Wave Drifters and Their Applications in Research and Operations

Luca Centurioni

Director, Lagrangian Drifter Laboratory

And Global Drifter Program

Cooperative Institute for Marine Ecosystems and Climate (CIMEC)

Climate, Atmospheric Sciences, and Physical Oceanography

Scripps Institution of Oceanography

La Jolla, California, USA

lcenturioni@ucsd.edu, http://gdp.ucsd.edu/

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Topics

- Observing the Global Ocean at the Air-Sea Interface
- What are Wave Drifters
- How are the Wave Drifters Used (Global Array, Targeted Deployments, Moorings)
- What is Measured by the Wave Drifters
- How are the Observations quality controlled

OBSERVING THE GLOBAL OCEAN AT THE AIR-SEA INTERFACE

The Global Drifter Program in a Nutshell

The Only Global Scientific Project for In-Situ Ocean Observing at the Air-Sea Interface

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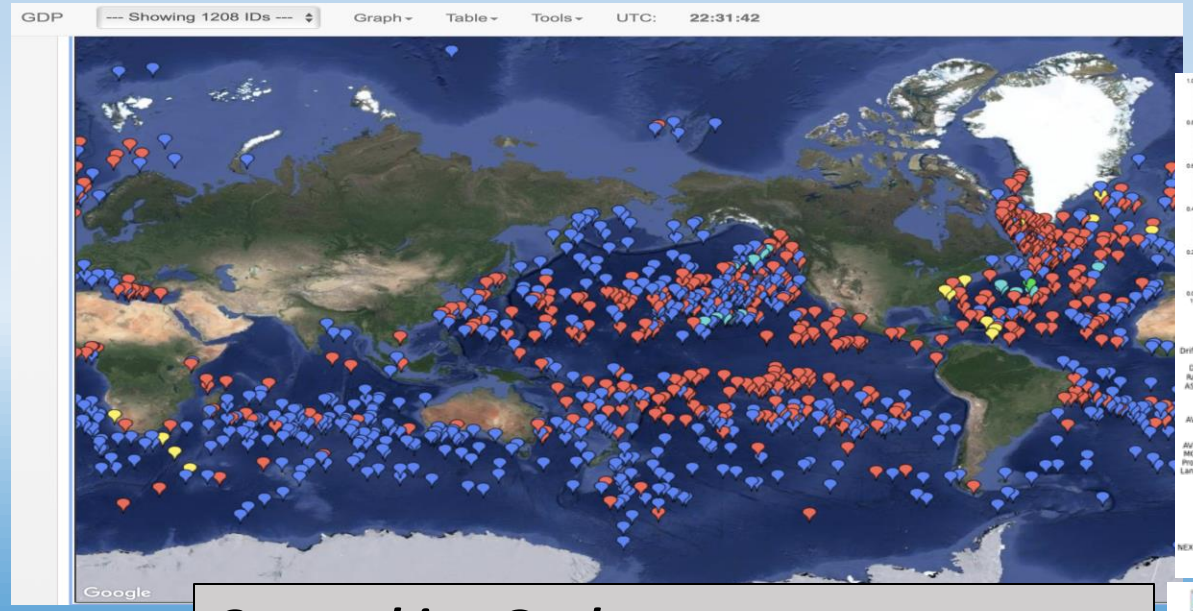
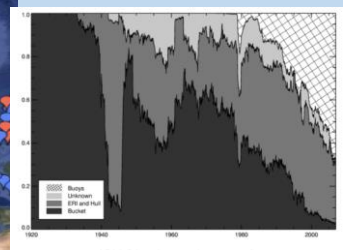
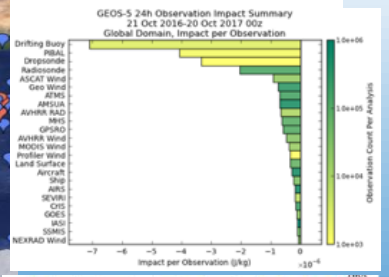


Main Critical Impact Areas



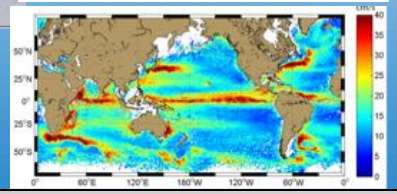
SST From Space Cal/Val

Left: Fractional contribution of SST data by platforms (buoys refers primarily to drifters, that provide more SST data than all the other sources combined). From Kennedy et al, 2011, JGR. Drifters provide X100 daily SST obs than Argo.



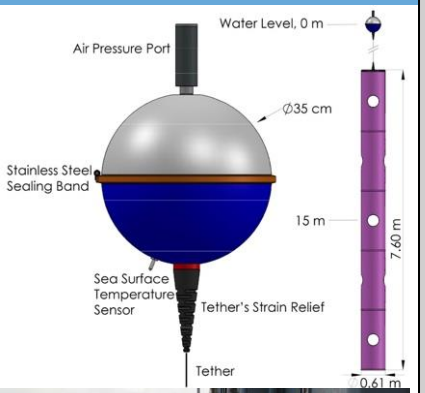
SLP for NWP and Climate Indices

Left: Drifters SLP data have the largest positive impact per observations (Centurioni et al. 2016, BAMS). Both forecasting and climate studies benefit from drifter data, especially in the southern ocean where the drifters are essentially the only source of in-situ SLP data.



Science

Over 1,100 paper published to date use drifter data directly



***Overarching Goals*:**

Maintain a global 5ºx5º array of surface drifting buoys to meet the needs for an accurate and globally dense set of in-situ observations: **mixed layer currents, SST**, **atmospheric pressure**, winds, and salinity.

Build a ***collaboration*** with the international community to maintain the array.

The GDP provides publicly available observational baselines in the upper-ocean mixed-layer and fills a unique role in the Global Ocean and Climate Observing System. The positive impacts of the GDP data are large and well documented

Measuring Waves

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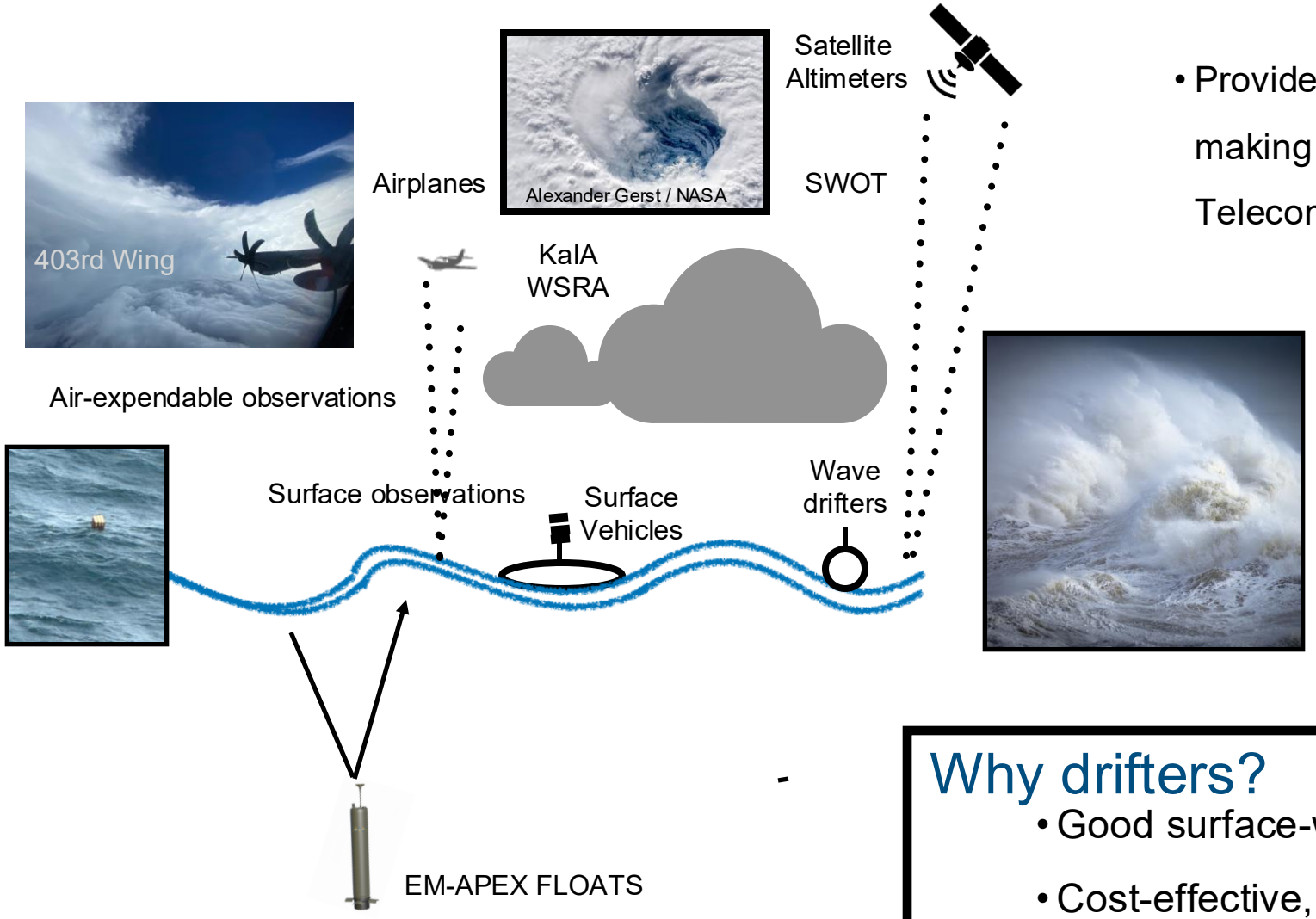


- Provide wave observations for **forecasting** by making data publicly available on the Global Telecommunication System (GTS)

Validation of open-ocean waves to coastal storm surge

Computation of surface roughness that influences drag coefficient, momentum and heat transfer

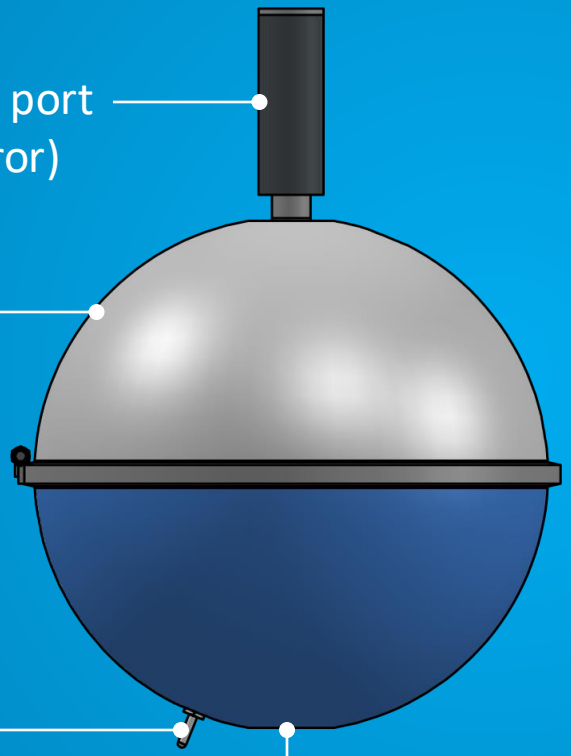
Why drifters?

