Responses to Reviewers on *Measurements of Nearshore Waves through Coherent Arrays of Free-Drifting Wave Buoys*

The Reviewer Comments are in red.
The Author's responses are in black.

General Response:

The initial version of this paper focused on estimating wave height statistics from the buoy dataset. Further reflection and the reviewer comments have prompted us to shift our focus to the utility of the Level 1 motion data, including the quality-controlled GPS locations and velocities of the buoys and the body-reference-frame accelerations and rotation rates. These data contain rich information on the kinematics of the ocean surface, how buoyant particles move in the nearshore, and the wave-breaking process. Wave height statistics and other Level 2 data are still a worthwhile avenue to pursue with this dataset; however, we have more clearly stated the caveats and challenges in estimating wave statistics from arrays of buoys rapidly transiting the nearshore region, which are sometimes moving with mean flows and sometimes with breaking waves and bores. In addition to text and figure changes reflecting this shift in focus, we have made a small change to the title: "Measurements of Nearshore Ocean-Surface Kinematics through Coherent Arrays of Free-Drifting Buoys." We have also added a section in the paper to discuss how these data can be used in further studies to address a few of the reviewers' concerns regarding applications. We have also expanded the analysis of the differences in significant wave height between the microSWIFT arrays and the 4.5-meter AWAC. Two other fixed instruments, the 6-meter AWAC and 8-meter array, have been added to the comparison to corroborate the measurements from the 4.5-meter AWAC. More specific comments are addressed below.

Dear Dr. Pezerat,

Thank you for taking the time to review this manuscript. We have changed our perspective on how to use this dataset best and therefore, we have shifted the focus of this study towards the Level 1 data capabilities to present the utility of the dataset. Please see the general comments on the paper above; your specific comments are addressed below.

This article reports on the development of the microSWIFT, a small wave buoys equipped with a GPS module and an IMU, building on the SWIFT buoys (Thomson, 2012), with the objective of providing measurements to investigate nearshore wave dynamics through the deployment of coherent arrays of microSWIFTs. As a proof of concept, several experiments were conducted at the FRF at Duck, NC, and the paper further presents data processing procedures, the results of which are compared with measurements from a fixed AWAC. The need for more nearshore measurements is unquestionable, and every related research efforts are thus welcome. I appreciate the authors detail the conception of the microSWIFT and how to manage the deployment and some aspects of data processing, although I have some technical concerns regarding the latter (see specific comments below). More generally, I have some doubt regarding the concept of employment, but I guess further research efforts beyond the scope of this study are needed, building on the dataset that have been constituted and made available to the community.

Specific Comments:

1. l.42 "However, it is challenging…" In situ measurements in the nearshore area are indeed challenging, however it is worth mentioning here some recent studies that reported comprehensive field campaign using fixed sensors in such environment (e.g. Guerin et al. 2018, Pezerat et al. 2022, Lavaud et al. 2022)

Discussion about successful, comprehensive field campaigns that have used fixed sensors has been added in Lines 46-49 and includes your suggested citations. The section where this is addressed is now the following: "While it can be challenging to deploy many fixed sensors and remote sensing systems, many field campaigns have been successful using these methods in the nearshore region (Guérin et al., 2018; Pezerat et al., 2022; Lavaud et al., 2022; Carini et al., 2015; Elgar et al., 2001)."

2. l. 43 "As an alternative…" I rather disagree, the use of Lagrangian device such as wave buoys faces inherent limitations for measuring steep waves that are typically found in the surf zone owing to the simultaneous vertical and horizontal motion of the buoy, the waves in the record tend to look more symmetrical around the mean sea level than they actually are such that non-linear effects cannot be properly investigated with a buoy (e.g. Magnusson et al., 1999; Foristall, 2000). Furthermore, remote sensing techniques, which ability to measure nearshore waves have been demonstrated in a myriad of studies, should be mentioned here.

