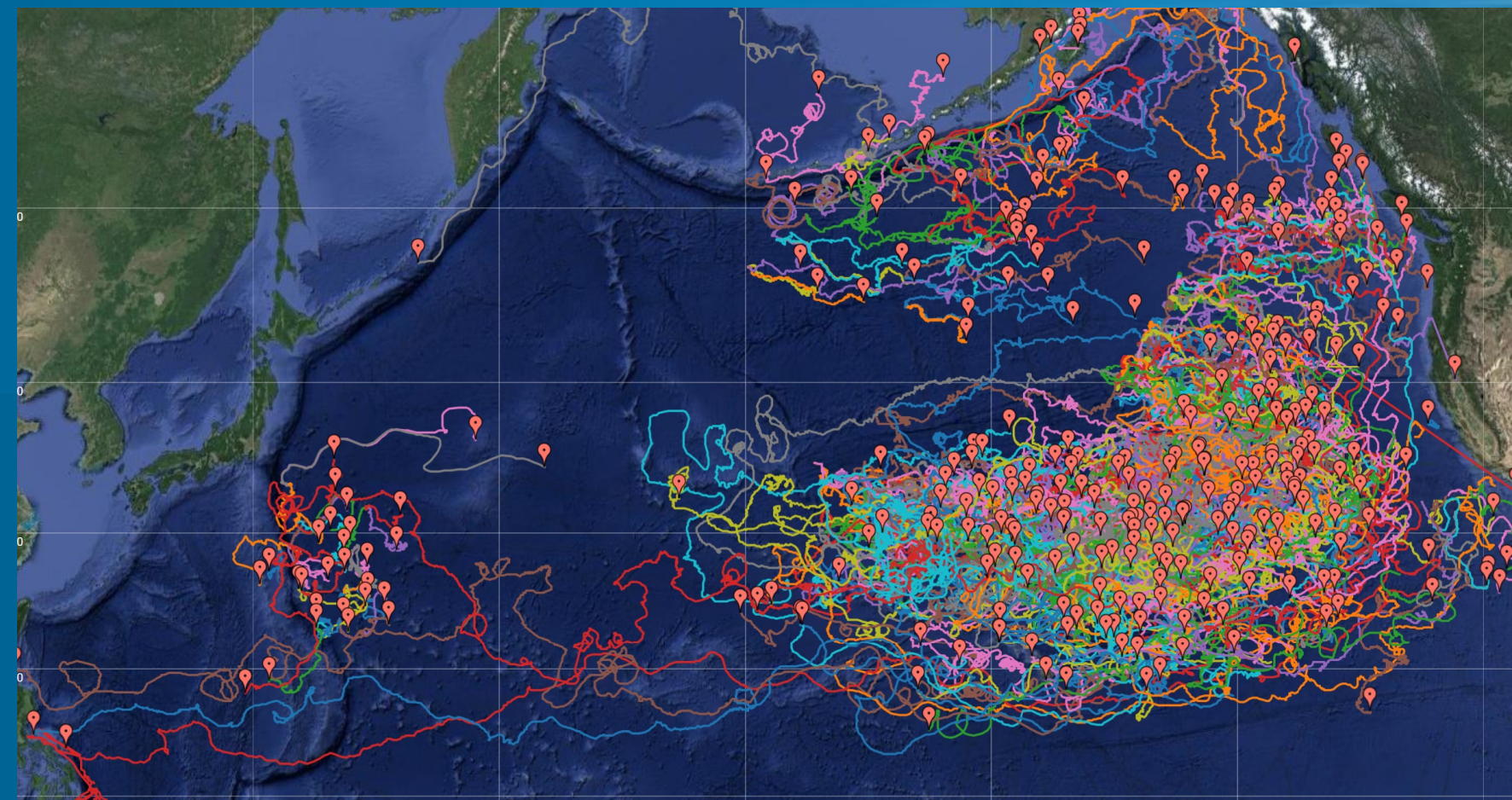
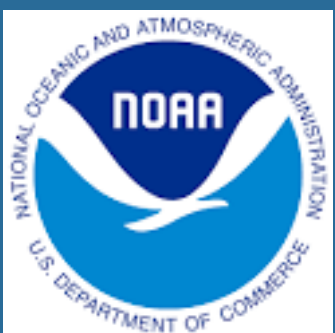


