Significant Wave Height Project - White Paper

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Subject: IOOS-NWS project to evaluate HF radar derived wave data.

Background: The purpose of this project was to investigate and assess the feasibility of using HF radar (HFR) wave data obtained from the IOOS network of radars in routine NWS operations. Three NWS Weather Forecast Offices (WFO) were selected to compare and assess the coastal wave data from the HF radars with the nearby buoy data. The WFOs who participated in the study were Mt. Holly, NJ; San Juan, PR; and Eureka, CA. The wave data was provided by three of the IOOS regions: Mid Atlantic (MARACOOS), Caribbean (CARICOOS) and Central California (CENCOOS). The points of contact for all project partners is listed in Appendix I.

These regions are geographically different and consequently experience different wave regimes. Table 1 lists the HF radar sites and buoys used for the comparisons. The SeaSonde HF radar was used at each radar site. The wave data assessment began in December 2017 and concluded in March 2019 for a total of 16 months of comparisons. Each WFO submitted progress reports to the NWS Office of Science and Technology Integration that are available as Appendix II to this white paper.

Table 1: List of HF radar sites and NDBC buoys used in the study along with the corresponding IOOS region and WFO that evaluated the wave data.

IOOS Region	WFO location	HFR Site	HFR Frequency (MHz)	NDBC Buoy
MARACOOS	Mt. Holly	SEAB	13	44065
		BRNT	13	44091
		SPRK	13	44091
CARICOOS	San Juan	FURA	13	41115
		MABO	5	42085
CENCOOS	Eureka	TRIN	5	46244
		SHEL	5	46213

Research Findings: Each WFO compared HFR wave data with the NOAA buoy data closest to the HF radar locations. HF radar data and buoy data show a clear correlation in magnitude. However, since they are not co-located, the exact wave height measurements typically do not match.

WFO Mt. Holly, NJ

The study area for the WFO Mt. Holly evaluation is shown in Figure 1. Figure 2 shows the typical comparison between the wave data from the HFR stations in New Jersey and the nearby wave buoys. This figure shows a feature of the HFR waves, a quick drop in wave height after the wind direction shifts, which will be discussed later in the document. Figure 3 provides a one-month time series for coastal parameters at WFO Mt. Holly for (1) wind direction, (2) wave direction, (3) wave height, and (4) wave period in March, 2018. In general, there is good agreement between the parameters comparing buoy 44091 and HF radar BRNT. Lastly, the SeaSonde wave software versions for all the wave tools as of April 1, 2019 are provided in Table 2.

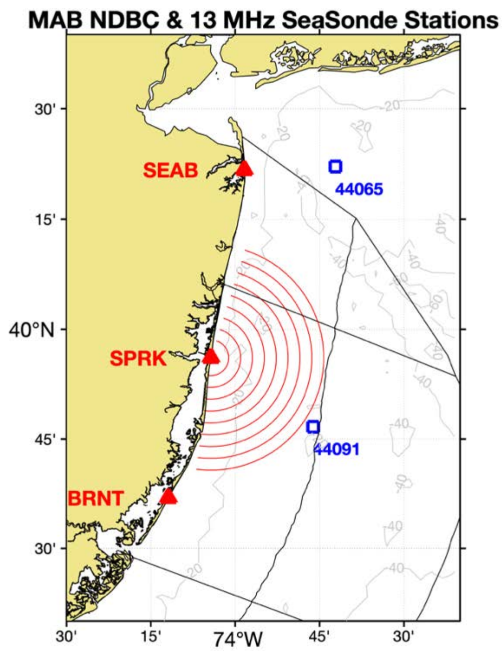

Figure 1: Study area for the WFO Mt. Holly wave evaluation showing the three HF radar stations and two NDBC buoys. Red arcs represent the range cells 1-8 from the SPRK radar. The thin black lines represent the WFO offshore forecast areas.

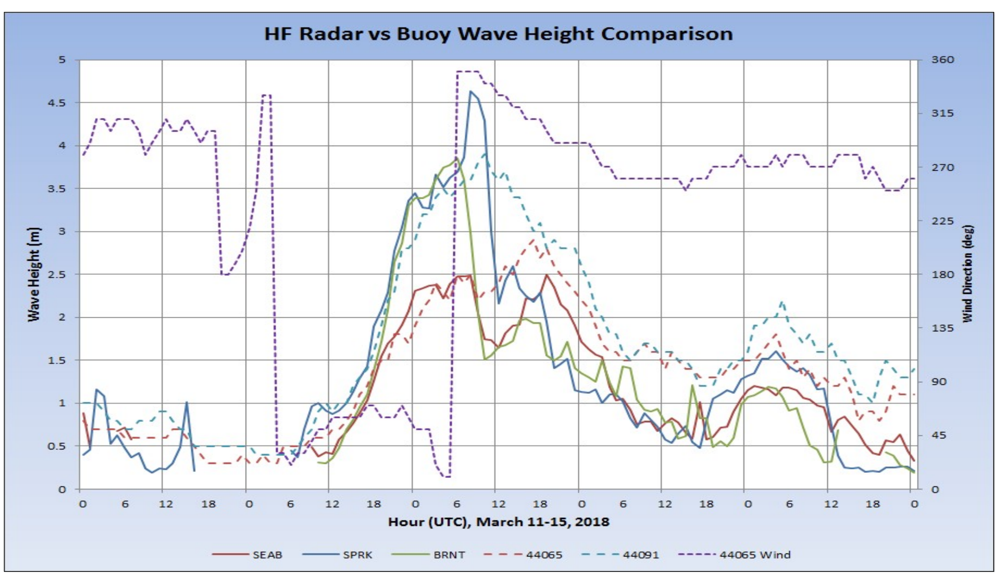

Figure 2: Time series plot of wave height and wind direction for March 11-15, 2018. The legend is provided at the bottom of the figure. HFR sites are solid lines, wave buoys are dashed lines and wind at buoy 44065 is purple dashed line.

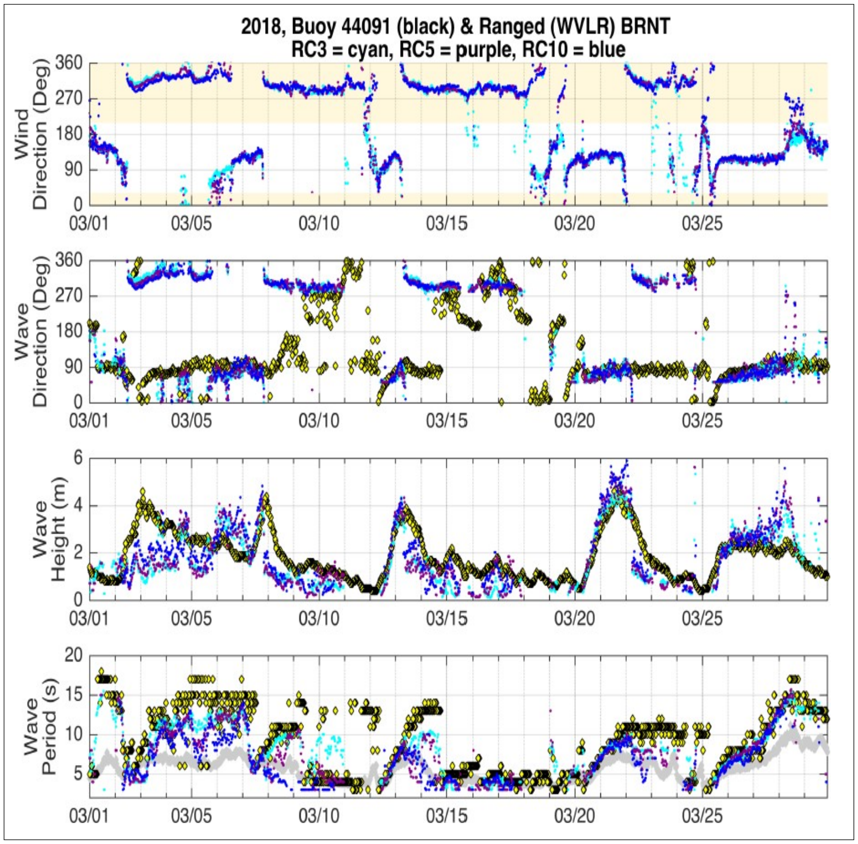

Figure 3: One-month comparison of wind direction, wave direction, wave height and wave period between buoy 44091 (yellow diamonds) and three range cells (3-cyan, 5-purple, 10-blue) from the BRNT radar station.

Table 2: SeaSonde wave software versions as of April 1, 2019 for each of the radar stations that were evaluated.

	SEAB	SPRK	BRNT	BRIG	CMPT
WaveModelForFive	11.5.0	11.5.0	11.5.0	11.5.0	11.5.0
WaveModelFilter	3.0.1	3.0.1	3.0.1	2.2.1	2.2.1
SpectraToWavesModel	11.6.2	11.6.2	11.6.2	11.6.2	11.6.2
WaveModelArchiver	12.1.3	12.1.3	12.1.3	12.1.3	12.1.3
AnalyzeSpectra	10.9.8	10.9.8	10.9.8	10.9.8	10.9.8

WFO San Juan, PR

The study area for the WFO San Juan evaluation is shown in Figure 4 giving locations of radar coverage areas and buoys for Puerto Rico. FURA (green circle) significant wave height estimations were compared with a nearby Waverider 41115 (blue diamond) and MABO (green square) was compared with a Waverider 42085 (blue triangle) south of Ponce, PR. The green areas within the coverage are what contributed to the spatial wave averages. Figure 5 shows the time-series of SWH validations for the FURA site with the Waverider. Note the difference in wave direction from the two measurements. FURA is in a spot where it is shadowed by the coastline north of the coverage area, whereas the buoy has a clear view to the north. Often waves come from the north in this area as reflected in the Waverider buoy measurements. The waves then refract around the coast and bathymetry as measured by the HFR station at FURA.

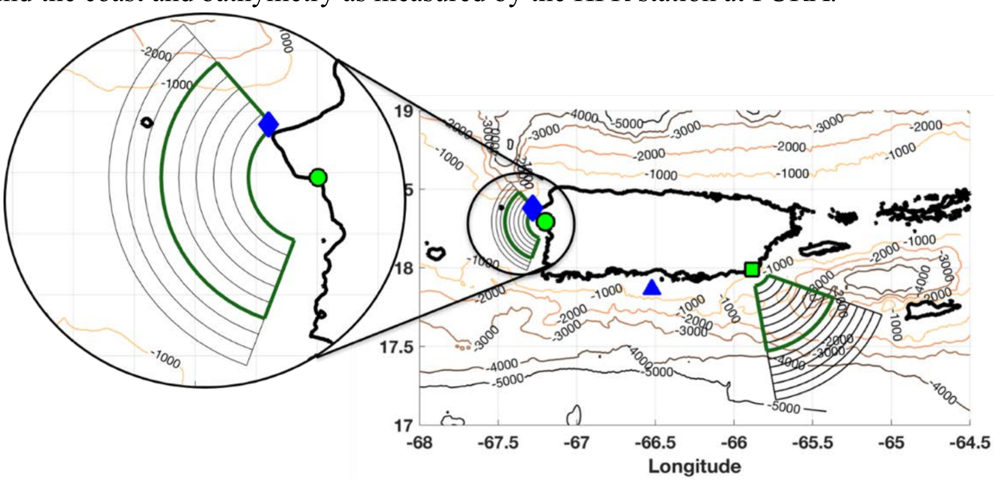

Figure 4: Study area for the WFO San Juan wave evaluation showing the two HF radar stations (FURA – green circle and MABO – green square) and two Waverider buoys (blue diamond blue triangle).

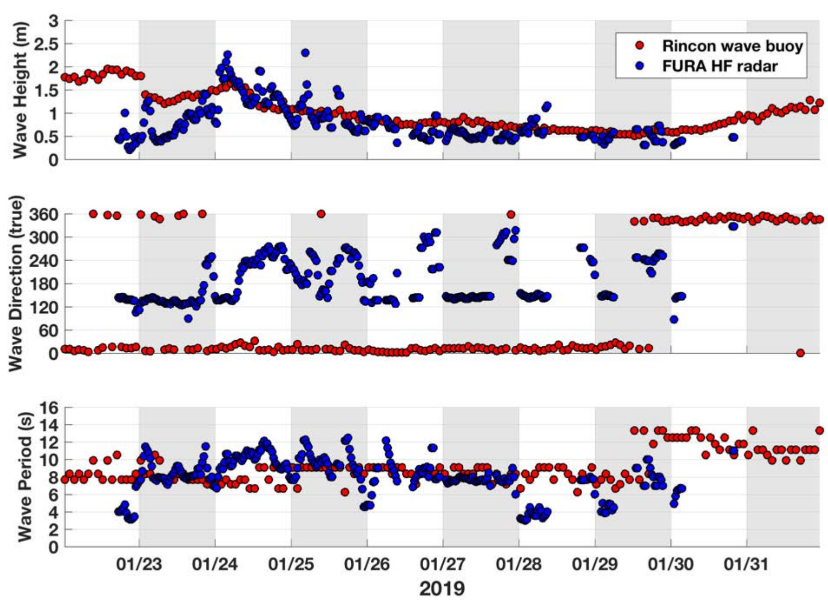

Figure 5: One-week (January 2019) comparison between the Waverider buoy (red) and FURA radar (blue).

WFO Eureka, CA

The study area for the WFO Eureka evaluation is shown in Figure 6. Two-month long comparisons between HFR and NDBC buoy 46213 are shown in Figure 7.

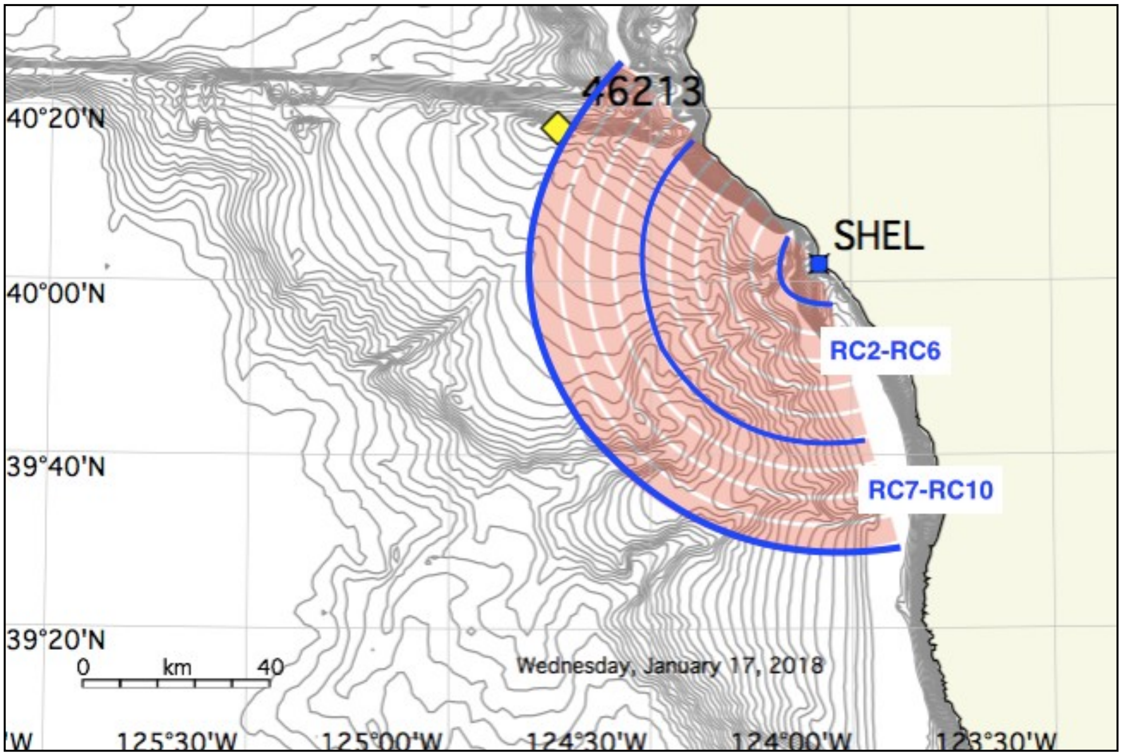

Figure 6: Study area for the WFO Eureka wave evaluation showing the one HF radar stations (SHEL – blue square) with range cells 2-10 shown along with NDBC buoy 46213 (yellow diamond).

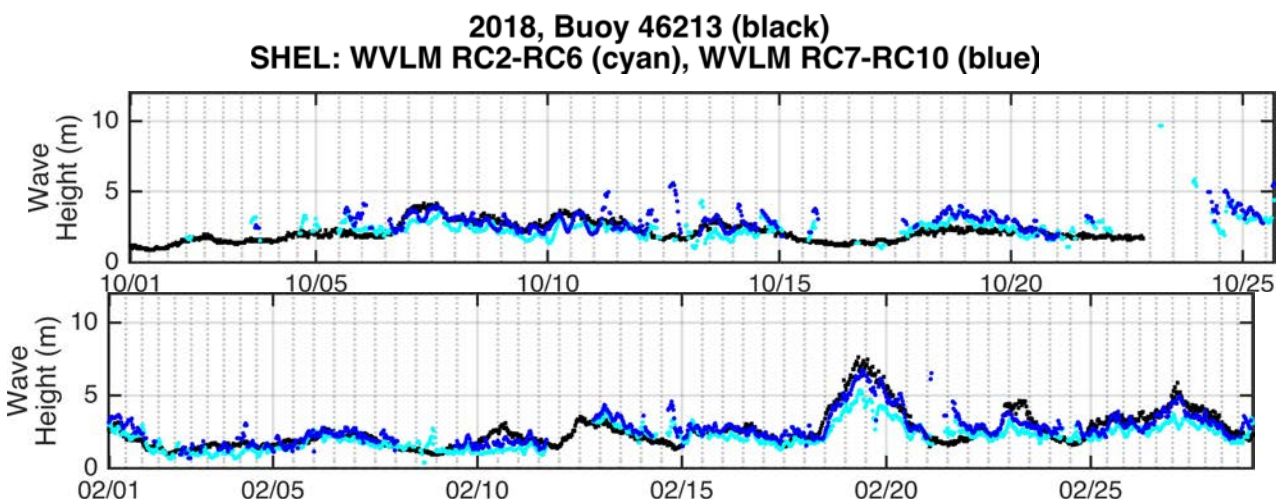

Figure 7: Wave height from HF radar SHEL (range cell 2cyan) and NDBC buoy 46213 (black) for October 2018 (top) and February 2019 (bottom).

Issues: During the 1.5 years of the research project, the following issues were found concerning temporal and spatial assessments and data comparisons.

Data latency was an initial issue early in the overall analyses, with a potential delay of ~2 hours. As a result, further investigation revealed that the long range HFRs (5MHz) have a 60-minute average with 30-minute output for spectra with resulting wave data averaged for 120 minutes with output every 30 minutes. The mid-range HFRs (13MHz) performed a 15 minutes average with 10-minute output for spectra, and wave data are averaged for 75 minutes with output every 30 minutes. In coordination with the HF radar developers at CODAR, a new process could result in a reduction to a 20-minute average with 15-minute output.

Data availability appears to not be a critical issue. Data is typically missing because the waves are minimal and the coastal conditions are not hazardous. A data indicator could help provide confirmation that the waves are minimal. However, this is not the practice at the current time. One of the issues with providing an indicator is that the missing data could be due to other situations, such as (1) the site being inoperable, (2) HF interference, or (3) other extenuating reasons.

HF radar wave height drops occur when the wind direction shifts from onshore to offshore, between the wave pattern shifts due to a frontal passage or other atmospheric phenomenon. In addition, this could also be a result of conflicting signals between local wind waves becoming offshore and long period swells continuing onshore. The west coast of Puerto Rico experiences this routinely during the winter season where swells from the north interact with the offshore trades. Onshore wind is rare but they do occur sometimes in the closer range cells from daily wake patterns. This happens when the easterly trades interact with the topographic features in the middle of the island, which makes it even more complicated. The wind velocities can change very quickly within the coverage area due to this effect. The CODAR developer is working on a new software version which targets handling waves transitioning from onshore to offshore and vice versa.

Expansion of areal coverage for HF radars is advantageous to provide more robust wave coverage of the coastal waters. All 3 WFOs involved in the research agree that additional HF radars would help cover data void areas and would be greatly beneficial. The developer has stated that one possible solution developer, that without new infrastructure, is to expand the existing sites running wave software.

HF radar interference has been a significant issue along the west coast for the Eureka WFO, but not for Mt. Holly. The large wave heights at SHEL are attributed to noise and interference (8%-9.5%). It appears that there is interference in the form of ionospheric echoes at times from other HF radar stations on the west coast. In 2019, WFO San Juan observed Doppler saturation from an unidentified source that appeared to skew wave parameter estimations.

Recommendations: The Mt. Holly, San Juan, and Eureka WFOs concur on the significant value of the HF radar wave data. The issues outlined in this paper have been communicated with the HF radar manufacturer, CODAR Ocean Sensors, and are being explored with potential solutions proposed. Given the data comparisons and the positive correlation between the HF radar data and buoy data, the Significant Wave Height Project conclusion is a strong recommendation that the HF radar data be used for routine NWS operations and incorporated over the Satellite Broadcast Network (SBN) to compliment the full suite of coastal data information.

Appendix I: Project Points of Contact

<table>
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</table>

Appendix II

The following are monthly reports submitted by each of the 3 WFOs during their research assessments of the HF radars with corresponding buoy data.

WFO Mt. Holly

Mt. Holly WFO Status Report - December 2017

Basic Information (data period, data locations, data access issues, etc.)

Dr. Roarty from Rutgers visited NWS Mount Holly on December 14 to discuss progress and plans for the HF-Radar SWH study. There are 13 HF-Radar sites along the NJ shore; data from these sites is available at https://rucool.marine.rutgers.edu/ocean-radar-mapping/ (see Figure 1 below). The data appears to go back for many months.

Status of Data Analyses (discoveries, limitations, advantages, etc.)

We (NWS) have just begun to look at this data. Time series plots show a lot of gaps in the data, especially during relatively calm periods. Plots for periods of higher waves, e.g., November 9 (Figure 2 below), look more complete and in reasonable agreement with buoy data.

Difficulties Encountered

Dr. Roarty and I discussed possible improvements to make the HF-Radar wave data more useful in operations. Probably the most important change would be to have the graphs update more frequently, i.e., every hour rather than once per day.

Solutions Found/Presented

Dr. Roarty will be working with colleagues at Rutgers to make suggested changes to the data displays. These should be implemented sometime in January.

Expected Activities in the Next Month

In January, the NWS will begin some level of regular evaluation of HF-Radar wave measurements. How much we can do depends on whether or not we can get a student to help out. We will try to provide weekly feedback to Rutgers regarding the accuracy and usefulness of the data. We will also provide a training session for the staff here, prior to the beginning of evaluation.

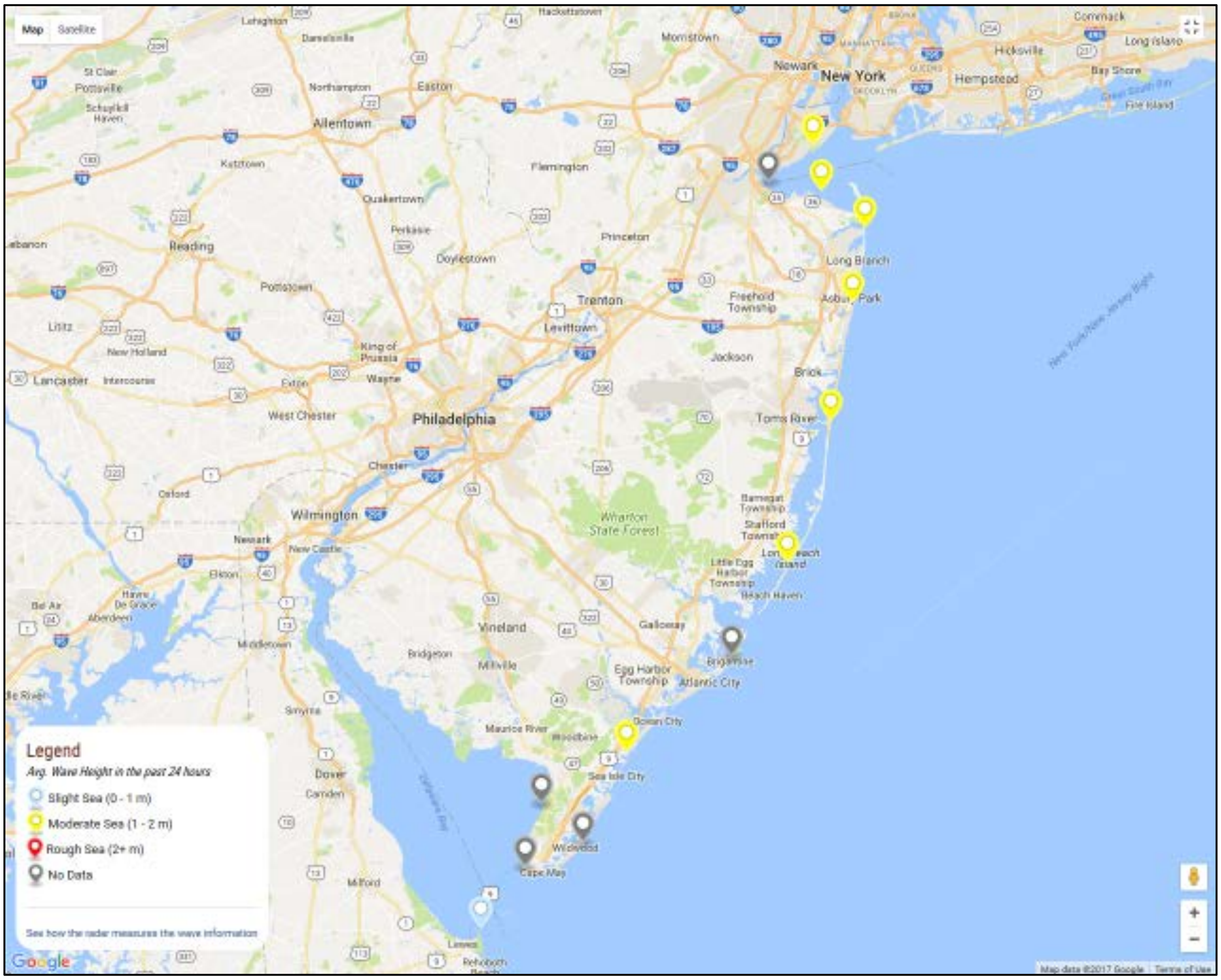


Fig.1 HF-Radar Site Map for NJ coastal waters.