We agree with you on this comment, and the sentence now reads, "As a complement to the fixed sensors and remote sensing methods, buoys have become a good option for obtaining direct measurements of the surface kinematics in various sea states." on Lines 52-53. We believe that the buoy measurements are not an alternative to fixed instruments but are rather a complement to the fixed instruments and remote sensing methods. A short discussion of remote sensing techniques has also been added on Lines 47-49. Further discussion about the limitations of buoys measuring the non-linearity of nearshore waves, including the suggested citations, is included further down on Lines 71-74 and reads as "While buoys have inherent challenges in measuring nearshore waves, including distortion of surface elevation from accelerometer measurements (Magnusson et al., 1999) and inability to resolve second-order non-linearity (Forristall, 2000), they are the only tool that can be used to obtain direct measurements of the kinematics of the surface and observations of the motion of real buoyant objects in the nearshore."

3. l. 44 "Free drifting buoys…" This assertion should be supported with some appropriate references, furthermore the sentence reads oddly (it looks like a word is missing), I suggest you reword it.

We agree that this sentence was a bit strange, but the point has been reiterated differently and is split between Lines 46-47, which reads, " These fixed sensors generally have robust statistics since they measure continuously in the same location." and Lines 54-56 which read as "Free-drifting buoys tend to move through the surf zone very quickly, other studies have reported buoys reaching approximately 50 cms^{-1} as a mean drift velocity, which can be further enhanced by breaking waves and bores (Schmidt et al., 2003; Deike et al., 2017).” The point we hope to make here is that the buoys are drifting and therefore do not collect data in one location as the fixed instruments do. Therefore, the data they collect at a specific location is generally shorter than that of a fixed instrument.

4. l. 51 “… however, they are limited to…” As pointed out above, I would say it is actually an inherent limitations of wave buoys.
As described above, this has been commented on on Lines 71-74. However, this specific sentence is still in the Lines 59-61 manuscript since it refers to the *GPSwaves* processing algorithm, which uses horizontal velocities and an assumption of circular wave orbits to estimate the scalar energy density spectrum. The sentence now reads: “GPS-based wave buoys have been effective at measuring deep water ocean waves; however, they are limited to measuring deep water waves due to an implicit assumption of circular wave orbital motion (Thomson et al., 2018).”

5. Fig. 3. The cap on the bottle seems fairly “standard”, have you encountered any problems with the seal?
The cap is standard. Generally, the bottles were robust, though we did add an O-ring to the lid to help keep water out. We found that when the bottles were smashed into the sand from the shore break, they could leak a little. While a few of the bottles leaked during the experiment, most of them were fine. At the end of each day, we also used compressed air and a towel to clean out each of the lids and inspect them to ensure they had the best chance of staying dry during consequent deployments. A sentence has been added to the manuscript to address this on Line 112: "The Nalgene water bottle has a standard lid, and an O-ring was added to the mouth of the bottle to reduce water intrusions.”

6. l. 99-107 Is there an SD card to keep a record of the data, if not would it be worthy?
There is an SD card that records all of the raw data. The dataset discussed here is all from the raw data downloaded from the SD card. While the buoys have an iridium modem, it was not utilized for this experiment other than some live time tracking to recover the buoys and all of the raw data. A sentence has been added in Lines 118-119 that reads, “The Raspberry Pi Zero also has an SD card where all raw data is stored and downloaded from when the buoys are recovered."

7. l. 123-124 “For nearshore applications…” After reading section 2.3, I see nothing in the processing method to account for non-linear effects. As pointed out above this is quite an important limitation of the concept of employment of these buoys, could you thus please elaborate a bit more?
We agree that this is an important limitation for the original use of the buoys. Due to changing our perspective to focus more on the Level 1 data than the Level 2, we have not continued with any corrections for nonlinearity in the sea surface elevation time series. We have rather noted the limitations of the buoys on Lines 67-69 as the following: “While buoys have inherent challenges in measuring nearshore waves, including distortion of surface elevation from

accelerometer measurements (Magnusson et al., 1999) and inability to resolve second-order non-linearity (Forristall, 2000), they are the only tool that can be used to obtain direct measurements of the kinematics of the surface."