# Targeted observations of Atmospheric Rivers with Surface Drifters

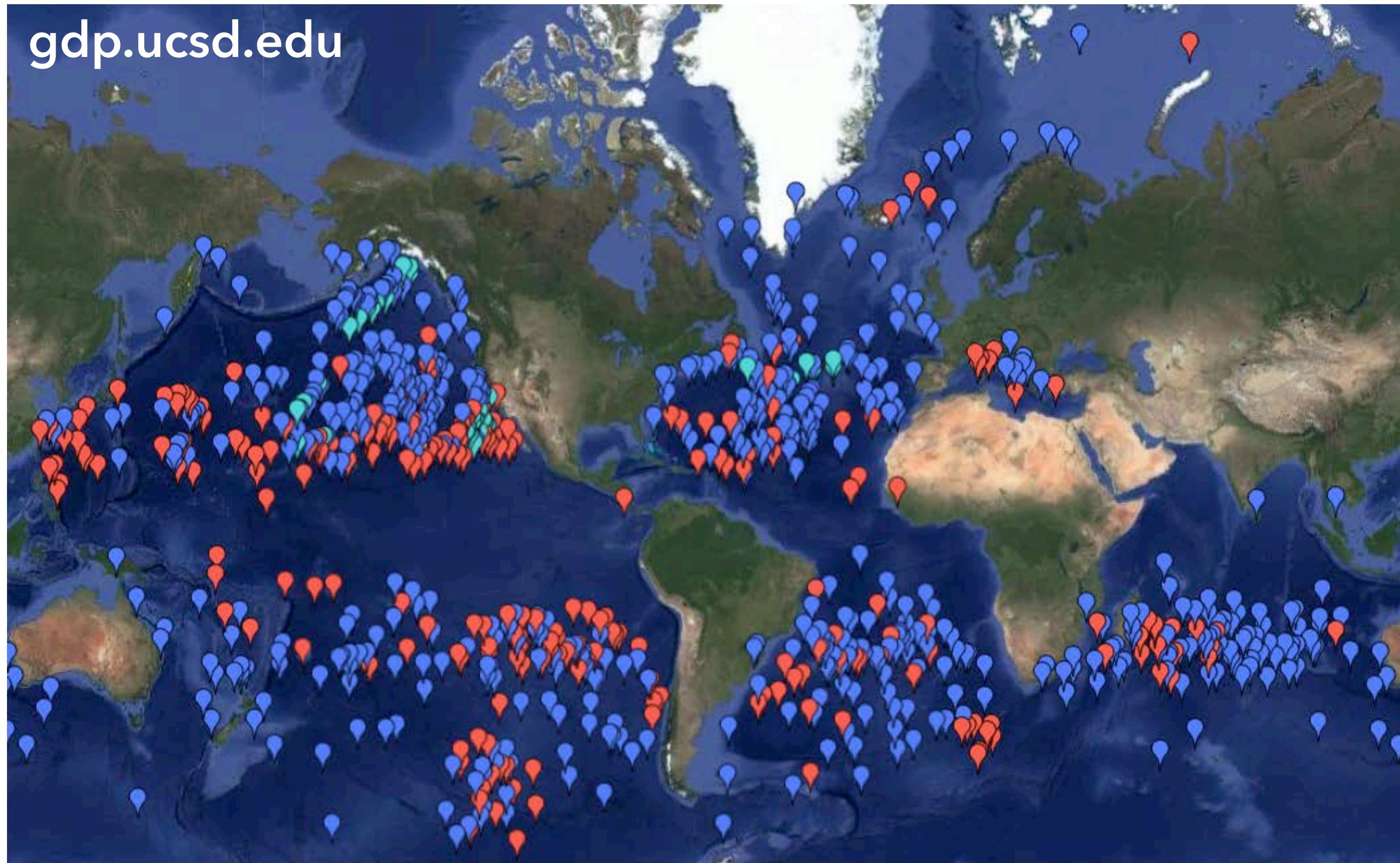


Luca Centurioni, Martha Schönau,  
Terri Paluszkiwicz

Lagrangian Drifter Laboratory,  
Scripps Institution of Oceanography



## Global Drifter Program at the Lagrangian Drifter Laboratory

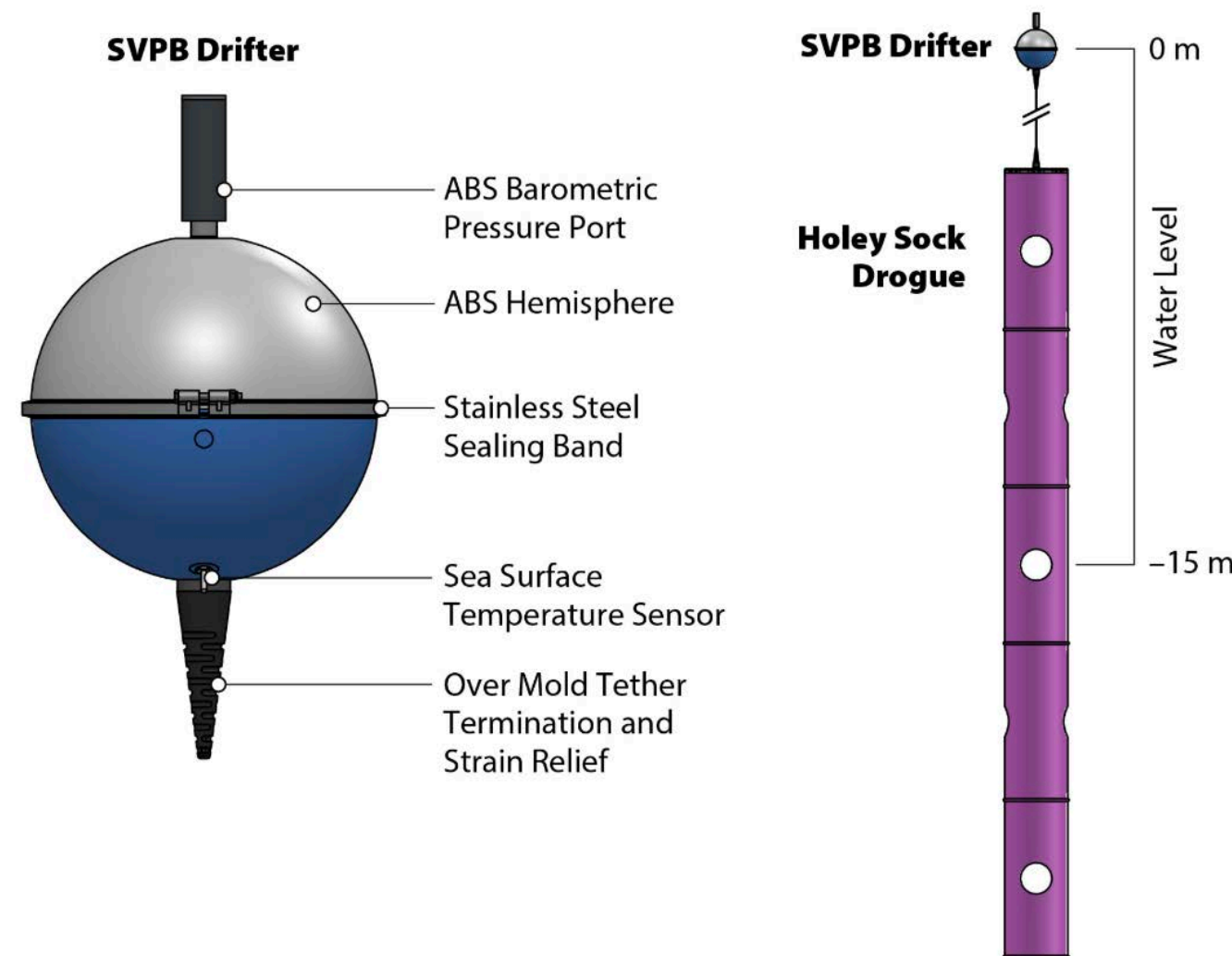


- Understand **ocean-atmosphere interaction** using a suite of surface observations
- Improve **weather forecast** by making data publicly available in near-real time
- Target extreme weather events: **Atmospheric Rivers, Tropical Cyclones, Monsoon Onset**

# Drifter Types: SVPB and DWSBD

## Surface Velocity Program (SVPB) Drifter

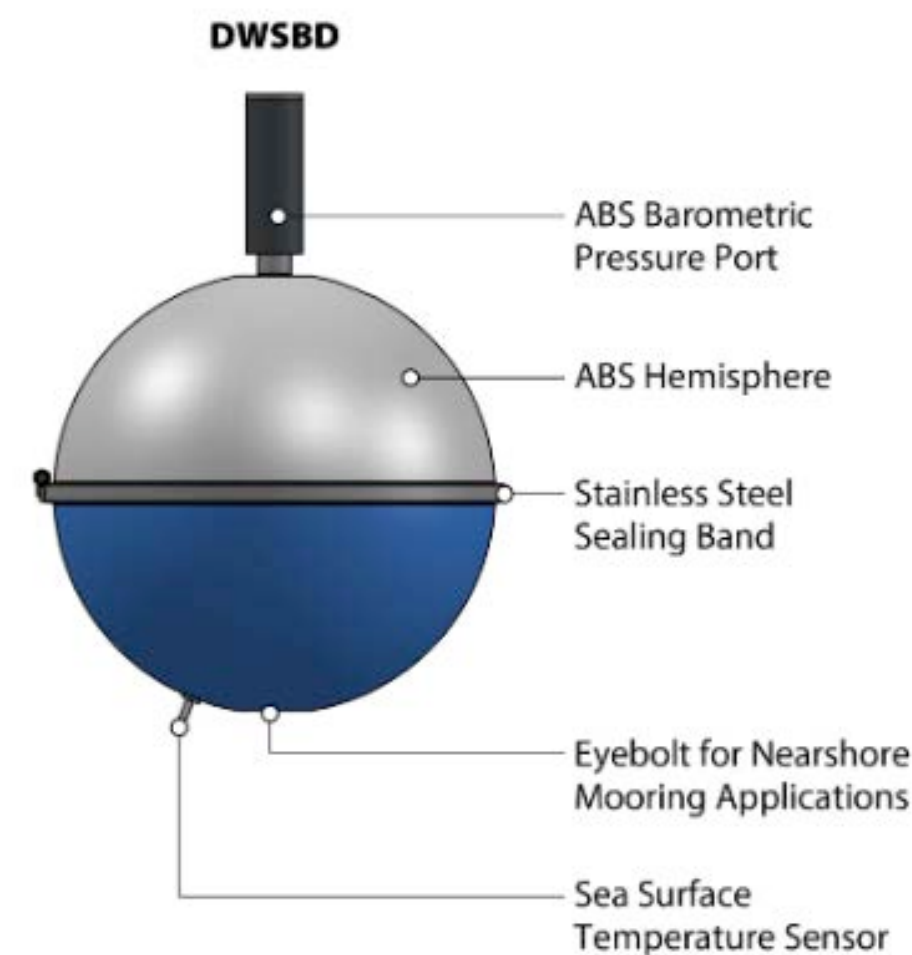
- Sea-Surface Temperature (SST) sea-level pressure (SLP) and currents
- **Drogued:** Measures ocean currents ~15 m



## Directional Wave Spectra Barometer Drifter (DWSBD)<sup>TM</sup>



- Measures wave energy and direction using GPS technology, delivering "First-Five"
- Measures SST, SLP
- **Undrogued:** Follows surface



## A-Size DWSBD! \*\*



- Equipped with 2-way Iridium satellite communications

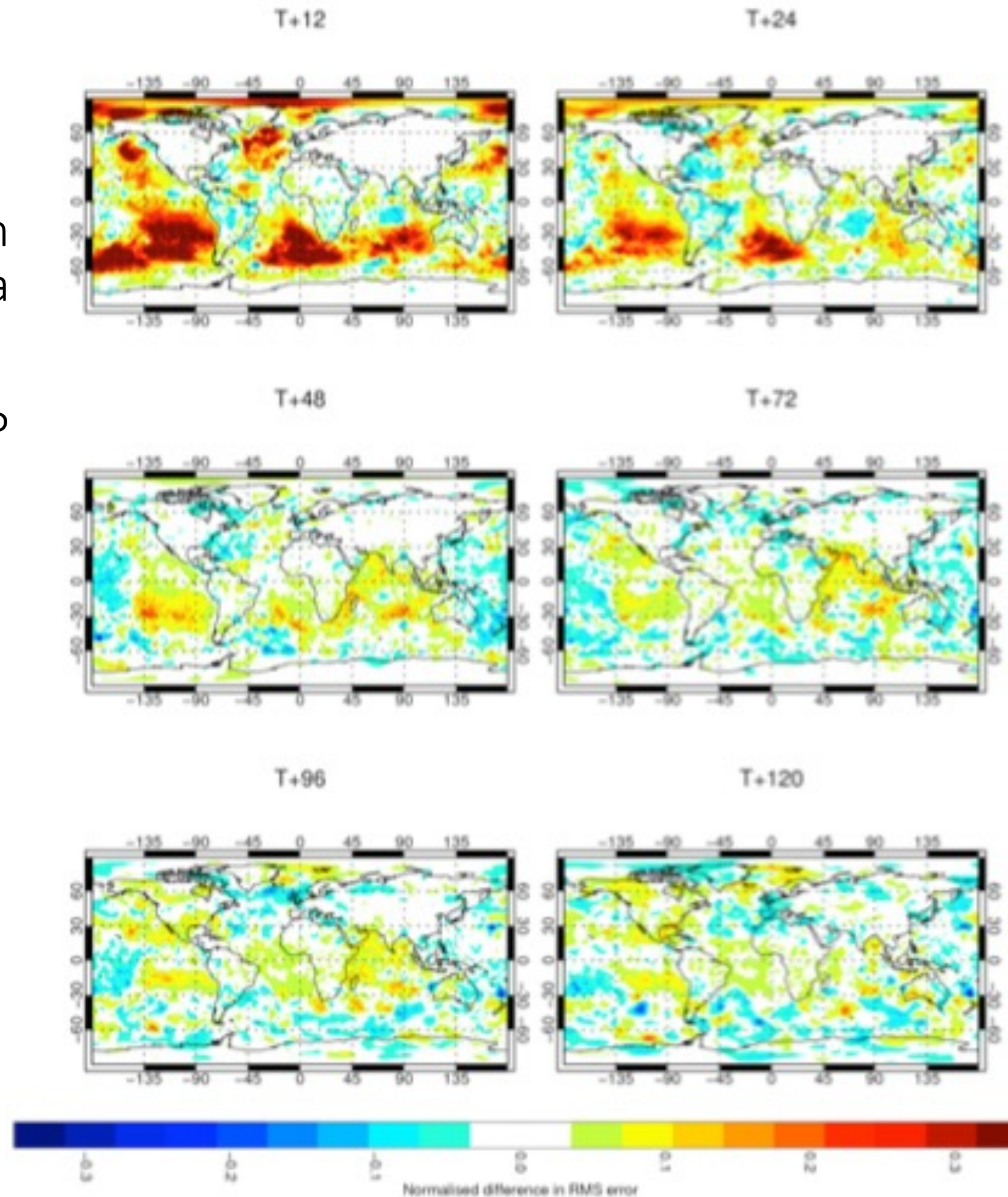
# Motivation for the CW3E/LDL Partnership