Mt. Holly WFO Status Report – February, 2018

<u>Basic Information (data period, data locations, data access issues, etc.)</u>

Dr. Hugh Roarty visited WFO PHI again on Thursday, Feb 8. He met with me (Al Cope), Walt Drag, Ray Kruzdlo and Lance Franck. Dr. Roarty provided some background info on the operation of the HF Radar Sites. We also discussed more potential improvements to the RU website. These included possible adjustment of sampled areas to get a better idea of wave heights at various distances offshore. We also asked about the possibility of creating a map of wave heights from all radars at a given time. We re-emphasized our operational need for hourly updates of real-time data.

<u>Status of Data Analyses (discoveries, limitations, advantages, etc.)</u>

There was a software update to the processing of HF-Radar data on Jan 23. Date reliability for most of the sites seems to have improved significantly. We still see a number of "spikes" or sudden artificial-looking changes in the wave height time-series plots. An improved QC method may be needed to correct this.

Difficulties Encountered

A number of stations have been missing from the web page since around mid-February. The cause is under investigation.

Solutions Found/Presented

Dr. Roarty will be working with colleagues at Rutgers to make suggested changes to the data displays. These will hopefully be implemented in the near future.

Expected Activities in the Next Month

We will continue to evaluate the availability and quality of data from the HF Radar wave measurement web site at https://rucool.marine.rutgers.edu/ocean-radar-mapping/. Until we have real-time date (updated at least hourly), the evaluation will have to be in a "hindcast" mode.

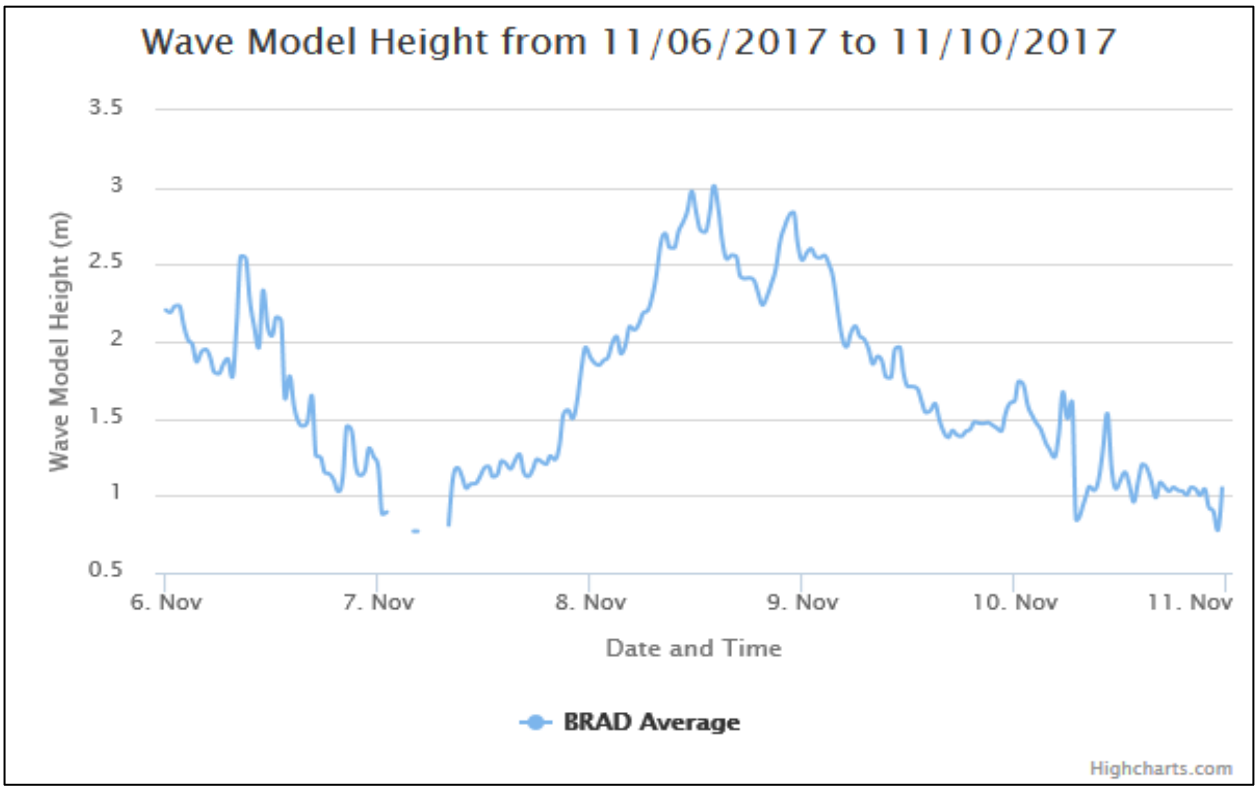


Fig. 2 Wave Height Graph for HF-Radar at Bradley Beach (Asbury Park) NJ.

Mt. Holly WFO Status Report – March 2018

Basic Information (data period, data locations, data access issues, etc.)

This report is for the month of March 2018. During this time our office had access to near real-time HF-Radar wave heights (2 to 3-hour latency) from three sites along the New Jersey shore, which are shown in Figure 1. Access continued to be via the web site https://rucool.marine.rutgers.edu/ocean-radar- mapping/. There are still some periods of missing data, but these are mostly during relatively calm seas, i.e., wave heights less than 1 m.

Status of Data Analyses (discoveries, limitations, advantages, etc.)

March was a very active month for weather, with coastal storms affecting New Jersey around March 2, 7, 13, and 21. Time-series plots of HF-Radar wave heights vs nearby buoys are shown in Figures 2 and 3 for the March 13 and March 21 storms, respectively. In both cases, as the storm developed, wave heights from SEAB match the building seas at buoy 44065 quite well; while farther south sites SPRK and BRNT match the reports from buoy 44091. However, in both cases, after reaching peak values, there is a sharp decrease in wave heights from the HF-Radar, which does not match the buoy data. This is apparently due to the shift in wind direction from northeast (on-shore) to northwest (off-shore) as the surface cyclone moves away to the northeast.

In the HF-Radar data there are still a few "spikes" or unrealistic sudden increases in wave height, but these should be easy to recognize subjectively, and probably could be removed via a fairly simple automated QC check.

Difficulties Encountered

Dr. Roarty has set up a web site to provide additional data (wave period, wave direction, wind direction) from site SPRK, however so far I have been unable to reach that site from our office.

Solutions Found/Presented

Dr. Roarty provided me with time-series plots for the month of March, comparing wave height, period and direction for site SEAB vs buoy 44065, and sites SPRK and BRNT vs buoy 44091. See the example shown in Figure 4. The wave height plots include values at different ranges, which correspond roughly to increasing distance offshore. During periods of offshore winds, there is some indication of HF-Radar wave heights increasing farther offshore (as expected), but this needs further study.

Expected Activities in the Next Month

We will continue to evaluate the HF-Radar wave data, especially during significant events, perhaps including some smaller-scale convectively driven events. Since data is now available in near real time, we will try to bring it more directly into operations.

Figure 1. Locations of New Jersey HF Radar sites Sea Bright (SEAB), Seaside Park (SPRK) and Brant Beach (BRNT); also offshore buoys 44065 and 44091, used for comparison.

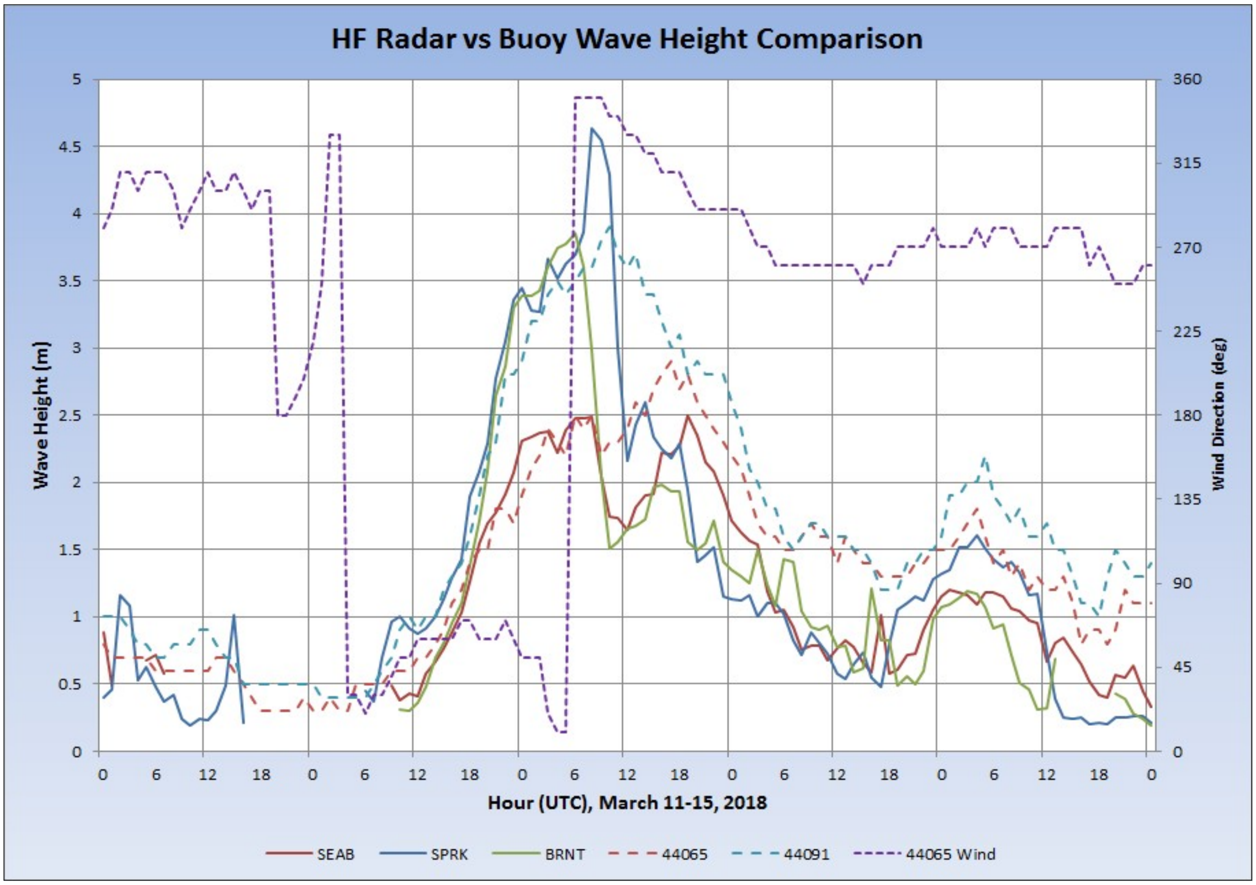


Figure 2. Observed wave heights around the time of the March 12-13, 2018 coastal storm. The purple dashed line is wind direction at buoy 44065.

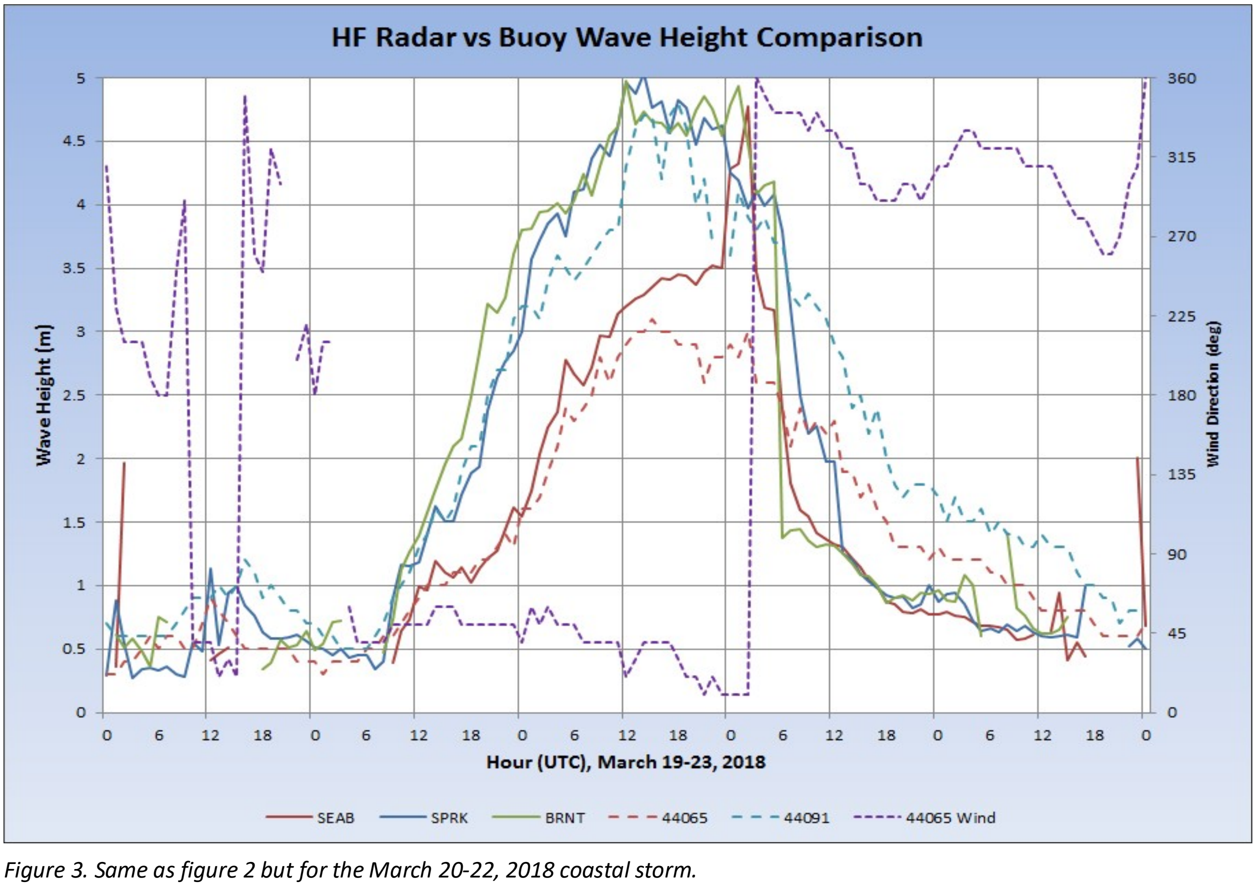


Figure 3. Same as figure 2 but for the March 20-22, 2018 coastal storm.

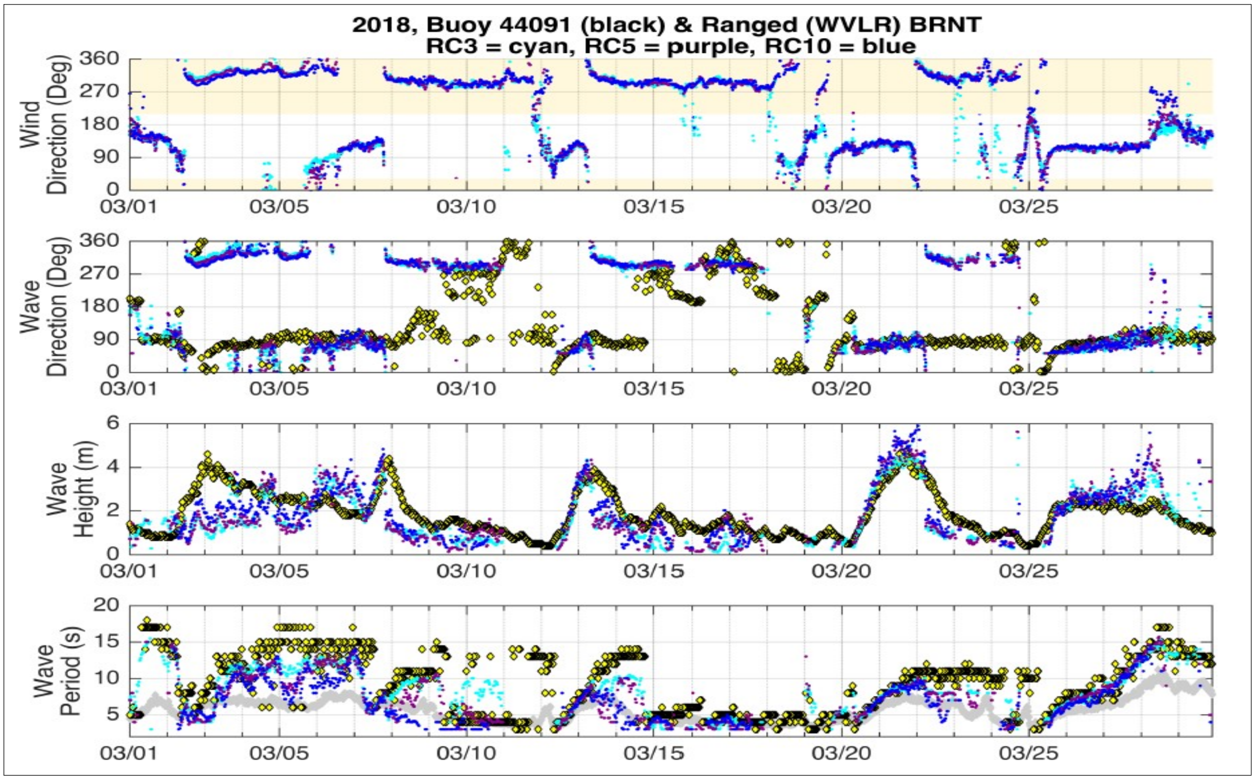


Figure 4. Time series plots for March 2018, HF-Radar site BRNT vs buoy 44091.

Mt. Holly WFO Status Report – June 2018

Basic Information (data period, data locations, data access issues, etc.)

During the month of June NWS Mount Holly has continued to receive HF Radar wave-height data as previously from the Rutgers web site. There do not seem to have been any significant changes, i.e., data is from three sites (Sea Bright, Seaside Park and Brant Beach, NJ), has about a two-hour latency, and contains some gaps, mostly during quiet periods with wave heights 1 meter or less. Data from the Seaside Park site (SPRK) seems more reliable overall, for whatever reason.

Status of Data Analyses (discoveries, limitations, advantages, etc.)

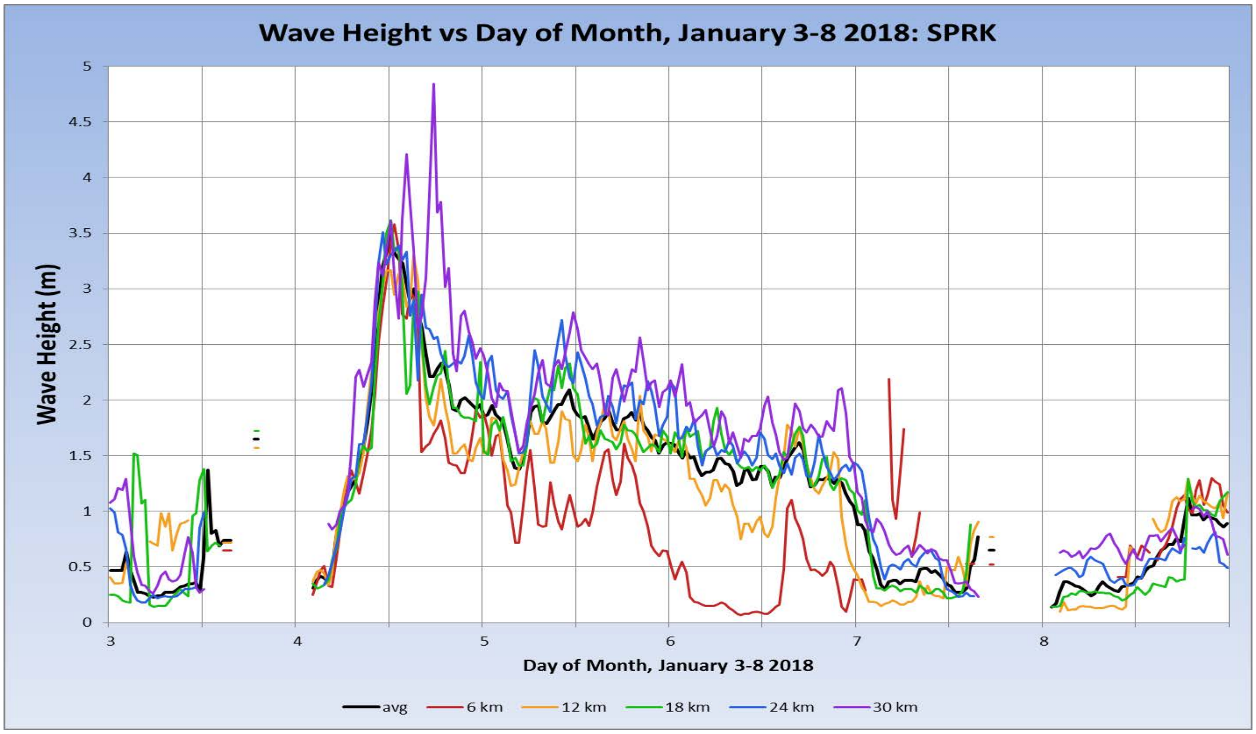
The main development for the month of June was the arrival on June 23 of a NOAA-CREST student intern, Siena Dante, who will be assisting with analysis of the HF Radar wave height data. Siena is an undergraduate at City College of New York and she has already created a lot of wave-height analysis graphs for data from January and February of this year. She has also been learning about operational marine forecasting here at NWS Mount Holly. Siena will be dividing her time between our NWS office and Rutgers DMCS. I met with Dr. Roarty and Siena at Rutgers on July 3 to map out what we'd like her to accomplish over the next few weeks. The last day of her NOAA-CREST internship will be August 9.

Difficulties Encountered

No new problems have been discovered since the last report.

Expected Activities in the Next Month

During July, Siena will continue to work part time at NWS Mount Holly and part time at Rutgers. She will be analyzing the HF Radar wave height data for March through June of this year. Her analysis will compare wave height, wave period and wave direction vs buoy data for each month, as well as more detailed examination of wave heights for specific "stormy" periods during each month. The figure below is an example of wave heights from the SPRK site during and after the early January blizzard. Siena will also be investigating the reason for occasional "spikes" in the data which seem unrelated to real wave activity.



Hourly wave heights for early January off the northern NJ coast, derived from the SPRK HF radar site, including a powerful nor'easter/blizzard on the 4th. The colored lines represent waves at different range bins, i.e., distances offshore from the radar site. In this case (which may not be typical) wave heights are clearly shown to increase with increasing distance seaward.

Mt. Holly WFO Status Report – July 2018

Basic Information (data period, data locations, data access issues, etc.)

During July we continued to receive HF Radar wave data from three NJ coastal sites via the Rutgers web site. Data for the month of June was downloaded, along with data from buoys 44065 and 44091. There were no data access issues.

Status of Data Analyses (discoveries, limitations, advantages, etc.)

Our NOAA-CREST student intern, Siena Dante, continued to help with analysis of the HF Radar wave height data. She spent the first and third weeks of the month at Rutgers analyzing the data with MATLAB software and flagging erroneous "spikes" which occur from time to time. No specific cause for the spikes has been determined as of yet. Siena was also able to visit the Seabright HF-Radar site and learned how the antenna is calibrated, thus gaining a better overall understanding of the instrumentation.

Otherwise Siena spent her time at the NWS Mount Holly office, using Excel spreadsheets to examine HF Radar and ocean buoy data for the months of March through June. In addition to numerous time series plots, she created scatterplots of wave height for Seaside Park vs. buoy 44091. Correlation between the two data sources improved steadily from February through June. Also, one of our forecasters noted that the HF Radar seemed to be over-estimating wave height during a period of higher waves in June.

Difficulties Encountered

No new problems have been discovered since the last report.

Expected Activities in the Next Month

On August 9, Siena will conclude her internship by presenting a poster at a NOAA-CREST symposium at CCNY. (She already started working on the poster at the end of July.) At the end of August, I will present a similar poster at the annual meeting of the National Weather Association in St. Louis.

Mt. Holly WFO Status Report – August/September 2018

Basic Information (data period, data locations, data access issues, etc.)

During August we continued to receive HF Radar wave data from three NJ coastal sites via the Rutgers web site. At the beginning of September, the Seaside Park site (SPRK) was taken down because of dune restoration activity. (SPRK is still down as of mid-October.) Available data for the months of August and September was downloaded, along with data from buoys 44065 and 44091.

Status of Data Analyses (discoveries, limitations, advantages, etc.)

On August 9, our NOAA-CREST student intern, Siena Dante, presented a poster of her summer research results at a NOAA-CREST symposium at CCNY. Al Cope presented a similar poster at the annual meeting of the National Weather Association on August 28.

Difficulties Encountered

Other than the loss of data from the SPRK site, no new problems have been discovered since the last report.

Expected Activities in the Next Month

Examination of wave data from the HF-Radars and buoys will continue as time allows. We are headed back into the winter storm season, so some more interesting cases may develop. Seas have been relatively quiet during August and September. A phone call is scheduled for mid-October to discuss the future of this SWH study project.

Mt. Holly WFO Status Report – November 2018

Basic Information (data period, data locations, data access issues, etc.)

Through late November we have continued to have access to data from the HF-Radar sites at Sea Bright (SEAB) and Brant Beach (BRNT). Data from the site at Seaside Park (SPRK) has been unavailable since the end of August and remains so as of late November.

Status of Data Analyses (discoveries, limitations, advantages, etc.)