8. l. 136-139 "The microSWFTS were retrieved…" have there been any losses, if so it is worth mentioning the rate of lost bottles such as the reader can have a proper idea of what involve such deployment?

During this experiment, 2,187 bottles were deployed (buoys were repeatedly deployed), and only one bottle was lost. The buoys deployed also included what we refer to as 'shepherd' buoys which were in the same hull and ballasted the same as the microSWIFTs but had GPS tracker (Garmin Astro) inside them so we could track the movement of the array in real time for recovery. This has been added to the manuscript on Lines 149-152 and reads as, "To track the buoys in live time, we deployed 'shepherd' buoys which had the same hull and ballast as the microSWIFTs but had a live tracking GPS in them to track the current movement of the buoys as they drifted. Over the course of the experiment, 2,187 buoys were deployed, including the shepherd buoys, and only one was lost."

9. l. 153 "Gaps are rare…" Is it also true for GPS data, as it seems to me it is quite common to find some gaps in GPS wave buoys measurements, presumably associated with waves passing over the buoys?

Any gaps in GPS data we expect to be due to temporary submersion or waves overtopping the buoys as well. However, any noticeable gaps in the GPS data called for the buoy to be removed during the quality control phase, so the data left have little to no gaps in the GPS record. Any small gaps in the GPS signals were filled using linear interpolation following the approach of Schmidt et al. 2003. This description has been added to the Lines 185-188 manuscript: " Gaps in GPS measurements occur due to the buoys being overtopped or plunged underwater. These gaps are filled using linear interpolation but are generally minor. Schmidt et al. (2003) used similar GPS-based drifters and found 95% data return rates seaward of the surf zone and 75% data return rates within the surf zone but found linear interpolation was an appropriate method to fill the data gaps, so this methodology is followed."

10. l. 201-202 "we use data when an individual microSWIFT…" Why not considering measurements from buoys inside a circle, centered on AWAC location, with a given radius, according to the bathymetry constraint? Here you might have considered data from buoys at quite different locations along the isobaths.

As part of a compromise with other researchers during DUNEX, we agreed to deploy buoys on the pier's south side primarily; therefore, measurements were limited near the 4.5 meter AWAC. Following another reviewer's suggestion, we have instead computed the significant wave height estimate from the aggregate of all wave realizations outside an approximate surf zone. Changing this analysis led to more measurements across all the missions rather than being constrained to just wave realizations near the 4.5 meter isobath. The analysis results are shown in Figure 9 in the revised manuscript and below. Here, we also include your suggestion as a dark ring around points where the centroid location that the aggregate measurements are within a 300 meter radius. This analysis shows that only 9 of the 63 significant wave height measurements have an average location within a 300 meter radius of the 4.5 meter AWAC. We appreciate this suggestion and think it is useful, so it is combined with the other reviewer's suggestion as a marker on the comparison scatterplot.