## DRIFTER SLP DATA OVER THE OCEAN: AN NWP DATA DENIAL STUDY

- Have largest positive impact per observation on NWP (from ECMWF data denial study using a dry energy norm metric)
- The beneficial impact of drifter's SLP (computed as rmse)
  - ✓ occurs for several variables other than SLP
  - ✓ Extends up to 5 days
  - ✓ propagates high in the troposphere

## DRIFTERS' SLP DATA ARE USEFUL ALSO FOR:

- Used for altimetry correction
- Used for climate indices
- Fill sparse region (e.g., Southern Ocean)



Normalized differences of mean sea level pressure root-mean-squared errors between the control and denial experiment. Red (blue) colours indicate degradations (improvements) in the denial experiment. Forecast ranges: 12h, 24h, 48h, 72h, 96h and 120h.

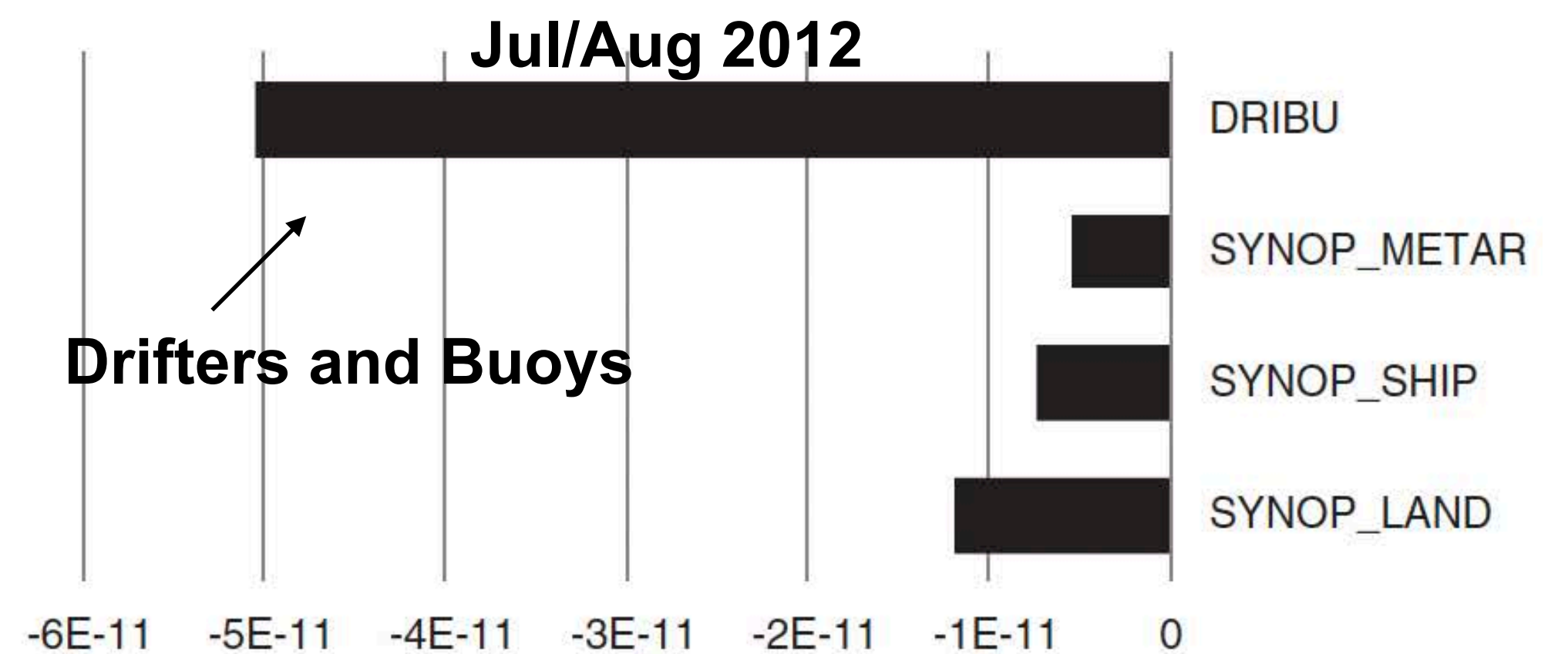
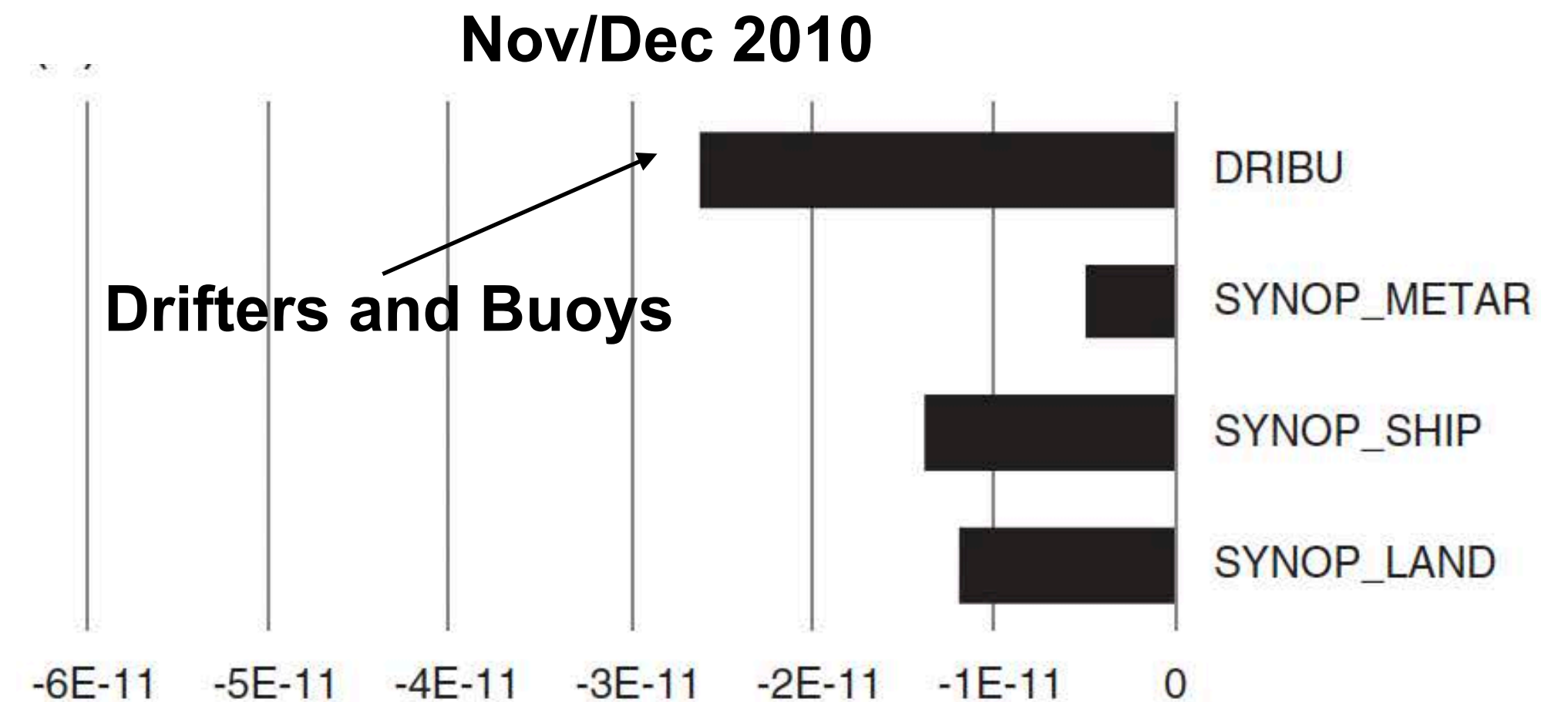
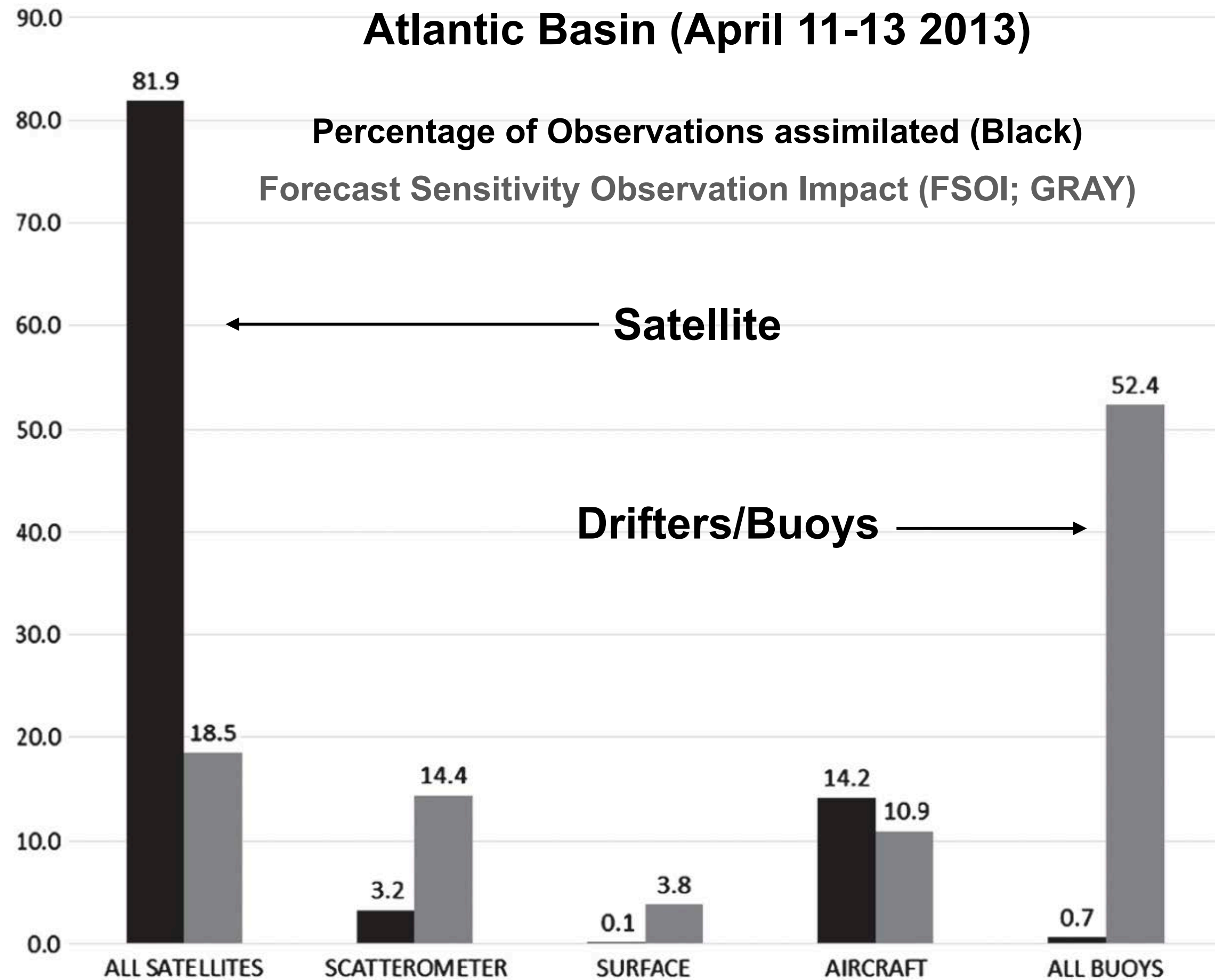
## IMPACTS