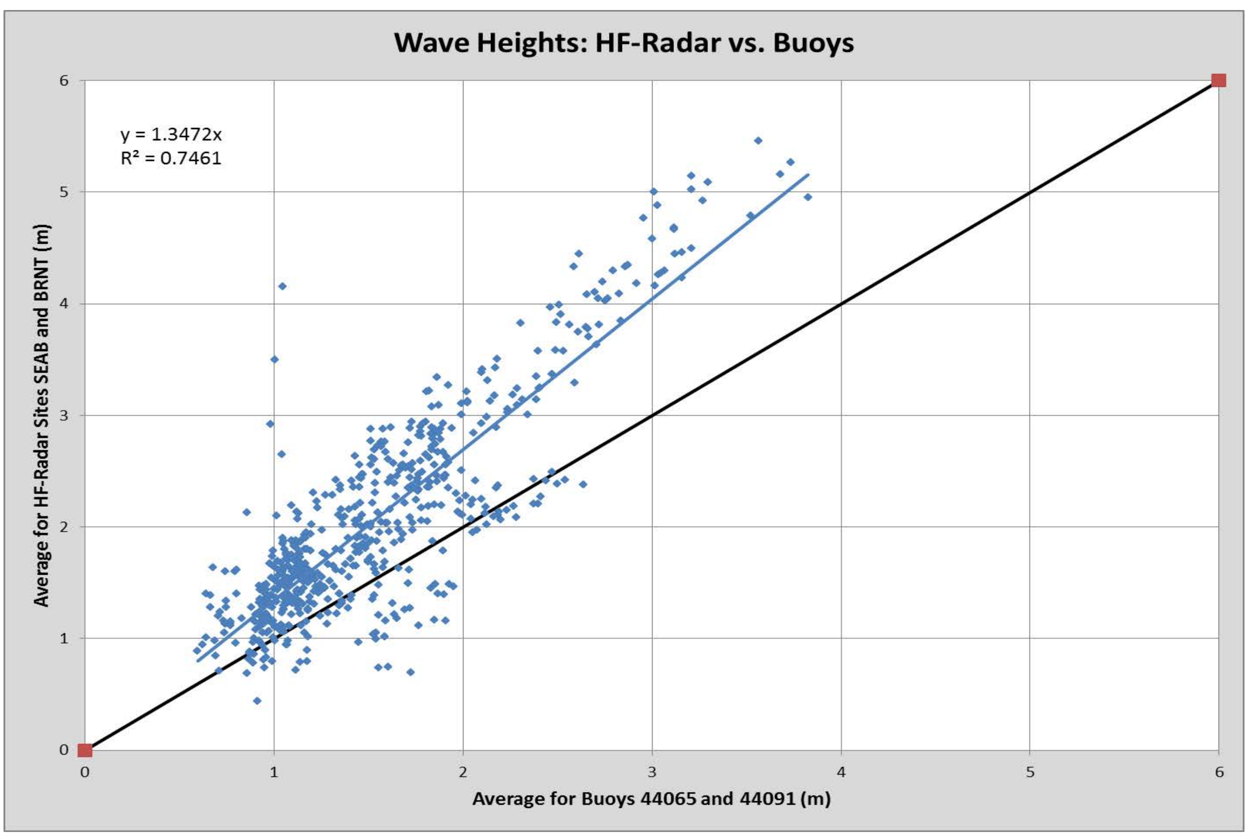
I downloaded wave height data for the month of September from HFR sites SEAB and BRNT, and from buoys 44091 and 44065. Data were entered in a spreadsheet and used to create the two plots below. There were two episodes of higher waves, one around the 10th and another around the 15th, both associated with strong onshore winds. In both cases, and in general through the month, the HFR wave heights were significantly higher than those from the buoys. This high bias began to appear late last spring and seems to be still present in the fall. We will monitor for further trends as we go deeper into winter storm season.

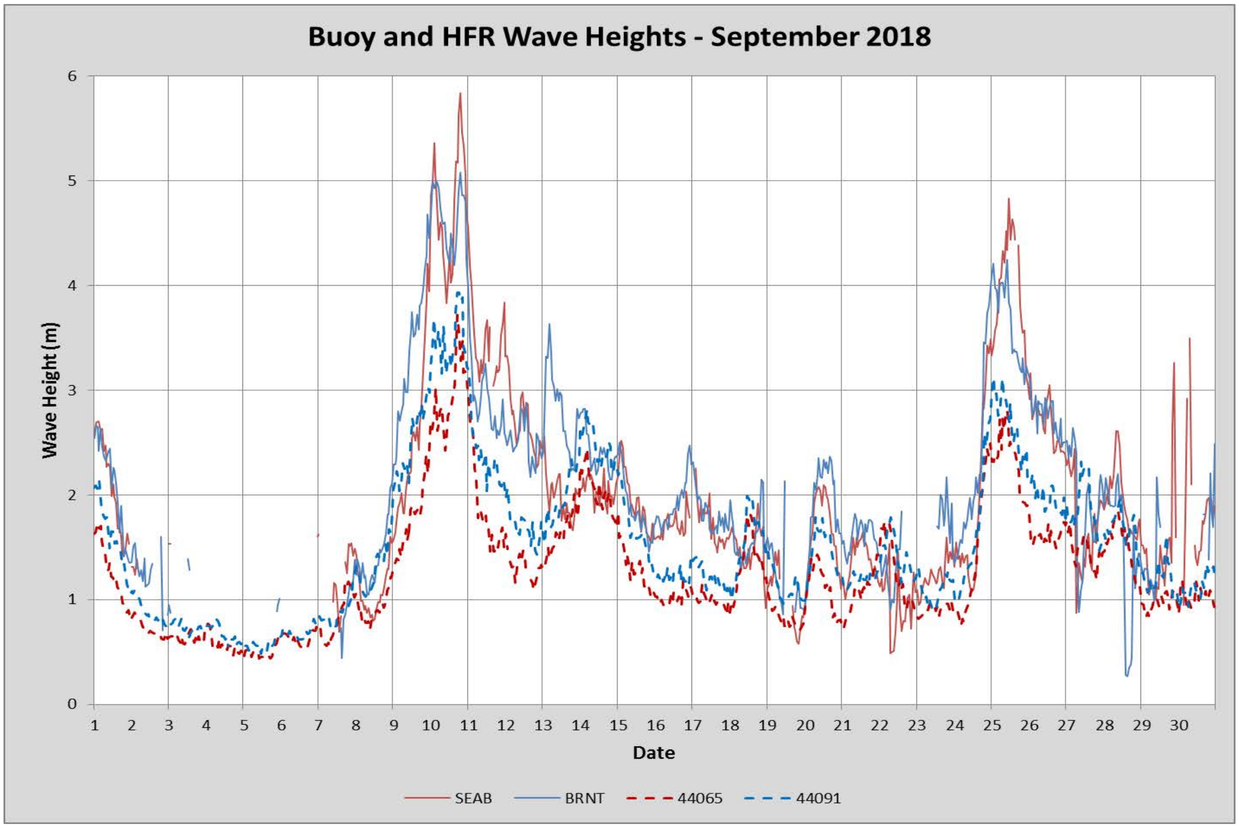
Difficulties Encountered

Because of short staffing at our office, I have been scheduled to work more than my usual number of operational forecasting shifts. Time available for research and coordination has been rather limited.

Expected Activities in the Next Month

Examination of wave data from the HF-Radars and buoys will continue as time allows. The weather pattern has been rather active so far this fall and there should be several storm events to look at for October and November. However, I'm not sure how much more there is to be learned at this point by comparing just two HFR sites and two buoys.





Mt. Holly WFO Status Report – Winter 2018-19

<u>Basic Information (data period, data locations, data access issues, etc.)</u>

This report covers the period December 1, 2018 through February 28, 2019. During this time data from the HF-Radar site at Seaside Park (SPRK) remained unavailable, while data continued to be accessible from the sites at Sea Bright (SEAB) and Brant Beach (BRNT). As of last fall, data from another site at Brigantine, NJ (BRMR) has become available from the web site

https://rucool.marine.rutgers.edu/ocean-radar-mapping/

The HF-Radar site locations SEAB and BRNT correspond roughly to the locations of near-shore buoys 44065 and 44091, respectively. Site BRMR is a few miles farther south along the NJ coast. However, buoy 44009 is much farther south, off the coast of Delaware, but is included in the analysis for additional comparison.

<u>Status of Data Analyses (discoveries, limitations, advantages, etc.)</u>

Hourly wave-height data for the three operational HF-Radar sites and three buoy sites listed above were downloaded for the months of December 2018, January 2019 and February 2019. The data were copied into separate spreadsheets for each month, quality controlled for missing report times and in the case of HF-Radar, removal of some erroneous high values (data "spikes"). Data were then plotted as hourly time series for each month, as shown in Figures 1 to 6 below. Each of the three months included several "stormy" periods with elevated wave heights above 2 meters.

Figures 1 to 6 show that the HF-Radar maximum wave heights during stormy periods are often about 0.5 to 1.0 meters higher than corresponding buoy values. There is good general agreement on the timing of elevated seas, however the HF-Radar data generally goes missing when seas are low, i.e., with buoy waves less than about 1 meter. This has been a consistent observation from previous months as well. Overall for these three months, hourly data availability was about 51 %, although it was higher for SEAB (~ 58 %) than for the other two sites (~48 %).

Careful inspection of Figures 1, 3 and 5, in comparison with Figures 2, 4 and 6 respectively, reveals a number of unrealistic high values or "spikes" in the wave-height data. For example, see Figure 1 at December 25 for site BRNT (blue), showing a sudden jump to just over 3 meters. Another example is in Figure 3 for the site SEAB (red) on January 6. (In fact, a handful of even more pronounced spikes were removed from the data before plotting.)

While the HF-Radar data seems fairly accurate during periods of building seas, it is more problematic when seas begin to subside. An example is shown in Figure 7, which shows buoy and HF-Radar wave heights for December 20th through the 23rd. Wave heights at SEAB and BRNT drop sharply around midday on the 22nd, while the buoy wave heights decrease much more gradually. The sudden drop is coincident with a wind shift from onshore to offshore, shown by the wind direction at site BRNT. This pattern has been noted with previous coastal storms, and some variation of it was again evident with most of the storms this past winter.

Most of this analysis has concerned HF-Radar wave heights averaged over all the range bins (6km to 30km). However, for the December storm mentioned above, wave heights from site BRNT were plotted for specific range bins at 6km, 12km, 18km, 24km and 30km, as shown in Figure 8. (Range bins at 9km, 15km, 21km and 27km were omitted for clarity.) During the period of highest seas, roughly from morning on the 21st to morning on the 22nd, there is some indication that waves farther offshore were perhaps 1.0 to 1.5 meters higher the wave close to shore. Winds were southeast during most of this time (Figure 7). This is an aspect of the data that needs further study.

Difficulties Encountered

Nothing new.

Solutions Found/Presented

Dr. Roarty of Rutgers University presented a paper at the March 2019 IEEE/OES 12th Currents, Waves, Turbulence Measurement and Applications Workshop in San Diego, CA. The paper, "Evaluation of Wave Data from HF Radar by the National Weather Service", described the collaborative research between Rutgers, our NWS office and our student intern, Sienna Dante, from CCNY.

Expected Activities in the Future

This will be my last report, so I will offer some thoughts on how the study might proceed from here. By comparing wave height data from three or so HF-Radar sites along the NJ coast with two to three nearshore fixed buoys ("ground truth"), we have identified both some strengths and weaknesses in the HF-Radar data. Overall, I think the HFR data shows potential for use in NWS marine forecast operations, however there are some significant issues that need to be resolved.

There is currently about a two-hour latency between the time of observation and when it is first plotted on the web page https://rucool.marine.rutgers.edu/ocean-radar-mapping. We would like to see that latency reduced to less than an hour. We should also explore ways to bring the data directly into our AWIPS system; maybe this would be faster.

As noted above, the records from the three operational HF-Radar sites showed HF-Radar wave data to be unavailable about half the time over the period December 2018 through February 2019. Most of the missing data seems to be during less critical periods, i.e., when seas are relatively calm and not as hazardous. This probably reflects the inherent limits to the wave-height retrieval process. Even so, every effort should be taken to make the data as reliable as possible, especially during stormy conditions. This is critical for forecaster acceptance and credibility in warning situations. Removal of erroneous data “spikes” is also highly desirable for credibility, even though in practice they should be relatively easy to identify and disregard.

Another issue is the tendency for the HF-Radar wave heights to drop off suddenly when the wind direction shifts from onshore to offshore. This is a consistent pattern which has been observed with many of our coastal storms during the past year or so, and especially over the most recent winter season. This may be a result of conflicting signals between local wind waves becoming offshore and longer-period swells continuing onshore. Perhaps processing of the raw signal can be adjusted as a function of wind direction to help alleviate this problem. Otherwise it is a training issue so forecasters know what to expect, but it still diminishes the overall value and credibility of the HF-Radar data.

Another area to explore is expansion of areal coverage to cover more of our NWS marine forecast area, which includes all NJ and DE coastal waters and the Delaware Bay. As of now the HF-Radar coverage (available to the NWS) is limited to northern and central NJ coastal waters. We would like to see at least one additional HF-Radar site somewhere along the Atlantic Coast between Atlantic City and Cape May. Also, a site on the west shore of Cape May, overlooking the Delaware Bay, would be a highly useful addition, since we have essentially zero information about waves on the bay. Perhaps this site could be “tuned” to detect the generally lower waves on the bay, compared to those on the ocean.

Finally, the data from existing HF-Radar sites should be examined further to see if they can provide information about wave height as a function of distance from shore, especially during strong offshore wind conditions. As noted above, our study has focused mostly on wave heights averaged over the nine distance bins (6km, 9km, ..., 30km), but data from a few cases has suggested that there may be useful information within each bin, or perhaps by comparing the averages of near-shore versus offshore bin combinations.

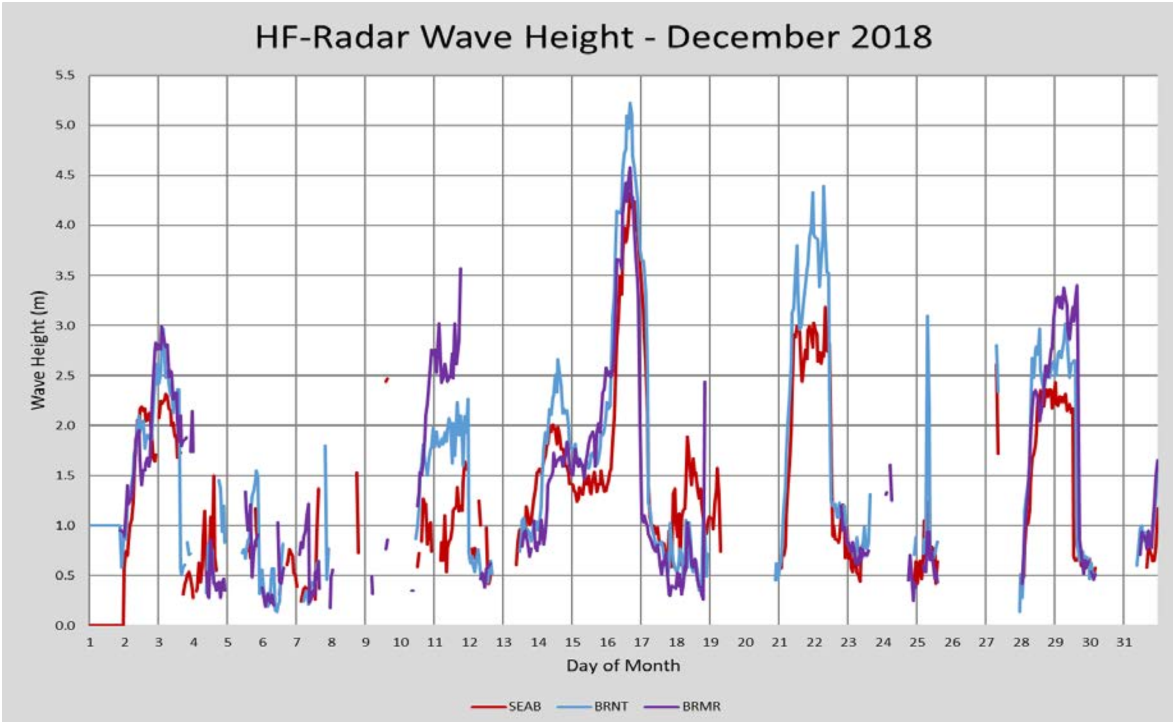


Fig 1. Hourly wave heights from three HF-Radar sites along the NJ coast, for the month of December.

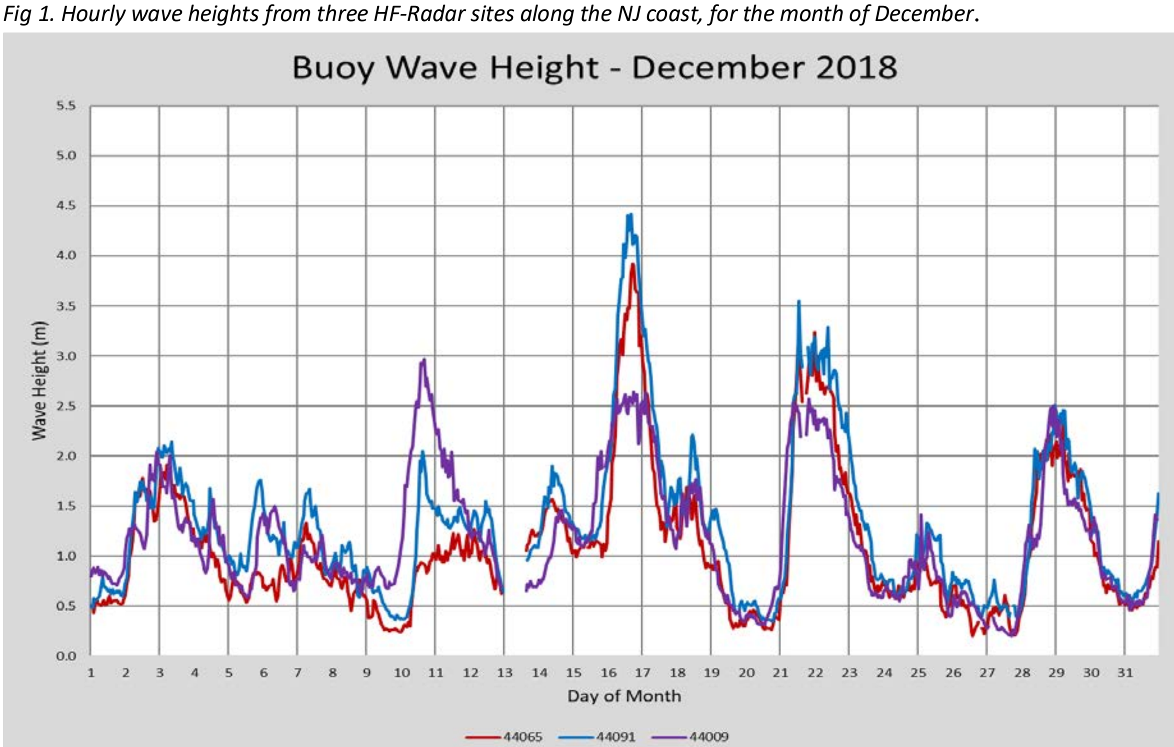


Fig 2. Hourly wave heights from three near-shore buoys off the NJ coast, for the month of December.

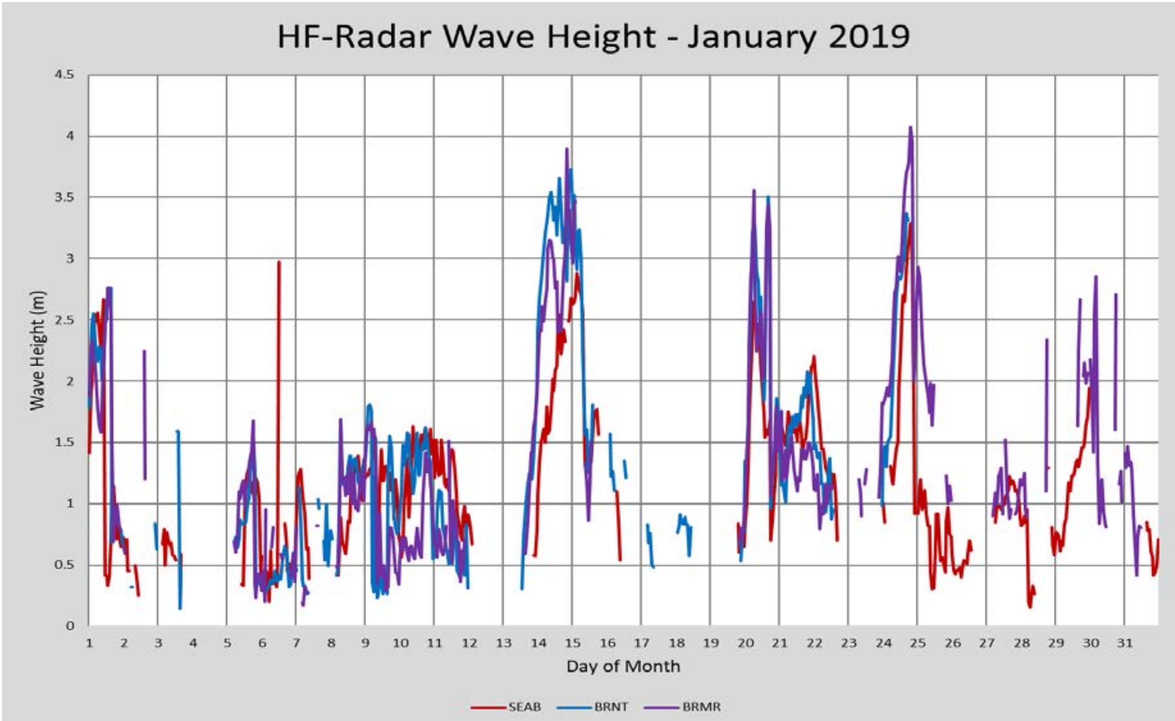


Fig 3. Same as Fig 1, but for January 2019.

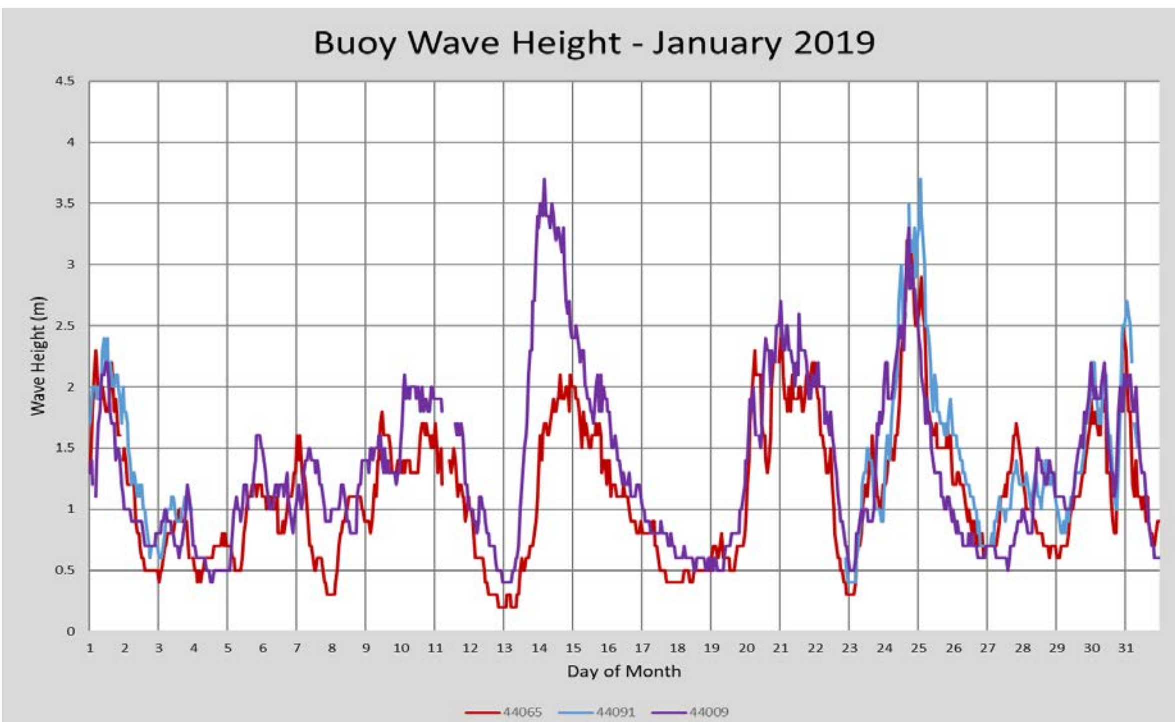


Fig 4. Same as Fig 2, but for January 2019. Data for buoy 44091 is missing until late in the month.

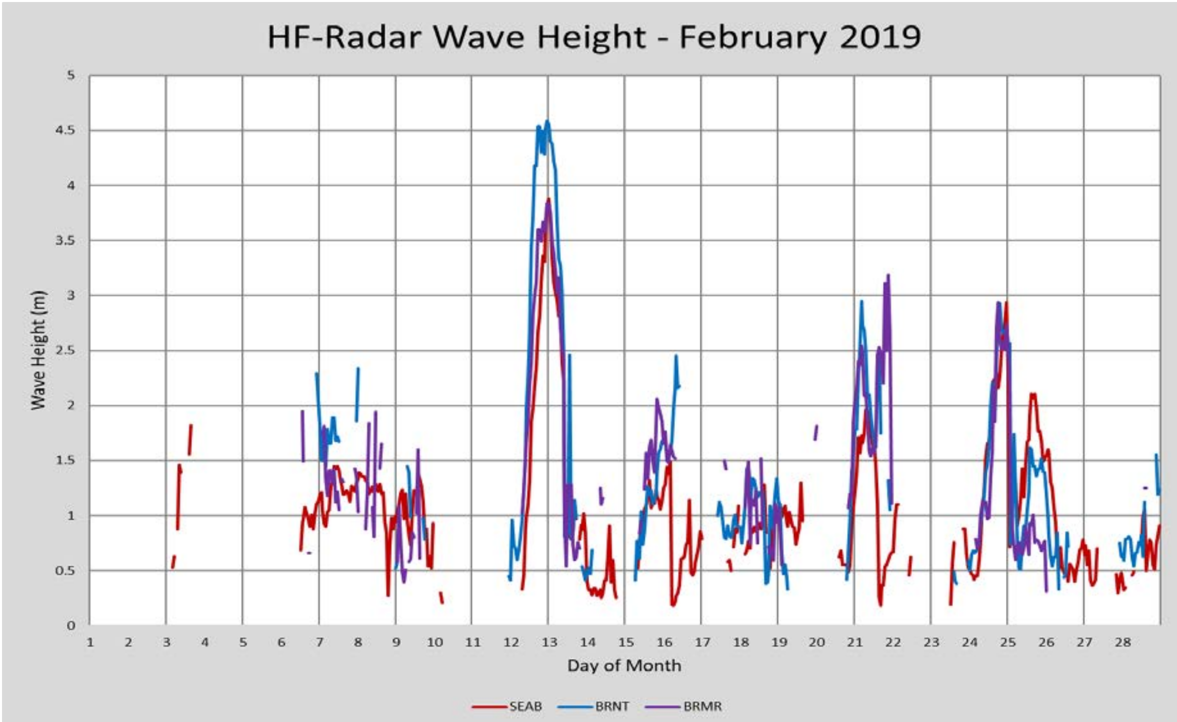


Fig 5. Same as Fig 1, but for February 2019.