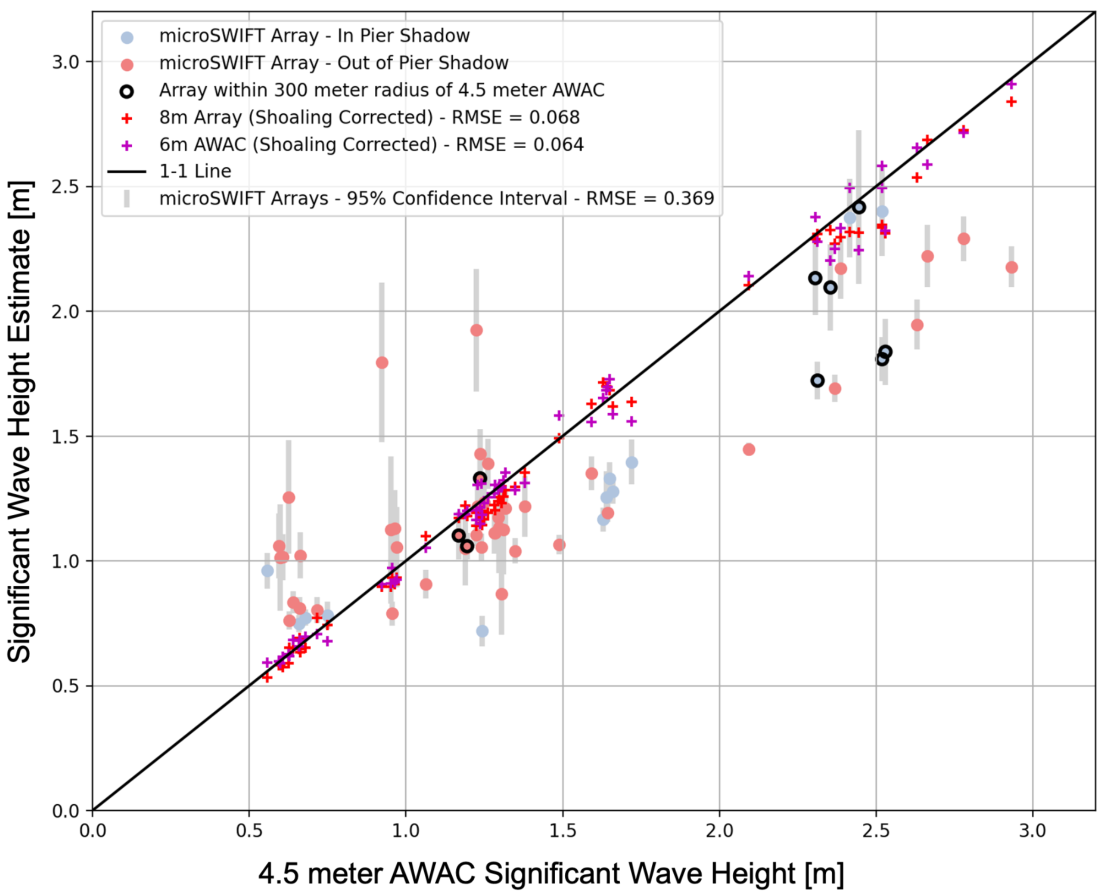

Figure 9. Comparison of the estimated significant wave heights from the microSWIFT arrays, 6-meter AWAC, and 8-meter pressure sensor array (6-meter AWAC and 8-meter array have been corrected for shoaling) to the estimates from the 4.5 m AWAC. While the microSWIFT arrays are not in the same water depth as the 4.5 m AWAC, we see that the microSWIFT arrays characterize the size of the waves with good comparison to the 4.5 m AWAC. The gray bars indicate 95% confidence intervals around each of the significant wave height estimates, computed using a bootstrap method from the distributions of wave heights. The colors of the estimates depict if the microSWIFT array is in the 'shadow' of the pier where we expect a reduction in wave energy.

11. l. 204-207 “The spectra are computed…” I get a bit lost here with the estimate of the number of DOF and the resulting spectral resolution. My understanding is that the 10 min (600 sec) records are divided into three overlapping windows (Nw=3) of 300 sec with a 50% overlap, and then, the average spectrum is band-averaged on five frequency bins (M=5). The number of DOF could be thus roughly estimated as: DOF = 2*Ns*(M+1)/2 = 18, as opposed to 51. Could you detail a bit more the way spectra are computed?

