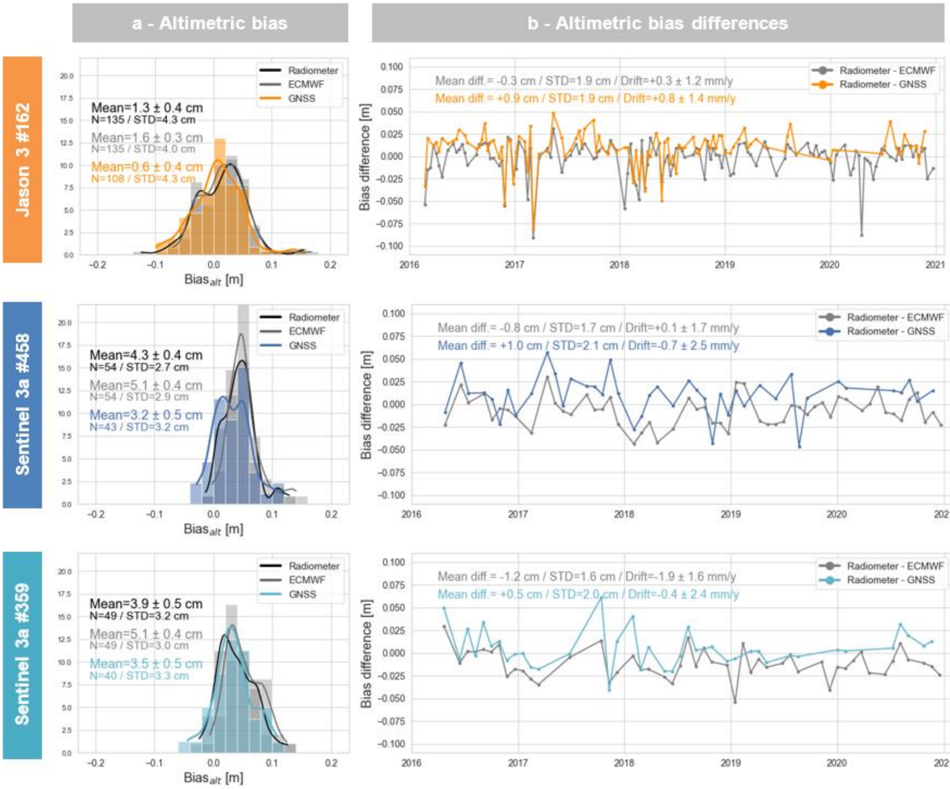


Figure 6. Altimetric bias at the comparison point according to different wet tropospheric models and for 3 altimetric tracks: the Jason 3 (orange) track #162, the Sentinel-3a tracks #458 (dark blue) and #359 (light blue) / (a) Altimetric biases distribution as a function of the wet tropospheric delay from the radiometer (black), the ECMWF model (grey) and the GNSS stations (coloured). / (b) Bias time differences from the radiometer solution with respect to the ECMWF model (grey) and GNSS stations (coloured).

Commenté [CC77]: nice. this is a minor point, if you used colour saturation to separate ECMWF and GNSS, you could maintain the orange=jason blue=s3a458 and cyan=s3a#359 for each panel, thus making it easier to associate with different missions.