The barometer drifter array has several large impacts, and it is implemented by the GDP in collaboration with major international weather services.

Horányi, A., C. Cardinali, and L. Centurioni (2017), The global numerical weather prediction impact of mean-sea-level pressure observations from drifting buoys, *Quarterly Journal of the Royal Meteorological Society*, 143(703), 974–985, <https://doi.org/10.1002/qj.2981>.

Centurioni, L., A. Horányi, C. Cardinali, E. Charpentier, and R. Lumpkin (2017), A global ocean observing system for measuring sea level atmospheric pressure: Effects and impacts on numerical weather prediction, *Bulletin of the American Meteorological Society*, 98(2), 231–238, <https://doi.org/10.1175/BAMS-D-15-00080.1>.

# Horányi et al. 2017: Impact of Drifter Observations



ECMWF operational Forecast Sensitivity Observation Influence (FSOI; in  $J\ kg^{-1}$ ) per measurement of different surface observing systems measuring surface pressure

“The lack of drifter surface pressure observations has a large and significant detrimental impact on the mean-sea-level pressure, temperature and wind fields. **The signal is detectable not only near to the surface but throughout the troposphere up to 250 hPa.**” Horányi et al. 2017

# Impact of Drifters: Improvements to 5 days

## ATMOSPHERIC RIVER RECON: IMPACT OF DRIFTER SEA LEVEL ATMOSPHERIC PRESSURE ON FORECAST SKILL

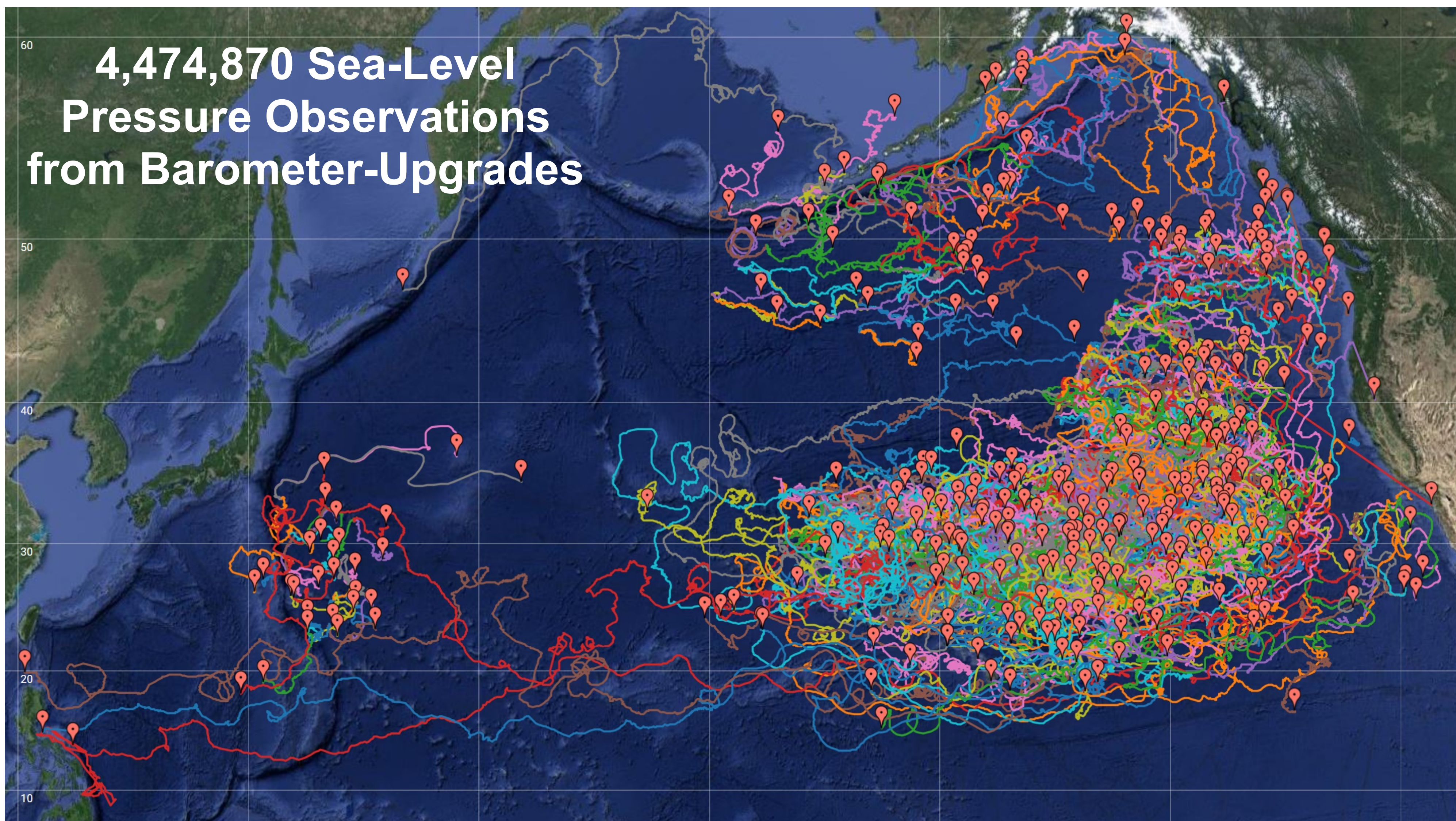
Reference	Level	Metric	Variable	Level type	Region	0	24	48	72	96	120
ECMWF Analysis	200.0	RMS Error	Geopotential Height	pressure	North America	☹️	☹️	☹️	☹️	😊	☹️
ECMWF Analysis	200.0	RMS Error	Geopotential Height	pressure	Northern Hemisphere	☹️	☹️	☹️	😊	😊	☹️
ECMWF Analysis	200.0	Vector RMS Error	Wind	pressure	Northern Hemisphere	☹️	☹️	☹️	☹️	☹️	☹️
ECMWF Analysis	500.0	Anomaly Correlation	Geopotential Height	pressure	North America	☹️	☹️	☹️	😊	😊	😊
ECMWF Analysis	500.0	Anomaly Correlation	Geopotential Height	pressure	Northern Hemisphere	☹️	☹️	☹️	😊	😊	☹️
ECMWF Analysis	500.0	Vector RMS Error	Wind	pressure	Northern Hemisphere	☹️	☹️	😊	😊	😊	☹️
ECMWF Analysis	850.0	Vector RMS Error	Wind	pressure	Northern Hemisphere	☹️	☹️	☹️	😊	😊	☹️
ECMWF Analysis	1000.0	Anomaly Correlation	Geopotential Height	pressure	North America	☹️	😊	☹️	😊	😊	😊
ECMWF Analysis	1000.0	Anomaly Correlation	Geopotential Height	pressure	Northern Hemisphere	😊	☹️	☹️	☹️	😊	☹️