A detailed description of how the degrees of freedom are computed is included in Lines 241-251. The discussion follows: “The microSWIFT spectra are computed using Welch’s method, with Hanning windows and 50% overlap between adjacent windows. The energy in each five adjacent frequencies is band-averaged to improve the statistical robustness of each estimate. The equivalent degrees of freedom for each spectrum is computed using the formulation in equation 2 for Hanning windows
from Thomson and Emery (2014).

$$DOF = (8/3)\frac{N}{M}$$ (Equation 2)

Here, N is the number of data points in the time series, and M is the half-width of the window in the time domain. For these spectra, N = 7200, which is 10 minutes (600 seconds) sampling at 12 Hz frequency, and M = 1800, which is the half-width of a single window. After band-averaging the five adjacent estimates, this results in approximately 53 degrees of freedom(rounded to the closest integer). The AWAC measurements consist of a 34-minute record with a sample rate of 2 Hz, and spectra are computed with 13 50%-overlapping windows (512 points per window) leading to approximately 42 degrees, comparable to that of the microSWIFTs (Christou et al., 2011).”

12. l. 210-211 and l.247-248 I am not convinced by the robustness of the spectral analysis. As pointed out in the two comments above I have some doubts on the way spectra are computed. Furthermore, the spectra show discrepancies that might result in quite important differences on bulk parameters, maybe not Hm0, but what about mean periods? These statements should be tone down, I would rather speak of a relatively good qualitative agreement.

The spectral analysis has been toned down to now show an example comparison with the 4.5 meter AWAC since very few measurements had 10 minutes of data along comparable isobaths. Following another reviewer's suggestion, the spectra from each individual microSWIFT are averaged together, and the significant wave height is computed by integrating the averaged spectra and the spectra from the 4.5 meter AWAC. The individual and averaged spectra compare qualitatively well with the 4.5 meter AWAC. The updated figure is shown below. The associated text is now on Lines 256-258: “The qualitative agreement of each microSWIFT spectra and the AWAC suggests that the measurements are useful for further investigating wave properties with the buoys. Future use of these data may investigate the estimation of directional spectra and directional moments, but they are not investigated in this study.” Since the paper has been restructured to move away from the focus on Level 2 measurements which, as stated in previous comments, have challenges, we do not compute the mean periods or focus more on bulk wave statistics.