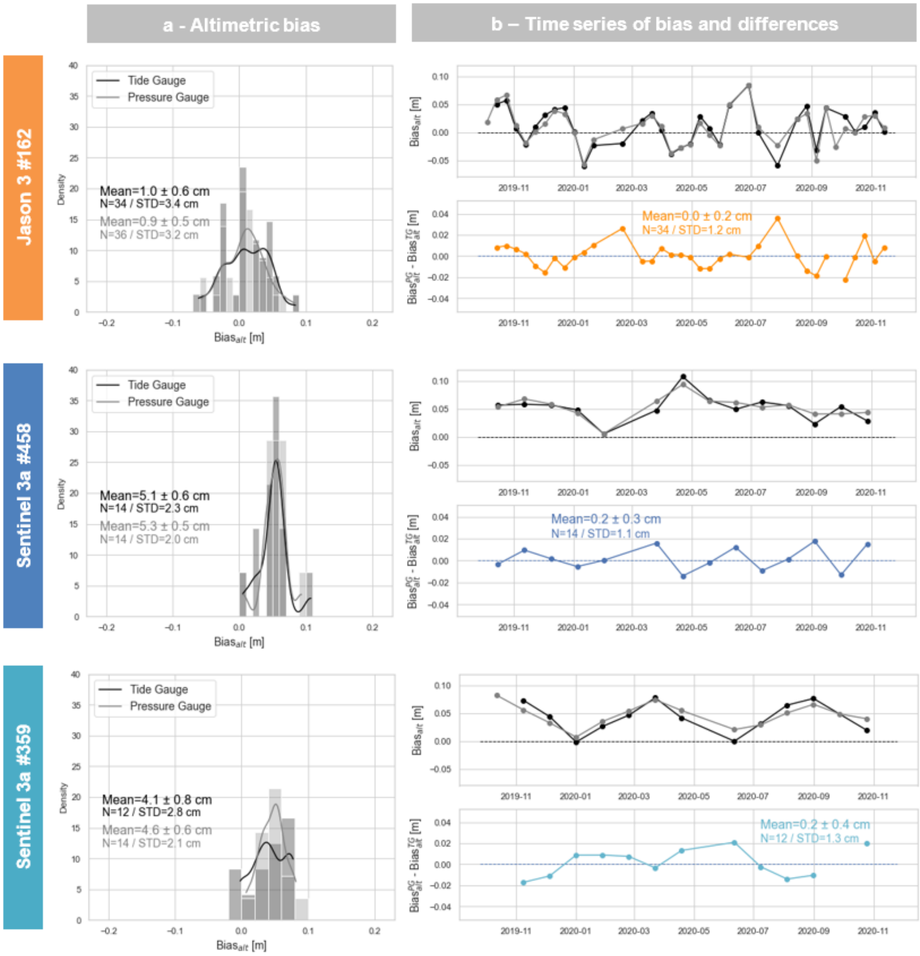


Figure 7. Altimetric bias at the comparison point according to different *in situ* datasets and for 3 altimetric tracks: the Jason 3 (orange) track #162, the Sentinel-3a tracks #458 (dark blue) and #359 (light blue). / (a) Altimetric biases distribution using tide gauge data (black) or 2019x pressure gauge (grey) as *in situ* reference. / (b) Bias time series using tide gauge (black) or pressure gauge (grey) as *in situ* dataset (upper panel) and bias time differences from the pressure sensor (lower panel).

4.2.3 Multi-mission comparison

Over period [2016-2022], both Jason 3 and Sentinel-3a are measuring sea level at our crossover point, that allow a direct inter-mission comparison. Figure 8 shows the altimetric biases time series for Jason 3 (mean bias of +12 ± 3 mm, orange line) and Sentinel-3a tracks #359 (+40 ± 4 mm, light blue line) and #458 (+39 ± 3 mm, dark blue line) at our comparison point. Table 3 summarises the last results of the three historical Cal/Val sites from the last Ocean Surface Topography Science Team (OSTST) meeting (Bonnefond et al., 2022a). For Jason 3, our mean bias estimate is close to the Harvest one (-2 mm), and slightly higher than the Corsica (+8 mm) and Bass-Strait results (+16 mm). For Sentinel-3a, we find a mean bias larger of about +16 mm compared to the Corsica and Bass Strait sites. Regarding the inter-mission bias [$Bias_{alt}^{S3a} - Bias_{alt}^{J3}$], we find a difference of +28 mm, which is in line with those determined at Bass-Strait (+29 mm) and Corsica (+18 mm) sites (see Table 3).

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.

Commenté [CC78]: Watson : 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 aboslute datum is therefore required.