- Good surface-wave follower OR current follower
- Cost-effective, dynamic
- Easily deployable
- Two-way Iridium communications
- Adaptive sampling

THE WAVE DRIFTERS

The Wave Drifter

LDL's Directional Wave Spectra Barometer Drifter (DWSBD™)



HIGHLIGHTS

- GPS-based tracking and wave engine
- Iridium Short Burst Data (SBD) telemetry
- Onboard datalogger with up to 16 GB of storage
- Fourier coefficients a0, a1, b1, a2, b2
- 1/256 Hz bandwidth from 0.03–0.50 Hz
- User-programmable sampling window
- Freely drifting or restrained mooring configurations
- One-year lifespan
- Configurable with anemometer

Wave parameters are obtained from the spectral analysis of time series of GPS-derived velocity

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The A-size Wave Drifter

LDL's Directional Wave Spectra Barometer Drifter (A-DWSBD™)

Sea level barometric pressure port
(±0.55 hPa total maximum error)

12 diameter tube

Sea surface temperature sensor
(±0.05 K accuracy)

HIGHLIGHTS

- GPS-based tracking and wave engine
- Iridium Short Burst Data (SBD) telemetry
- Onboard datalogger with up to 16 GB of storage
- Fourier coefficients a0, a1, b1, a2, b2
- 1/256 Hz bandwidth from 0.03–0.50 Hz
- User-programmable sampling window
- Freely drifting
- Air-deployable
- ~3 months life span, longer if adaptive sampling is used

Same functionalities as the full-size wave drifter

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OUR COMMITEMENT FOR A CLEAN ENVIRONMENT
The Bio-Plastic Drifters

- In recent years the GDP has deployed several SVP and DWSBD drifters made with oil-free, non-toxic bioplastic; While all the LDL made drifters have used recycled materials for years, our goal is to improve our efforts to minimize the impact of our critical observations on the environment.
- Our interest in the recent deployments of biodegradable drifters is into determining if this new material is suitable for long term applications, in other words, we want to see how long they will survive in a real application.
- Approximately two years of data on the performance of the biodegradable drifters indicate that these products are a viable alternative to petroleum-based plastic

The biodegradable DWS™

Timeline of A-DWSD/Full-size DWSD development

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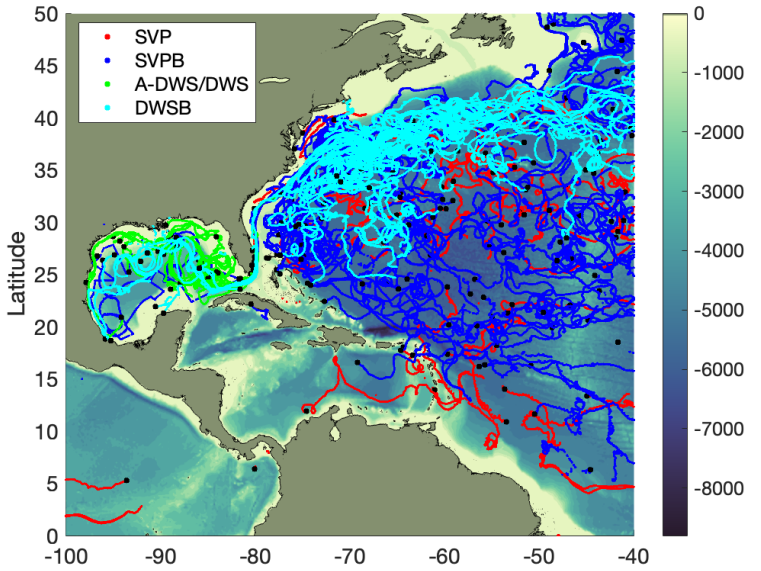
DWSD Buoys: Waves, SST, Barometer, Wind

- GPS wave buoy
- Deliver "first-five"
- Adaptive sampling
- SST, optional barometer

North Atlantic Hurricanes: 2024



- 50 Full-size DWSB drifters for wave monitoring
- 37 A-size DWS hurricane targeting drifters

2003 — CBLAST

2005 — DWSDs developed, global barometer

2015 — DWSDs released to global array

2018 — DWSD targeting of hurricane (Hurricane Michael)

2019 — Targeting of Atmospheric River, DWSBD

2021 — Release of A-DWSD

2022 — Targeting of Hurricane Ian with ADWSD

2024 — ADWSBD

Drogued vs Undrogued Drifters. Examples from Bay of Bengal

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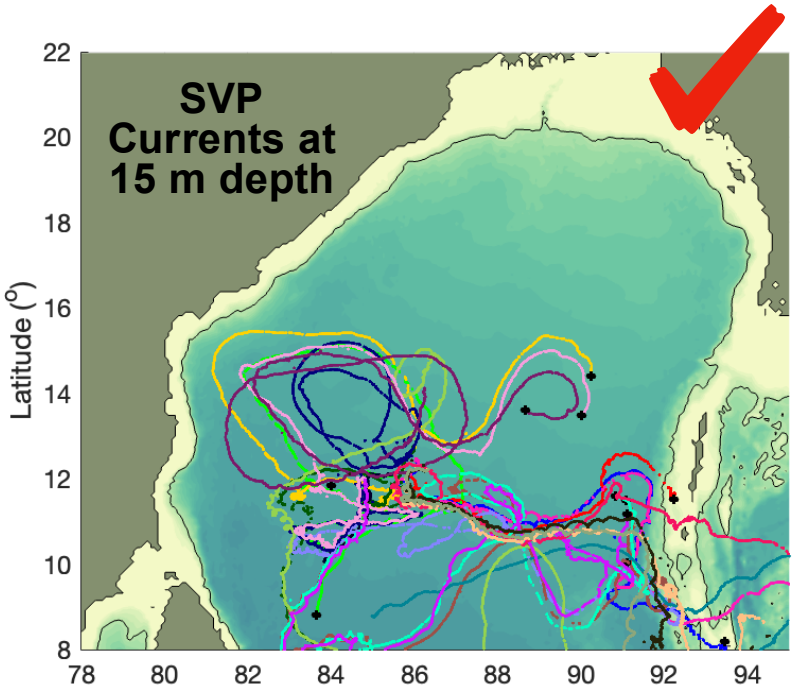
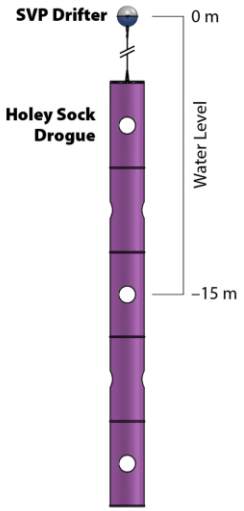


Drogue!



Lagrangian Drifter? Example from Bay of Bengal

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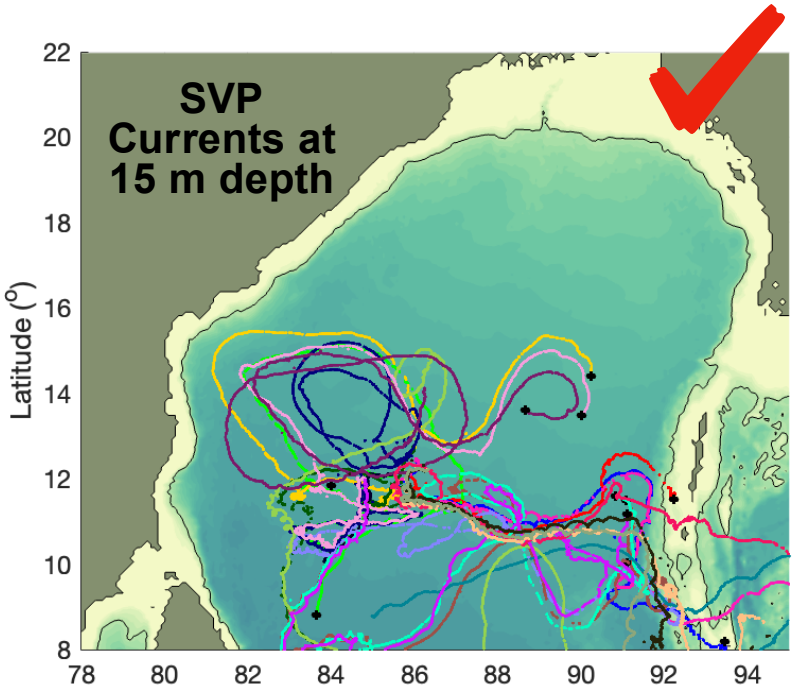

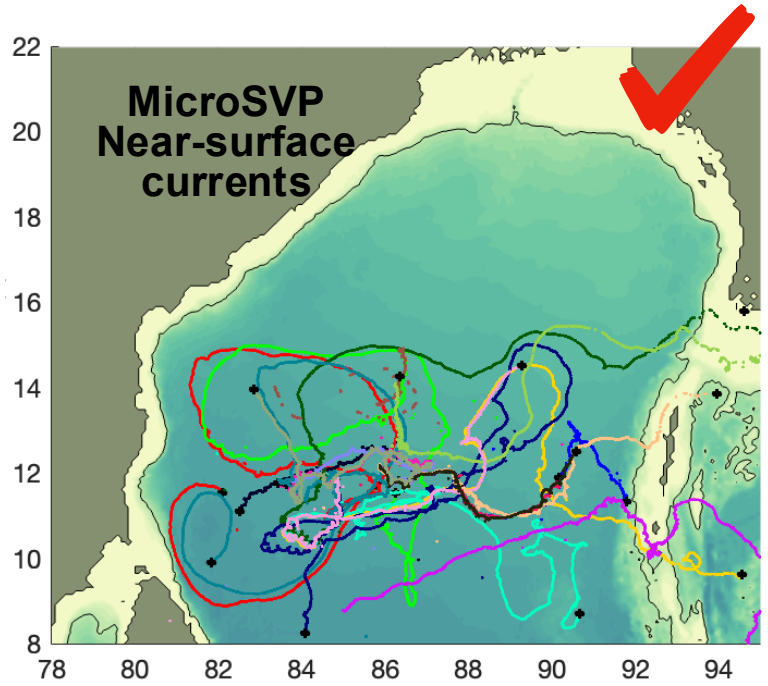

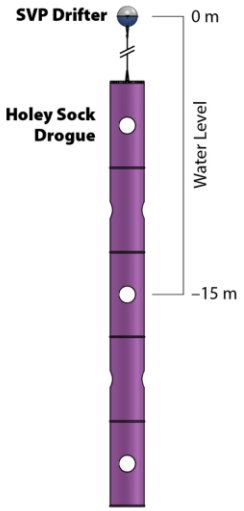

Drogue!

