Manuscript EGUSPHERE-2026-3219
Response to Reviewers

Dear Editor,
Thank you for giving us the opportunity to submit a revised draft of our manuscript titled *"Assessing SWOT performance to measure waves and sea level variability over Rangiroa atoll, French Polynesia"*. We also thank the reviewers for their constructive and insightful comments. Below is a point-by-point response to the reviewers' comments, with changes highlighted in the revised manuscript.

Reviewer 1

Reviewer Comment: This manuscript presents a valuable and timely assessment of SWOT performance for measuring sea level and wave variability in a large coral atoll environment. The study is well structured, scientifically relevant, and addresses a topic of clear interest for both the SWOT community and researchers working on reef and atoll hydrodynamics. The results regarding the use of KaRIn-derived SWH to improve the sea-state-bias correction and the reconstruction of a local mean SSH field are particularly interesting.

I recommend publication after minor revisions. My comments mainly concern the positioning of the work within the existing coastal altimetry literature, clarification of some methodological aspects and some results, and improvements to the presentation of some figures and interpretations.

Response: We are grateful to the reviewer for taking time to carefully review the manuscript and give detailed and constructive comments, which has greatly helped to improve this paper. Below is our point-by-point response to each respective comment.

Specific comments

Reviewer Comment: Lines 30-31 and introduction

The discussion of coastal altimetry in the Introduction and especially this sentence appear somewhat outdated and do not reflect the substantial progress achieved in the last two decades. Numerous studies have demonstrated the capability of modern coastal altimetry products to retrieve sea-level information much closer to the coastline than was previously possible. For example, the Sea Level CCI project provides sea-level trends and variability estimates very close to the coast in many regions. Other products, un-retracked such as XTRACK, and retracked such as OpenADB-ALES, have been extensively used for many different coastal studies.

I therefore encourage the authors to substantially revise this part of the Introduction and provide a more comprehensive review of developments in coastal altimetry. In addition, land contamination is only one of several sources of degradation affecting coastal altimetry measurements. In environments such as coral reefs, lagoons, and enclosed bays, the assumption of homogeneous backscatter within the radar footprint may not hold even in the absence of land contamination because different water surfaces within the footprint can exhibit very different backscatter characteristics (e.g., due to spatially varying wind conditions).

I was also surprised not to see any reference of recent developments from the ESA Sea State CCI project, especially considering recent studies that have used altimetry to quantify wave attenuation across coral reef environments. Including these developments would provide a more balanced and up-to-date overview of the state of the art while still clearly highlighting the important advances brought by the SWOT mission.

Response: Thanks for this relevant comment. We agree that the statement on coastal altimetry limitations was a bit outdated and did not reflect the recent advances on this topic. We have therefore rephrased some parts of the Introduction in order to provide a better (yet not exhaustive) overview of the state of the art in coastal altimetry. The corresponding paragraph now reads as:

> Conventional open-ocean altimetry measurements have historically suffered from land contamination in coastal areas where the back-scattered signal is disturbed by interference from land or heterogeneous surface properties in the radar footprint (Vignudelli et al., 2011) making atoll monitoring particularly challenging. However, substantial progress in coastal altimetry processing over the past two decades - including dedicated retracking algorithms, waveform editing, and improved geophysical corrections - has considerably reduced this limitation, enabling sea-level

and significant wave height retrievals much closer to the coastline (e.g. Birol et al., 2021, Passaro et al., 2021, Cazenave et al., 2022). More recently, the European Space Agency (ESA) has integrated some of these recent developments to long-term satellite archives within the Climate Change Initiative (CCI) program (Piollé et al., 2026, Passaro et al., 2026), which enabled the study of wave attenuation within large barrier reef lagoon systems (Usoltseva et al., 2025).