As per email, I suspect that this offset is related to the permanent component of the solid earth tide. I see that Bruce Haines also made this comment in the OSTST forum.
I do think that regardless of the length of the mooring or tide gauge, the absolute accuracy is constrained only by the buoy - hence in this case you only have 48 hours of observations to constrain that datum.

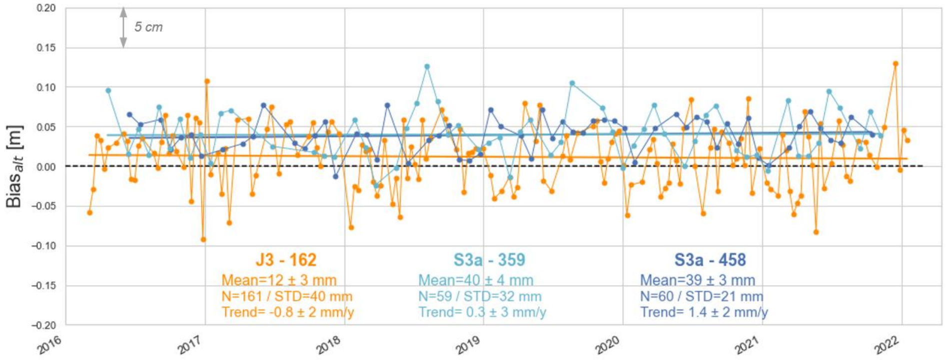


Figure 8. Altimeter bias time series at the comparison point for Jason 3 track #162 (orange) and Sentinel-3a tracks #458 (dark blue) and #359 (light blue) during their common flying period.

4.2.4 Long-term altimetric bias evolution

Thanks to the long-term measurements of the Noumea tide gauge, we compute the Jason altimeter bias time series between 2002 and 2022. The absolute bias estimates are detailed in Figure 9a for Jason 1 (with a mean bias of +66 ± 2 mm), Jason 2 (+39 ± 3 mm) and Jason 3 (+12 ± 3 mm). The Jason 1 and Jason 2 mean biases are slightly higher than in other Cal/Val studies (Table 3), with a mean difference of about +24mm (J1) and +23mm (J2) compared to Corsica and Bass Strait sites. Regarding the inter-mission biases, we find -27 mm for $[Bias_{alt}^{J2} - Bias_{alt}^{J1}]$ that is consistent with the Bass Strait estimate. For $[Bias_{alt}^{J3} - Bias_{alt}^{J2}]$, we find inter-mission bias of -27 mm to compare with the -19mm and -12mm of Bass Strait and Corsica sites. These results are very encouraging and show the interest of the Noumea site to conduct further Cal/Val activities. As discussed previously, a more robust referencing of the *in situ* data could lead to the determination of better constrained biases.

Commenté [CC79]: reword if permanent tide resolves this issue

To the first order, the altimeter bias, differences between altimetry sea level variations and those seen by tide gauge (see Eq. 4) can be related to Vertical Land Motion (VLM) at the tide gauge site (Wöppelmann and Marcos, 2016). We therefore analysed the linear trend estimated on our altimeter bias time series to compare with the vertical motions of nearby GNSS stations. A review of the GNSS stations in New Caledonia and the associated trend estimates is available in Appendix A. 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.).

Commenté [CC80]: I suspect that the J3 series has a few outliers - experimenting with some outlier detection routines maybe beneficial.

Commenté [CC81R80]: We add a basic outlier algorithm method based on interquartile range to remove some outliers on the final bias time series. We add a sentence to explain that in the introduction of section 4.2.

Commenté [CC82]: you mention multiple GNSS but don't really discuss variation between their rates before getting to alt-TG results. This needs some clarification.