Standard scorecard metrics for North America and Northern Hemisphere NAVGEM forecasts as a function of forecast hour as verified against ECMWF analyses. Green colors indicate improvements in the metric with the assimilation of the AR-Recon drifter surface pressure observations that are statistically significant at the 95% level. Pink colors indicate degradations at the 95% level.

Reynolds, C.A., R.E. Stone, J.D. Doyle, N.L. Baker, A.M. Wilson, F.M. Ralph, D.A. Lavers, A.C. Subramanian, and L. Centurioni (2023), Impacts of northeastern Pacific buoy surface pressure observations, *Monthly Weather Review*, 151(1), 211–226, <https://doi.org/10.1175/MWR-D-22-0124.1>.

Ralph, F.M., et al. (2020), West Coast forecast challenges and development of atmospheric river reconnaissance, *Bulletin of the American Meteorological Society*, 101(8), E1357–E1377, <https://doi.org/10.1175/bams-d-19-0183.1>.

# Atmospheric River: Deployment since 2019



- 443 barometer equipped drifters have been deployed to date (337 SVPB, 106 DWSBD)
- Hourly data cycle
- Real-time data available to Global Telecommunication System (GTS) through GDP/LDL
- Curated drifter datasets available at LDL ERDDAP server and NOAA's delayed-mode GDP processing center