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Lagrangian Drifter? Example from Bay of Bengal

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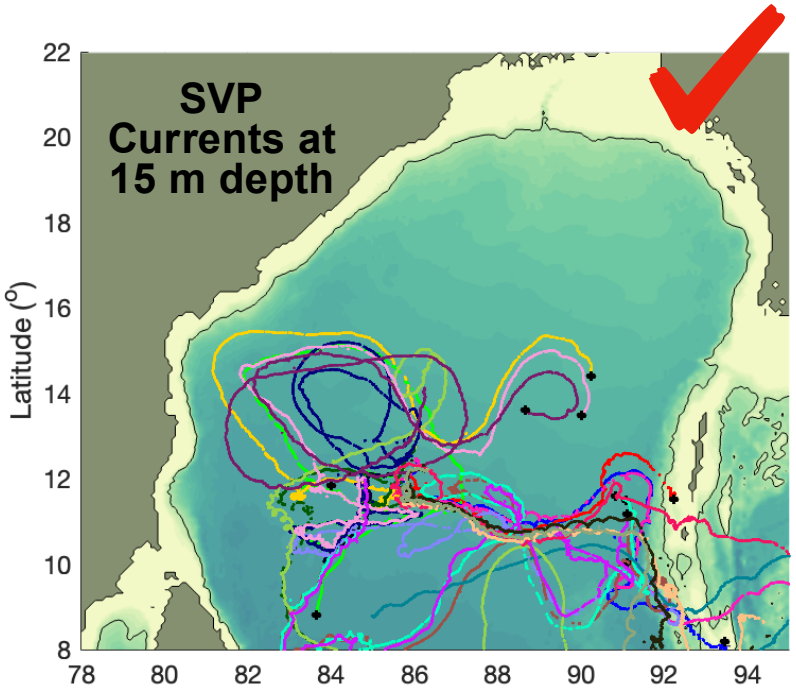
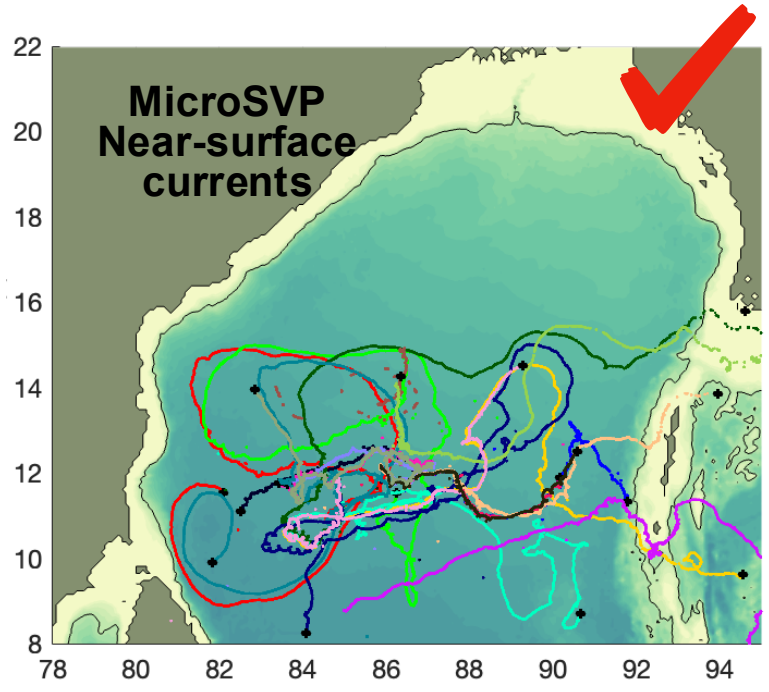
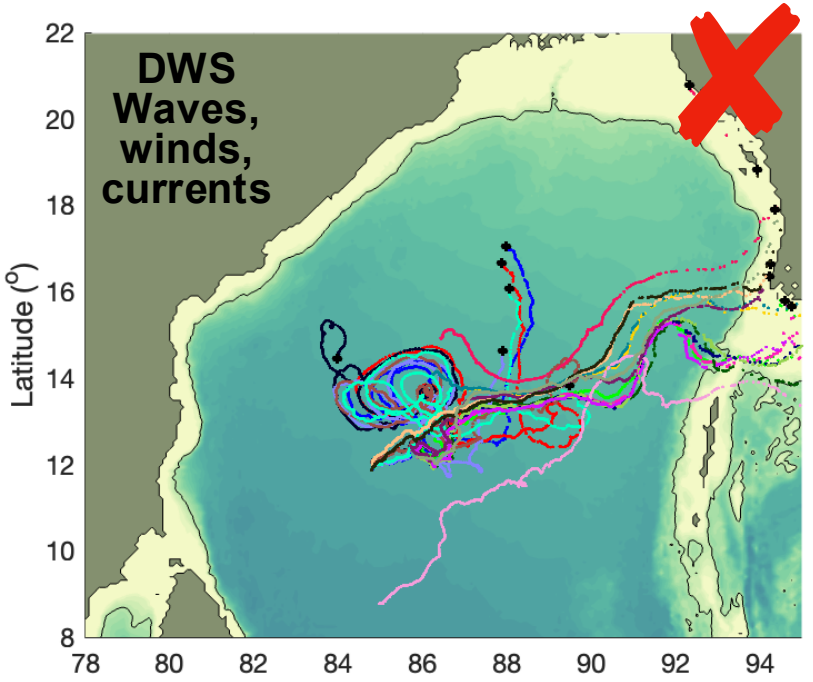
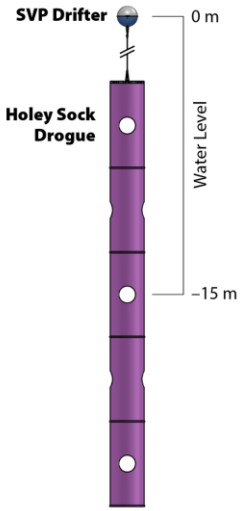




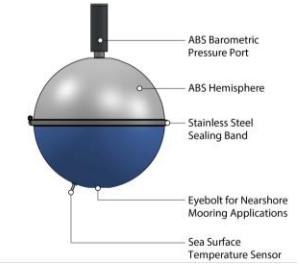


Drogue!



Drogue!

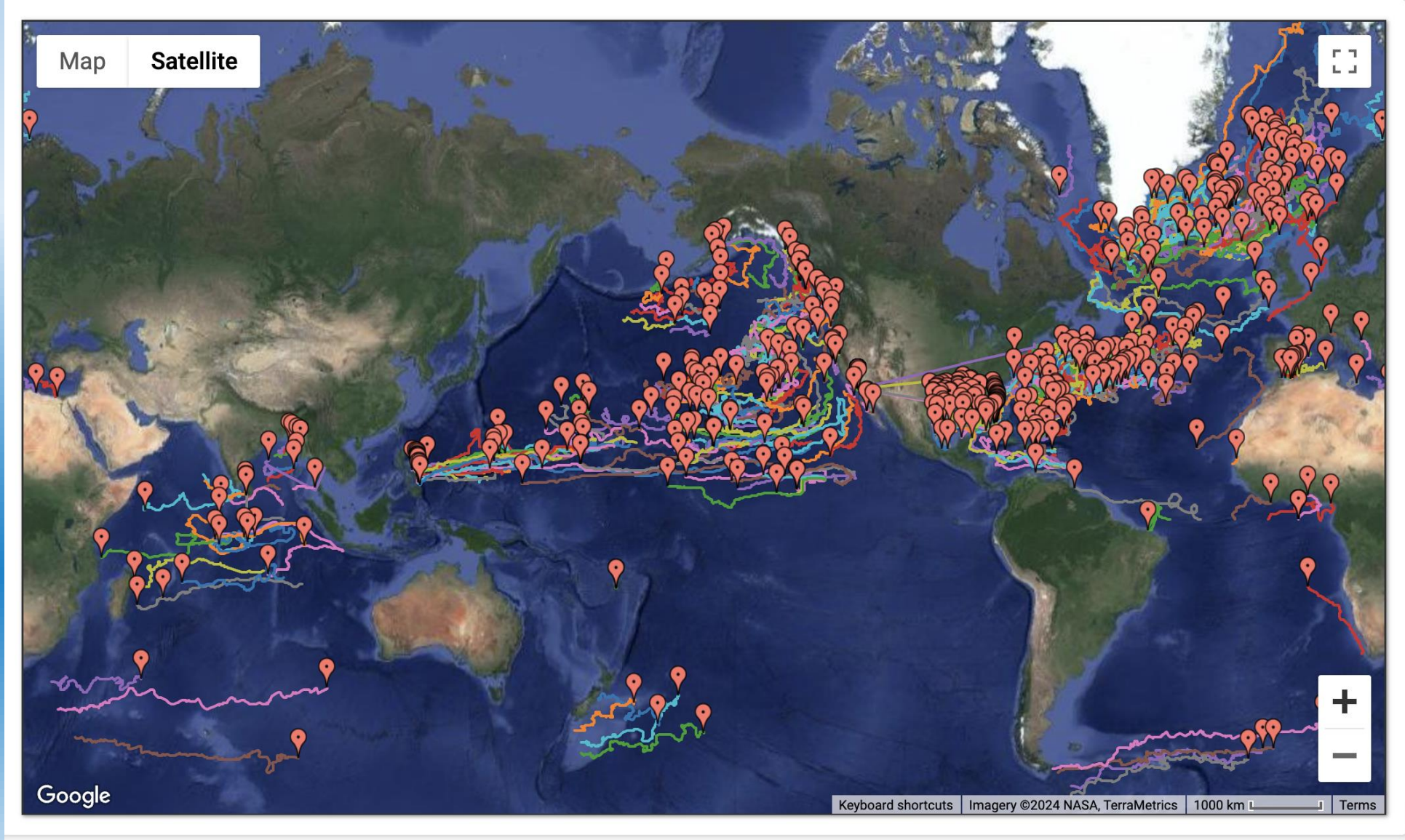
Undrogued!