As detailed in Section 2.2 and Appendix A, the question of long-term sea level evolution in the Lagoon is not fully resolved. With the 20 years of altimeter and tide gauge differences, we are able to estimate our own trend. First, we realign the 3 bias time series by applying the mean biases computed in this paper (i.e. -66mm for J1, -39mm for J2, -12mm for J3) (Fig. 9b). To have a more robust estimate of the trend, we then used a bootstrapping method, which consists in estimating the trend 200 times on a random sample of 85% of the original series. Over the whole Jason period [2002-2022], we obtain a linear trend of -0.2 ± 0.1 mm/year. It is important to note that this trend is sensitive to the biases applied: for example, using Bass Strait mean biases (i.e. -41/-15/+4 mm instead of -66/-39/-12 mm), we find a trend of -0.7 ± 0.1mm/y.

This being said, our results do not show any significant uplift in Noumea. This differs from the conclusions of Aucan et al. (2017), that find an uplift of +1.41 ±0.67 mm/y over the altimetric period [1993-2013] inferred from the difference between satellite altimetry and tide gauge. The difference likely originates in the method used by Aucan et al. (2017), where the satellite altimetry time series was extracted from a multi-mission gridded dataset at a point far outside the lagoon, before being compared to the tide gauge (see Figure A4 in Appendix A). Section 4.2.2 showed that, even being only a few km apart, there is SSH differences between the tide gauge and the pressure sensor: the difference with a point outside the lagoon can therefore be even greater. Other studies that compare altimetry and tide gauges also find a significant uplift in the area (resp. 1.7 ± 0.2 and 2.5 ± 1.5 mm/y for Nerem and Mitchum, 2002 and Martínez-Asensio et al., 2019). By using along track altimetry products and a closer comparison point, our approach led to a slightly different conclusion.

Regarding VLM estimates from GNSS permanent stations, one thing to note is that most of them highlight a small subsidence in New-Caledonia (see Appendix A). For example, thanks to the combined results of multiple computing centres, Ballu et al. (2019) found an average subsidence of -1.3 ±0.3 mm/y in Noumea. However, authors also show that this VLM estimation can be very sensitive to the integration (or not) of a discontinuity in the time series. To solve the question of long-term sea level change in the lagoon, further studies are thus needed on GNSS data analysis as well as on altimetry and tide gauges. For

Commenté [CC83]: 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?

Commenté [CC84R83]: 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 as detailed in Appendix A.

Commenté [CC85]: I feel there needs to be more mention/review of the GNSS results in the introduction section.

Commenté [CC86R85]: This is done through Appendix A.

Figure 9. (a) Altimeter bias time series at the comparison point for Jason 1 (red), Jason 2 (green) and Jason 3 (orange) track #162. / (b) Altimeter bias time series after applying mean biases found in this study (i.e. -66mm for J1, -39mm for J2 and -12mm for J3). The black line represents the resulting trend compute over the whole Jason period [2002-2022].

example, extending our time series with TOPEX/Poseidon or Sentinel-6 observations would give us a longer and more robust trend estimate. Having longer observations from the GNSS permanent station collocated with Numbo tide gauge could also help to constrained vertical land movements at tide gauge.

5. Conclusion

In this paper, we demonstrate the potential of the New Caledonia lagoon near Noumea to host Cal/Val activities. Using *in situ* data acquired as part of the GEOCEAN-NC campaign, this study proposes a method to link and compare observations from the Noumea long-term tide gauge site and an offshore altimetry crossover point from Jason and Sentinel-3a missions. Thanks to the measurements of a GNSS buoy and a bottom pressure sensor, we are able to virtually transfer long-term Noumea tide gauge data at this altimeter crossover. A comparison over the common year of measurement of the tide gauge and the pressure sensor show that this method is relevant for estimating altimeter bias at the cm-level. The use of along-track altimetry product allows us to test and adapt altimeter correction parameters, especially for the wet tropospheric delay. We consider the up-to-date GDR parameters and thanks to a CalNaGeo survey, we validated the use of the XGM2019 gravity field model to account for geoid gradients.