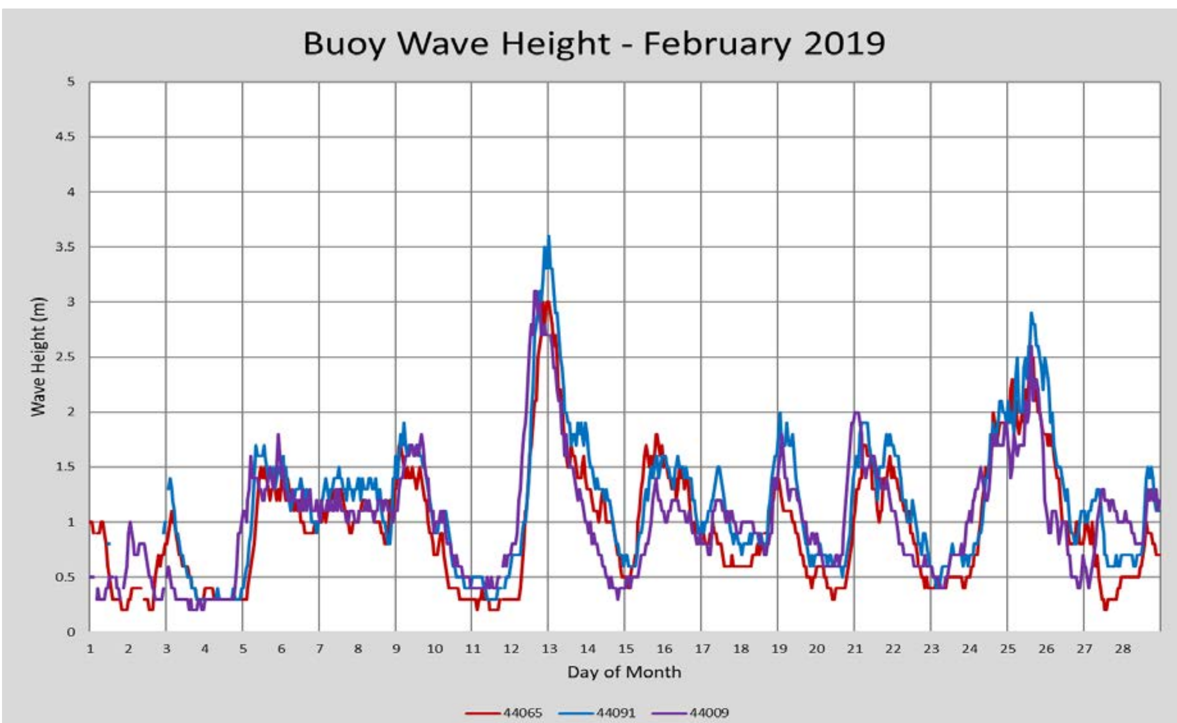


Fig 6. Same as Fig 2, but for February 2019.

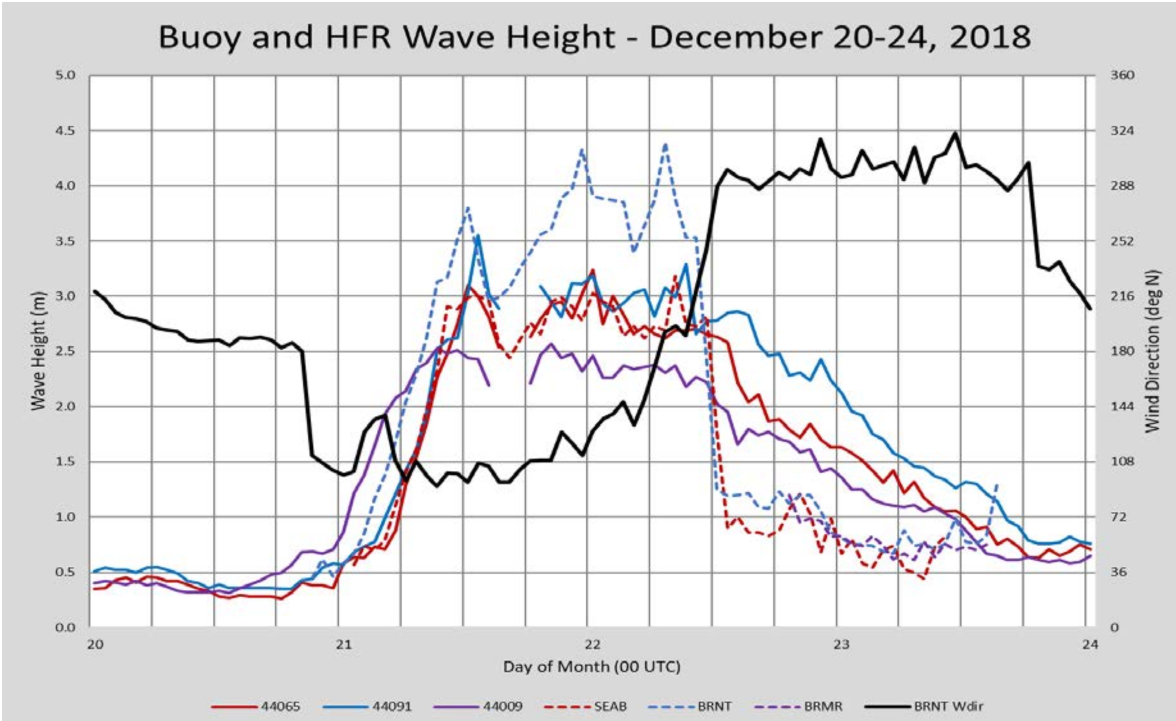


Fig 7. Buoy (solid lines) and HF-Radar (dashed) wave height plots for a late December coastal storm. Heavy black line is wind direction from HF-Radar site BRNT.

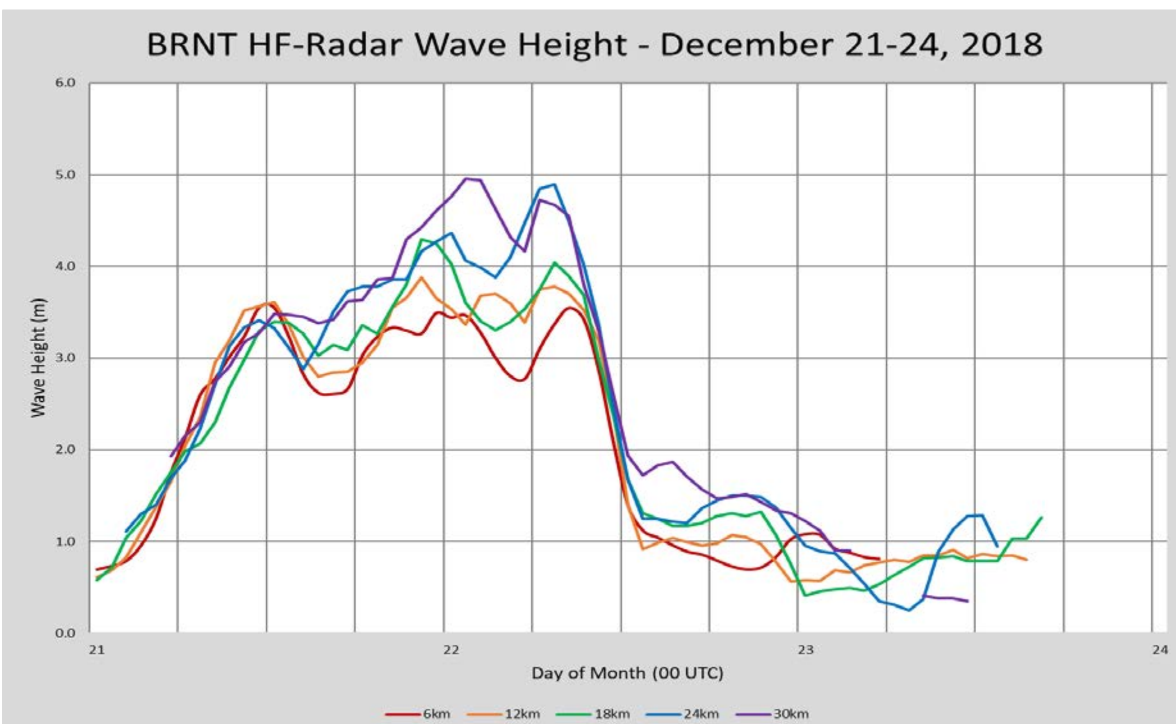


Fig 8. Wave heights at different range bins, from HF-Radar site BRNT, for the same event as in Fig 7.

WFO San Juan

San Juan WFO Status Report – August 2018

Before Hurricane Maria made landfall last September, the updated SeaSonde Release 8 software was installed on CDDO and MABO which transmit at 13 MHz and 5 MHz center frequencies, respectively. Figure 1 shows the locations and coverage of the HF radar sites selected for the SWH project.

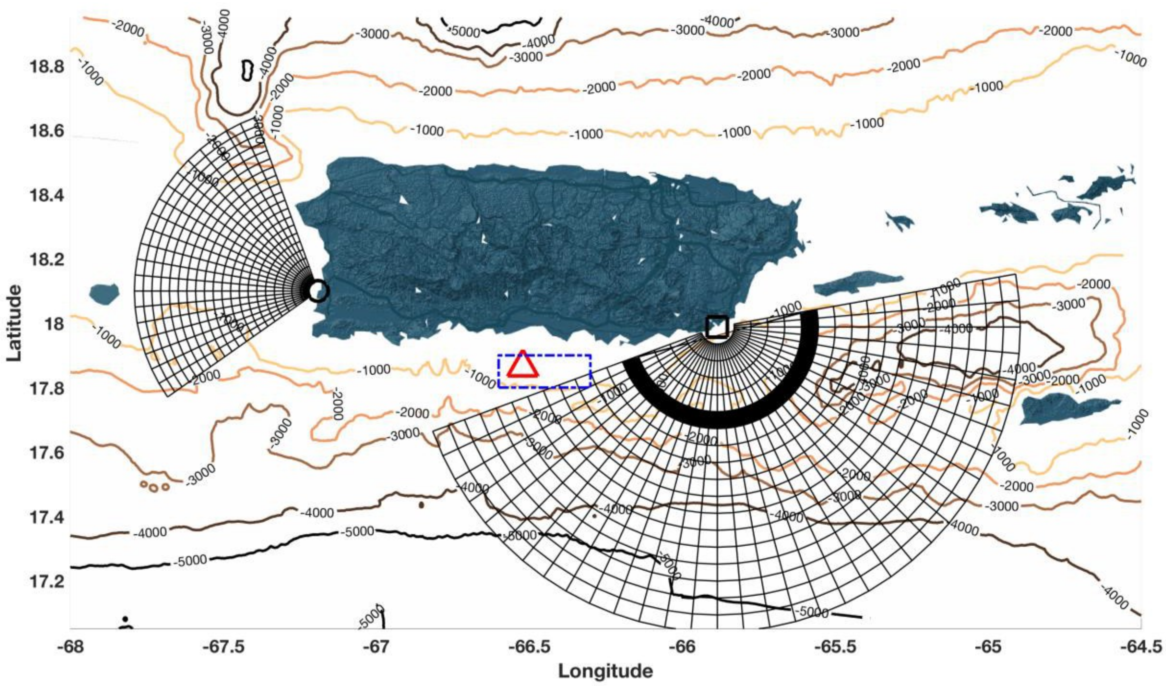


Figure 1.Locations of CDDO (black circle) and MABO (black square) HF radar locations with associated coverage areas, Ponce mooring (red triangle), and a selected area from the SWAN model (blue box). The solid black area in in the MABO coverage area is range cell 6 (approximately 30 km radially distant from the CODAR location).

The real-time R8 data acquisition on the MABO site was reinstated on April 5th of this year, however there were hardware issues within the electronic board inside the receive antenna. The Bragg and second-order energy return were extremely weak and, therefore, did not resolve any valid wave measurements until April 12th when a replacement antenna was installed.

Significant wave height (Hs) measurements were spatially averaged over all range cells processed within the cross short-time spectra (CSS) files and recorded every half hour when the long-wave energy was visible above the noise floor. This data is saved in the default WVLM files. The spatially-averaged Hs was compared with range-dependent Hs (range cell 6 in this case), which are still saved in the WVLR wave files. Figure 2 shows the HF radar comparisons with a mooring deployed at 66.51°W, 17.86°N in 17 m. depth as well as with grid points from the SWAN model output sampled near the buoy location for consistency.

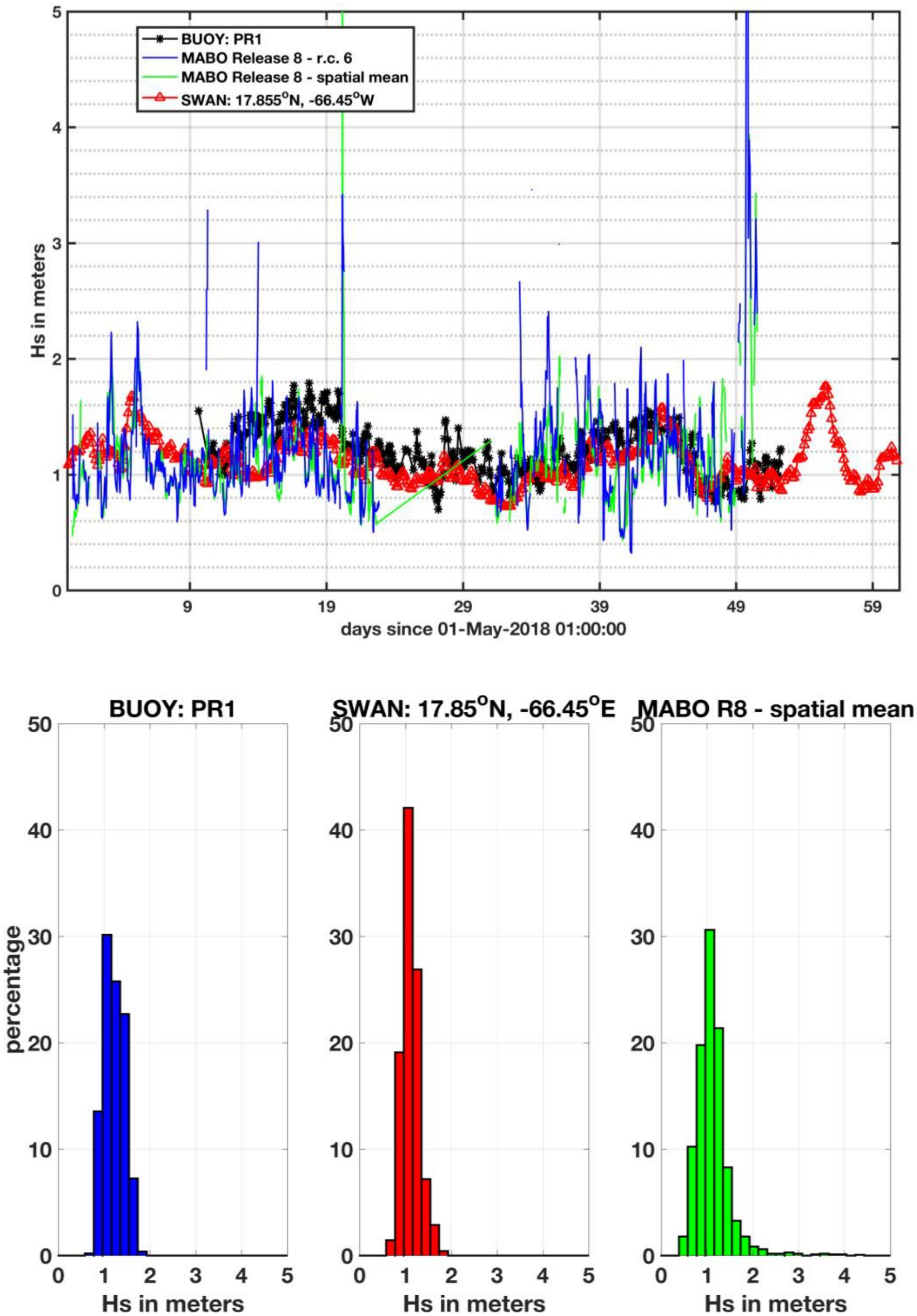


Figure 2. [top] Comparison in time and [bottom] distribution of Hs for the HF radar, Ponce mooring station, and SWAN model.

The initial analysis is an introductory and qualitative look at how well the real-time two- pass filtering method eliminated noisy data in the MABO second-order spectrum. Overall the MABO Hs spatial mean shows less outliers than the range cell 6 azimuthal mean but show similar trends throughout most of the 2-month period. More analysis regarding the validity of the phases and amplitudes of the HF radar-derived Hs will follow in the upcoming months.

The CDDO reinstallation required the most time and was the last site to resume operation within the HF radar network; the site officially came back online May 25th. Wave measurements have been sparse due to severe diurnal noise floor spikes that occur at night, which significantly reduces the signal to noise. A 100W bulb within close proximity to the receive antenna is suspect and we are working on resolving this matter to get better results in the data acquisition.

San Juan WFO Status Report – September 2018

The wave parameter outlier mitigation software was in operation at MABO and CDDO for the last few months. MABO has been getting consistent measurements but there is still evidence of overestimated significant wave height and wave period, shown in Figure 1. The mean significant wave height from derived from the MABO site was 1.37 ± 0.68 m; mean significant wave height derived from the buoy and model were 1.11 m and 1.11 m with standard deviations of 0.19 m and 0.20 m, respectively. The HFR-estimated mean wave period was 9.92 ± 1.09 s compared to 6.12 ± 0.66 s and 4.05 ± 0.36 s for the Ponce buoy and SWAN model output, respectively.

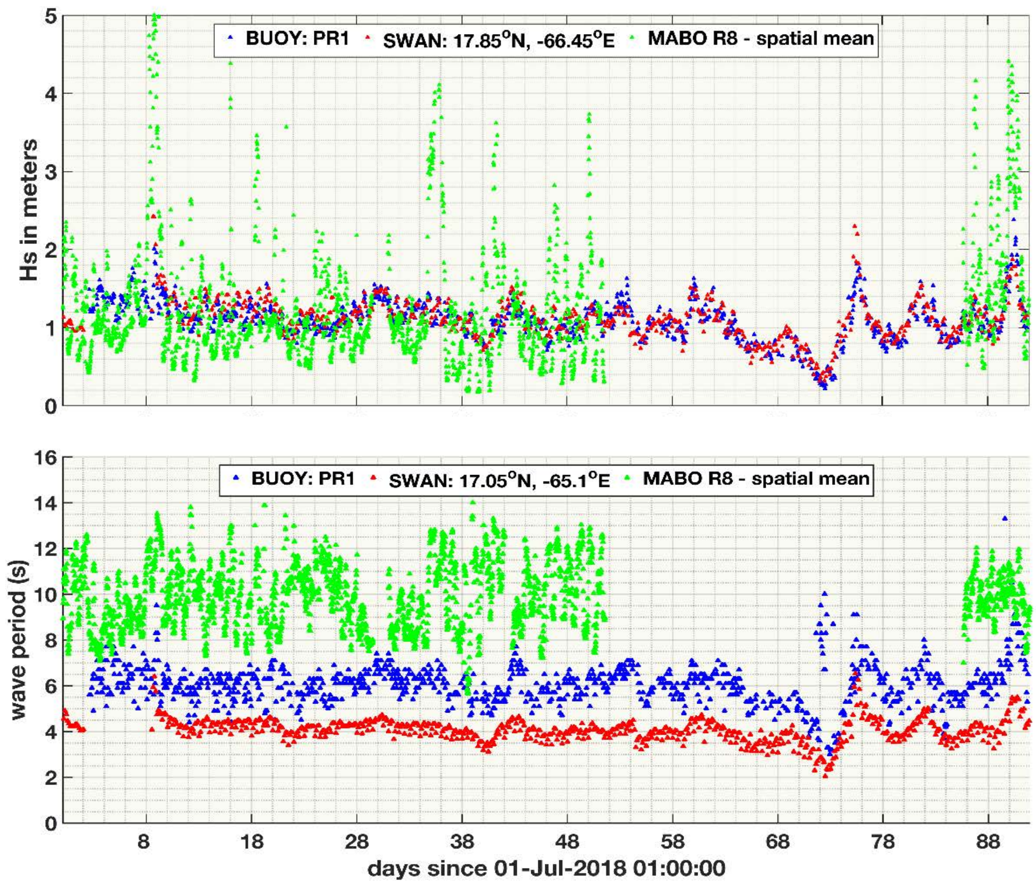


Fig. 1. [top] Significant wave height comparisons between the HF radar, Ponce buoy, and SWAN model. [bottom] Wave period comparisons.

An initial attempt at cleaning up the HFR-derived significant wave height estimations is shown in Figure 2. An EMD (Empirical Mode Decomposition) + Hurst component analysis was done with the intention of eliminating more of the outliers that passed the outlier threshold tests in the MABO dataset. The HFR wave data was averaged in 3-hr bins to match the SWAN output data.

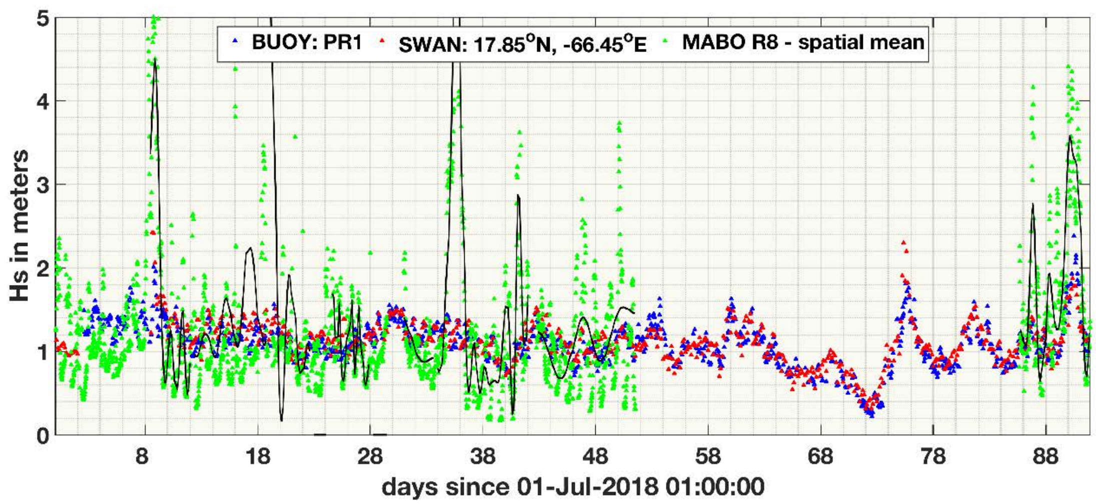


Fig. 2. Significant wave heights estimated from the HFR, buoy, and SWAN model overlaid with the reconstructed MABO measurements using EMD + Hurst analysis (black line).

CDDO is still experiencing severe spectrum saturation from the nearby marina flood lights during the night so we recently decided to move the software to its neighboring site to the north (FURA). Figure 3 shows the location and coverage. Initial results from that site will be included in the next report.

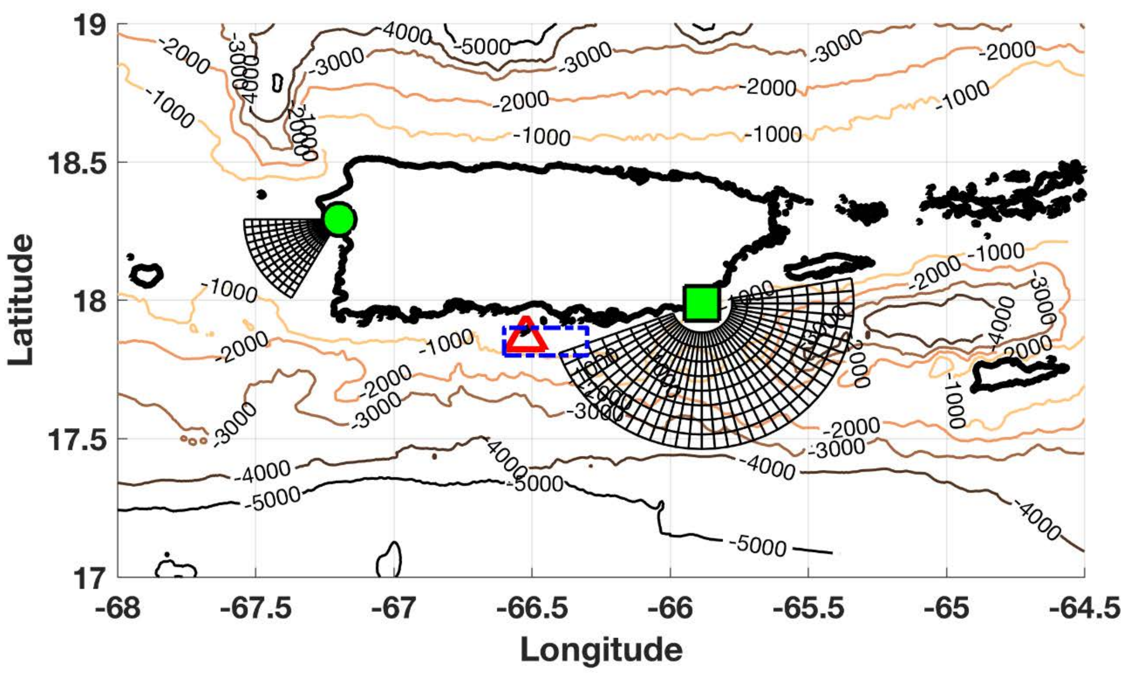


Fig. 3. Current locations of the R8 outlier-mitigation software. The software was moved to FURA (green circle) while we deal with the interference issue at CDDO.