Reviewer Comment: Line 191 and other occurrences In many instances where "SWOT Science Team (2024)" or similar references are cited, corresponding peer-reviewed publications are already available. Whenever possible, I encourage the authors to cite the relevant peer-reviewed literature rather than user handbooks, presentations, or technical documentation.

Response: Thank for this point. As suggested, we have replaced two citations to the SWOT user handbook with citations to peer-reviewed publications:

> [...]KaRIn can also provide information about the sea state by exploiting the measured power in each of the SAR images and the interferometric correlation between both acquisition channels. This last quantity, sometimes referred to as interferometric coherence, is directly affected by the presence of surface waves. This, in turn, provides an opportunity to measure, for the first time at a global scale, significant wave height (SWH) at kilometric resolutions (well below the reach of nadir altimeters) and in two dimensions((~~SWOT Science Team, 2004~~Bohé et al., 2025).

> Additionally for KaRIn instrument, a crossover correction is also needed to reduce systematic errors caused by misalignment and phase error in the two-antenna interferometric system (~~SWOT Science Team, 2004~~Ubelmann et al. 2024).

Reviewer Comment: Line 194 I am unsure about the statement that tide-gauge measurements are not affected by the solid Earth tide, pole tide, and load tide. A tide gauge compares sea level to a benchmark attached to the Earth's crust, and the treatment of these effects in altimetry vs tide-gauge comparisons is discussed extensively in the calibration and validation literature.

For example, Section 2.3 of Kleinherenbrink et al. (2018, https://doi.org/10.5194/os-14-187-2018) discusses these corrections in the context of altimetry validation. It may well be that these effects are considered negligible in the present application, but the categorical statement that tide gauges are not affected by them appears too strong. I would therefore encourage the authors either to provide references supporting this approach or to clarify the assumptions underlying the correction strategy.

Response: Thanks for pointing this out. The statement that tide-gauge measurements are not affected by the solid Earth tide, pole tide, and load tide was indeed confusing. What we meant was that the tide gauge measures relative sea level with respect to the Earth's crust, which is itself affected by solid Earth tide, pole tide, and load tide. As a result, the tide gauge measurements do not contain these signals, while the satellite measurements do, which is why we apply such corrections to SWOT SSH data only. This is now explained in Section 4:

> We also applied geophysical corrections to the SWOT SSH to make it comparable with GNSS-based and tide gauge SSH. Indeed, GNSS-based SSH is corrected by default for the load tide, pole tide and solid earth tide (including the permanent tide). Moreover, the tide gauge measures sea level relative to the Earth's crust, which is itself affected by the solid Earth tide, the load tide, and the solid Earth

and load components of the pole tide. As a result, the tide gauge measurements do not contain these signals, and can be directly compared to the SWOT SSH once this latter has been corrected for these effects. A similar procedure was applied for instance in Kleinherenbrink et al., (2018) to estimate vertical land motion from altimeter and tide gauge measurements. Note that in our case we have used the total pole tide corrections (including the ocean component) provided in SWOT L2 products. Over all the considered SWOT cycles, this correction amounts to 3.2mm on average and never exceeds 8 mm near Rangiroa atoll.

Reviewer Comment: **Section 5.1** I am somewhat puzzled by the very good agreement reported for SWOT SWH. Several users working with coastal SWOT SWH products have identified known issues affecting both Version C and Version D products. In particular, significant across-swath SWH biases have been observed, varying as a function of beta angle, and these effects are currently only partially corrected through external calibration files (which are not yet included in the baseline). In addition, very low SWH conditions in coastal regions often appear as zero values.

The reported performance is remarkably good, and I encourage the authors to discuss these known issues explicitly and to demonstrate that the statistics shown in Figure 4 are not affected by such artefacts. This additional discussion would substantially strengthen the confidence in the conclusions.