Commenté [CC87]: Given your variability and absolute offset, I don't agree with mm-level conclusion.

Following the philosophy of Cal/Val studies, we are thus able to compute a precise absolute altimeter bias time series. For the 3 Jason missions and Sentinel-3a, we find mean altimeter biases slightly higher than other historical Cal/Val sites estimates, except for Jason 3 mean bias which is close to the Harvest one. Our estimates of the inter-mission biases are also consistent, especially with the results of the Bass Strait site (see Table 3). 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 future, this site also gives the opportunity to reanalyse data from the TOPEX/Poseidon to the recent Sentinel-6 missions. Extending the comparison will allow to answer new questions, and particularly try to reconcile the sea level trends seen by altimetry, tide gauges and terrestrial permanent GNSS stations. One could also consider transposing this method to other study areas, thus increasing the potential number of Cal/Val studies around the world. However, in addition to enabling the deployment of offshore geodetic campaigns, these potential sites require having suitable altimetry measurement in the vicinity of a reliable sea level observatory (e.g. a long-term tide gauge site), and a good knowledge of the local geophysical and hydrodynamic context to account for the difference in oceanographic signals.

Commenté [CC88]: not quite - you have produced a *precise* time series, not yet an accurate one.

Commenté [CC89]: I think this needs rewording - the hydro context is required to enable the quasi-indirect observation of SSH (i.e. at the TG site, but tidally corrected to the CP). This implies negligible differential oceanogrpahic signals between the two locations - a little more could be made of this point as at this site, the difference in sea level between the CP and TG locations appears to be mostly tidal - there doesn't appear to be other effects dominating (e.g. surges that take a long time for the lagoon to drain and introduce gradients in doing so).

Finally, although the GEOCEAN-NC campaign is not directly related to the preparation of the future SWOT mission, a better knowledge of the lagoon dynamics and the mapping of the fine-scale geoid will be useful for the exploitation of its future large-swath measurements. Thus, the Noumea lagoon represents a real opportunity to establish an absolute and relatively low-cost Cal/Val site, to better understand current and future altimetry data.

Table 3. Altimetric mean biases and inter-mission biases for Jason 1-2-6 and Sentinel-3a missions for three historical Cal/Val sites and the Noumea lagoon (Harvest, Corsica and Bass Strait results are extract from the last OSTST sessions - Bonnefond et al., 2022a)