Directional Wave Spectra Drifter (DWSD)

HOW ARE THE WAVE DRIFTERS USED

DWS/DWSB for Global Deployments: over 700 deployed to date



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METHODOLOGY: TARGETED DEPLOYMENTS : HURRICANE MILTON (OCTOBER 2024)

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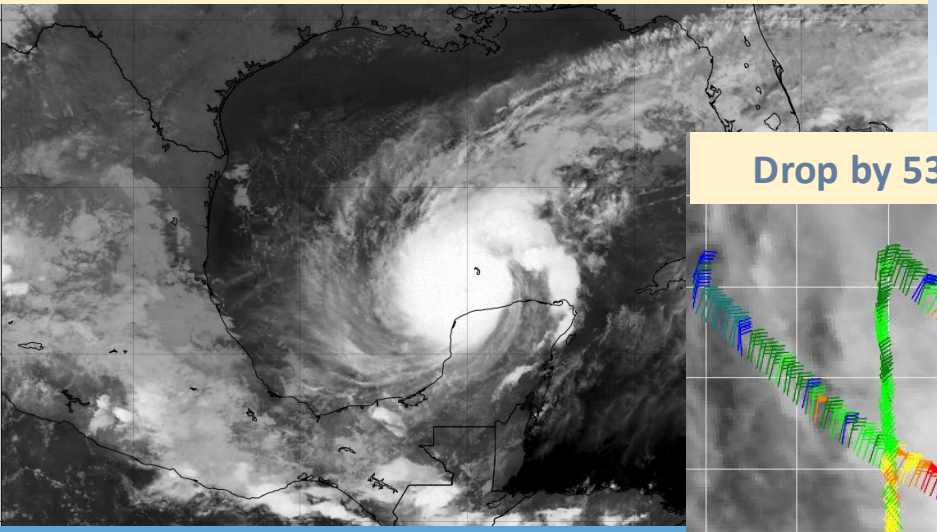
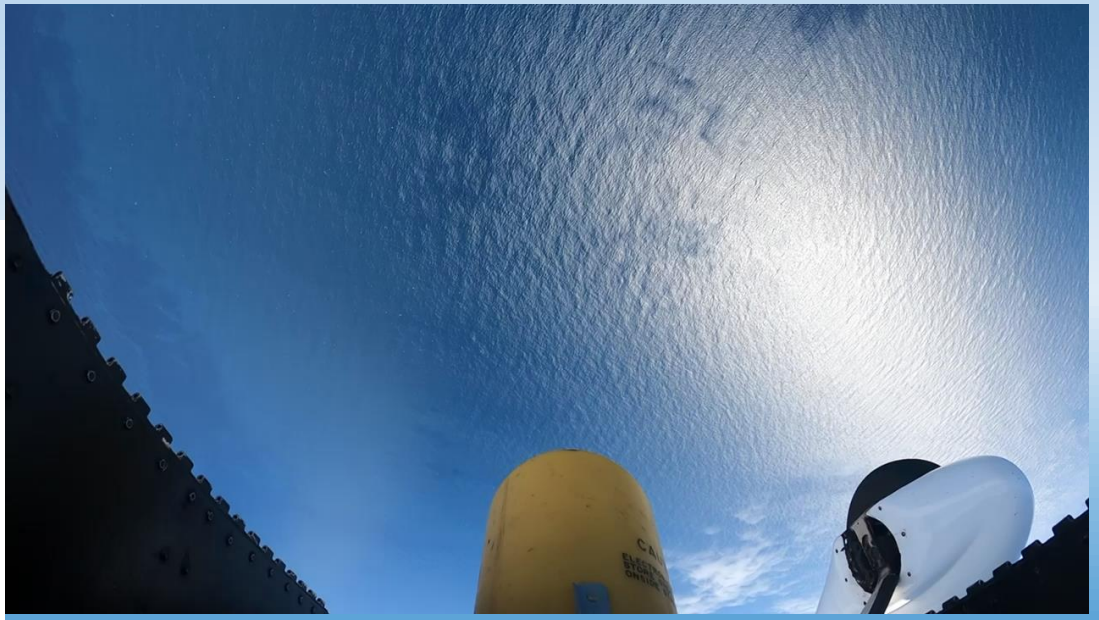
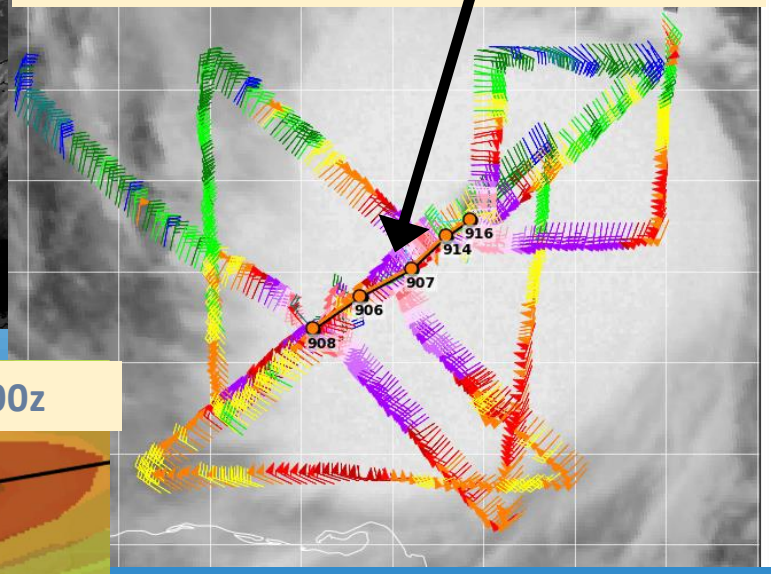
Hurricane Milton
GOES16; 8OCT2024; 0200Z



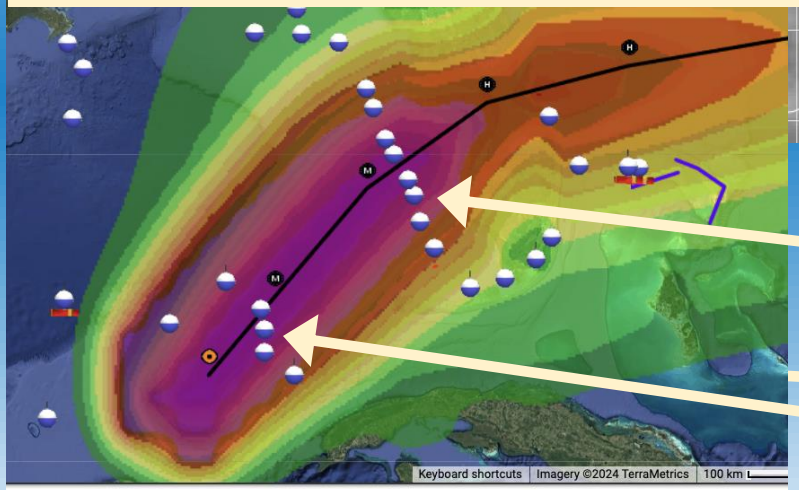
Deployment inside Milton



Drop by 53rd and NOAA 9OCT 0200z



ADWSD/ADWSBD Array 9OCT 0500z



Deployment two days ahead of storm

Deployment during RECON flights

- A-size Directional Wave Spectra Barometer Drifters (ADWSBD)
- Wave, SST, SLP
- 7 Atlantic Hurricanes since 2022
- 39 total deployed in 2024 by NOAA P-3, USAF 53rd and NRL VXS-1 aircraft
- 4 deployed within Milton (2024)

Example of Moored deployment, Validation Campaign, Napoli, Italy

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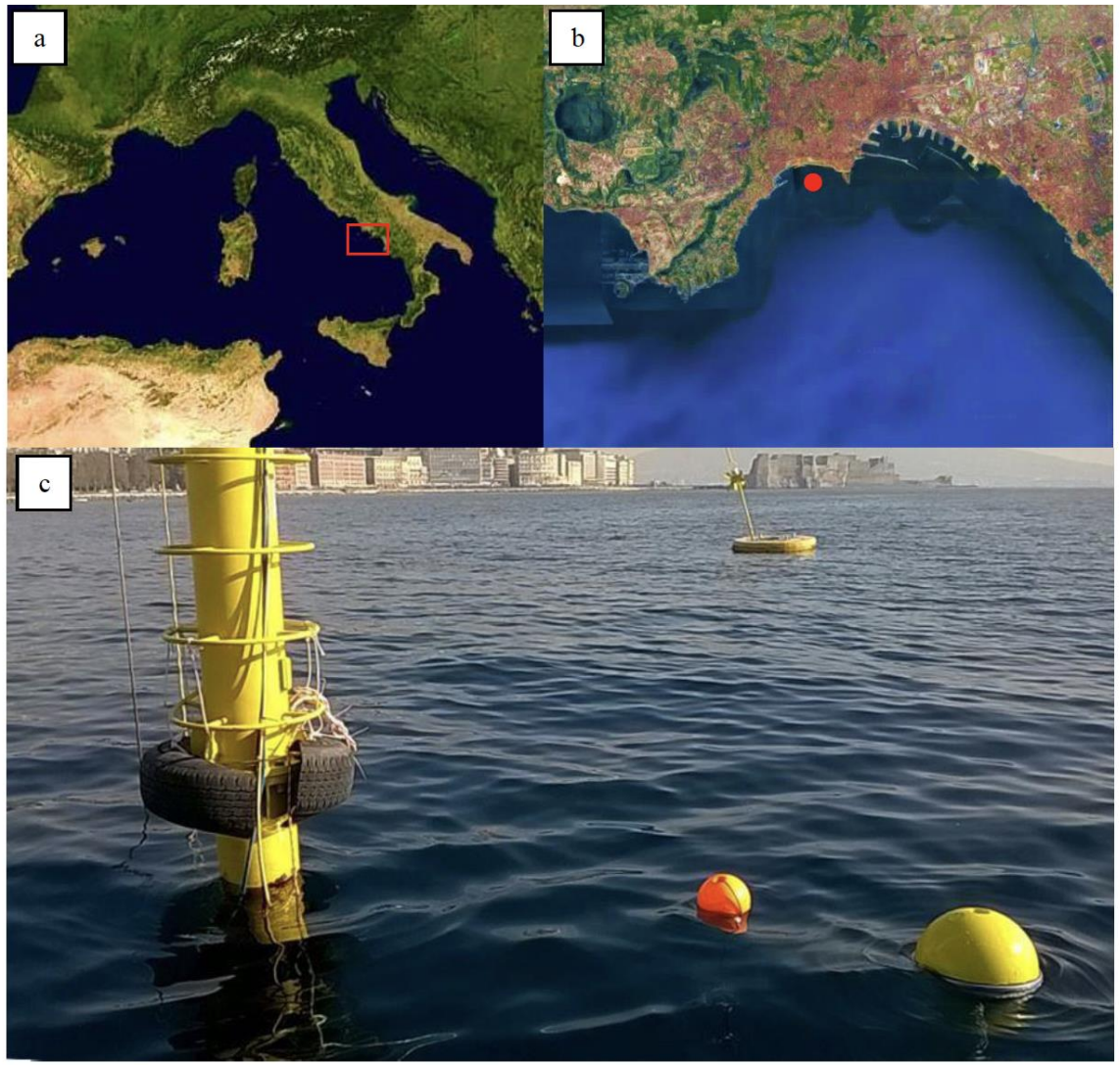

Figure 3. (a) Location of the field site of the test campaign at the Gulf of Naples (Italy) and (b) detail of the test site. (c) the DWSD is the yellow buoy located next to the measurement station where the ADCP was bottom-mounted.