San Juan WFO Status Report – October 2018

This report covers the HFR-estimated significant wave height (SWH) results for October 2018. MABO, located on the southeast coast of Puerto Rico, was consistent in deriving secondary wave parameters for this report period. The outlier software was relocated from CDDO to FURA, which also has a center frequency of 13.45 MHz, on October 23rd so there is less available data to validate. Time-series and statistical analysis between the radars, nearby buoys, and averaged SWAN model outputs are presented. Figure 1 shows the locations of each sensor that contributed SWH data to this report.

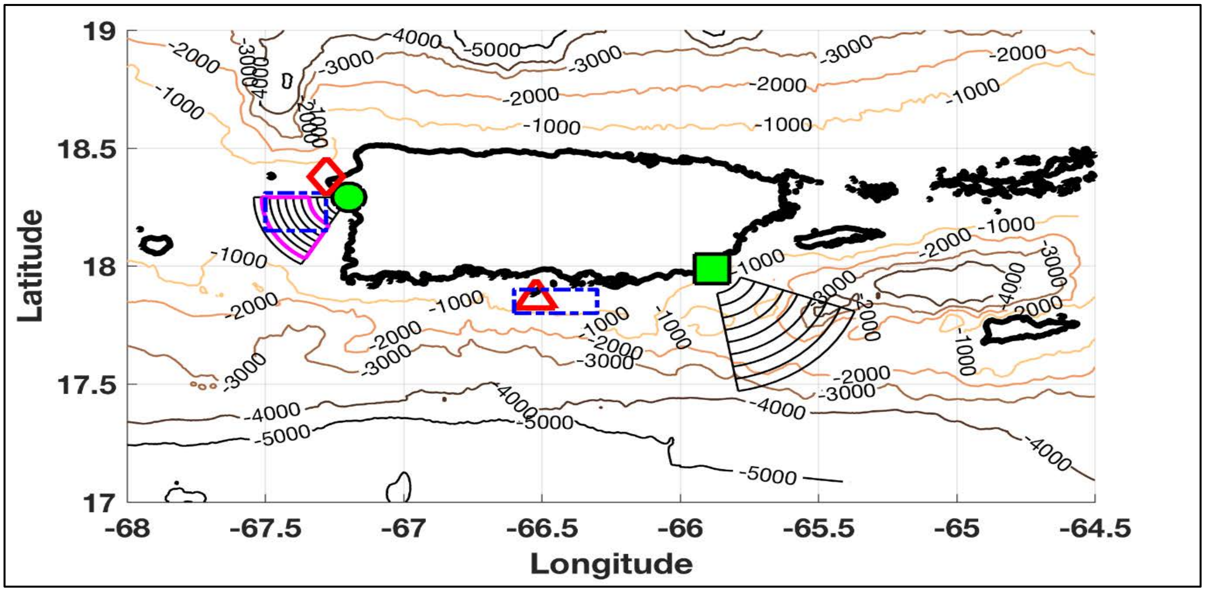
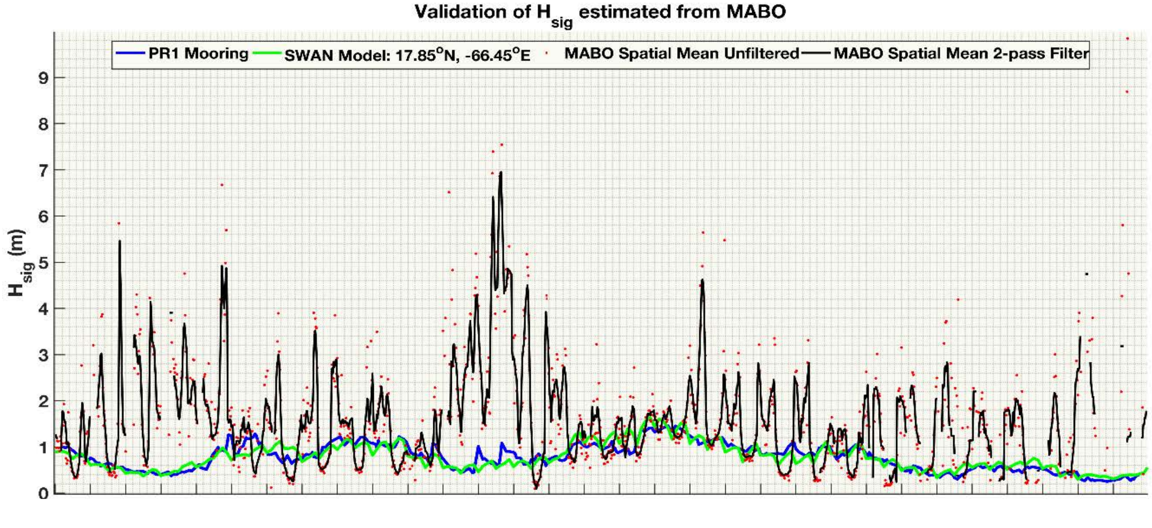


Fig. 1. Map of locations and areas of each sensor/model for HFR SWH validations. FURA (green circle) was compared to SWAN (blue box off the west coast) and a Waverider (red diamond). The magenta area within the FURA coverage area indicates the region of least outliers. MABO (green square) was validated with a SWAN area (blue box off the south coast) and a moored buoy (red triangle).

Figure 2 shows the time-series H_{sig} validations for the MABO site along with statistical figures. Although the real-time 2-pass filtering of the raw data removed some of the outliers, there is still evidence of significantly over-estimated wave heights. This site is still experiencing daily noise/clutter that saturates he first and second order Bragg return, resulting in unrealistic outputs. We are currently working with CODAR to try and pinpoint the source of the contamination. Although this is a common occurrence, there are still time periods where the spectrum is "clean" and the software can define the nulls separating the energy return as a function of Doppler frequency. Offline, spectra reprocessing was performed on the unfiltered MABO data with refined filtering thresholds. More specifically, the wave height drop/change per hour was set to 0.8 m and the wave period change per hour was set to 3.5 s. The real-time parameters were set to 1 m wave height drop per hour and 4 s period change per hour. The RMSE improved with the strict filtering thresholds, but the cost is less data points. The next report will include the effects of bimodal second order spectrum.



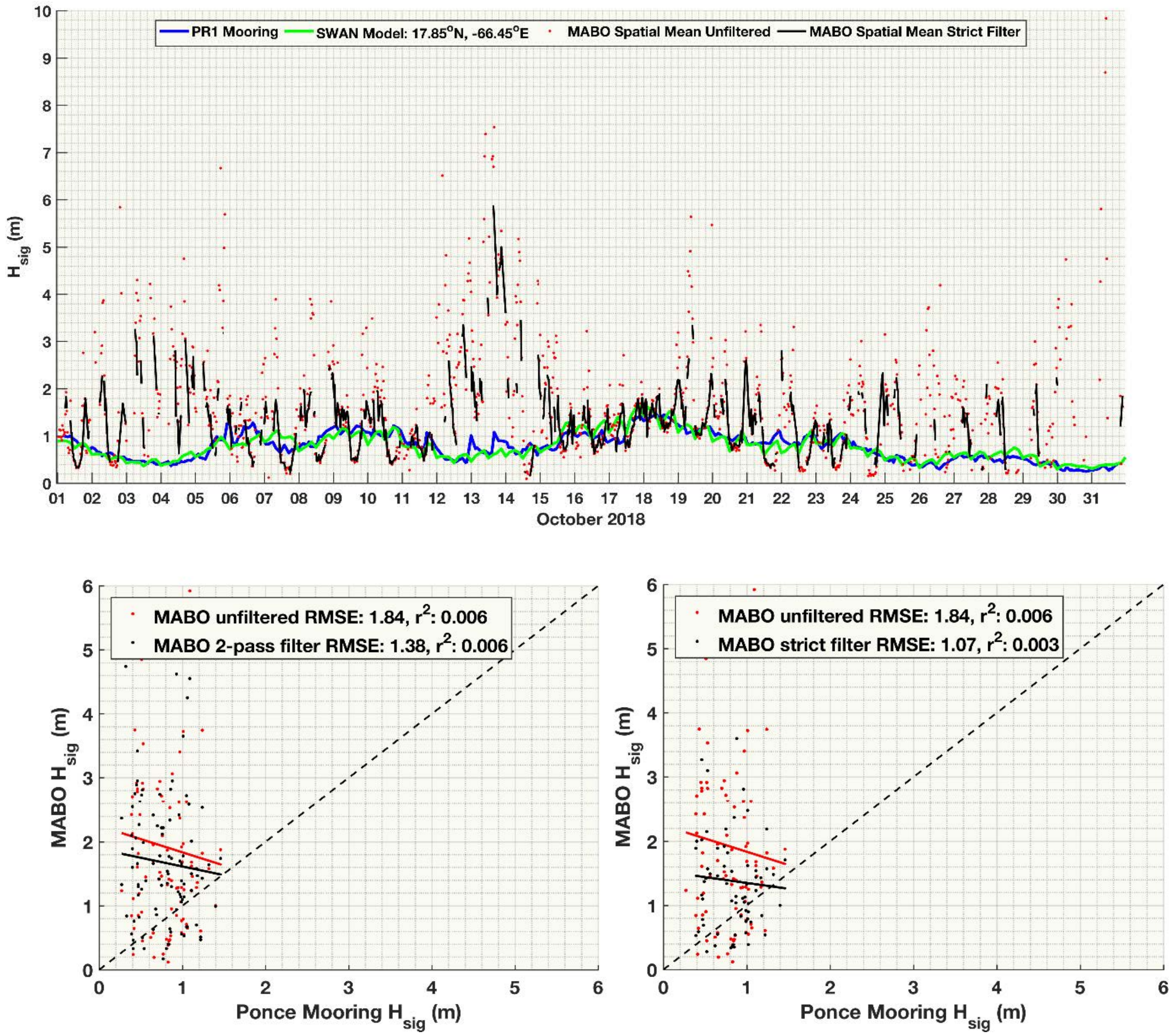


Fig. 2. [top] MABO estimated H_{sig} comparisons for filtered and real-time, 2-pass filtered spatial mean with Ponce buoy and SWAN model output. [middle] Same comparisons with stricter filtering of MABO H_{sig}. [bottom] RMSE and r^2 results for unfiltered, real-time 2-pass filtered spatial mean, and reprocessed strict filtering of MABO H_{sig} with Ponce mooring.

The R8 outlier mitigation software ran for less than two weeks on FURA so analysis will be brief until next month's report. Figure 3 shows the time-series comparison of Hsig between for the unfiltered/2-pass filtered FURA data with the nearby Waverider and the averaged SWAN model output referenced to the HF radar coverage area. Overall, most of the outliers were

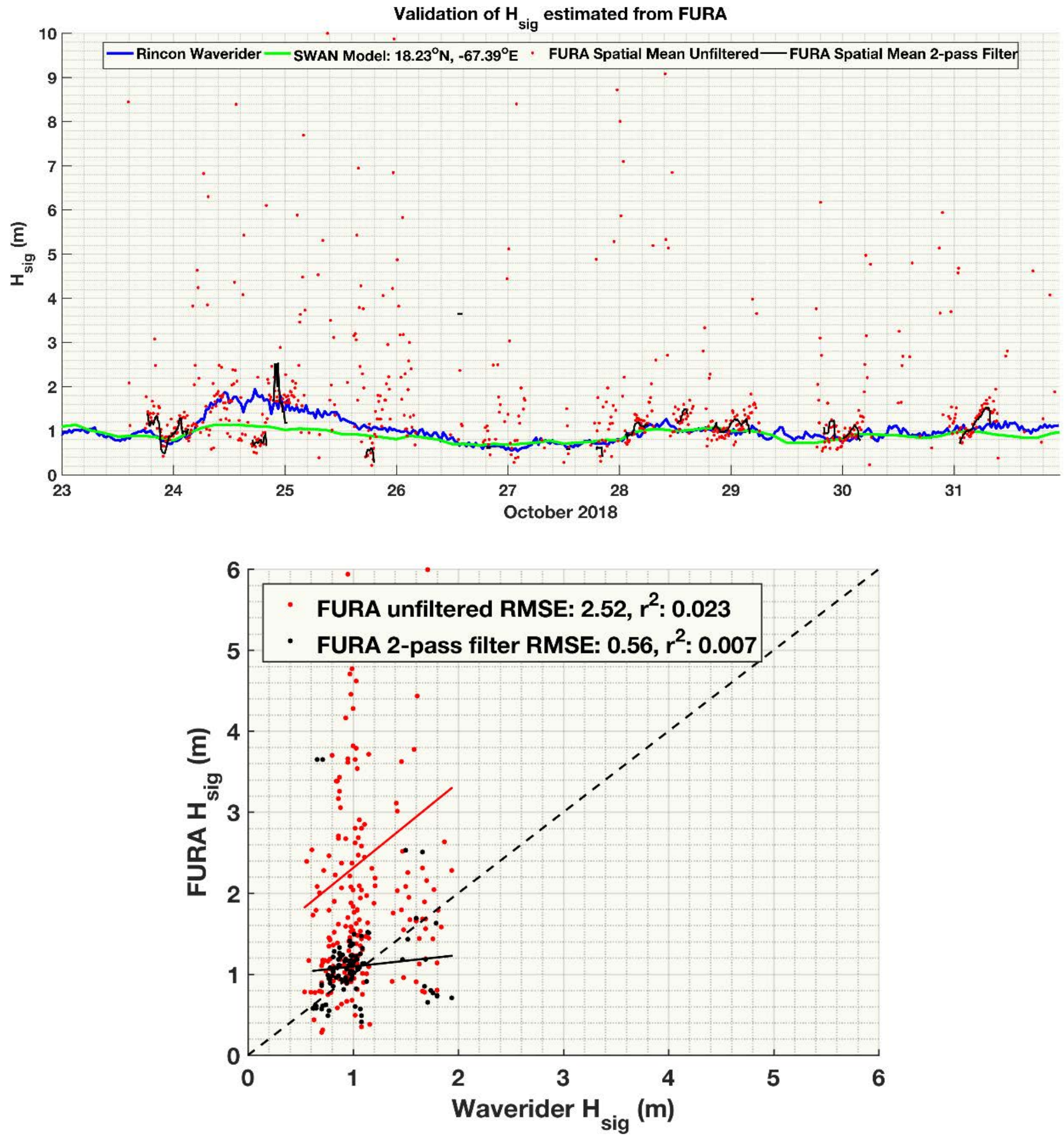


Fig. 3. [top] FURA estimated H_{sig} comparisons for filtered and real-time, 2-pass filtered spatial mean with Waverider buoy and SWAN model output. [bottom] RMSE and r^2 results for unfiltered, real-time 2-pass filtered spatial mean, and reprocessed strict filtering of MABO H_{sig} with Waverider.

flagged in real-time but a large percentage of data was eliminated. The RMSE improved significantly because of the outlier mitigation filter, with values of 2.52 and 0.56 m for the unfiltered and filtered waves, respectively. Correlation coefficients are still very low for the filtered wave output, but this could be attributed to the few large outliers (> 0.5 m). the r^2 improves to 0.48 when an RMSE threshold is set to < 0.5. Optimal parameters are still being investigated to provide best results, specifically which range cells to use, wave bearing limits as a function of range cell, and

San Juan WFO Status Report – November 2018

Significant wave height validations are presented for November 2018 for two CODAR stations in the west (FURA) and southeast (MABO) regions of Puerto Rico. Figure 1 shows the locations of the buoys and HFR coverage areas where the estimated wave parameters were calculated. Although less severe, we are still experiencing intermittent spectra contamination at MABO which CODAR has been assisting in determining the source. The plan is to bring an SDR device on the next visit to scan for periodic interference.

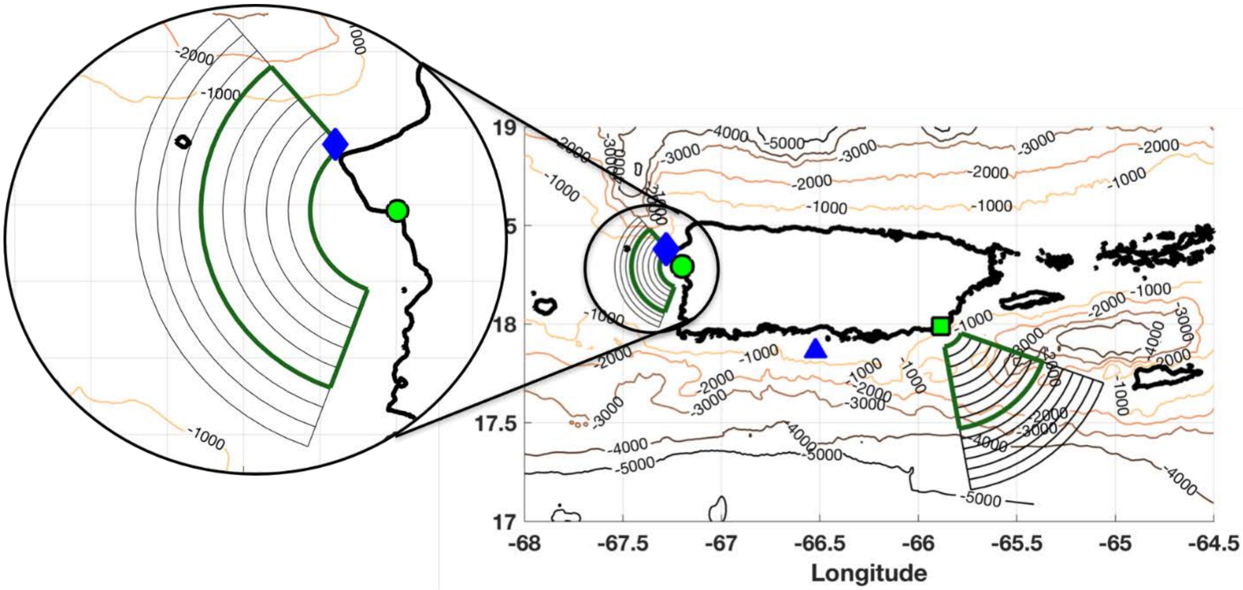


Fig. 1. Map of locations and areas of radars and buoys. FURA (green circle) significant wave height estimations were compared with a nearby Waverider (blue diamond) and MABO (green square) was compared with a mooring (blue triangle) south of Ponce, PR. The green areas within the coverage are what contributed to the spatial averages.

Figure 2 shows the time-series H_{sig} validations for the FURA site with the Waverider. Most of the outliers were flagged but the most notable observation is the number of gaps that occurred when the conditions were extremely calm. There were a lot of days where wind speeds did not exceed more than 5 knots and 2^{nd} order was not visible above the noise floor. There was one notable swell than came through the region during the last week of November; FURA did capture some of it but the derived wave heights were underestimated with respect to the Waverider.

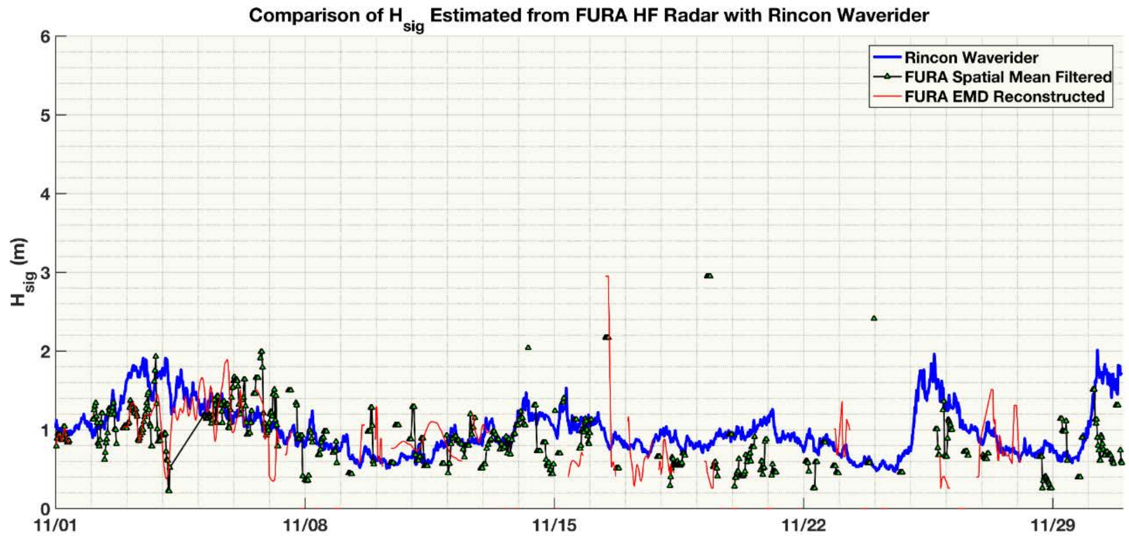


Fig. 2. Time-series comparison between FURA spatial-averaged and 2-pass filtered significant wave height with a Waverider just outside the coverage area. The FURA data was reconstructed with selected mono-components via empirical mode decomposition (EMD).

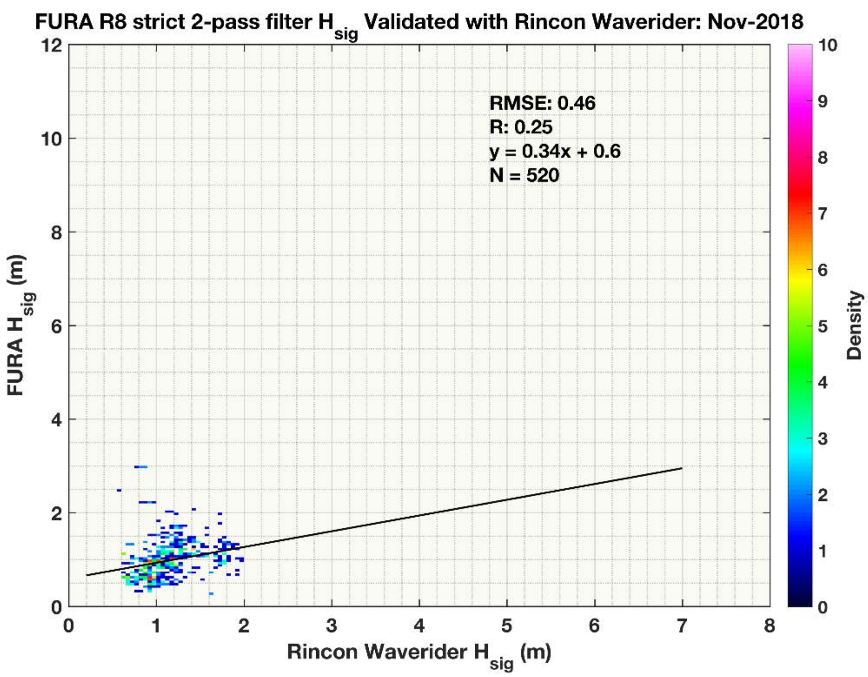


Fig. 3. Linear regression between Waverider and FURA station H_{sig} with RMSE and correlation.

The spatial mean was cross-correlated with the Waverider, shown in Figure 3. Overall, the RMSE (Root Mean Square Error) improved compared to the previous month but the correlation is not very strong. However, this does not indicate an issue with the radar since it is difficult to compare a spatial average with a point measurement. The goal of these validations was to show a fair comparison between sensors, which is why we selected range cells 5-10 to compare with the Waverider where the wave environment might be similar (Figure 4); Figure 5 also shows the H_{sig} distribution as a function of range cell for FURA. But depending on the direction of propagation, each sensor could be exposed to different conditions. Nevertheless, a major positive is the improvement in the number of outliers and lower RMSEs.

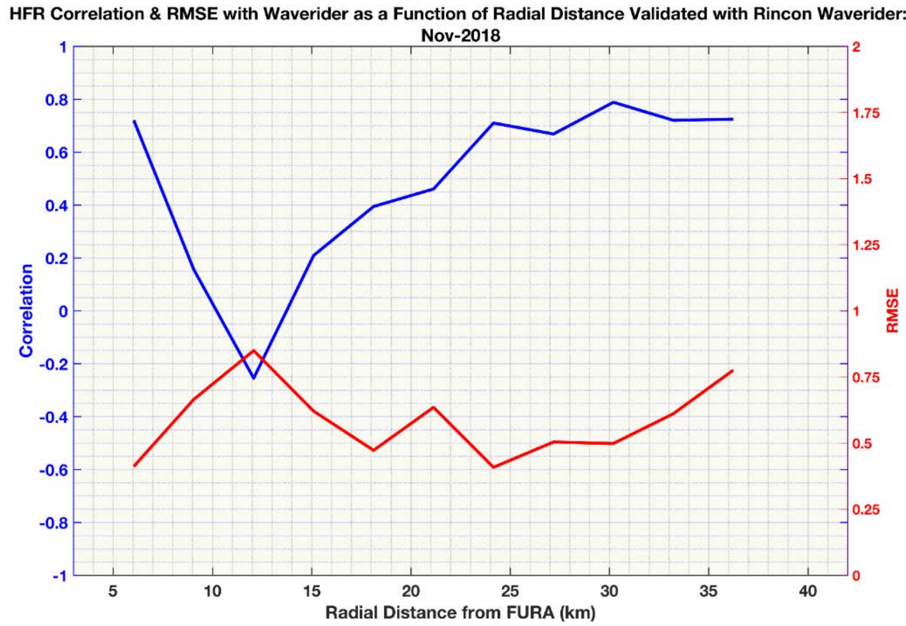


Fig. 4. RMSE and correlation between each range-bin, averaged H_{sig} with Waverider measurements. The RMSE is lowest between range cells 5-10, except for range cell 2 which typically does not have a lot of data available.