Response: Thanks for these suggestions. First we would like to stress that although the absolute error values computed between KaRIn SWH and the two wave buoys SWH appear quite low, they still represent error comprised between 20 to 90%, once normalized by the mean SWH values, which never exceeds 1m in this sheltered environment. This is why we also provide normalized error values. Also, the cross-track dependence of the error (Bohé et al. 2025) was already mentioned at line 306, but no significant relationship was found between the error levels and the cross-track distance (represented with the symbol size in Figure 4). Regarding the effect of the beta-angle on KaRIn SWH measurements, we did not investigate it since our dataset (covering a 3-months period) is too limited to produce robust conclusions. This is now mentioned at line 315 :

> Another environmental factor known to affect KaRIn SWH measurements is the angle β between the vector from the Earth to the Sun and the plane containing the spacecraft orbit around the Earth, which varies cyclically over a monthly timescale for SWOT (Bohé et al., 2025). However, due to the limited number of observations available for this study, this effect could not be further investigated here.

Reviewer Comment: **Section 5.1** Some of the co-authors are closely involved in the SWOT nadir altimetry reprocessing activities within the ESA Sea State CCI framework. They will know that retracked and cross-calibrated low-rate and high-rate SWOT-nadir SWH products should be available in the region of interest and, importantly, exactly along the section located between the two deployed wave buoys.

Including these dataset as an additional comparison in Figure 4 would provide valuable context.

Response: Thank for this excellent suggestion. We have added a new panel on Figure 4 (Figure 1 herein) in order to include the comparisons between Poseidon-3C and the buoy measurements. The method used to select the along-track data is given at line 289 :

> For each SWOT cycle during this period (10 cycles for SPOT1 and 8 cycles for SPOT2), we interpolated KaRIn SWH data at the two buoy locations. For the Poseidon-3C measurements, we extracted the lagoon nadir value the most distant

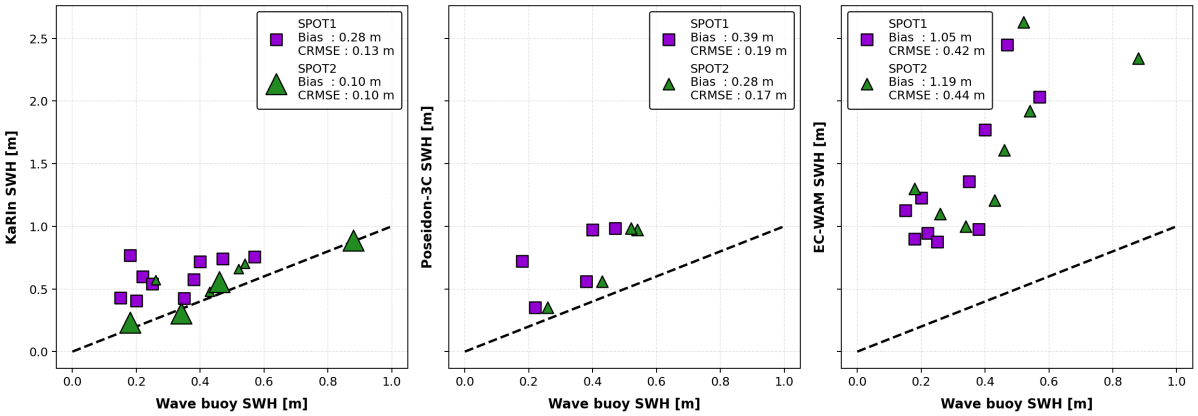


Figure 1: Scatter plots of the SWH measured by KaRIn (left panel), Poseidon-3C (middle panel) and the ECMWF model (right panel) versus the wave buoy estimated SWH. In the left panel, marker size qualitatively represents the cross-track distance of each wave buoy: approximately 12 km (SPOT1, SWOT track 388), 15 km (both buoys, SWOT track 485), and 40 km (SPOT2, SWOT track 388).

> from the atoll rim (approximately 10km) to reduce interference from land in the radar footprint. Only SWH records from track 485 were used since lagoon SWH records from track 388 were too close to the coast ($< 3km$) and systematically flagged as invalid.