Table 1: Deployment configuration setting of the ADCP

Water depth	17.7 m
Sampling interval	3600 s
ADCP altitude above bottom	0.5 m
Number of samples per burst (at 2 Hz)	2100
Size of the depth cell	0.5 m
Bins used for directional spectrum	1,13,27,28,29
Bins used for height spectrum	1,13,27,28,29
Maximum cutoff frequency	0.95 Hz
Minimum Included wave period	1.05 s
Frequency range	0 to 1.0 Hz

Table 2: Parameters used for the ADCP wave processing

Frequency bandwidth	0.0078 Hz
Maximum upper cutoff frequency	0.49 Hz
Minimum lower cutoff	0.11 Hz
Number of direction frequency bands	128 bands

Centurioni, L., L. Braasch, E. Di Lauro, P. Contestabile, F. De Leo, R. Casotti, L. Franco and D. Vicinanza (2017). "A new strategic wave measurement station off Naples port main breakwater." Coastal Engineering Proceedings **1**(35): 36.

Model Validation: 2022 Hurricane Season

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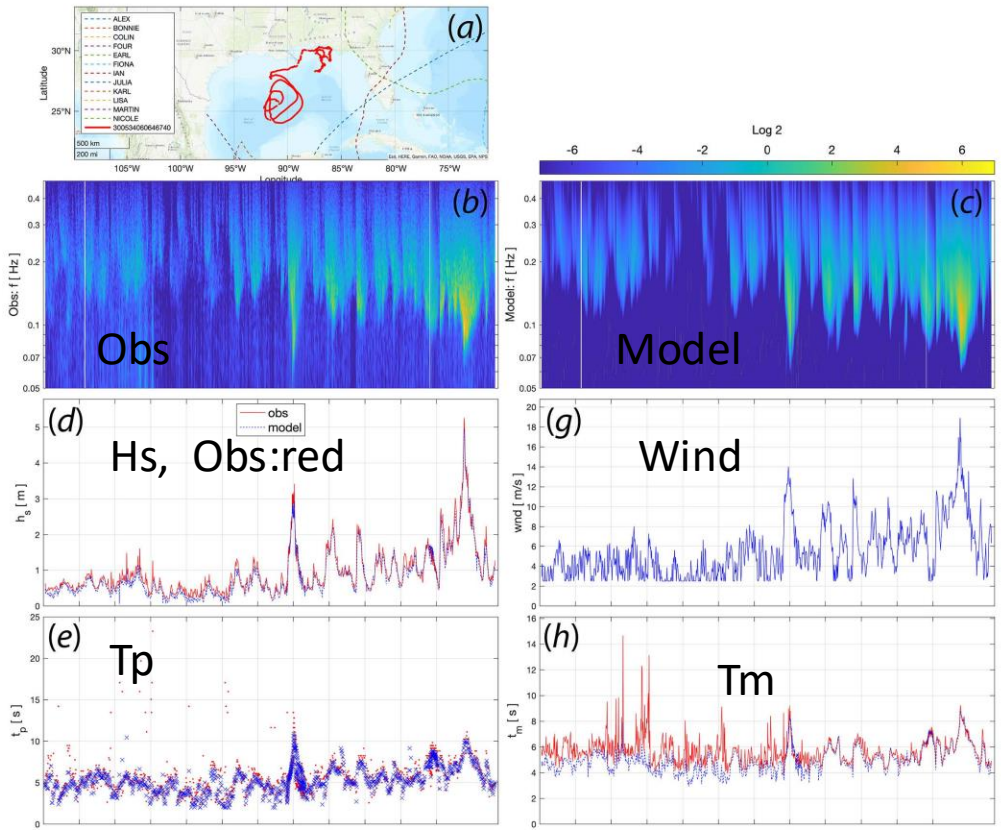
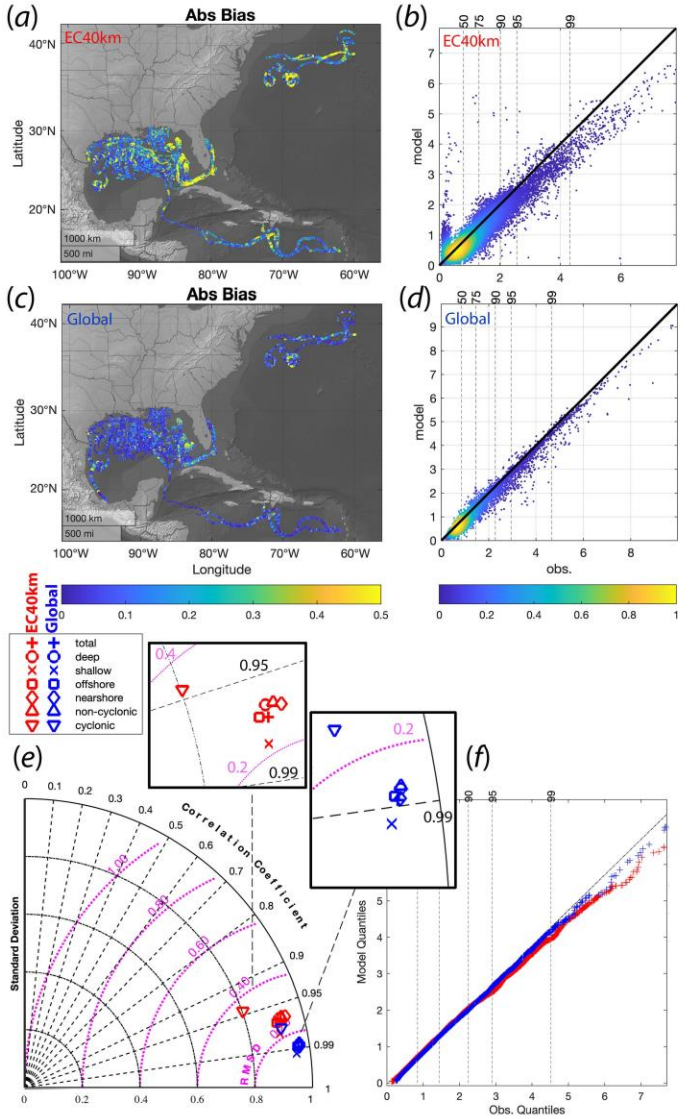


While data assimilation techniques are still being developed, wave data from drifters are instrumental for validating wave models and to show where biases occur

All data/model comparison Hs



Abdoali et al., 2025, *Advancing Multi-Scale Wave Modeling with WAVEWATCH III: Global and Coastal Applications During the 2022 Atlantic Hurricane Season*, Submitted to Coastal Engineering

WHAT IS MEASURED BY THE WAVE DRIFTERS

Measuring the Directional Spectra

The five coefficients, a_0, a_1, b_1, a_2 and b_2 obtained from the onboard FFT algorithm can be combined into a truncated Directional wave spectra in which the a_0 term provides the total wave energy and the other four terms provide the directional information. An example of a model for the directional function from Longuet-Higgins (1962) is:

$$F_1(\sigma, \phi) = \tfrac{1}{2}a_0 + (a_1 \cos\phi + b_1 \sin\phi) + (a_2 \cos 2\phi + b_2 \sin 2\phi),$$

Other more advanced methods (e.g. Maximum Entropy Method) to estimate *F* exist:

Further readings:

Longuet-Higgins, M. S. (1962), The Directional Spectrum of Ocean Waves, and Processes of Wave Generation, *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *265*(1322), 286-315.

BENOIT, M. (1997), Analysing multidirectional wave spectra: A tentative classification of available methods, paper presented at Proc. IAHR Seminar on Multidirectional Waves and Their Interaction with Structures, 27th IAHR Congress, National Res. Council of Canada.

Herbers, T. H. C., P. F. Jessen, T. T. Janssen, D. B. Colbert, and J. H. MacMahan (2012), Observing Ocean Surface Waves with GPS-Tracked Buoys, *J Atmos Ocean Tech*, *29*(7), 944-959, doi:10.1175/JTECH-D-11-00128.1.

Integral Wave Parameters from the DWS™ drifter

Zero Moment: $m_0 = \pi \Delta f \sum_{i=1}^{n} a_{0,i}$

First Moment: $m_1 = \pi \Delta f \sum_{i=1}^{n} f_i \cdot a_{0,i}$

Second Moment: $m_2 = \pi \Delta f \sum_{i=1}^{n} f_i^2 \cdot a_{0,i}$

- Significant Wave Height (**3 waves of amplitude 2*Hmo can be expected every hour**)

$$H_{mo} = 4\sqrt{m_0}$$

- Average Period

$$T_{av} = \frac{m_0}{m_1}$$

- Peak Period (estimated at max a_0)