<table>
<tr><th></th><th></th><th colspan="5">Jason 1</th><th colspan="5">Jason 2</th><th colspan="5">Jason 3</th><th colspan="5">Sentinel-3a</th></tr>
<tr><td rowspan="3">Harvest</td><td><i>Products</i></td><td colspan="5">GDR-E</td><td colspan="5">GDR-D</td><td colspan="5">GDR-F</td><td colspan="5">-</td></tr>
<tr><td><i>Bias</i></td><td colspan="5">+12 ± 2 mm</td><td colspan="5">+8 ± 2 mm</td><td colspan="5">+14 ± 2 mm</td><td colspan="5">-</td></tr>
<tr><td><i>Inter-mission</i></td><td colspan="4">-</td><td colspan="4">-1 mm</td><td colspan="4">+6 mm</td><td colspan="4">-</td><td colspan="4">-</td></tr>
<tr><td rowspan="3">Corsica</td><td><i>Products</i></td><td colspan="5">GDR-E</td><td colspan="5">GDR-D</td><td colspan="5">GDR-F</td><td colspan="5">PDGS</td></tr>
<tr><td><i>Bias</i></td><td colspan="5">+43 ± 3 mm</td><td colspan="5">+16 ± 2 mm</td><td colspan="5">+4 ± 2 mm</td><td colspan="5">+22 ± 4 mm</td></tr>
<tr><td><i>Inter-mission</i></td><td colspan="4">-</td><td colspan="4">-27 mm</td><td colspan="4">-12 mm</td><td colspan="4">+18 mm</td><td colspan="4">-</td></tr>
<tr><td rowspan="3">Bass Strait</td><td><i>Products</i></td><td colspan="5">GDR-E</td><td colspan="5">GDR-D</td><td colspan="5">GDR-F</td><td colspan="5">NTC, BC4/BC5</td></tr>
<tr><td><i>Bias</i></td><td colspan="5">+41 ± 2 mm</td><td colspan="5">+15 ± 2 mm</td><td colspan="5">-4 ± 2 mm</td><td colspan="5">+25 ± 2 mm</td></tr>
<tr><td><i>Inter-mission</i></td><td colspan="4">-</td><td colspan="4">-26 mm</td><td colspan="4">-19 mm</td><td colspan="4">+29 mm</td><td colspan="4">-</td></tr>
<tr><td rowspan="4">Noumea</td><td><i>Products</i></td><td colspan="5">GDR-E</td><td colspan="5">GDR-D</td><td colspan="5">GDR-F</td><td colspan="5">NTC, BC4</td></tr>
<tr><td><i>Cycles</i></td><td colspan="5">1-259</td><td colspan="5">1-303</td><td colspan="5">1-219</td><td colspan="5">3-81</td></tr>
<tr><td><i>Bias</i></td><td colspan="5">+66 ± 2 mm</td><td colspan="5">+39 ± 3 mm</td><td colspan="5">+12 ± 3 mm</td><td colspan="5">+40 ± 4 mm (#359)
+39 ± 3 mm (#458)</td></tr>
<tr><td><i>Inter-mission</i></td><td colspan="4">-</td><td colspan="4">-27 mm</td><td colspan="4">-27 mm</td><td colspan="4">+28 mm</td><td colspan="4">-</td></tr>
</table>

Commenté [CC90]: Update with the latest results

Author contribution

C.C., V.B., L.T. and Y.-T.T. designed the study, V.B, C.C. and J.A. designed and conducted the field campaign, C.C. processed the data and wrote the original draft of the paper. Writing—review & editing, C.C., V.B., L.T., Y.-T.T. and J.A. All authors have read and agreed to the published version of the manuscript.

Data availability

Navigation data for the 2019 GEOCEAN-NC campaign are available online (https://doi.org/10.17600/18000899). Altimetry products are available for download online (see Section 4.1.1) and sensor data used in this paper are available from the authors upon request.

Competing interests

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Funding

This study has been conducted and funded thanks to Centre National d’Etudes Spatiales (CNES) through the FOAM project of the TOSCA program, Centre National de la Recherche Scientifique (CNRS), and French Ministry of Research. Funding for C.Chupin PhD is provided by the Direction Générale de l’Armement (DGA) and the Nouvelle Aquitaine region.

Acknowledgements

For the GEOCEAN-NC mission in Noumea lagoon in October 2019 (DOI : https://doi.org/10.17600/18000899), the authors want to thank Etienne Poirier for the instrument management during the campaign, and the commandant and crew of the R/V Alis. We acknowledge the help of IRD, Shom and DITTT for logistics and on-land tide and GNSS data collection. We also thank the US IMAGO Noumea teams for their logistic support during the campaign, and more particularly Bertrand Bourgeois and Mahé Dumas for the deployment and recovery of the pressure sensors. We acknowledge the CNFC (Comission Nationale de la Flotte Côtière), Ifremer, IRD and the Government of New Caledonia for rapidly adjusting and obtaining permissions for the new cruise plan. We also want to thanks the GINS community and especially the GET laboratory for helping with GNSS computation, and the LEGOS altimetry experts (especially Florence Birol and Fabien Léger) for their help and advices analysing altimetry dataset in the lagoon. The pressure sensor data were analysed using code kindly provided by Marc Pezerat from LIENSs. We would like to thank the anonymous reviewer for his pertinent comments, as well as Christopher Watson for his detailed proofreading which allowed us to point out inconsistencies and omissions in the original paper, and certainly improve the quality of our study.

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