The performance of Poseidon-3C relative to KaRIn are discussed at line 297:

> KaRIn SWH shows biases of 0.28 m (89.0% of the mean buoy SWH) and 0.10 m (22.2%), and a CRMSE of 0.13 m (41.2%) and 0.10 m (22.2%), at SPOT1 and SPOT2 respectively (right panel, Figure 1, left). Poseidon-3C nadir altimeter SWH (middle panel, Figure 1) shows biases of 0.39 m (122.4%) and 0.28 m (62.0%), and a CRMSE of 0.19 m (60.3%) and 0.17 m (37.7%), at SPOT1 and SPOT2 respectively. This indicates that KaRIn provides more accurate and more precise SWH estimates at the buoy position, thanks to its 2D sampling, compared to the 1D along-track sampling of Poseidon-3C, which provide SWH observations at more than 10km from the buoy positions.

Reviewer Comment: Line 340 and similar occurrences The manuscript reports several interesting performance metrics in terms of bias and random error. I encourage the authors to compare these values with those reported in the existing literature on SWOT coastal performance. Providing such context would help readers better assess the significance of the reported results and understand how Rangiroa compares with other validation sites.

Response: Thanks for this constructive suggestion. We agree that situating the error metrics obtained over Rangiroa atoll against other published KaRIn validation efforts strengthens the interpretation of our results. We have therefore added references to recent SWOT KaRIn validation studies in coastal environments:

> These performance metrics obtained at Rangiroa are consistent with recent SWOT KaRIn validation studies in coastal environments. For instance, Ho et al. (2025) compared SWOT KaRIn SWH data (version D) against 126 buoys along the East, West, and Gulf Coast of the United States and found a bias of 8 cm and a CRMSE

of 14 cm. Using coastal GNSS buoys in Bass Strait, Hay et al. (2025) reported a KaRIn SWH bias of 6 cm and a CRMSE of 21 cm, reducing to 3cm (bias) and 12cm (CRMSE) when low wave states (SWH $< 1m$) were excluded. Here also the performance of KaRIn SWH appears to vary with sea state conditions. At SPOT1, where wave buoy SWH measurements are mostly in the range 0.2-0.4 m, KaRIn SWH exhibits a higher bias than at SPOT2, where wave buoy SWH measurements are mostly greater than 0.4 m. This behavior is consistent with previous studies showing that SWH retrievals are more challenging under low sea state conditions (Bohé et al., 2025; Turki et al., 2025)

Reviewer Comment: **Figure 7** I recommend improving both the caption and the description of this figure. In particular, it is unclear: what quantity is represented by the color scale and what its units are; what exactly is meant "the black line" in the left panel; what the grey curves represent in the central and right panels. In addition, the methodology used to select SWOT pixels and minimize land contamination deserves a more detailed explanation. More generally, the reader is left wondering what conclusions can be drawn from this analysis regarding the minimum distance from shore at which SWOT SSH measurements remain reliable.

Response: As suggested, the figure and its caption have been modified to improve clarity. In addition, we have revised the methodology to select the SWOT pixels along the pass. Before they were extracted along a straight line. Now these points are manually selected to match the track of the Nano-Cyclopee while locally deviating to avoid land-contaminated pixels (especially on the eastern edge of the pass). This analysis indicates that SWOT SSH measurements remains reliable at a minimum distance of 300m from the coast. Section 5.3.1 has been revised accordingly.

Reviewer Comment: **Figure 8 and Section 5.3.1**

The discussion regarding the influence of temporal sampling is helpful and suggests that differences in averaging periods do not explain the observed discrepancies between the various mean SSH products. However, if temporal sampling is not the dominant issue, it would be useful to discuss why the CNES/CLS MSS appears to perform better than the SWOT-derived mean SSH in the vicinity of the tide-gauge location (as suggested by the smaller residuals of the green curve near the tide-gauge position in the lower panel of Figure 8).