$$T_p = \frac{1}{f_{peak}}$$

Mean wave direction

$$\theta_1 = \arctan\left(\frac{b_1}{a_1}\right)$$

Principal wave direction

$$\theta_2 = \frac{1}{2}\arctan\left(\frac{b_2}{a_2}\right)$$

Examples of DWSD observations using the LDL Viewer

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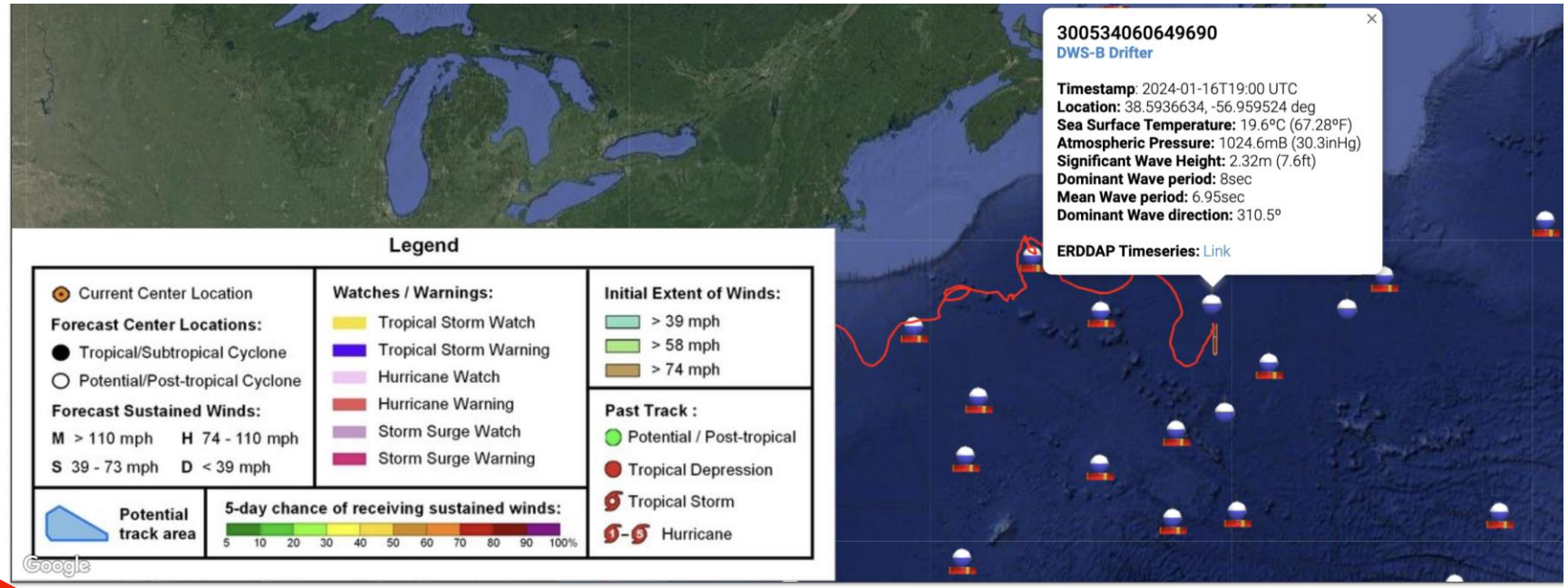
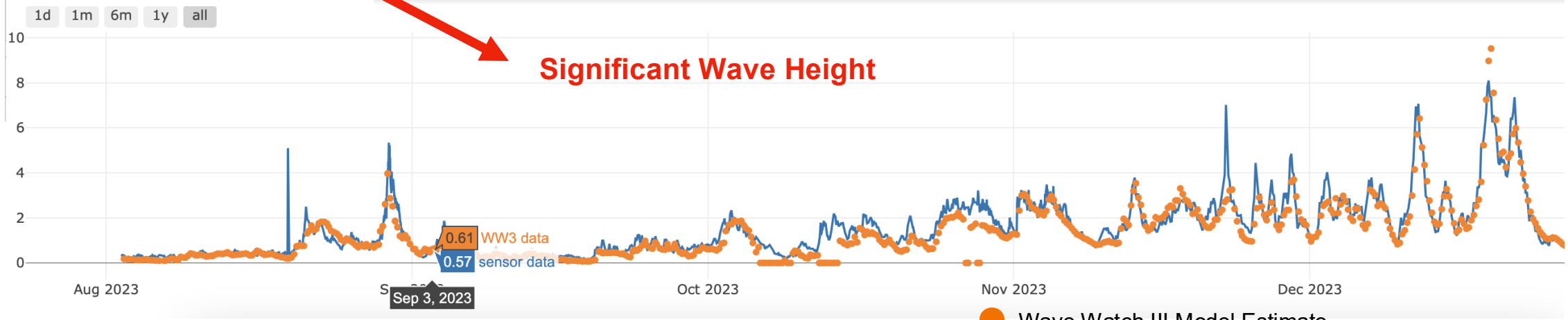
Graph ▾ | Table ▾ | Tools ▾

Met Sensors
- SST
- Air Pressure

Waves
- Energy Spectra [Bar]
- Wave Energy Spectra
- Significant Height
- Dominant Period
- Avgerage Period
- Dominant Direction

Diagnostic
- Battery
- Drogue
- SBD Xmit Time
- SBD Retries
- GPS TTFF
- Hull Humidity
- Hull Pressure
- Hull Temperature





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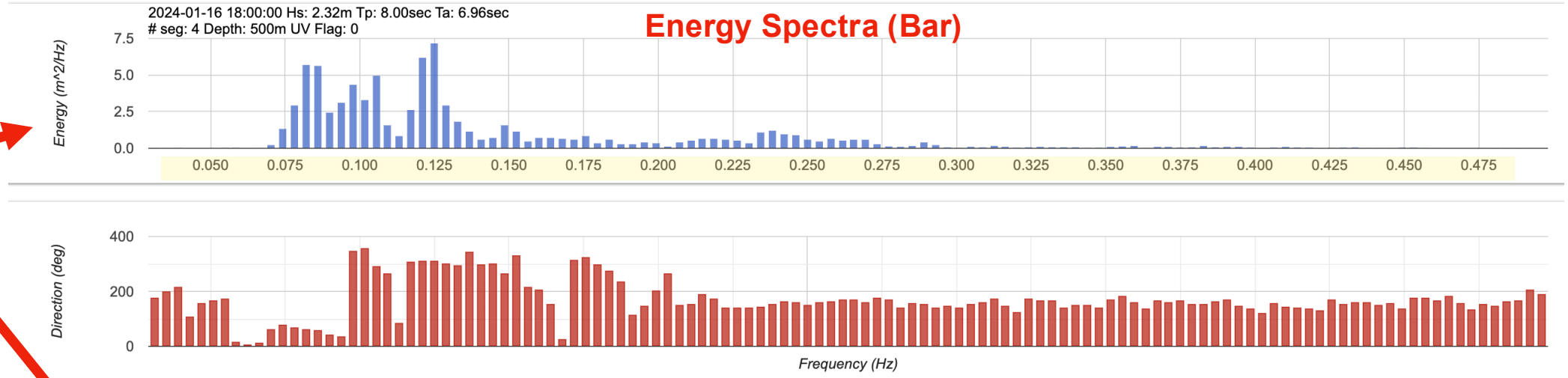
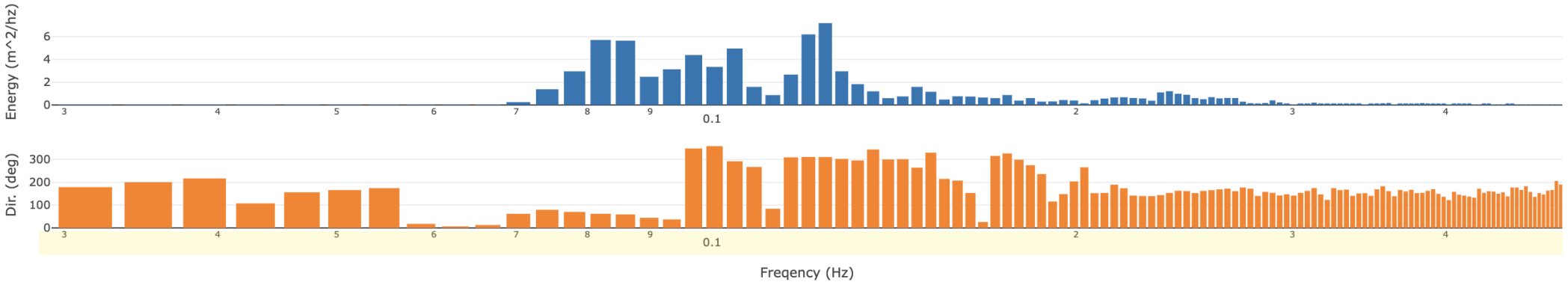
Energy Spectra (Bar)



Wave Energy Spectra (Uses Log10 scale)



Examples of DWSD observations using the LDL Viewer

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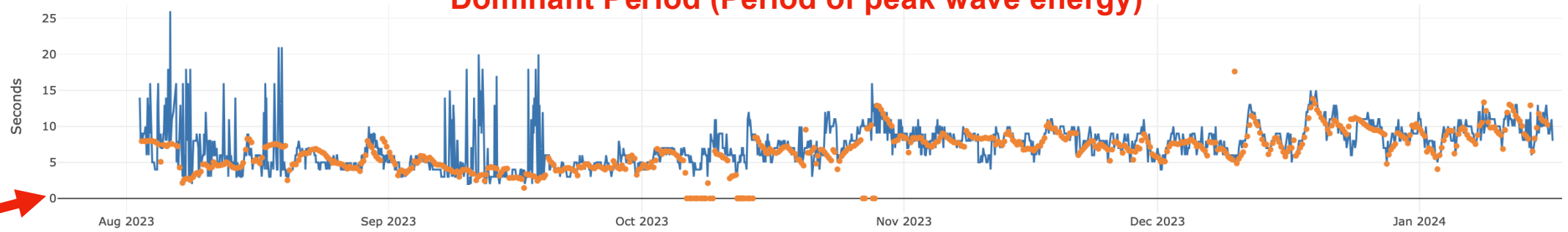
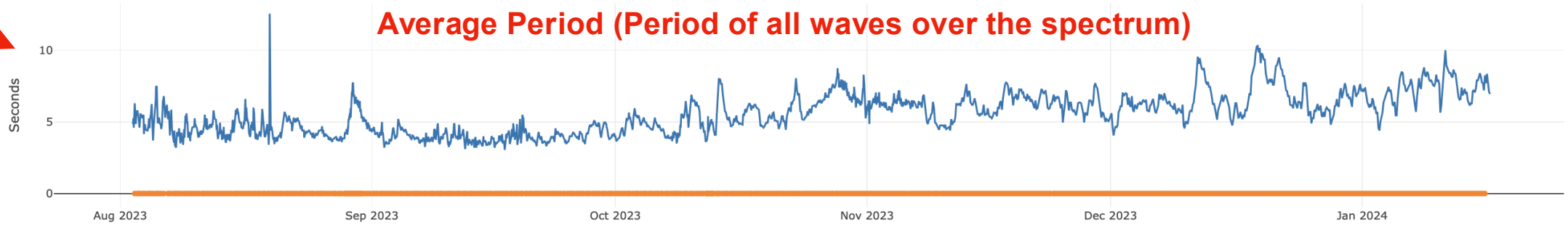
- Hull Temperature

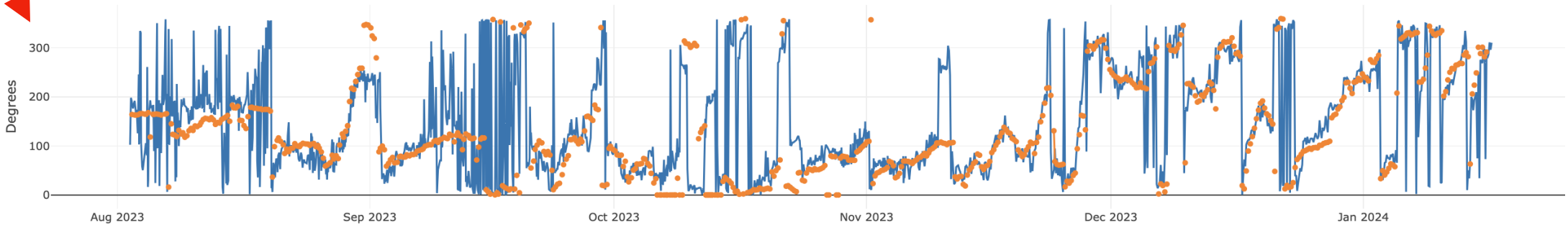
Dominant Period (Period of peak wave energy)