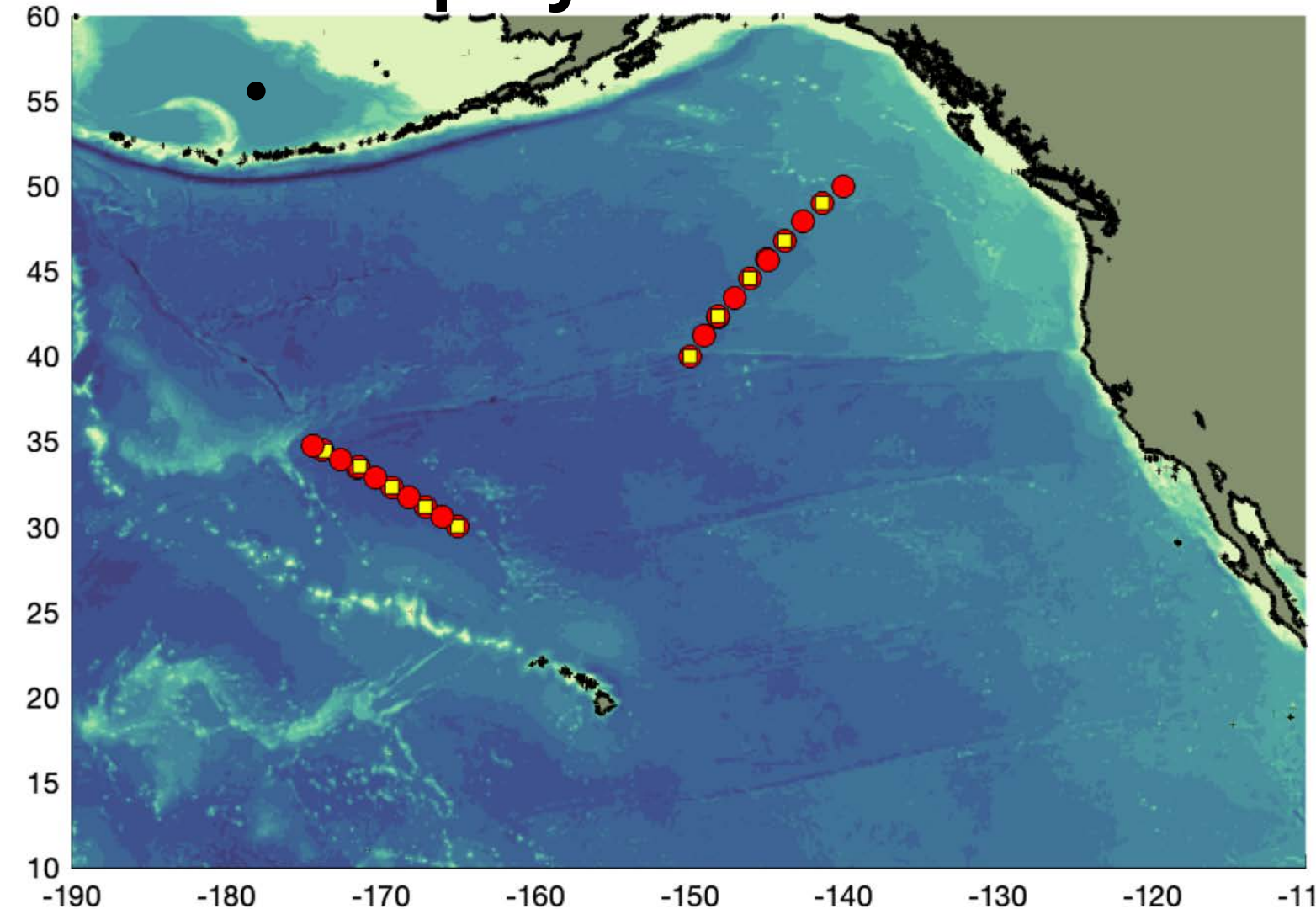
# Atmospheric River: Buoy Deployment

## USAF 53rd Weather Reconnaissance



\*Courtesy of Jay Latham

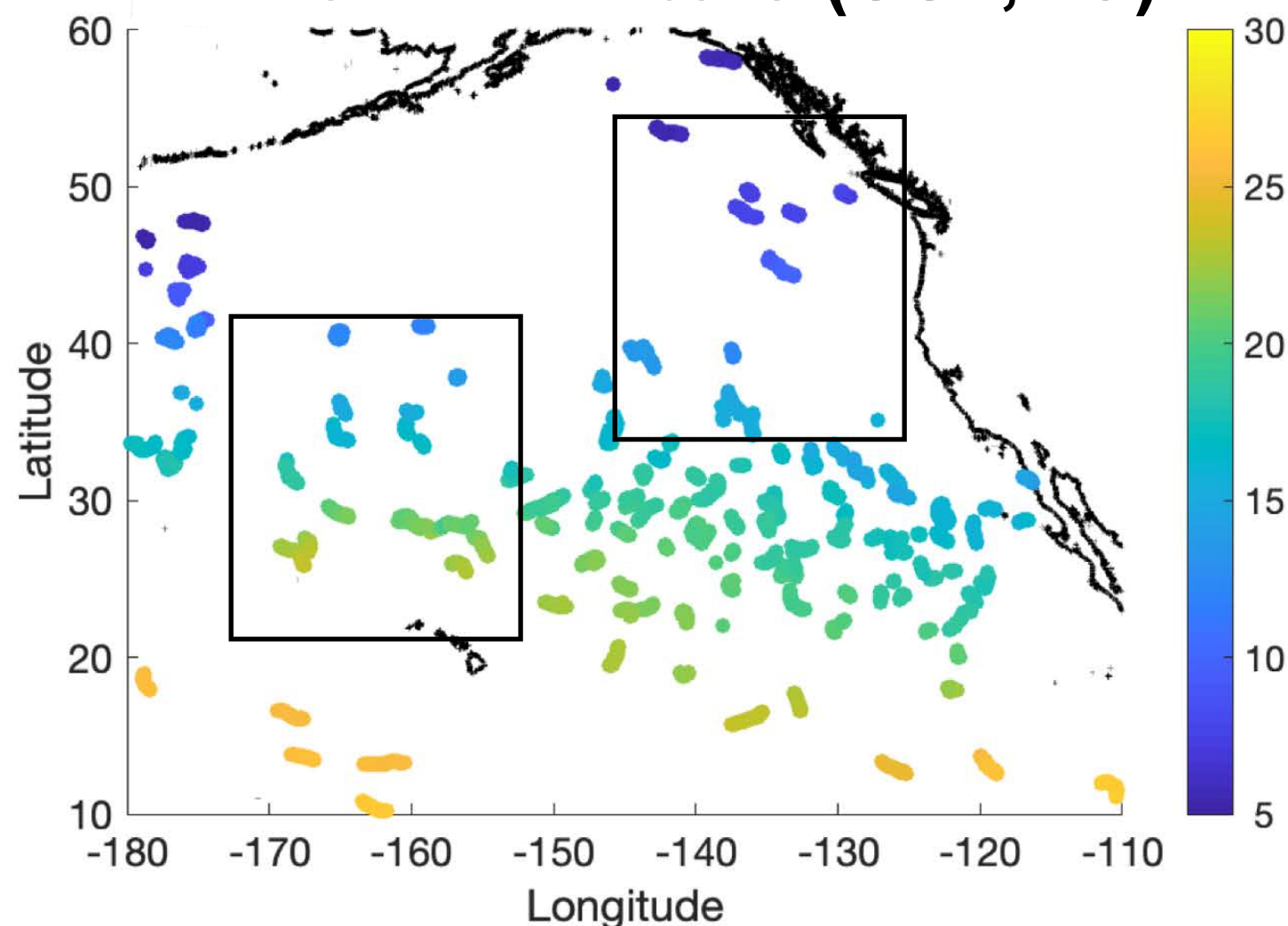
## AR Deployments 2023-34



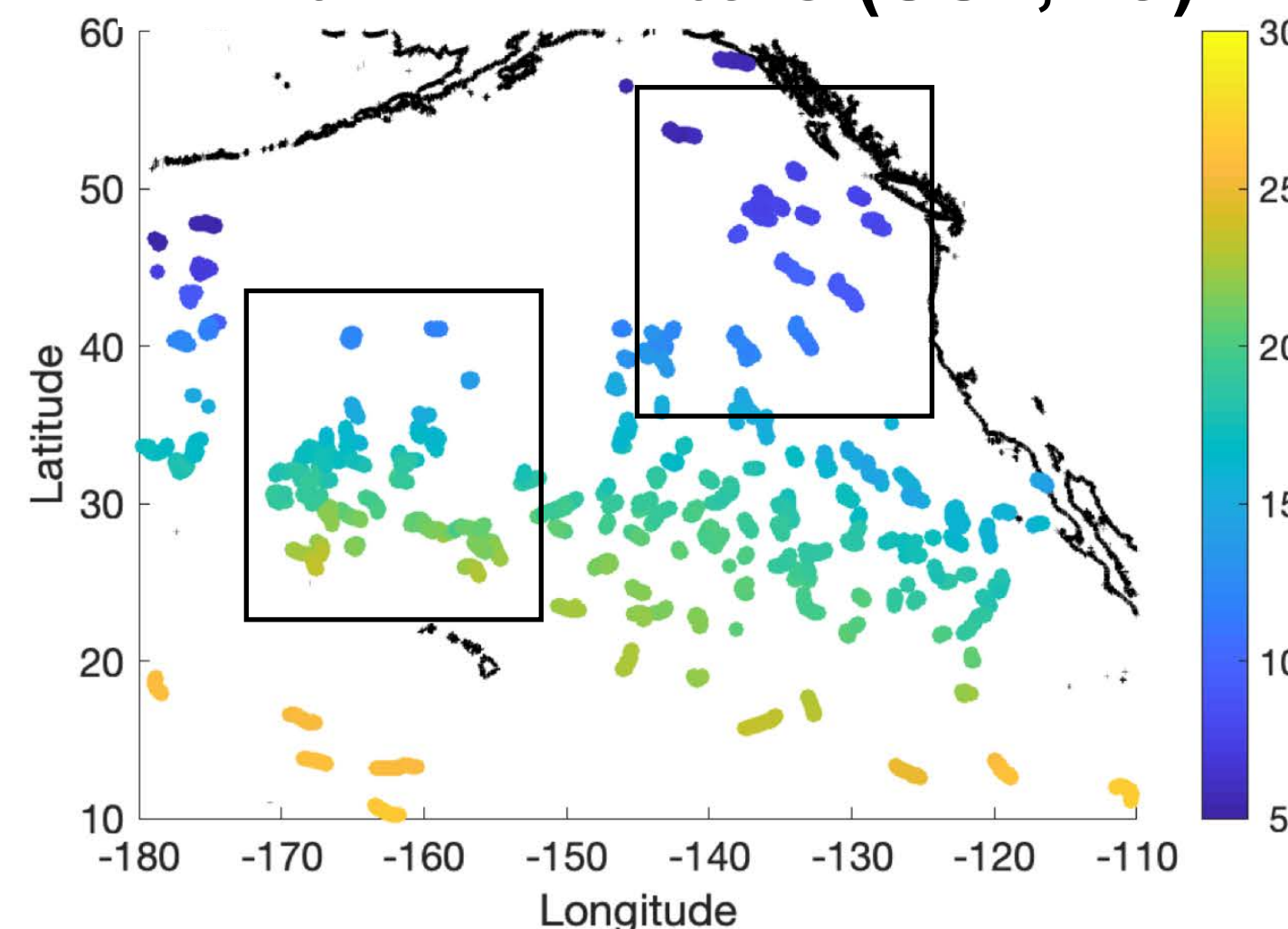
- Increase **regional observations** in locations of AR genesis and transit

- Provide **sea-level pressure** and **SST** observations that are assimilated into weather forecast models

## No AR Drifters (SST; °C)



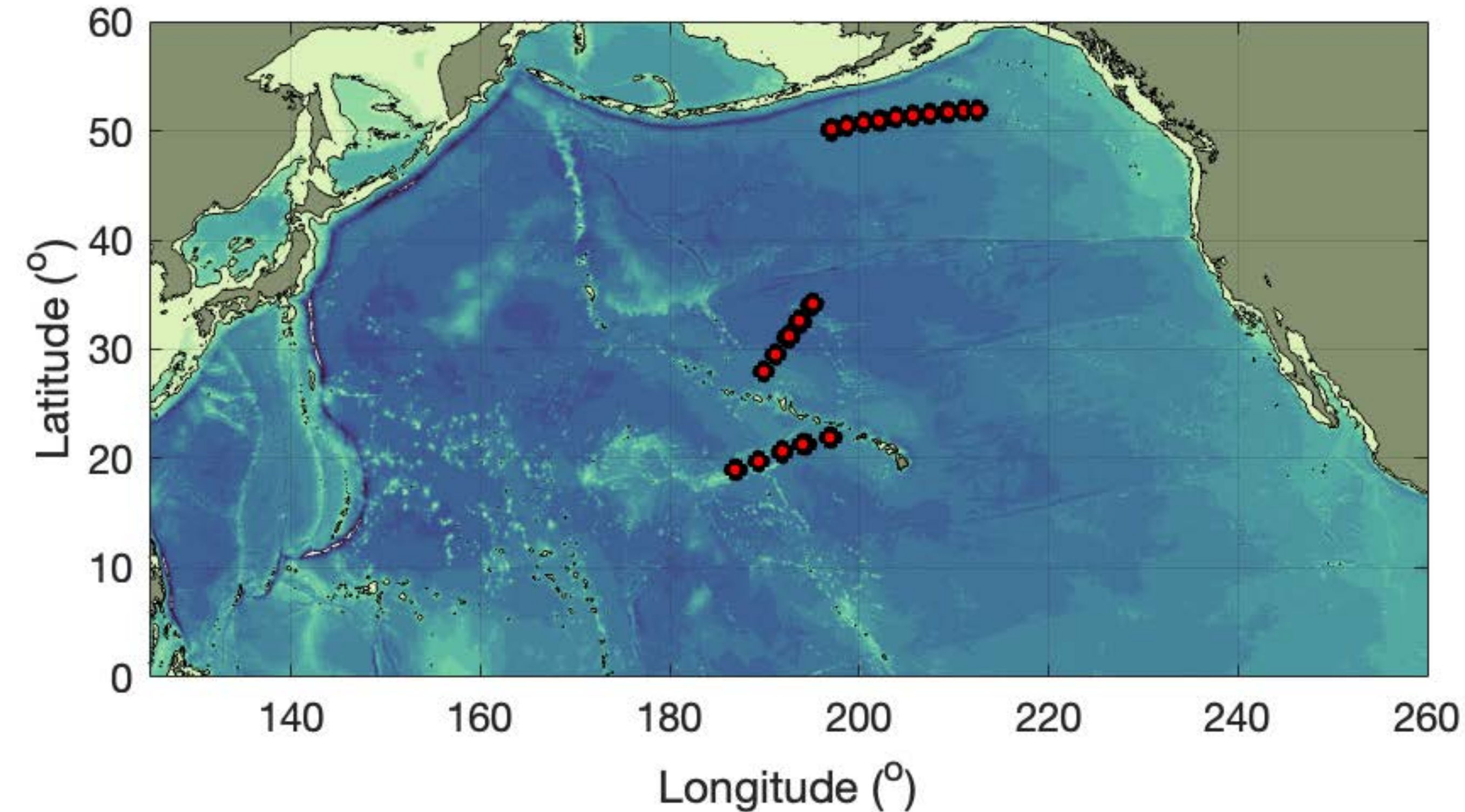
## With AR Drifters (SST; °C)