Response: As detailed in Section 5.3.1 (line 421), we found that the SWOT mean SSH present a vertical offset of approximately 9 cm compared to the Nano-Cyclopée mean SSH. If we deduce this offset, the SWOT mean SSH would show residuals of the same order than the CNES/CLS MSS at Avatoru. While the temporal coverage of the Nano-Cyclopée data is not sufficient to construct a MSS product, we estimated that the influence of the temporal sampling on the mean SSH is low (less than 1 cm, Table 3), making possible to use the Nano-Cyclopee mean SSH as a proxy of the true MSS. This is also confirmed by the fact that the Nano-Cyclopée mean SSH at Avatoru is close to the tide gauge estimate of the MSS, as close as the CNES/CLS value. We therefore conclude that the SWOT MSS exhibits a systematic error of about 9 cm over the atoll, which explains the larger residuals near the Avatoru tide gauge, while it captures well the spatial gradient of the GNSS-derived MSS, which was overestimated by the CNES/CLS 2022 MSS.

Reviewer Comment: **Figure 9** The figure would benefit from some improvements in presentation. In particular, the color bars in the first row do not appear to include either a variable name or units. Adding these elements would improve readability and facilitate interpretation of the results.

Response: Thank for the remark, the missing label has been added.

Reviewer Comment: Finally, there are typos and incorrect English expressions in the text. I recommend reviewing the manuscript with an AI-based proofreading tool (or another automatic grammar checker) to identify and correct them. Here are a few examples:

- Line 39: “the the trend”
- Lines 83–85: ”originating from the North Hemisphere storms” -¿ ”originating from the Northern Hemisphere storms”
- Figure 10: “alongthe”
- Lines 161–163 ”echoes fromEarth surface”-¿ ”echoes from the Earth’s surface”
- Lines 188–190: ”corrected of atmospheric...”-¿ ”corrected for atmospheric...” (appears multiple times in the manuscript).
- Lines 280–282: ”KaRIn SWH shows bias of 0.28 m and 0.10 m”-¿ ”KaRIn SWH shows biases of ...”.
- Lines 309–311: ”in most atoll lagoon in the world”-¿ ”in most atoll lagoons worldwide”
- Line 364: “Avatory”

The same is true for typos in the list of references, for example:

- Dutheil et al. (2020): “AndrefouÃt”-¿ should be ”Andréfouët” maybe
- ECMWF (2024) -¿ Retains placeholder text ”accessed: YYYY-MM-DD”

Response: All these minor comments have been considered and appropriate changes in the manuscript have been applied. Moreover, the entire manuscript has been revised to correct remaining grammar errors and typos.

Reviewer 2

Reviewer Comment: This paper utilises in-situ measurements in the Rangiroa Atoll in French Polynesia to assess SWOT derived SSH and SWH measurements. By comparing the SWOT observations with rare sea level and wave buoys, they show the value of the high resolution capabilities from SWOT and the future possibilities of studying these atolls. It is very well written and contains details of the instruments to understand the degree to which the assessment is able to function, and would be very valuable for the scientific community. I recommend some minor revisions that mainly relates to clarification on a few questions

Response: We are grateful to the reviewer for taking time to carefully review the manuscript and give detailed and constructive comments, which has greatly helped to improve this paper. Below is our point-by-point response to each respective comment.

Overall comments

Reviewer Comment: The central lagoon is surely large enough that the coastal contamination from nadir altimetry would be minimal directly in the center (with a width of 14 km)?

Response: We agree that coastal contamination is expected to be minimal in the center of the lagoon given the distance to the reef rim. It should be noted yet that isolated patched reefs are present on the western and eastern part of the lagoon and could possibly contaminate the radar signal. This feature is now added in Section 2.