Average Period (Period of all waves over the spectrum)



Dominant Direction (Direction of peak wave energy - Clockwise from North, Waves coming from)



HOW ARE THE OBSERVATIONS QUALITY CONTROLLED

Quality Control

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Quality Control of wave's spectral observations requires special attention because waves conditions can evolve quickly. Our QC procedure of spectral wave data is L2, and, for the most part, we let the user decide which data should be be discarded. Curated datasets, however, also exist

Example of H_{mo} time series with gross errors

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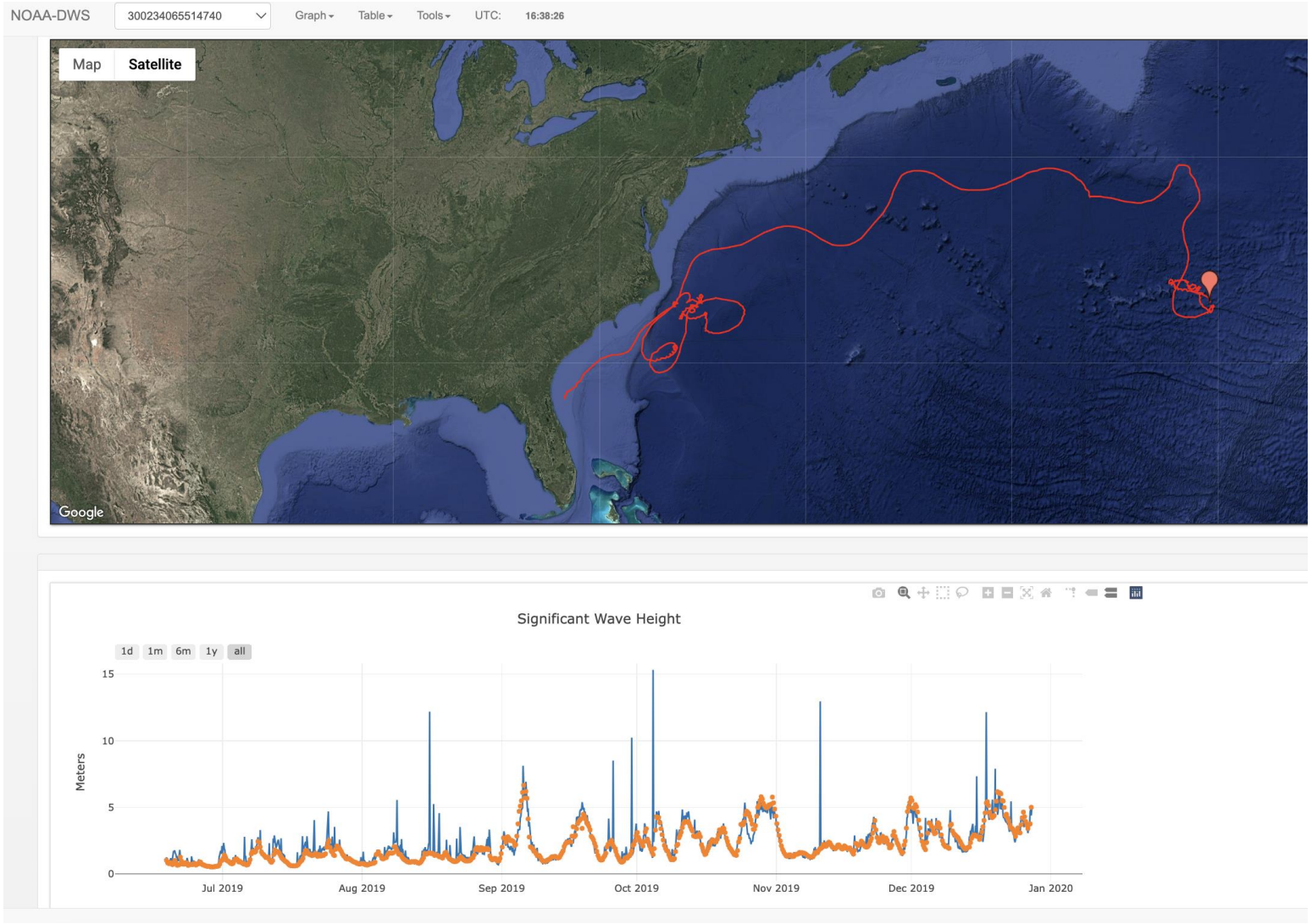

Blue: DWS
Orange: WW3 model

Example of H_{mo} time series with more subtle errors

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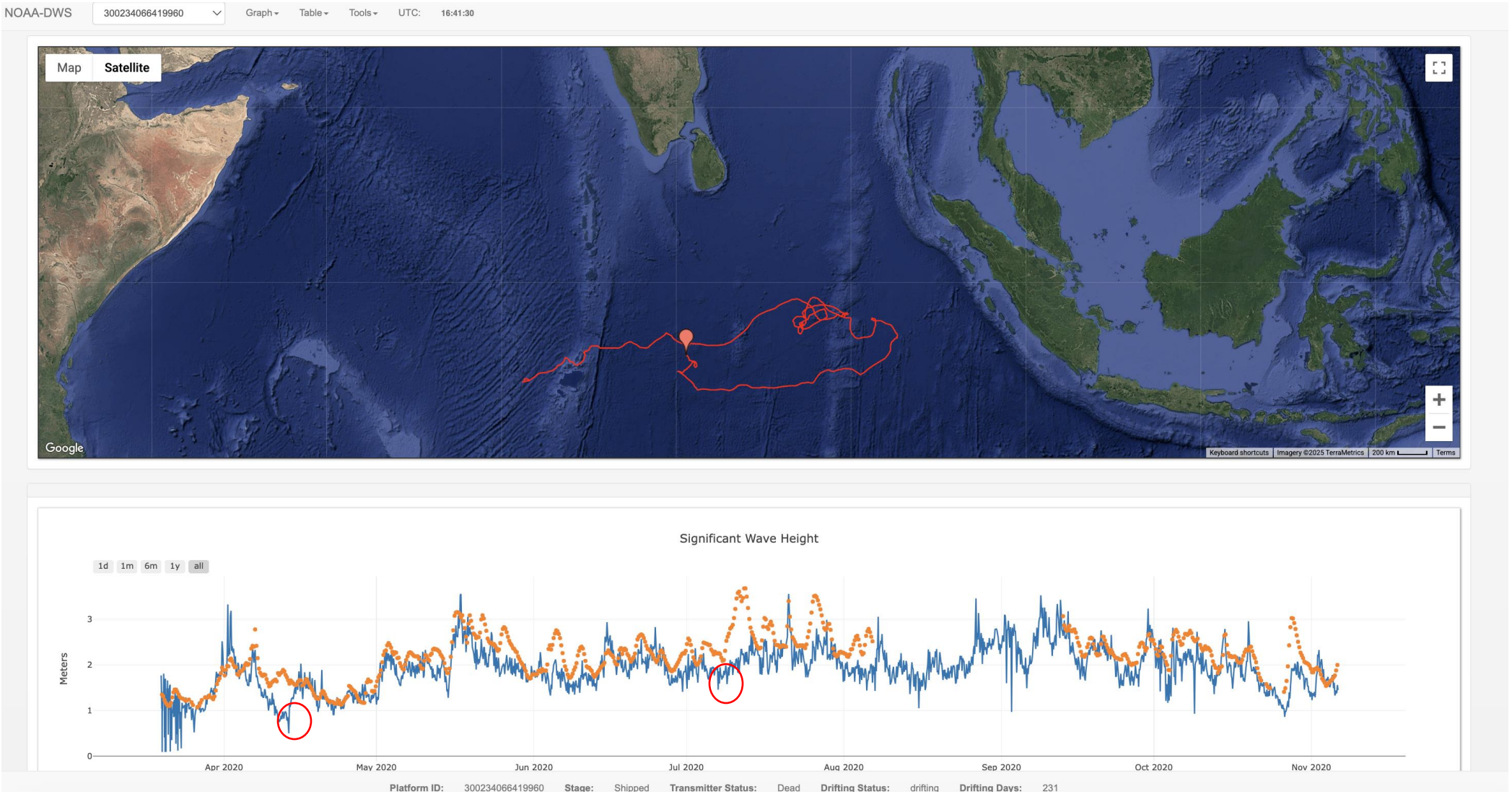

Blue: DWS
Orange: WW3 model

Levels of data for the DWS™ drifter family

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The four levels of data are:

1. **Level 1 (L1)**: Raw data that is acquired by the instrument. This would be the actual time series of the drifters' moments, providing a time series of u, v, and w. This is **available for moored buoys** as it can be stored locally, **but unavailable for drifting buoys** that telemeter the data as the battery and iridium costs would be prohibitive (or the instrument would be exceptionally short-lived.)
2. **Level 2 (L2)**: Observations that are delivered via Iridium. This provides **calculated bulk wave statistics and the wave spectral energy and directional moments**. The **resolution and degrees of freedom (ie., spectral certainty) will depend on the length of time series**, and segmenting of the raw-GPS time series (ie., FFT size). There is **no QC performed** on data, but an **advised QC flag is made available**. L2 data has **8 DOF for 120 spectral bins**, and **16 DOF for 60 spectral bins**.
3. **Level 3 (L3)**: Observations with **quality flag applied**, and **additional processing** to provide directional spectra with **higher degrees of freedom**. This could be 24-, 32- or 48- DOF depending on the originally sampled data. This is achieved by **averaging over adjacent spectral bins**.
4. **Level 4 (L4)**: These include **L3 observations with additional parameters such as Stokes Drift**, wave-slope and partitioning of swell and wind-sea components

DWSD observations: integral parameter

3.1 Sensor Data and Bulk Wave Parameters

- **latitude**: Latitude of SST / SLP and bulk wave parameters (if wave measurement occurred)
- **longitude**: Longitude of SST/ SLP and bulk wave parameters (if wave measurement occurred)
- **time**: Time of observations
- **significant_wave_height**

$$Hs = 4 * \sqrt{m_0}; \tag{1}$$

where

$$m_n = \int_0^\infty f^n E(f) df. \tag{2}$$

Here, we integrate them as:

$$m_0 = \sum_{f=0.035}^{0.5} a_0(f) * \Delta f. \tag{3}$$

- **peak_period:** defined as the wave period at the variance spectra energy maximum
- **average_period:** Wave period corresponding to the mean frequency of the spectral range: $T_{m01} = m_0/m_1$
- **dominant_wave_direction:** direction of waves at the spectral energy maximum
- **wave_quality_flag**: Range is from 0 (no flags) to 12 (all flags), based on the quality criteria described below. The QC flag for the individual criteria are in the quality_flag in the First-Five file. If the First-Five are not reported, the wave_quality_flag will be -999 (missing).