- Use data in research (**waves** and **currents**) to improve air-sea interaction parameterization

# AR Recon (Present Year): 2025-2026

## December 4 and 11 February Deployments



SVPB	DWSBD
40	20

- **Two Deployments of 10 Drifter Packages:**

- 4 December (Gulf of Alaska)
- 11 February (West of Hawaii)

- **Each package:**

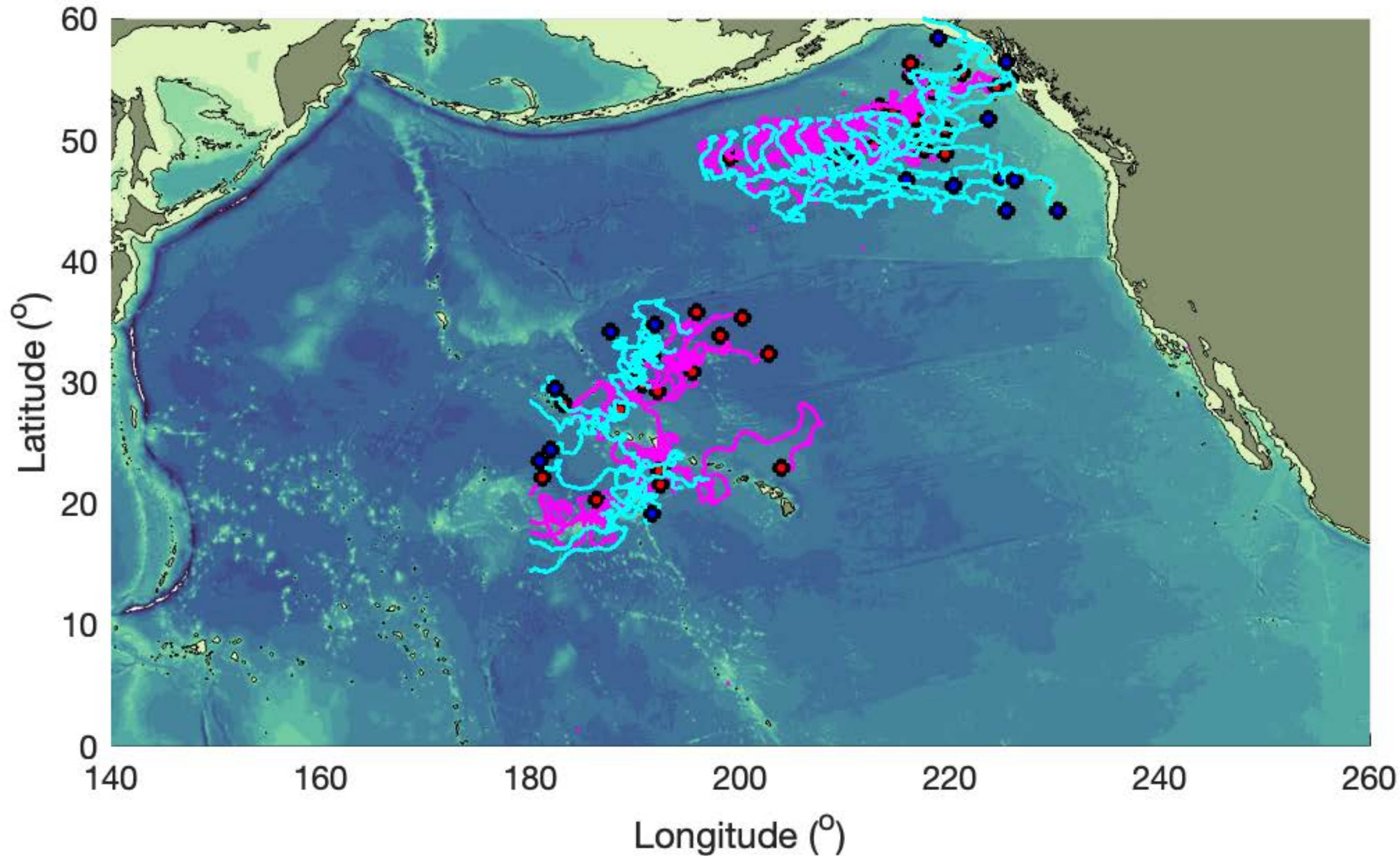
- 2 SVPB and 1 DWSBD

## AR Recon Drifters in the Gulf of Alaska December 8, 2025



# AR Recon (Present Year): 2025-2026

**Position: June 28, 2026**



<b>Drifter</b>	<b>SVPB</b>	<b>DWSBD*</b>
Number	40	20
SLP Obs	165,206	76,985

\* And 27,430 wave field observations

## • Two Deployments of 10 Drifter Packages:

- 4 December (Gulf of Alaska)
- 11 February (NW of Hawaii)