Reviewer Comment: Line 34: surely this correlates with the SSH in the outer side of the island chain, however the signal might have a different temporal component inside of the lagoon, which would then be unable to be compared with conventional altimetry?

Response: Indeed, comparing altimeter measurements on the outer side of the atoll with tide gauge measurements on the inner part of the atoll (i.e. in the lagoon) is not necessarily meaningful because the tidal signal is severely distorted along the narrow reef channels. For extensive atoll such as Rangiroa, conventional altimetry is however able to provide valid SSH records in the central part of the lagoon. Yet the separation distance between the tide gauge and the altimeter records can still induce some differences, making GNSS buoys particularly useful to validate altimeter measurements (see for instance Chupin et al., 2023).

Reviewer Comment: How do you compute the mean using the 250 m Unsmoothed data, when it is not fixed to a constant geographical grid? Do you grid it to another grid, or interpolate onto specific locations? And at what resolution?

Response: The mean SSH field is interpolated on a fixed 100-m resolution grid. This information was missing in the manuscript and has now been added in Section 4.1.

Reviewer Comment: What is the expected cause of the large deviations that span in the order of 15 minutes that are present in the Nano-Cyclopée and not in the Tide gauge (figure 5)? It did not seem to be addressed in the text, and the GNSS buoy and Nano-Cyclopée both seem to detect them.

Response: In Appendix 6.1, the two components of the Nano-cyclopée SSH signal (GNSS altitude and air draft) are analyzed separately in order to better characterize uncertainties in GNSS data. The large deviations shown on Figure 5 can be attributed to the GNSS signal only but their origins remain uncertain. At this stage we can only hypothesize that they likely result from changes in the GNSS satellite constellation, errors in atmospheric corrections or limitations of the PPP method. These errors are now more clearly pointed out in the description of Figure 5, and a reference to Appendix 6.1 has been added.

Despite significant fluctuations of the GNSS-based measurements with local amplitudes up to 7cm and periods around 15-20min (see Appendix 6.1 for a discussion on GNSS-related errors), the slowly-varying part of the signal agrees very well with the tide gauge measurements.

Reviewer Comment: In figure 8, it seems that there is some kind of smoothing or cubic interpolation, as you have a SWOT mean profile on land, which might cause coastal contamination and explain the large positive anomalies when compared to Nano-Cyclopee. This relates to the missing explanation of the gridding of the SWOT unsmoothed data, and would be an important point in the utilisation of the data in these regimes. Additionally for figure 8, the grey and blue colours are not explained in the legend, and the profiles have values outside of the lagoon, that Fig 8a does not illustrate, that would be helpfull. The legend would be more easily explained if it said Mean SWOT as well.

Response: No cubic interpolation or smoothing has been applied to the SWOT SSH data presented on this figure, but the linear interpolation of the original 250-m Unsmoothed data onto a fixed 100-m resolution grid could have slightly smoothed the mean SSH profile. Yet, the large positive anomalies that is observed over and beyond the emerged reef part (grey zone) mostly reflect deviations in the raw observations at similar distance, not interpolation error, and we can deduce from this plot that the 250-m Unsmoothed data start to degrade around 300m from the coast. This is now indicated in Section 5.3.1. Moreover, Figure 8 has been updated in order to improve clarity based on the above suggestion.

Reviewer Comment: Minor comments:

- Line 8: Maybe add a short note about where Rangiroa atoll is here also
- Line 10: Outperforming by how much?
- Line 72: it would be very helpfull if the Avatoru and Tiputa passes were marked on the map in Figure 1(right), as the coastline (black line) makes it seem like there is quite a lot of passes to the open ocean.
- Line 268: Just to ensure readability, I would recommend stating that the bar in equation 5 is the mean.
- Figure 7: Missing unit on the time axis, is it minutes? Or hours? Or local time?
- Line 458: "collocated"

Response: All these minor comments have been considered and appropriate changes in the manuscript have been applied.