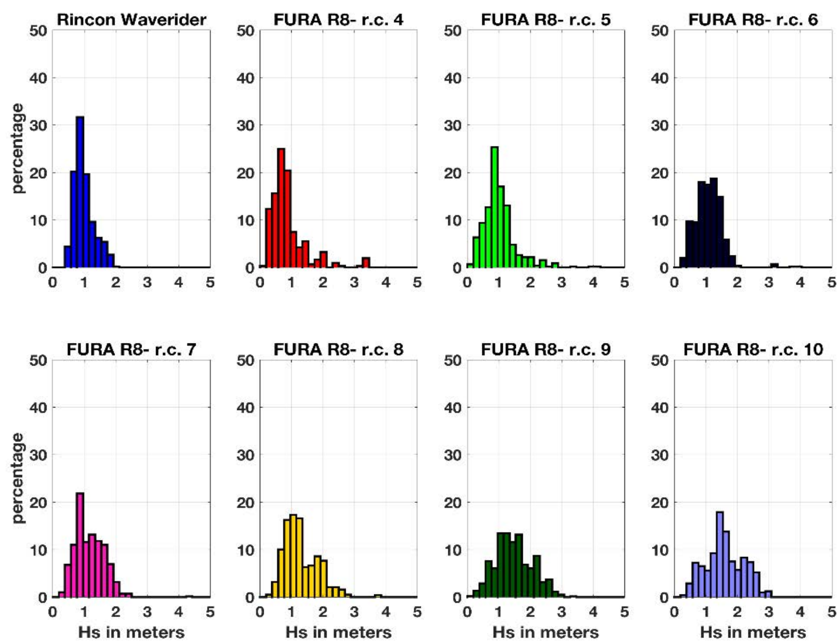


Fig.5. Significant wave height distribution as a function of range cell for FURA HF radar station for November 2018.

MABO experienced high reflected power issues during the 2nd week of November. Prior to this, severe spectrum contamination was saturating the 1st and 2nd order energy return that resulted in periodic overestimations in significant wave height. After replacing the damaged feed wire at the base of the transmit antenna, interference appeared to improve but there is still evidence of intermittent interference that skews the wave parameter estimations. Figure 6 shows the correlation between the spatial-averaged MABO data with the data measured from the Ponce mooring west of the coverage area.

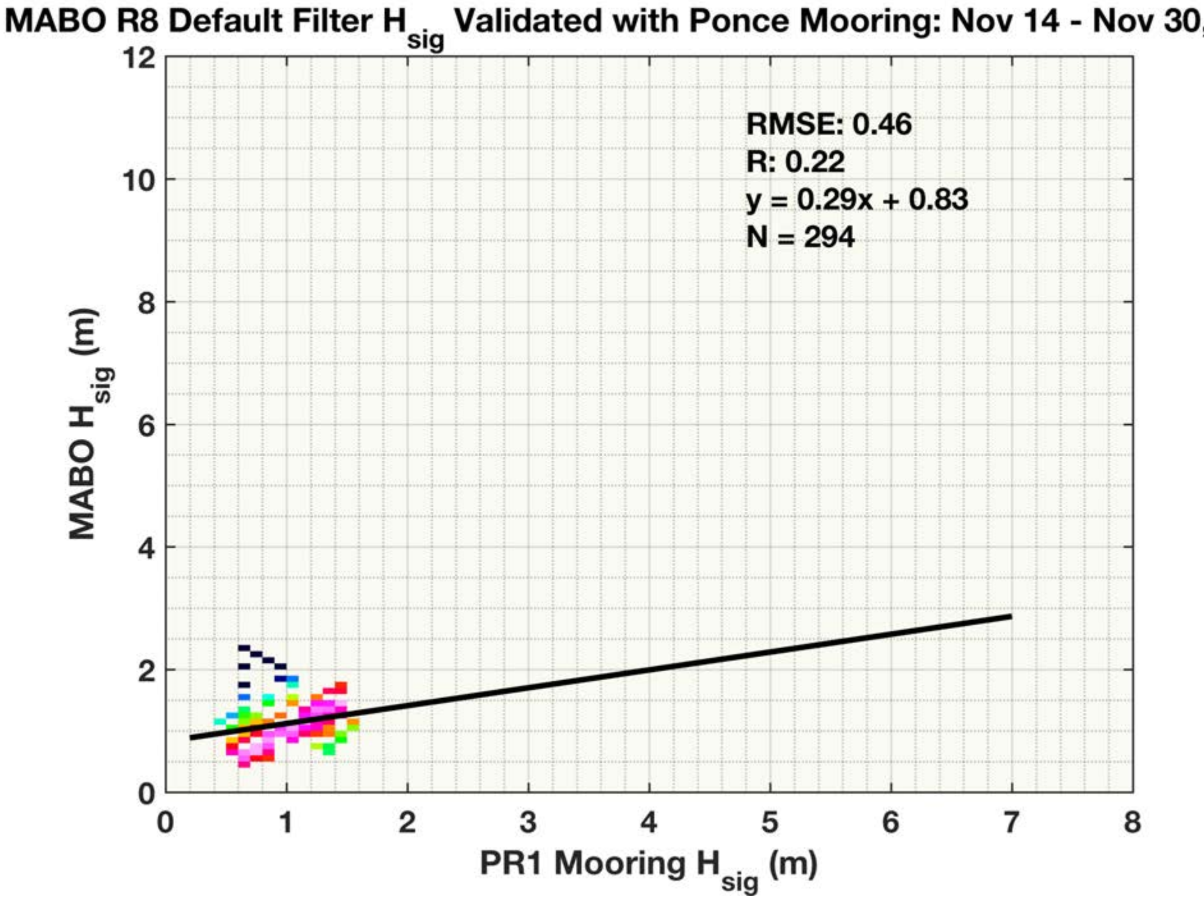


Fig. 6. Linear regression between Ponce mooring (PR1) and MABO station H_{sig} with RMSE and correlation.

Although the correlation is still not very strong, the positive is that the RMSE is much lower than when the interference was significantly skewing the wave parameter estimations earlier this month. As mentioned before, we are working with CODAR to hopefully identify the source and figure out a way to improve the data quality.

San Juan WFO Status Report – January 2019

Wave parameter validations are presented for January 2019 for two CODAR stations in the west and southeast regions of Puerto Rico that are currently running the Release 8 CODAR software with outlier mitigation. Figure 1 shows the locations of each instrument included in the validations, as well as the SWAN grid points within each range cell polygon.

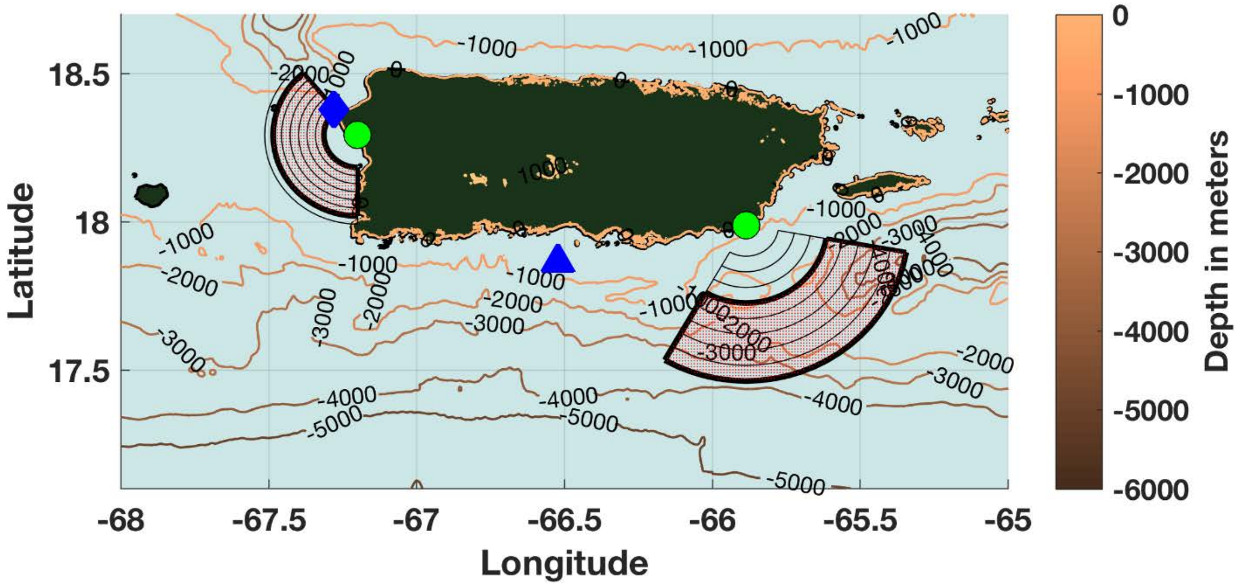


Figure 1. Map of locations and coverage areas of radars (green circles), wave buoy (blue diamond), mooring (blue triangle), and SWAN grid points (red dots). The FURA HFR is positioned on the west coast and the MABO station spans the southeast.

As in past months, spatially-averaged wave parameters from the radars were temporally compared with nearby buoys. Figure 2 shows the FURA HFR wave estimations compared with the wave buoy just north of the radar coverage area off the west coast. In contrast to previous winter seasons, swell propagation from the north has seldom reached the Puerto Rico coastline. In January of this year, the most notable peak occurred on the 24th where FURA and the wave buoy recorded maximum significant wave heights (H_s) of 2.75 m and 3.7 m, respectively. Earlier in the month, both the HFR and wave buoy were showing wind wave conditions but the peak directions varied. Figure 3 shows the wind direction recorded from FURA, which coincides with the wave direction seen from the radar. The offshore trade winds in this region typically come from the ENE but after interacting with the mountains in the central part of the island, a daily wake forms. At this point, much of the wind direction comes from the ESE. It should be reiterated that the HFR-measured wave heights are a spatial average in this context. Range-dependent derived wave parameters compared with SWAN are shown in Figure 4. Here, the SWAN output was spatially averaged over each ascending HFR range cell polygon. The significant wave height peak on the 24th becomes more prominent in the outer range cells associated with swell-like conditions. Overall, the radar shows similar patterns with both the wave buoy and SWAN but the significant wave height is consistently underestimated.

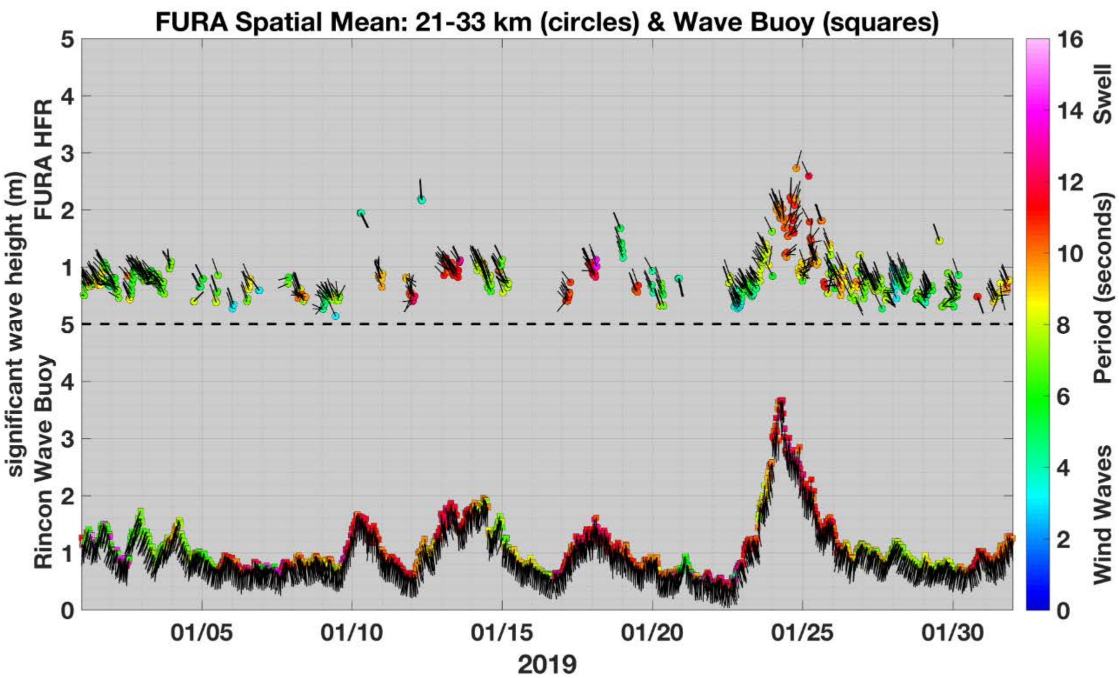


Figure 2. FURA estimated wave parameters spatially averaged over range cells 6-11 [top] compared with the wave buoy located in Rincon [bottom] (see Figure 1 for instrument locations).

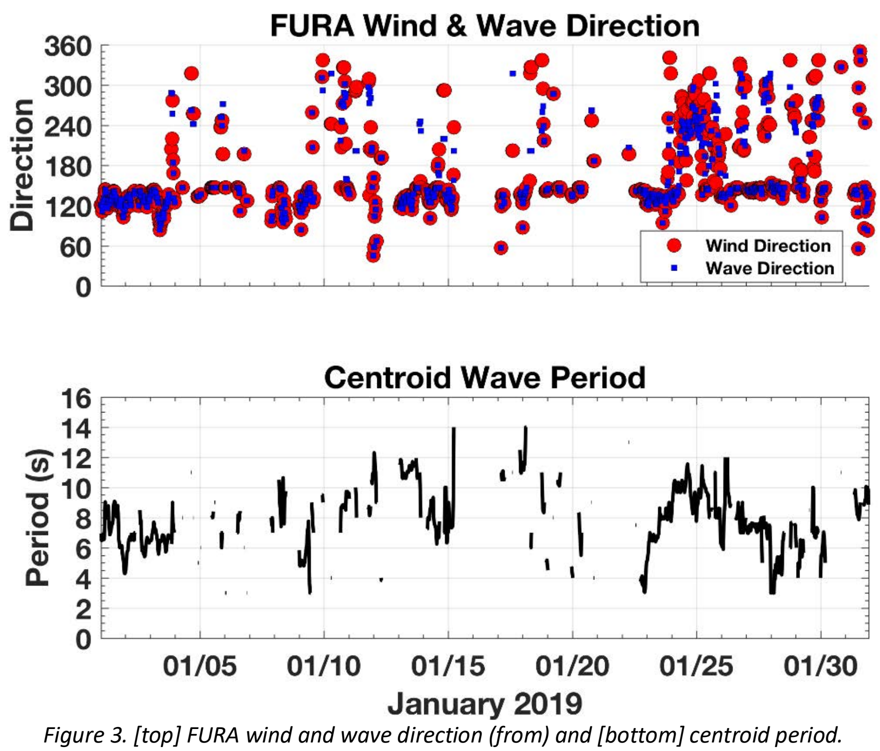


Figure 3. [top] FURA wind and wave direction (from) and [bottom] centroid period.

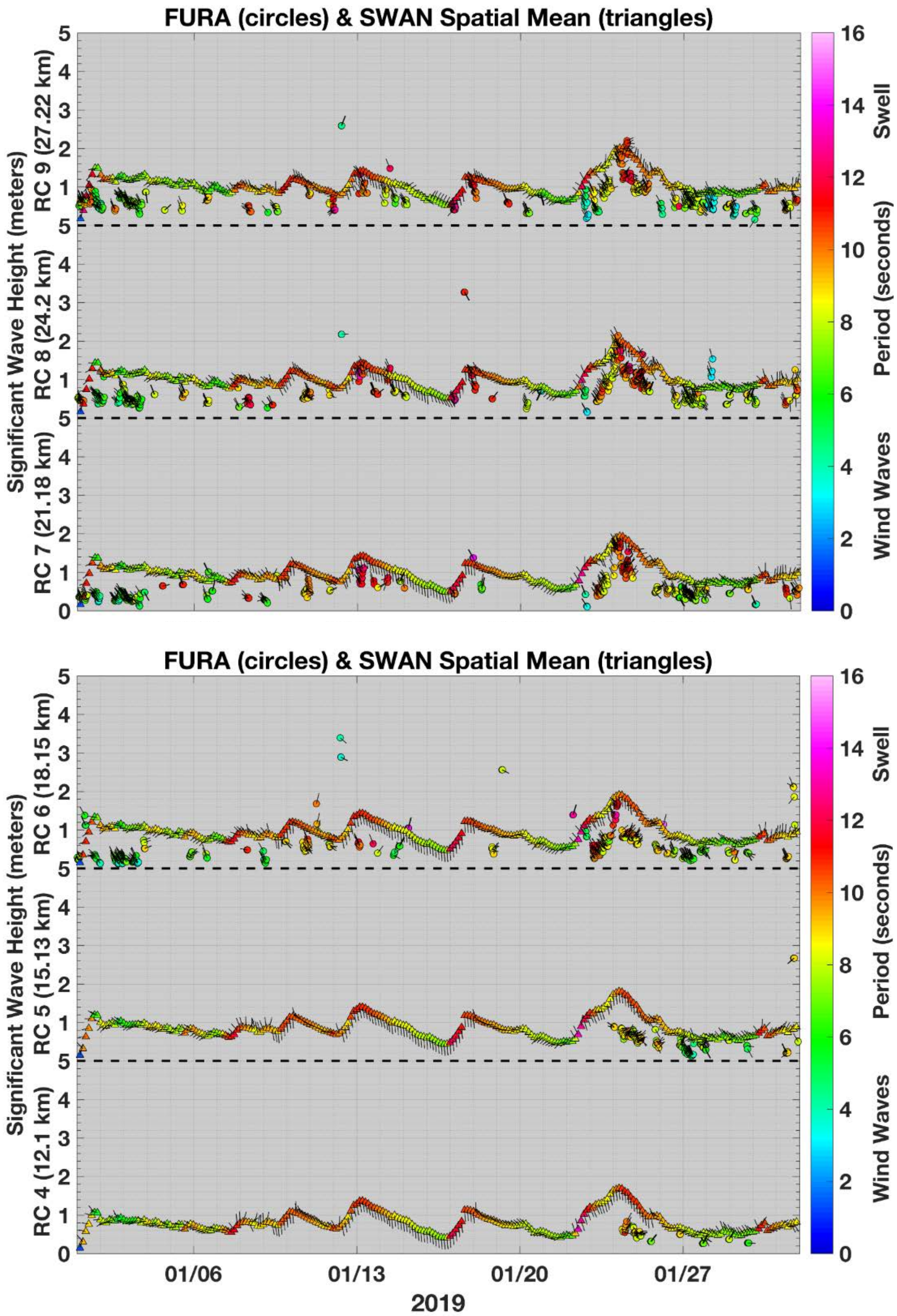


Figure 4. Range-dependent HFR-derived wave parameter estimations with SWAN spatially-averaged parameters. The SWAN model grid points within each range cell polygon contributed to the mean compared with each associated FURA range cell. The amplitude is given by the significant wave height, the color bar shows the peak period, and the stems indicate the peak direction the waves are traveling towards.

A similar assessment was done for the MABO radar station. Figure 5 shows the spatial mean between range cells 8-11 compared with a mooring located off Ponce, PR. These range cells were selected because of the ongoing, intermittent interference that saturated much of the spectrum in the nearby range cells, which is more evident in Figure 6 where the range-dependent wave parameters are shown. Bimodal spectra were common at this site where the two peaks typically occurred at wave periods of 6-7 s and 10-11 s. The centroid period is essentially an average between the two components, which commonly resulted in wave periods of ~9 s while the buoy and the model were showing peak periods of 6 s.

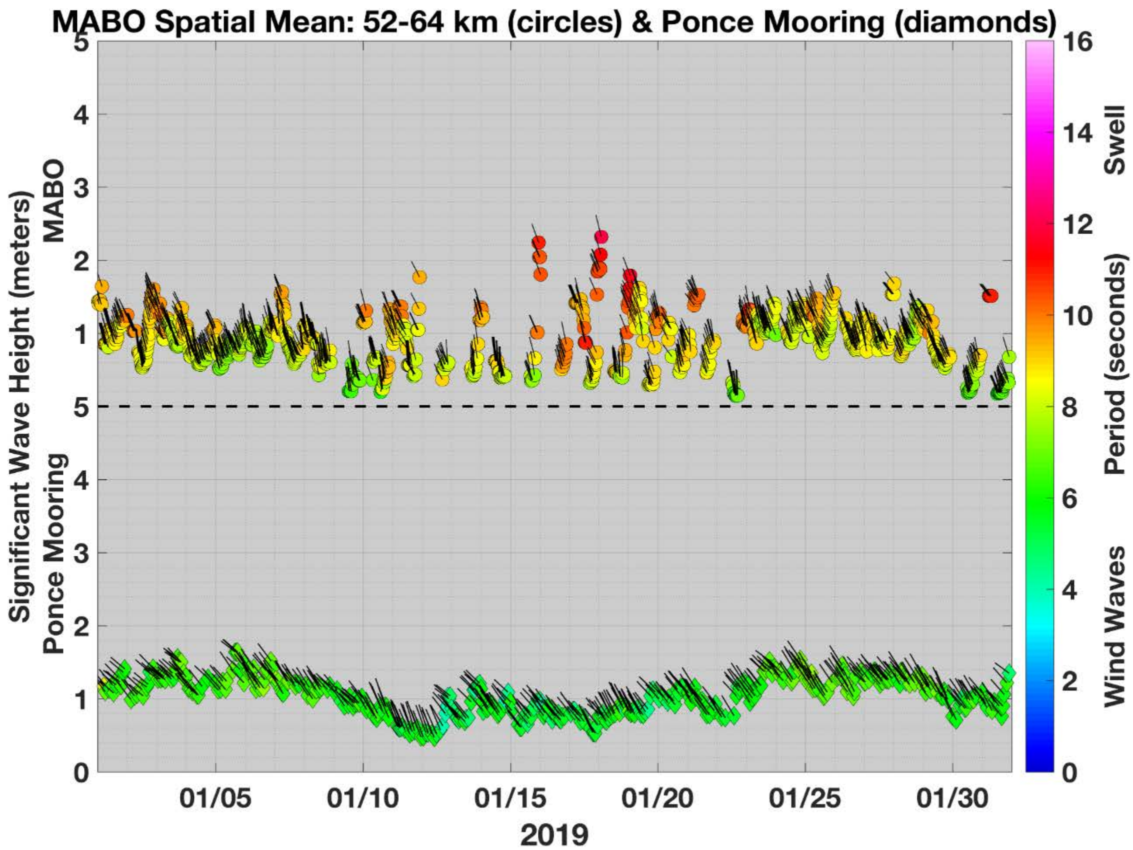


Figure 5. MABO estimated wave parameters averaged over range cells 8-11 compared with Ponce mooring.

Overall, significant wave heights were generally close between MABO and the buoy except for obvious outliers that occurred in the middle of the month. Peak wave directions were in relatively close agreement as well.

Figure 6 shows the range-dependent comparisons between MABO and SWAN. Outliers caused by interference are more evident in the closer range cells and becomes more mitigated farther offshore. Similar to the buoy, SWAN consistently showed wind-wave conditions with peak periods ranging between 5-8 s for the entire month. Peak wave direction was quite different showing more SSE-SE and ENE for the radar and SWAN, respectively. As was seen in the FURA estimations, significant wave height was consistently underestimated by the radar (not including the outliers).

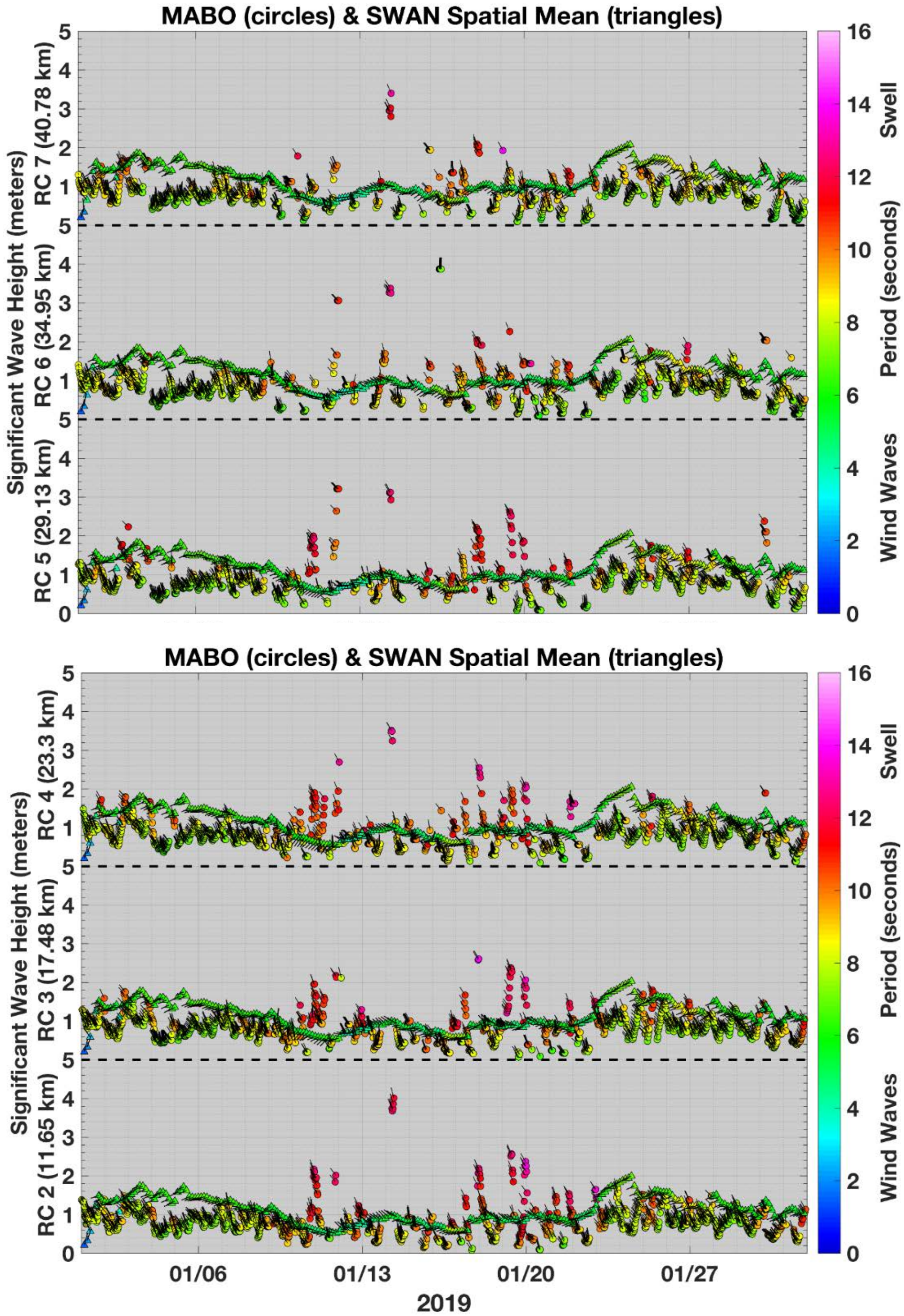


Figure 6. Range-dependent HFR-derived wave parameter estimations with SWAN spatially-averaged parameters. The SWAN model grid points within each range cell polygon contributed to the mean compared with each associated MABO range cell. The amplitude is given by the significant wave height, the color bar shows the peak period, and the stems indicate the peak direction the waves are traveling towards.