Data that are sent back: spectral

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3.2 First-Five Data

First 5 wave data have the following variables:

- **latitude**: Latitude of wave observations
- **longitude**: Longitude of wave observations
- **time**: Time of wave observations
- **Frequency:** spectral frequency
- a_0: wave variance spectral energy
- a_1: first-directional coefficient
- b_1: first-directional coefficient
- a_2: second directional coefficient
- b_2: second directional coefficient
- **wave_quality_flag**: 12 column flag for variables listed in quality_flag_criteria
- **quality_flag_criteria** Description of quality flag - full explanation below.

This is the heaviest file to send back, which ramps up telemetry costs and reduces the endurance of the instrument

Quality control criteria- 1

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4.1 QC flags based on PDFs from a dataset:

Data is flagged if value is outside of 4 standard deviations from the mean. (local mean)

- **Hs**: The significant wave height.
- **Ta**: Average period
- **Hs spikes**: The significant wave height minus a 3-point median filter of significant wave height
- **a0 (wave energy)** first three values: a0(1), a0(2), and a0(3): The GPS-style wave buoys can have spurious low frequency noise. A large value of a0 in the first few frequency bins can cause unrealistic wave energy. Flagging these values helps identify these locations
- **Gradient between the first a0 values**: Similar to to the values themselves, strong gradients in the first three values may indicate low-frequency noise contamination
  - $grad\_a0(1) = (a0(1) - a0(2))/df$;
  - $grad\_a0(2) = (a0(2) - a0(3)0/df$;
  - $grad\_a0(3) = (a0(3) - a0(4))/df$;

Quality control criteria- 1I

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4.2 QC flags based on data reporting and continuity

- **Missing data**: Flagged if the raw time series reports less than 95% of data. Missing data lead to gaps in the time series of drifter motion. Depending on the number of missing data points, these discontinuities can create problems in wave energy, such as leading to data spikes or drop outs. Inspection of the spectra directly and surrounding values can allow the user to see if it varied significantly from previous or following data. Data dropouts can be caused by the drifter being underwater or from issues with the GPS. We have found that these can vary geographically and depend on sea-state. The decision to use this data should be carefully considered.
- **Spectral Continuity:** Following NDBC temporal continuity of spectral values: 'NDBC data QC'. **NOTE:** It is not applicable under tropical cyclones. It is, however, useful to pick up tropical cyclones from an array of buoys. The dramatic change in sea state always sets it off!
- **Number of segments:** The drifters are shipped in low-power mode. At times the re-programming is delayed when drifter deployment is unknown or a reprogramming message was sent but the drifter did not receive it. Wave observations in low-power mode have less than 8-degrees of freedom with high uncertainty and should be discarded. This is the only "hard flag".

Definition of Spectral Continuity: the change of the Spectral Wave Densities for frequency bands above 0.08 Hz is not more than $0.006f^{-4}$ m2/Hz in one hour.

Applying QC to DWSD measurements

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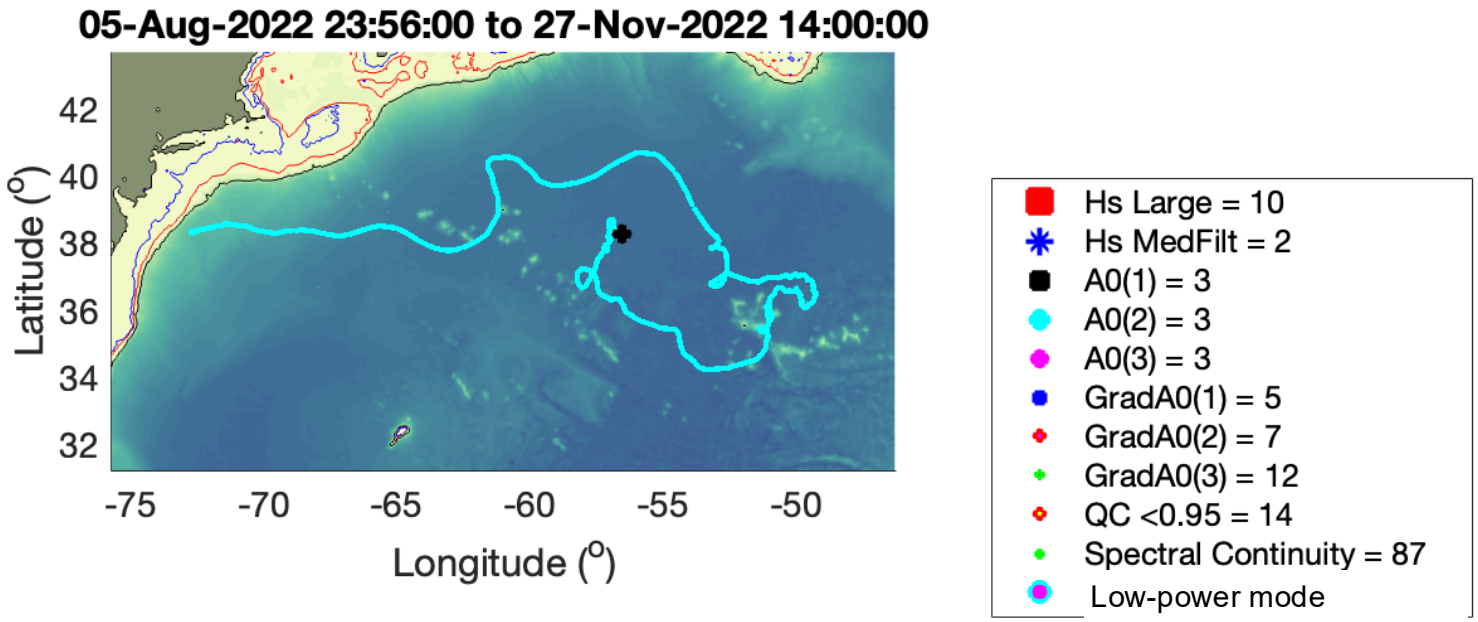
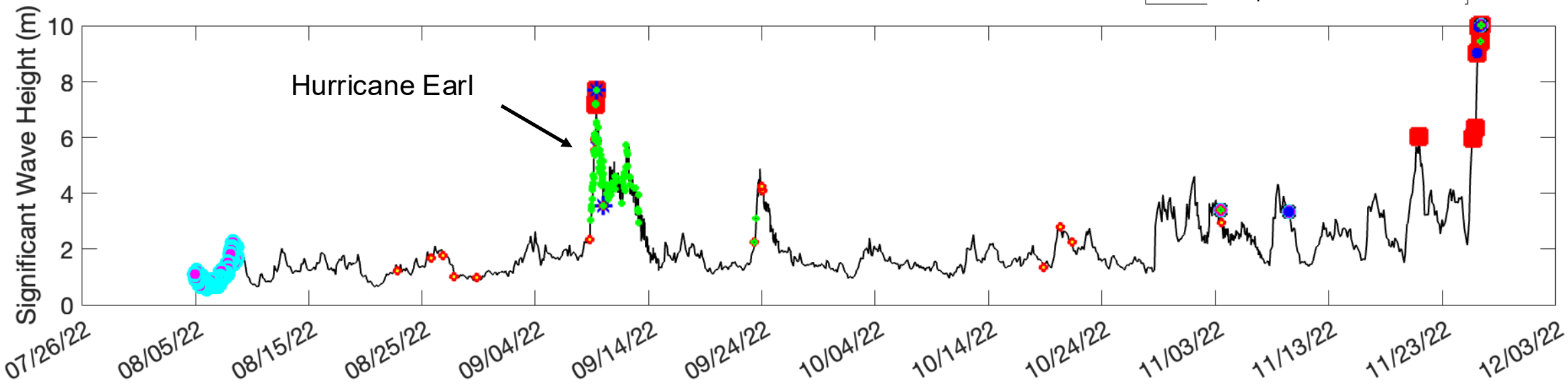
- Flagging high values of standard deviation: Hs, Ta
- Spurious low-frequency noise: anomalous first values of a0
- Spectral continuity (can use to pick out Hurricanes)
- QC flag is now being offered for the ERDDAP server data



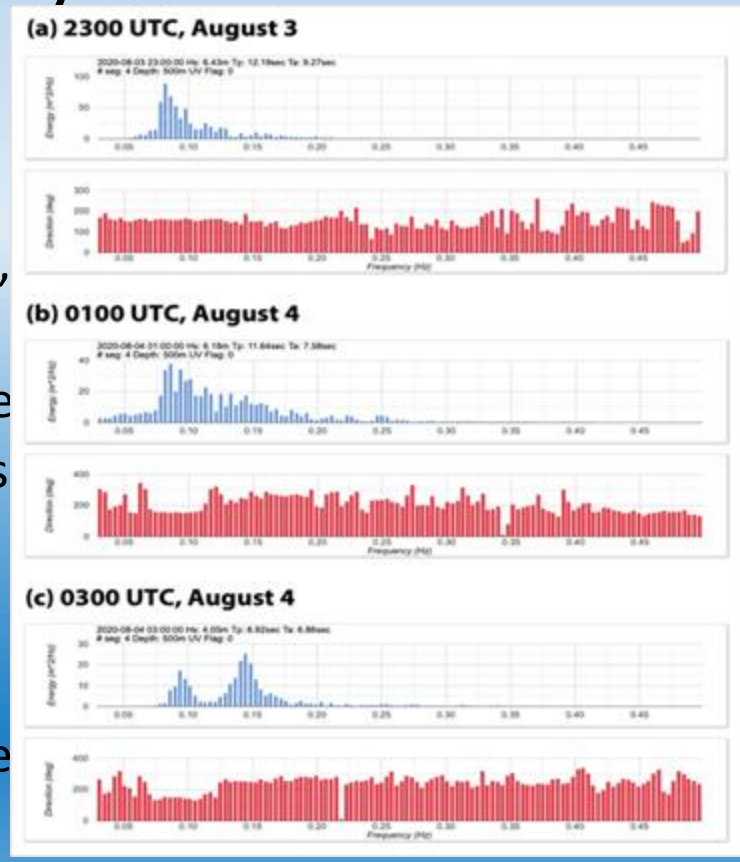


Sustained, open access wave observations for science and society

Air deployment of GDP's DWSD in the North Atlantic by the 53rd WRS "Hurricane Hunters." Photo Credit: 53rd WRS

- The open access GDP wave drifter array is already benefiting citizens and scientists. Sustaining this global, open access wave sensing array provides an observing baseline to be used by ocean and climate scientists

- To date, data from the East Coast array have been used to evaluate hurricane tracks and wave and surge models. We envision that in the future, data will aid in the design of offshore structures such as oil rigs, wave and wind energy farms, and ships.



Transition of swell and locally generated wind waves under different parts of Hurricane Isaias.

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Suggested References

General:

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Thank You For Your Attention
Questions?

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