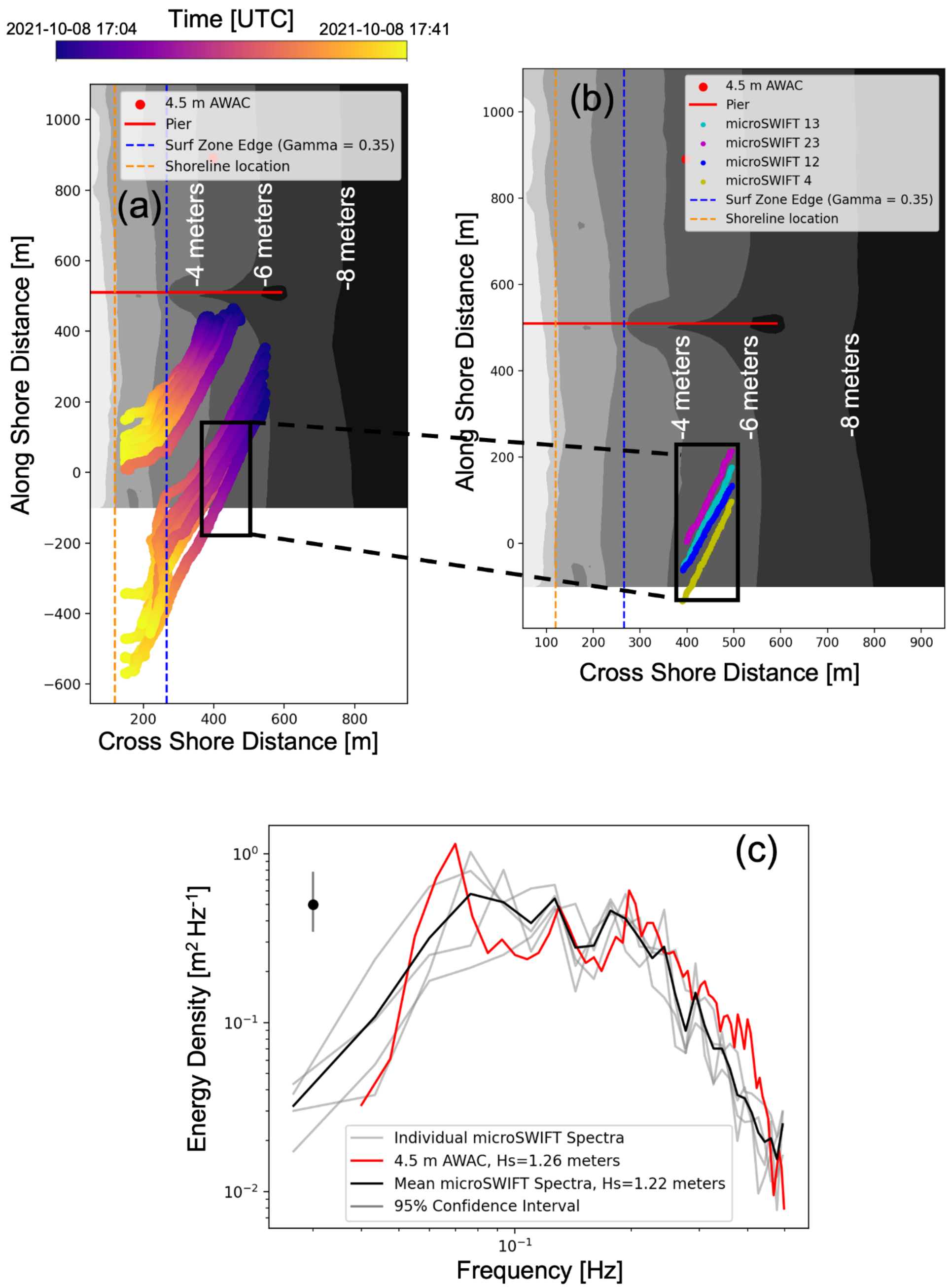

Figure 7. Comparisons of Panel (a) shows the drift tracks of the microSWIFTs from mission 18 plotted over the surveyed bathymetry DEM. Panel (b) shows a subset of the drift tracks where the bathymetry along each track is between -4.3 and -5.3 meters, and each microSWIFT is a different color. Panel (c) shows the spectra computed from a subset of the sea surface elevation time series for each microSWIFT. One error bar is shown for a confidence interval of

the spectra with 53 degrees of freedom. Significant wave heights are computed by numerically integrating the AWAC and averaged microSWIFT spectra.

13. l. 215-218 “Since the microSWIFTs…” In practice how individual waves measured by different buoys are tagged? Could you detail a bit more the “sampling with replacement method”?

In practice, we cannot determine whether two buoys measure the same wave; thus, individual waves are not tagged. Therefore, we define a wave realization as any wave measured by a buoy using a zero-crossing method (data between two adjacent upward zero-crossings in sea surface elevation). Since multiple buoys can measure the same wave as the wave propagates past the buoys, this example wave is included in the aggregate distribution of waves multiple times. We gave an analogy to ‘sample with replacement’ methods such as monte carlo simulations and bootstrap methods that use a limited dataset and sample with replacement to improve the statistics of the limited dataset. This is what the array of microSWIFTs is doing physically as multiple waves propagate through the array. Further explanation and discussion of this idea is given in Lines 267-273: “Since the microSWIFTs are spatially distributed in the nearshore and sampling simultaneously, some microSWIFTs will measure the same wave as it propagates past multiple buoys. We treat this like a physical ‘sampling with replacement’ method similar to Monte Carlo or Bootstrap simulation methods known as re-sampling techniques. These re-sampling techniques improve confidence in a statistical estimate from a finite amount of data (Thomson and Emery, 2014). In this case, the finite data is the short period that the buoys sample an area, but multiple datasets from different microSWIFTs, occasionally containing measurements of the same wave, can help improve confidence in the statistics.”