FURTHER NOTES:

We took an SDR meter out to MABO to narrow down the source of the interference in mid-February and it does not appear to be environmental. After further speculation, we think it could be attributed something internal (possibly due to the A/C compressor) but these are just ideas until we can get back out there and do some more testing. The interference is worse in the closer range cells so, while we try to figure out the cause, we will continue to analyze the outer range cells in the wave processing.

WFO Eureka

Eureka WFO Status Report – October 2018

Significant wave height time series for August, September, and October 2018 are included herein. The ongoing investigation of blanking and interference at Trinidad (TRIN) and Shelter Cove (SHEL) has expanded to include SeaSondes along the west coast. As discussed on our call, the signal to noise ratio is lower in the portion of the Doppler spectrum from which waves are extracted, therefore, waves output is more vulnerable to interference than currents.

Next steps will include a re-evaluation of filtering settings if coordinated blanking significantly reduces interference. We will re-process spectra (CSQ) offline with various levels of filtering and re-establish appropriate settings in the field.

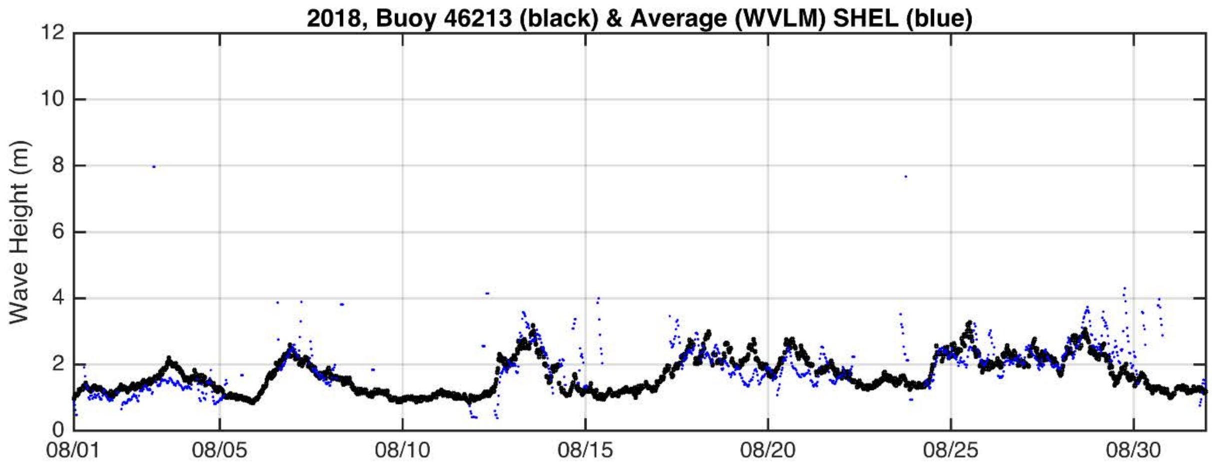
Whether the offset between HFR and buoy wave heights reflects ocean conditions or is due to some other factor(s) remains a topic of exploration.

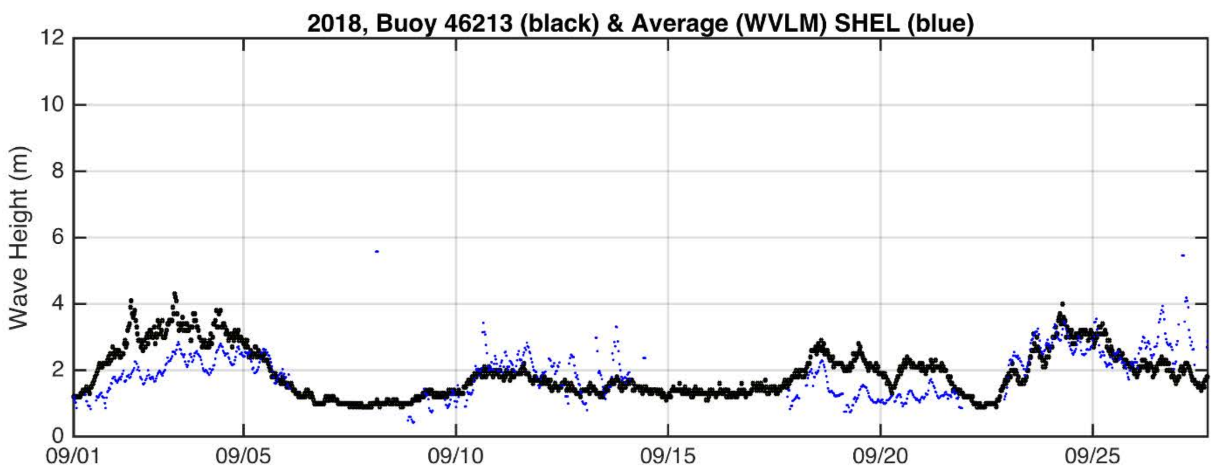
SHEL Subgroup Analysis

Preliminary results from an analysis that groups range cells at SHEL into two sub-groups is included as well. This means the filtering and averaging applied to the entire waves coverage area in normal processing is applied to the two sub-groups.

Refer to page three for a map showing the two sub-groups and wave height time series results. February yielded high quality waves output, therefore, data for this month were used. October was also analyzed as there is some improvement in data quality there.

A notable distinction between significant wave height in the inner and outer regions of the waves coverage area at Shelter Cove is visible. Waves in the inner region generally appear to be lower than in the outer region. Next steps include statistical analysis of the two sub-groupings. Also, observations from mariners would be valuable to include in our evaluation.


2018, Buoy 46213 (black) & Average (WVLM) SHEL (blue)
Wave Height (m)
0
2
4
6
8
10
12
08/01
08/05
08/10
08/15
08/20
08/25
08/30


2018, Buoy 46213 (black) & Average (WVLM) SHEL (blue)
Wave Height (m)
0
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12
09/01
09/05
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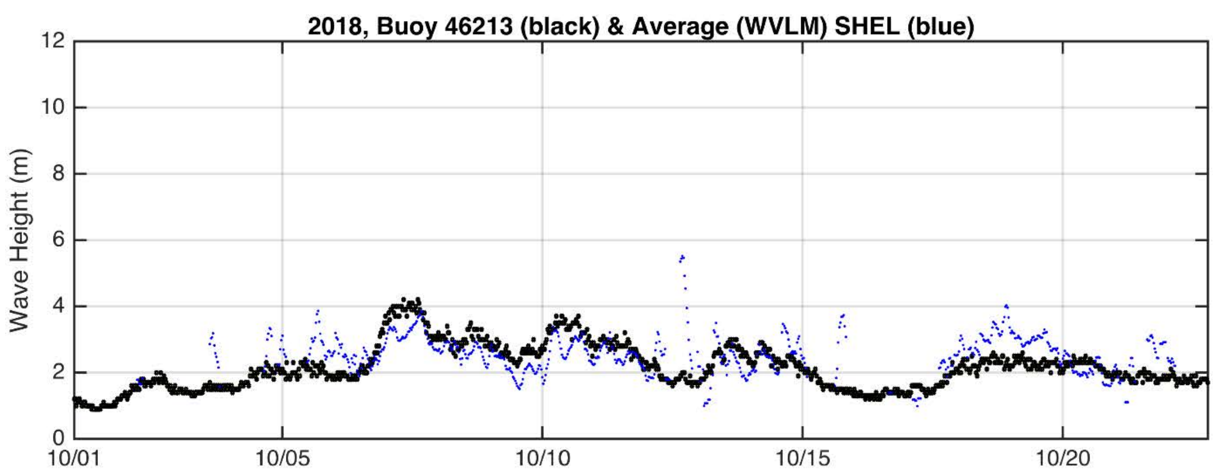
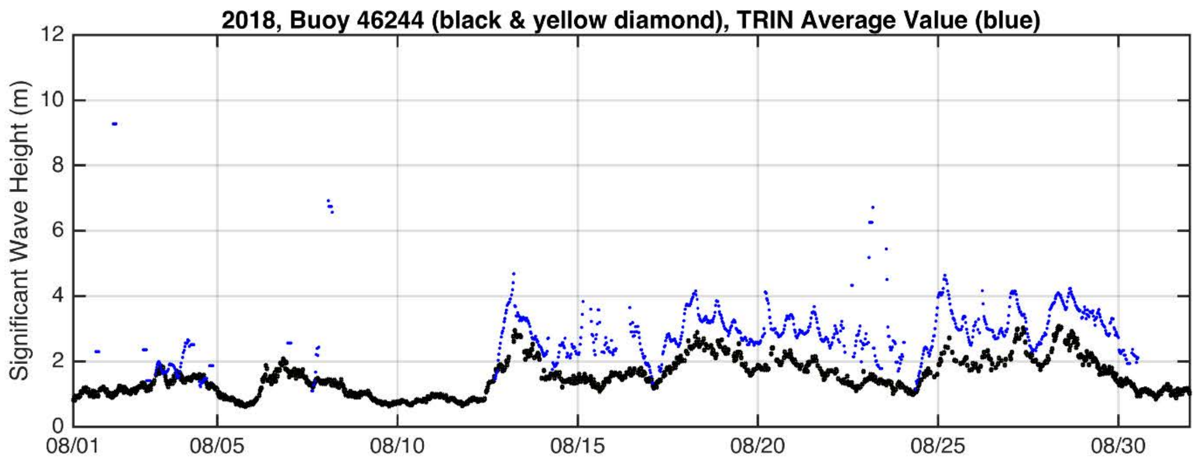
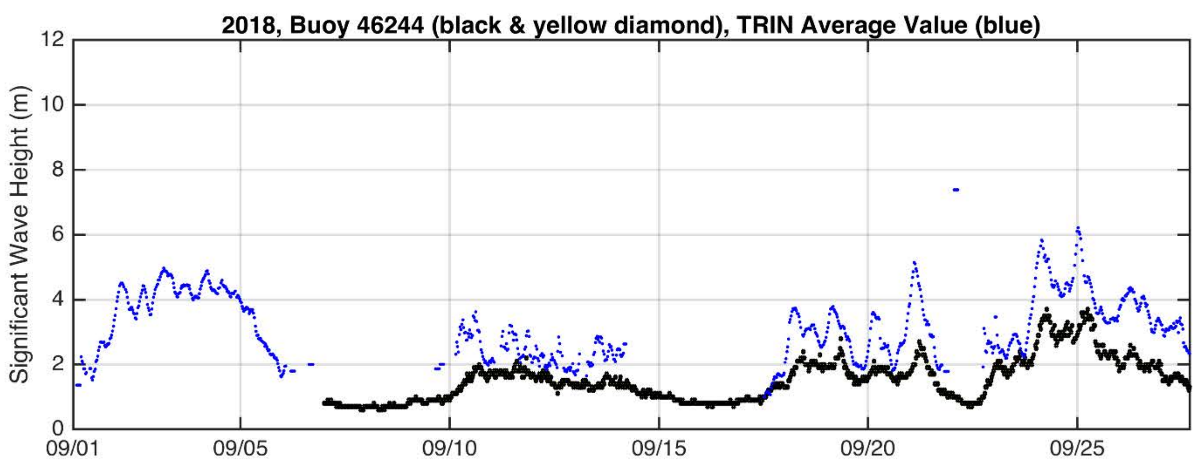
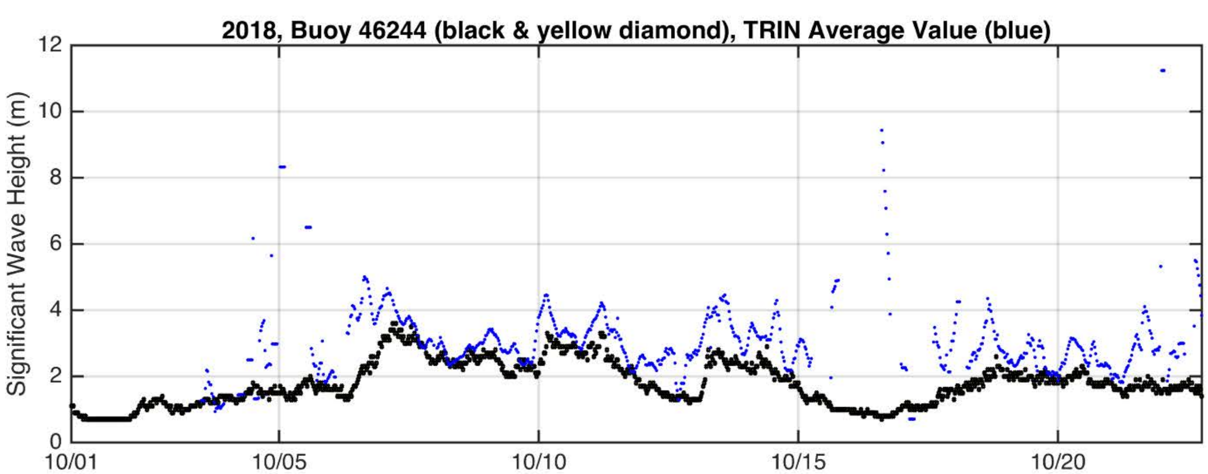
09/15
09/20
09/25


2018, Buoy 46213 (black) & Average (WVLM) SHEL (blue)
Wave Height (m)
0
2
4
6
8
10
12
10/01
10/05
10/10
10/15
10/20

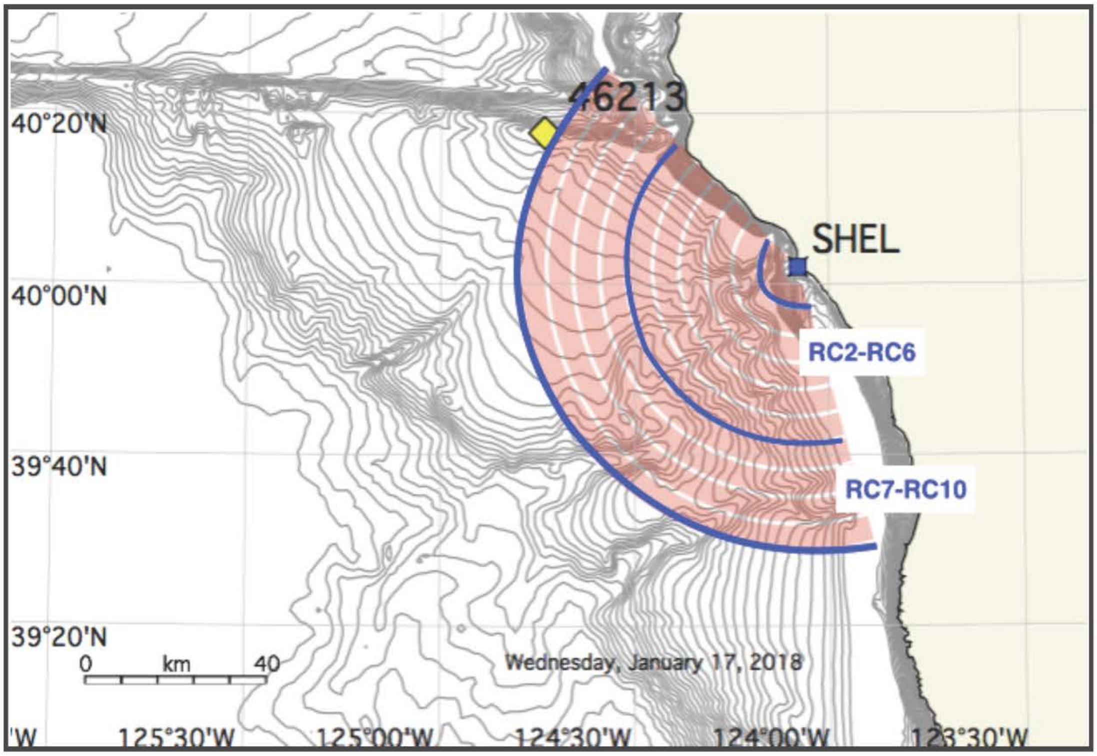
2018, Buoy 46213 (black)
SHEL: WVLM RC2-RC6 (cyan), WVLM RC7-RC10 (blue)



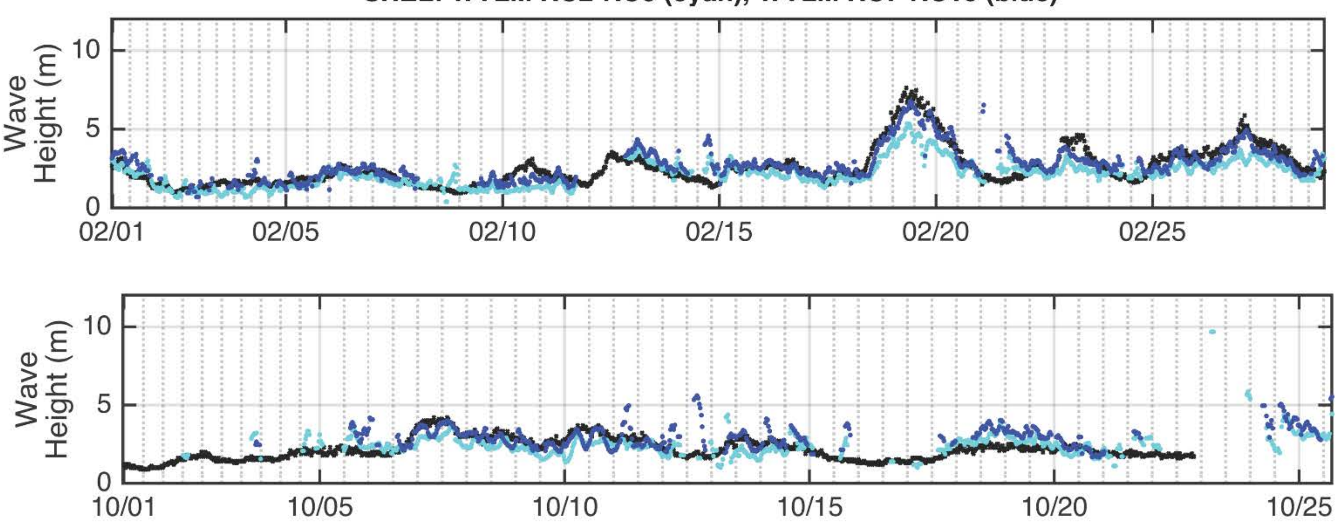




SHEL Subgroup Analysis



2018, Buoy 46213 (black)
SHEL: WVLM RC2-RC6 (cyan), WVLM RC7-RC10 (blue)



Eureka WFO Status Report – November 2018

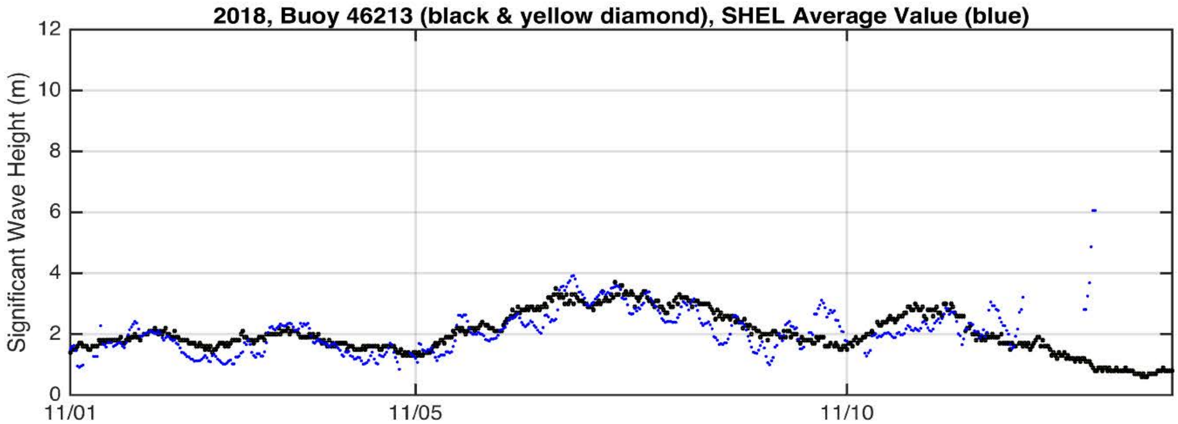
The significant wave height (wave height) time series for the first part of November 2018 is included herein. An overall improvement in wave height is visible at Shelter Cove (SHEL) until the end of the time series when a low signal condition prevails. Wave heights at Trinidad (TRIN) reflect a contaminated condition at the start of the time series, after which improvements are visible and agreement with buoy 46213 persists for about five days. Following, TRIN wave height is dominant. Spectra during the dominant period suggest bimodal conditions, unimodal swell, and contamination. TRIN wave height values drop off with low signal conditions towards the end.

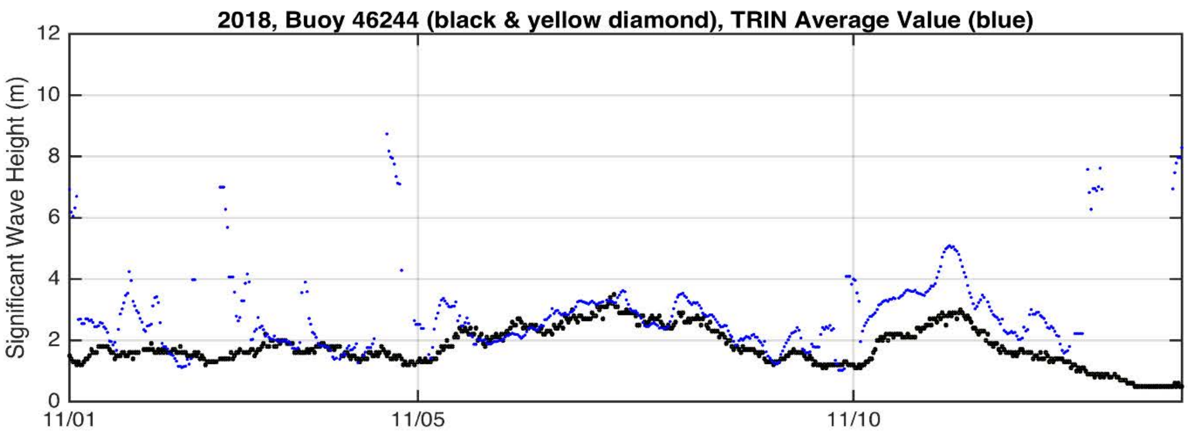
Because interference is seen throughout both SHEL and TRIN spectra, aggressive filtering remains on both sites. Explorations of interference source will continue. Enhancing filtering at spectral and/or raw wave data levels may be explored.

An additional means of measuring waves in the inner region of Shelter Cove would be ideal. Does NOAA have access to feasible methods?

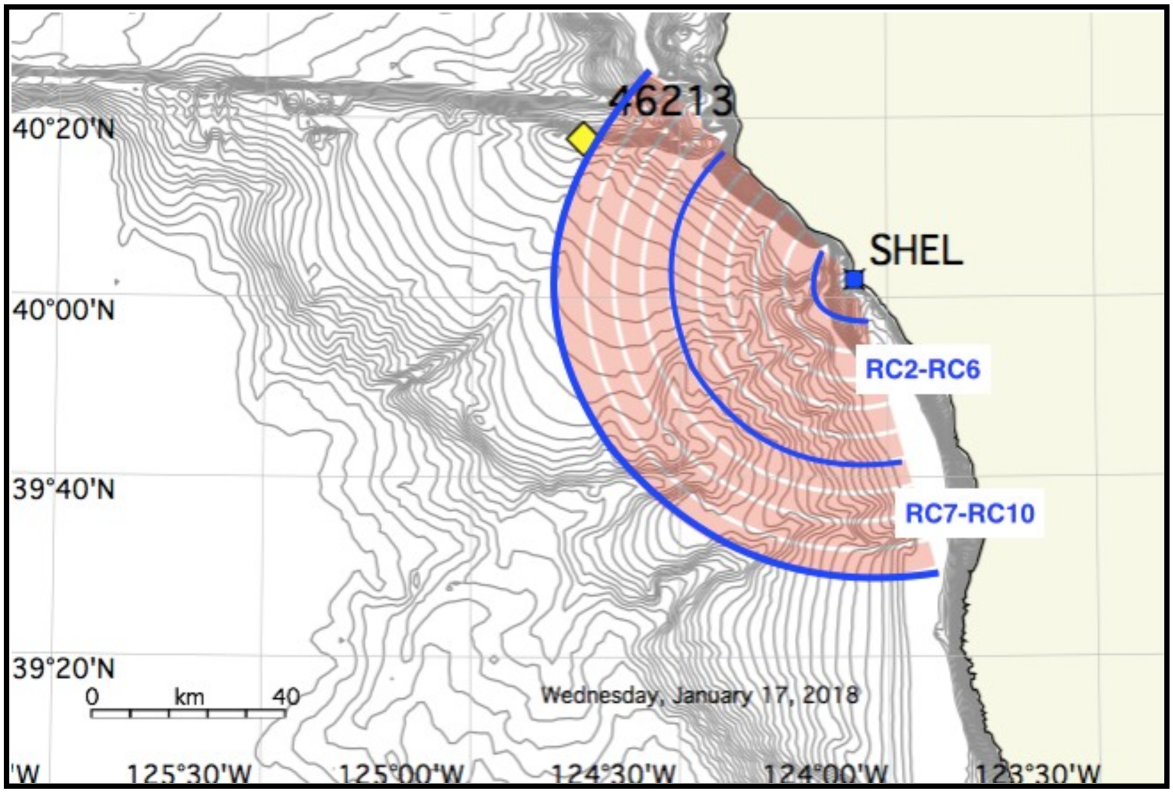
<u>SHEL Subgroup Analysis</u>
November plots from the sub-grouped analysis is also included here at two different horizontal scales. The tighter y-axis gives a view of the overall trend, while the second y-axis provides a better view of the detail.