14. l. 222-226 and Fig. 8e I am not convinced of the relevance of such an aggregated distribution, as the buoys did not measure the same sea state as they drift; what is the meaning of this significant wave height? The following of the paragraph makes more sense to me. I suggest to remove Fig. 8e and the associated discussion.

The goal of aggregating the wave realization measurements from the buoys is to provide a more robust statistic than just those from a single buoy since they drift quickly through the nearshore. While you are correct, by measuring a larger area of the surf zone and in multiple depths, this significant wave height is not exactly the same as that computed by the AWACs and pressure gauges. We recognize that there is spatial variability in the wave heights, but we maintain that aggregating the wave realizations together should give us a statistical picture of the wave field that should be qualitatively comparable to the fixed sensors. The distribution of wave heights shown in Figure 8e is used just to demonstrate what wave heights were measured during a singular mission and see the contributions from each individual buoy (colors on the histogram correspond to the different colors shown on the drift tracks). The significant wave height that is now shown in Figure 8e is computed only from wave realizations outside of the surf zone. The updated Figure 8 is shown below.

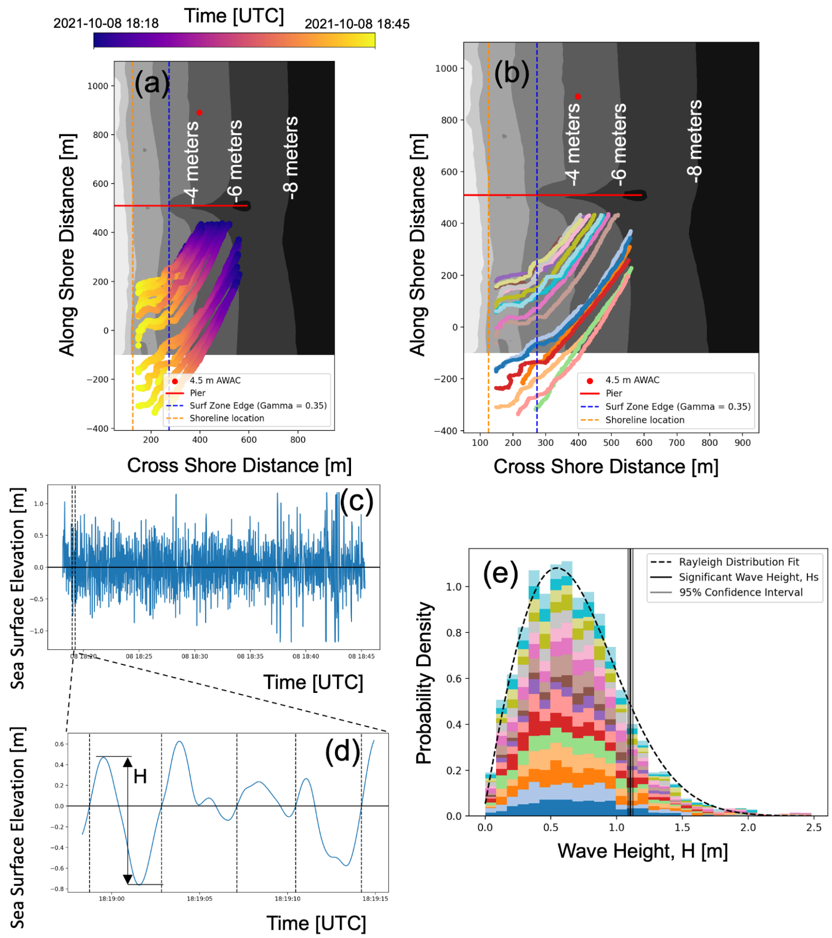

Figure 8. Example of steps in processing each mission. Panel (a) shows the drift tracks of the microSWIFTs from mission 19 plotted over the surveyed bathymetry DEM. Panel (b) shows the same drift tracks as Panel (a) but shows each microSWIFT as a different color. Panel (c) show the time series of computed sea surface elevation, with one-time series being highlighted as an example. Panel (d) is a zoomed-in portion of the overall time series showing the locations of zero crossings and how we define the height of an individual wave in a time series. Panel (e) is the probability density of all wave heights from the entire time series, where the colors show the contribution from each microSWIFT with the corresponding color. The probability density distribution fits a Rayleigh distribution. The vertical line shows the computed significant wave height for this distribution and the 95% confidence interval of the estimate.

15. l.233-247 Did you processed AWAC measurements the same way, i.e. zero-crossing processing method using AST measurements or did you consider the spectral estimates of the significant wave height? For sake of clarity, I suggest you dedicate an appendix to the processing of AWAC measurements