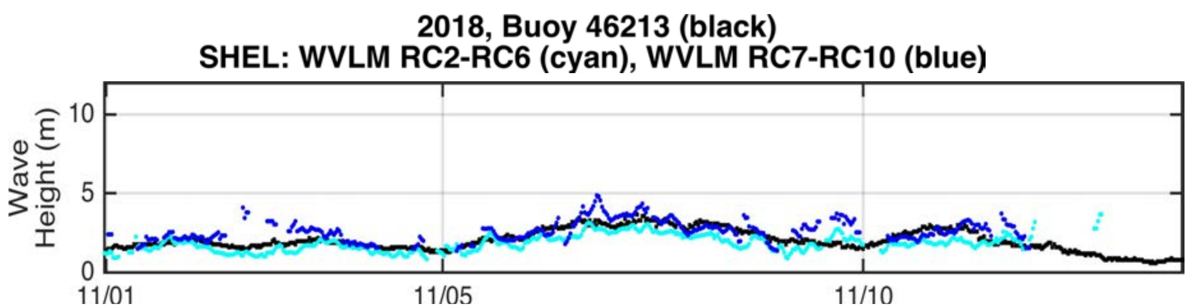
The lower wave height that was seen in October remains during the November time period. Next steps include statistical analysis of the two sub-groupings. Also, observations from mariners would be valuable to include in our evaluation.

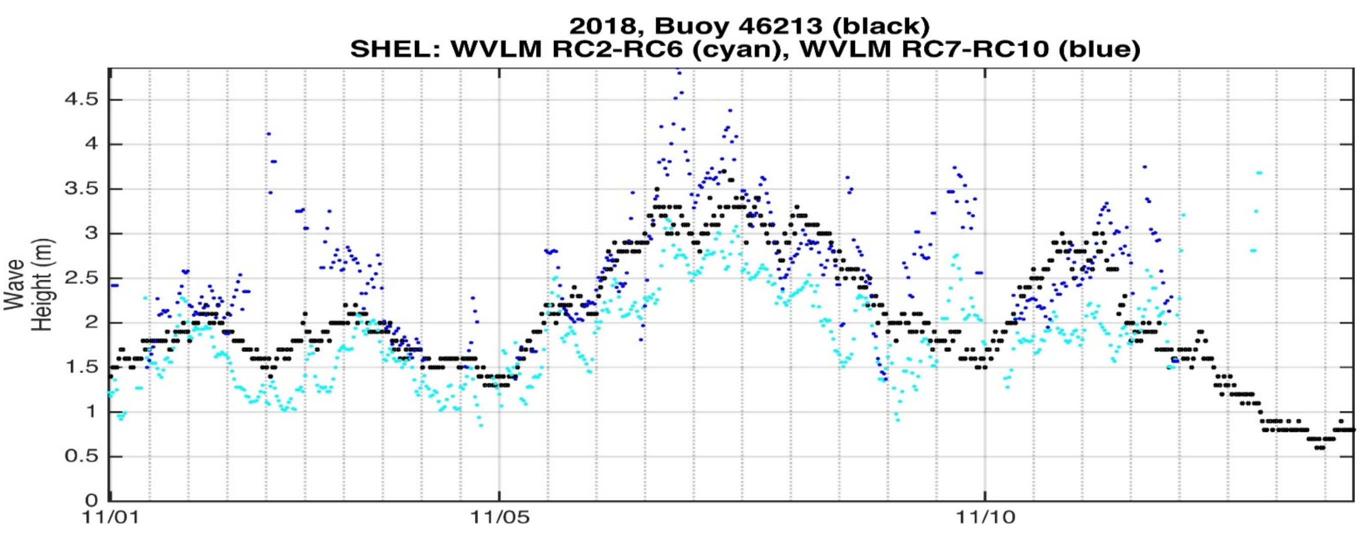

2018, Buoy 46213 (black & yellow diamond), SHEL Average Value (blue)
Significant Wave Height (m)
0
2
4
6
8
10
12
11/01
11/05
11/10


2018, Buoy 46244 (black & yellow diamond), TRIN Average Value (blue)
Significant Wave Height (m)
0
2
4
6
8
10
12
11/01
11/05
11/10

SHEL Subgroup Analysis



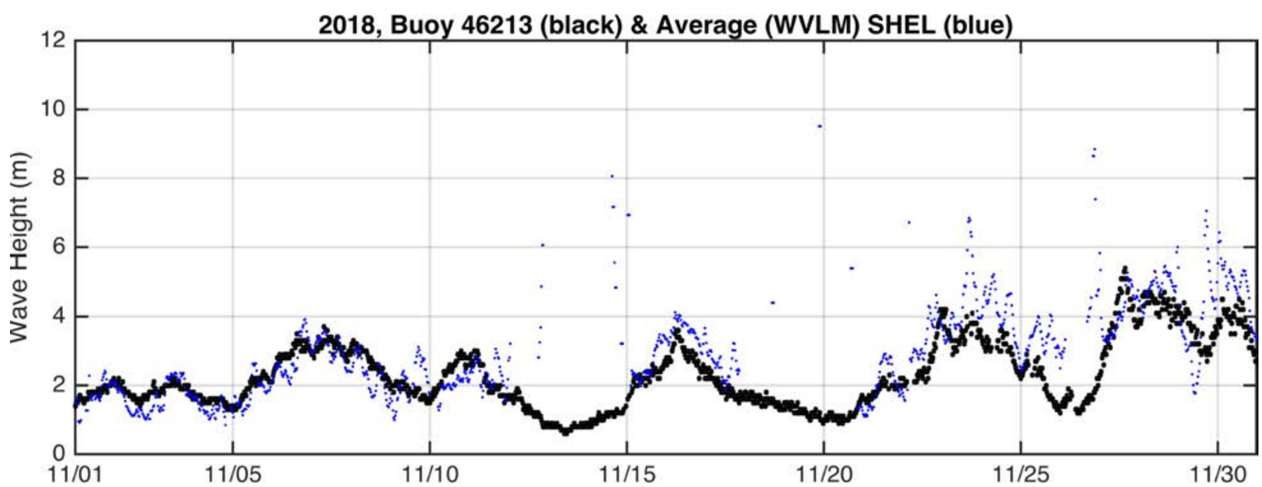


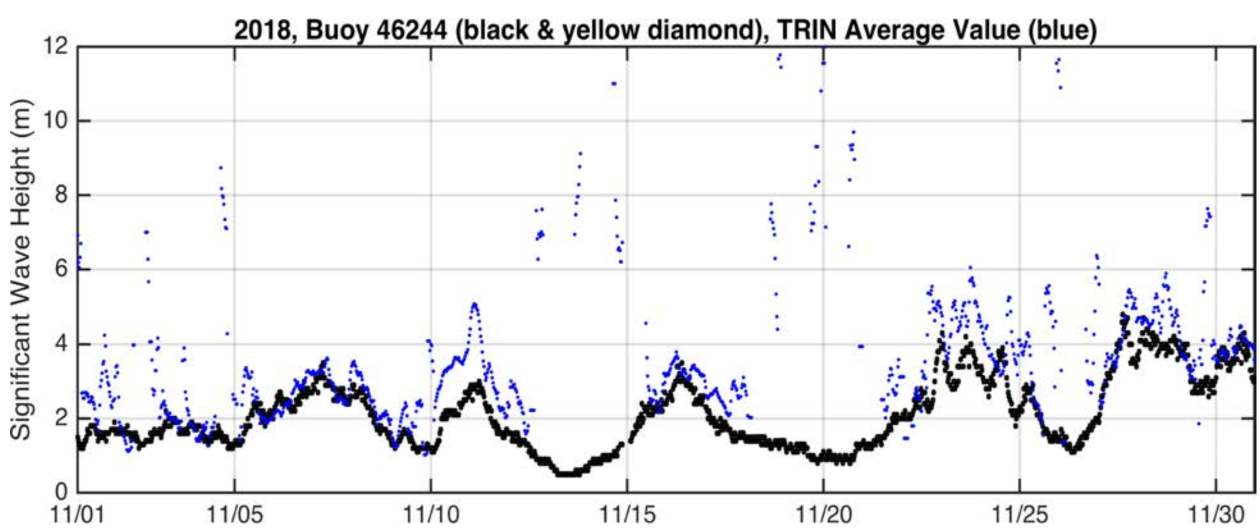


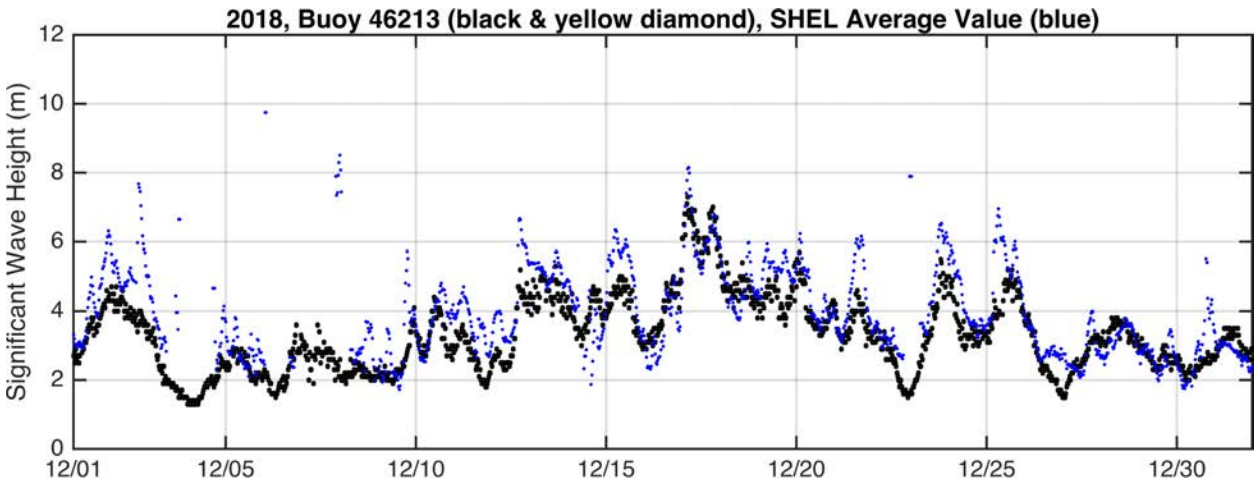
Eureka WFO Status Report – February 2019

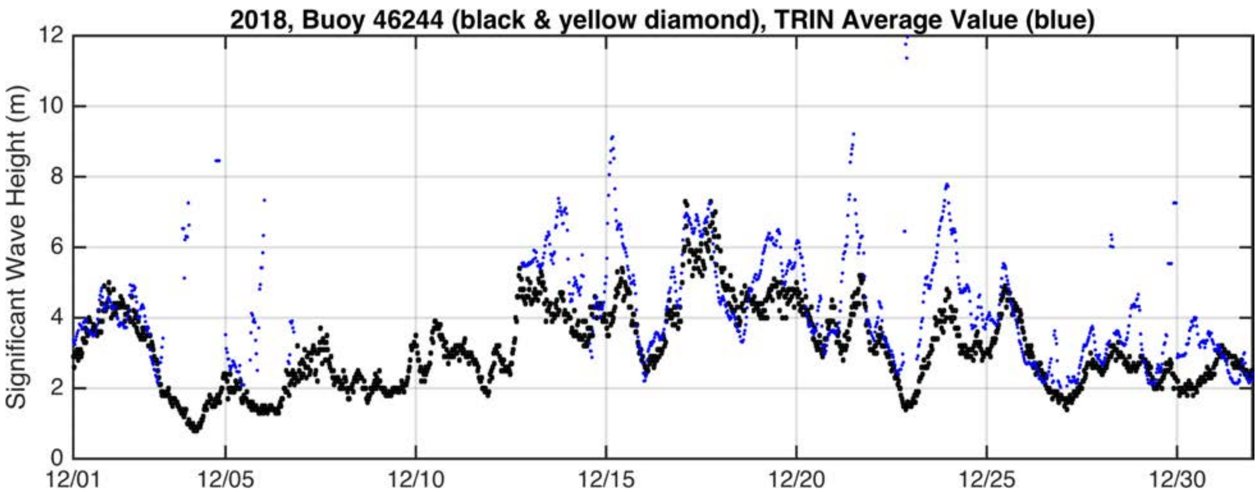
Status Report

The significant wave height time series for November 2018, December 2018, and January 2019 are included herein. Interference continues to appear in spectra and manifest in waves output. While the spectral filtering is as advanced as we can make it without removing too much data, CODAR has updated its WaveModelFilter algorithm and adjusted the settings that filter raw waves data. Improved results for week 50, 2018 are seen at SHEL and TRIN on pages 5 and 6. Note the elevated significant wave height at TRIN on December 15th is ameliorated. After the new algorithm and configurations have run on both sites for a few weeks, the settings will be further assessed.






2018, Buoy 46213 (black & yellow diamond), SHEL Average Value (blue)
Significant Wave Height (m)
0
2
4
6
8
10
12
12/01
12/05
12/10
12/15
12/20
12/25
12/30


2018, Buoy 46244 (black & yellow diamond), TRIN Average Value (blue)
Significant Wave Height (m)
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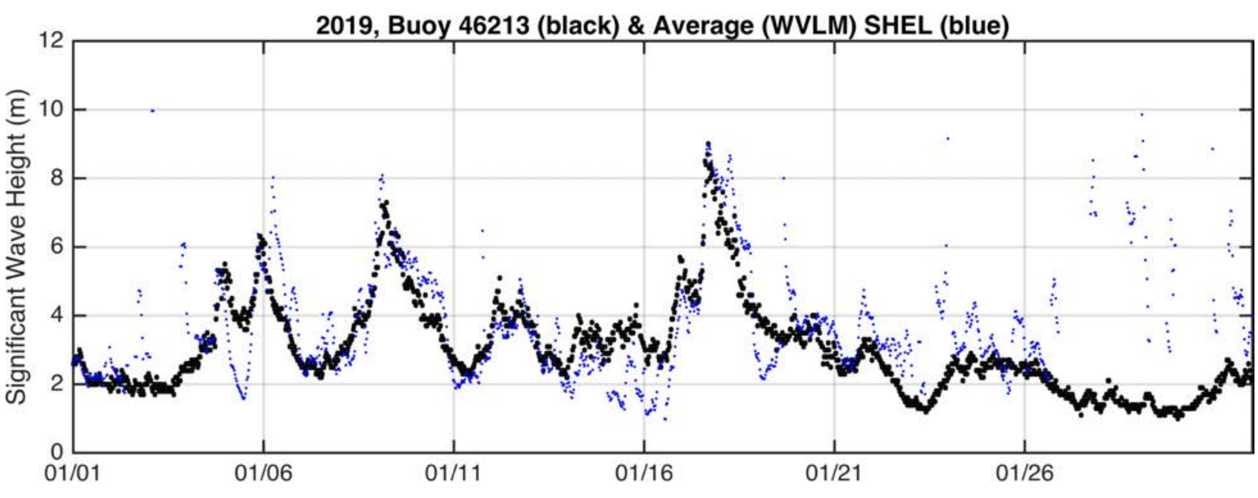
12/05
12/10
12/15
12/20
12/25
12/30


2019, Buoy 46213 (black) & Average (WVLM) SHEL (blue)
Significant Wave Height (m)
0
2
4
6
8
10
12
01/01
01/06
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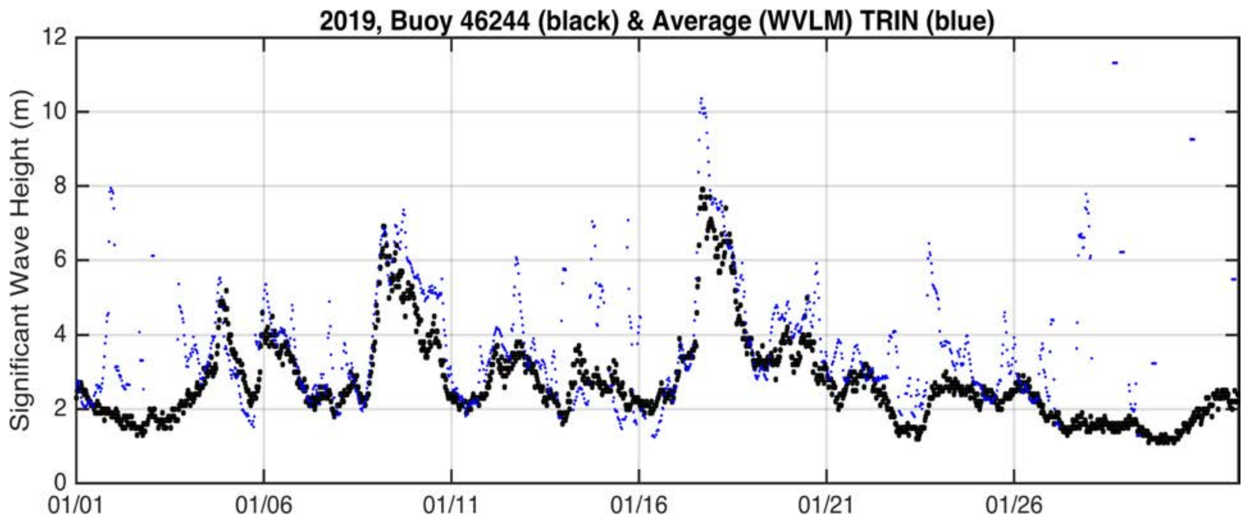
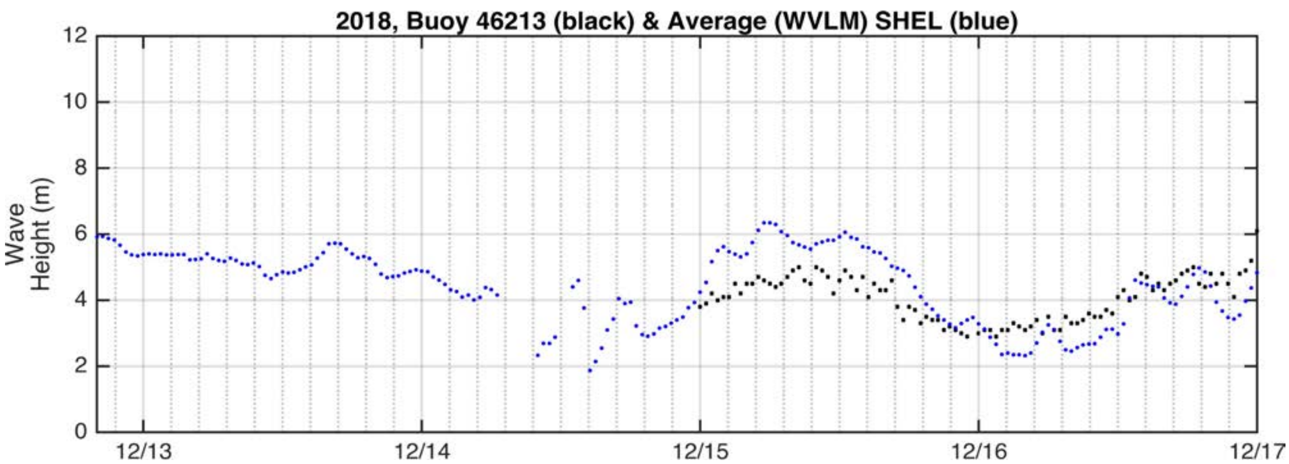
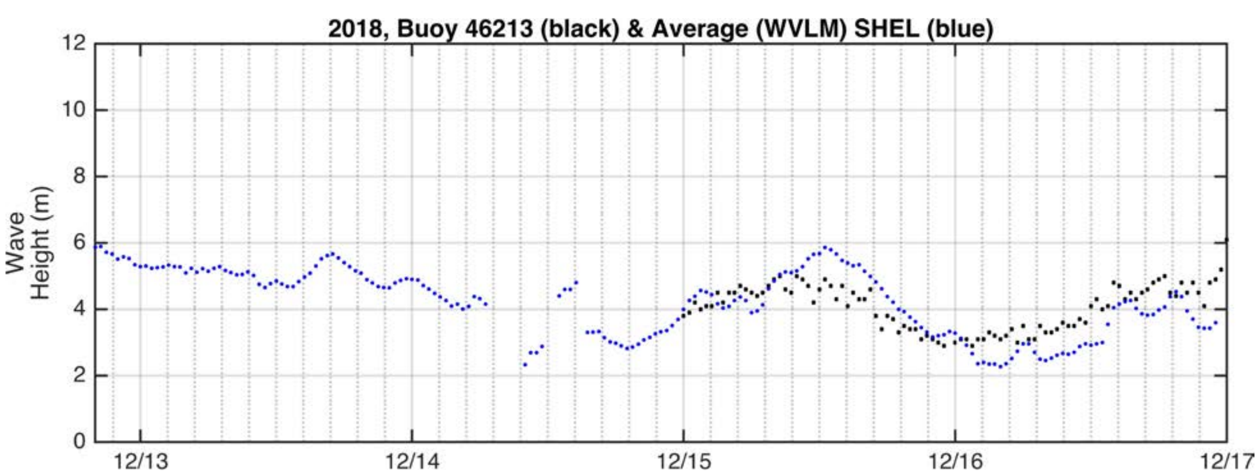
01/16
01/21
01/26

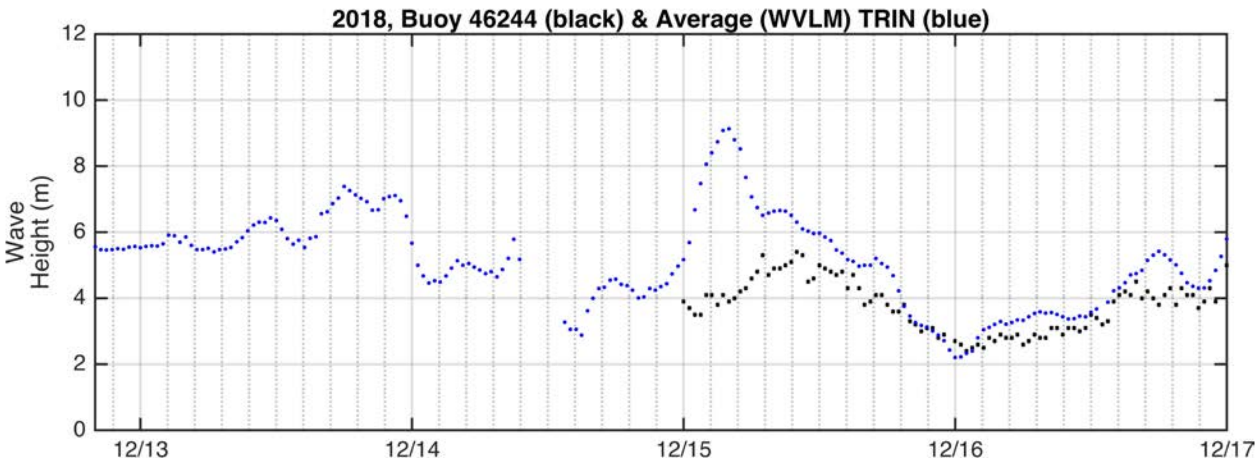




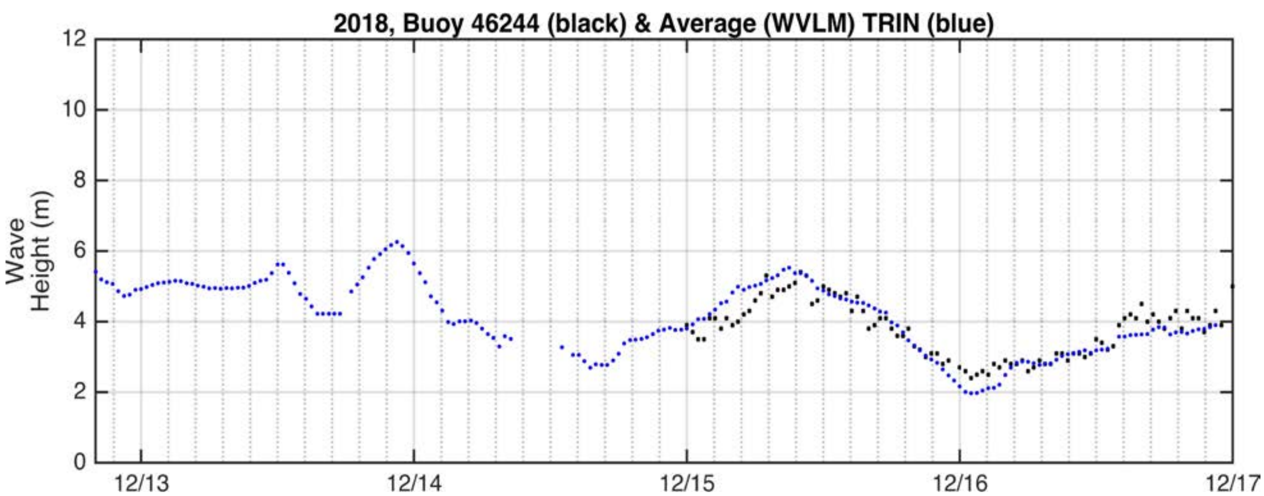
Existing wave model filter and configurations.



Improved wave model filter and configurations.



Existing wave model filter and configurations.



Improved wave model filter and configurations.