The AWACs are managed by the US Army Corps of Engineers at the Field Research Facility (FRF) where the experiment took place. Since this is the case, we did not do any processing of the AWAC measurements, rather, we just used the data products that they publish on their data portal (https://frfdataportal.erdc.dren.mil/). This is clarified in the manuscript in Lines 100-102: “The data from these sensors are processed by the FRF staff to produce estimates of the bulk parameters of significant wave height, mean wave period, and mean wave direction for the duration of the field experiment (Figure 2) along with many other wave and current data products.” It is also discussed in Lines 244-249 as the following: “The AWAC measurements consist of a 34-minute record with a sample rate of 2 Hz, and spectra are computed with 13 50%-overlapping windows (512 points per window) leading to approximately 42 degrees, comparable to that of the microSWIFTs (Christou et al., 2011). The staff of the Field Research Facility process the AWAC data following the methods described by Earle et al. (1999). These spectral characteristics result in a frequency resolution of 0.016 Hz. Note, however, only the data products processed by the FRF are used in this study, and no processing of the raw AWAC data is done in this study.”

Technical Corrections:
l. 73 “our team” and elsewhere, please avoid the “we” and the “us”.
This suggestion is appreciated and this choice of language has been reduced as much as possible within the text. However, we believe this is a stylistic choice and an effective way to write in an active voice, which is generally more engaging for the reader. We are also following the style described in Zinsser 2006. The correction has been taken into account, and this type of language has been reduced in the paper.

l. 84 and below the positions should be given with the appropriate distance unit from the origin of the local frame, I assume meters.
Thank you for catching this; it has been corrected in the manuscript.

l. 93 “mean wave period” are you referring to Tm01 or Tm02 or the mean period issued from waveby-wave analysis? This is in line with my comment 15 above.
In this case, the mean wave period is the inverse of the energy-weighted mean frequency or the inverse frequency moment, Tm-10. This is provided as a standard product within the AWAC and pressure sensor data processing on the FRF data portal. Further description of each data product is provided in the metadata contained within the netCDF files for the data. The data from the 8 meter array of pressure sensors, which we present the mean wave period in Figure 2, can be accessed through this link: https://chlthredds.erdc.dren.mil/thredds/dodsC/frf/oceanography/waves/8m-array/2021/FRF-ocean_waves_8m-array_202110.nc.html. Since we do not use this data for other analysis than context to the microSWIFT dataset, we have chosen to leave the sentence as the mean wave period for simplicity.

References:

1. Thomson, J., Girton, J. B., Jha, R., and Trapani, A.: Measurements of Directional Wave Spectra and Wind Stress from a Wave Glider Autonomous Surface Vehicle, Journal of

Atmospheric and Oceanic Technology, 35, 347–363, https://doi.org/10.1175/JTECH-D-17-0091.1, 2018.
2. Thomson, R. E. and Emery, W. J.: Data analysis methods in physical oceanography, Newnes, 2014.
3. Zinsser, William. "On writing well: The classic guide to writing nonfiction." New York, NY (2006).