## • Each package:

- 2 SVPB and 1 DWSBD

**AR Recon Drifters in the Gulf of Alaska  
December 8, 2025**

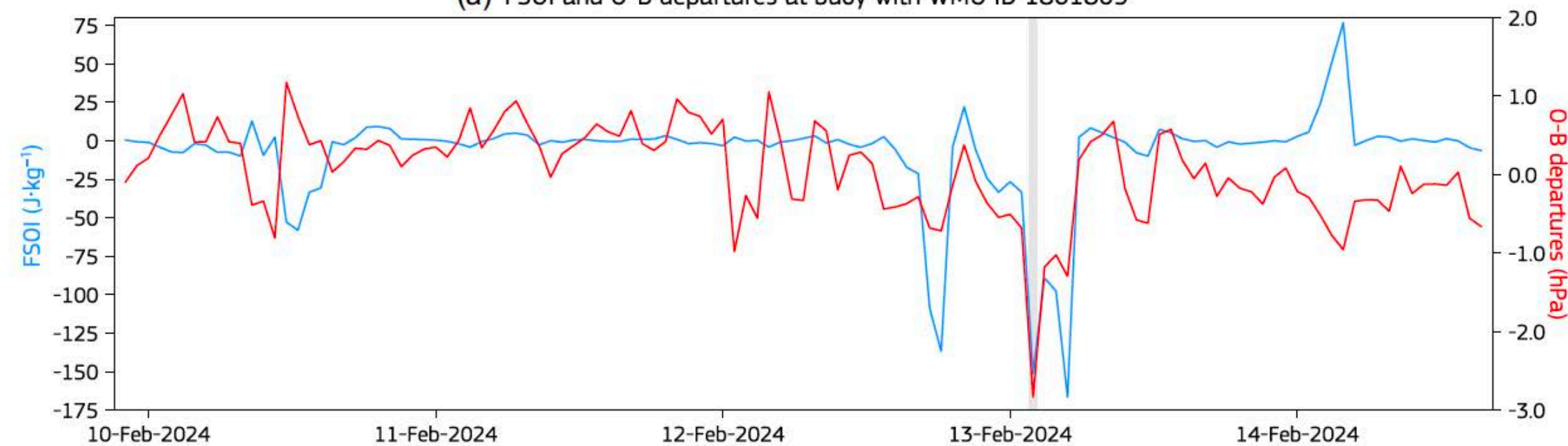


# Increasing the Impact: Drifter SLP Observations

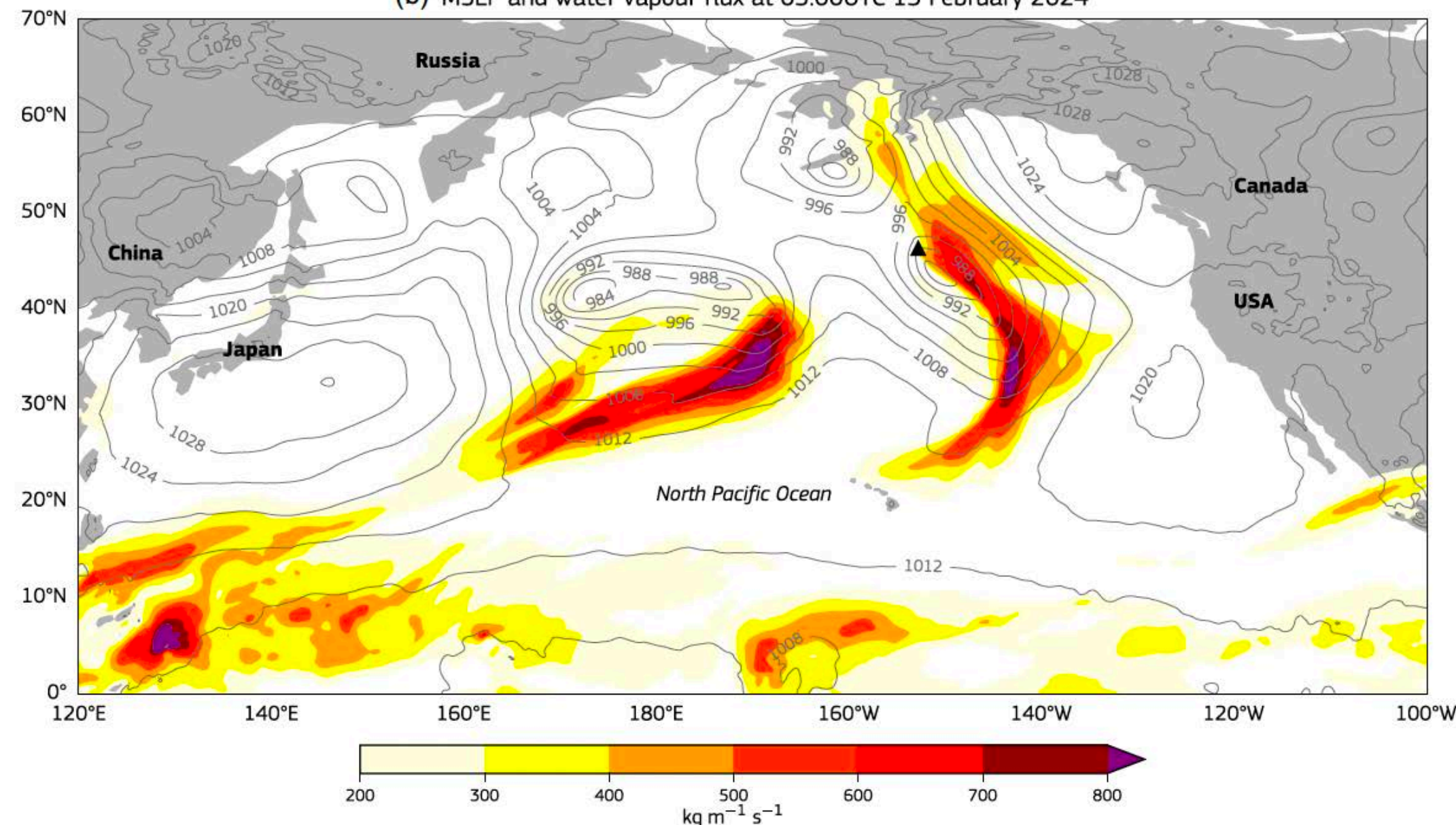
## ATMOSPHERIC RIVER RESEARCH: IMPACT OF SEA LEVEL PRESSURE OBSERVATIONS

— with Dr. David Lavers, ECMWF

(a) FSOI and O-B departures at buoy with WMO ID 1801809



(b) MSLP and water vapour flux at 05:00UTC 13 February 2024



- Error reduction and Observations-Background (dry energy norm) of drifters' SLP data is largest in regions of significant SLP gradients and fast evolving systems
- This recent finding confirm results of Horanyi et al., 2017, and Reynolds et al., 2023

Horányi, A., C. Cardinali, and L. Centurioni (2017), The global numerical weather prediction impact of mean-sea-level pressure observations from drifting buoys, *Quarterly Journal of the Royal Meteorological Society*, 143(703), 974–985, <https://doi.org/10.1002/qj.2981>.

Reynolds, C.A., R.E. Stone, J.D. Doyle, N.L. Baker, A.M. Wilson, F.M. Ralph, D.A. Lavers, A.C. Subramanian, and L. Centurioni (2023), Impacts of northeastern Pacific buoy surface pressure observations, *Monthly Weather Review*, 151(1), 211–226, <https://doi.org/10.1175/MWR-D-22-0124.1>.

Lavers, D.A., Centurioni, L., Wilson, A.M., Ingleby, B. & Ralph, F.M. (2025) An overview of drifting-buoy deployments in atmospheric river reconnaissance from 2019 to 2024. *Quarterly Journal of the Royal Meteorological Society*, <https://doi.org/10.1002/qj.5049>

These results suggest that an optimal configuration of the drifter array can be complemented with targeted deployments.

# Targeted Deployment of Drifters in Hurricanes

- \* Waves, SST, \*\*Pressure \*\*Wind
- Follows surface wave motion, measuring waves with GPS
- Deliver “first-five”: wave energy and direction
- “Real-time” reporting



**2015** DWSD released to global array



**2018** DWSD targeting of hurricane



**2019** DWSBD for ARs

**\*Air-Deployed Drifters targeting extreme events since 2005**

## \* A-size Directional Wave Spectra Drifter (ADWSD)



**\* Developed to be deployed during OPERATIONAL Weather Reconnaissance Missions**



**2021** Release of ADWSD



**2022** ADWSD targeting of hurricane

**2024** ADWSD with BAROMETER (ADWSBD)

**2025** 20 ADWSBD resolve pressure, sea-surface temperature, and wave field in Hurricane Erin

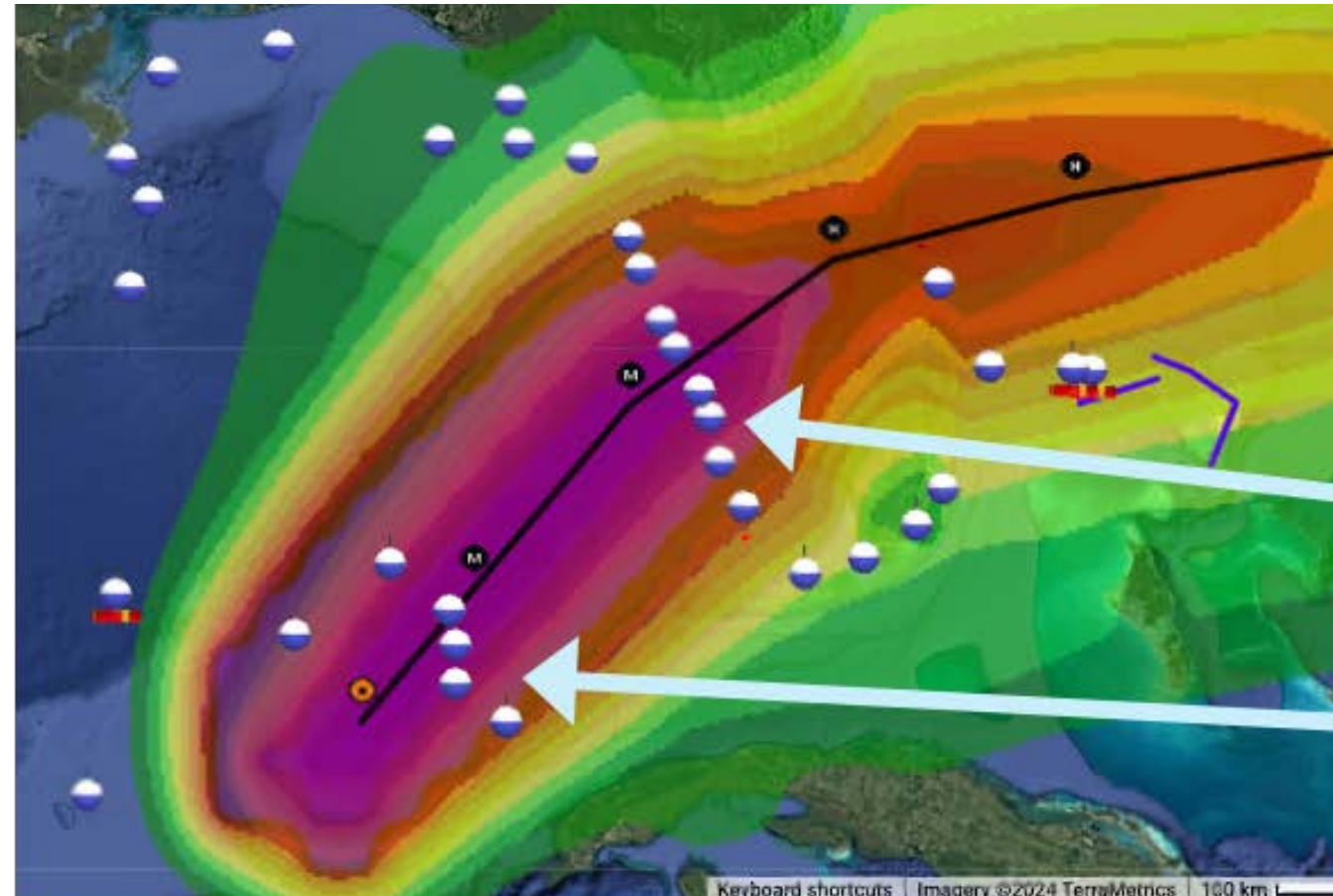
## Targeted Storms

- **2003:** CBLAST, 2013: ITOP
- **2018:** Hurricane Michael (Schönau et al. 2024)
- **2020:** Hurricanes Isaias, Teddy, Epsilon
- **2022-2023:** Hurricanes Ian, Idalia, Lee, Nigel
- **2024:** Hurricanes Francine, Helene, Milton, Raphael
- **2025:** Hurricanes Erin and Gabrielle

# Targeted Deployment of Drifters in Hurricanes

**Before...** Composite of many storms or large field campaigns

**Now...**



**Hurricane Milton (2024)**

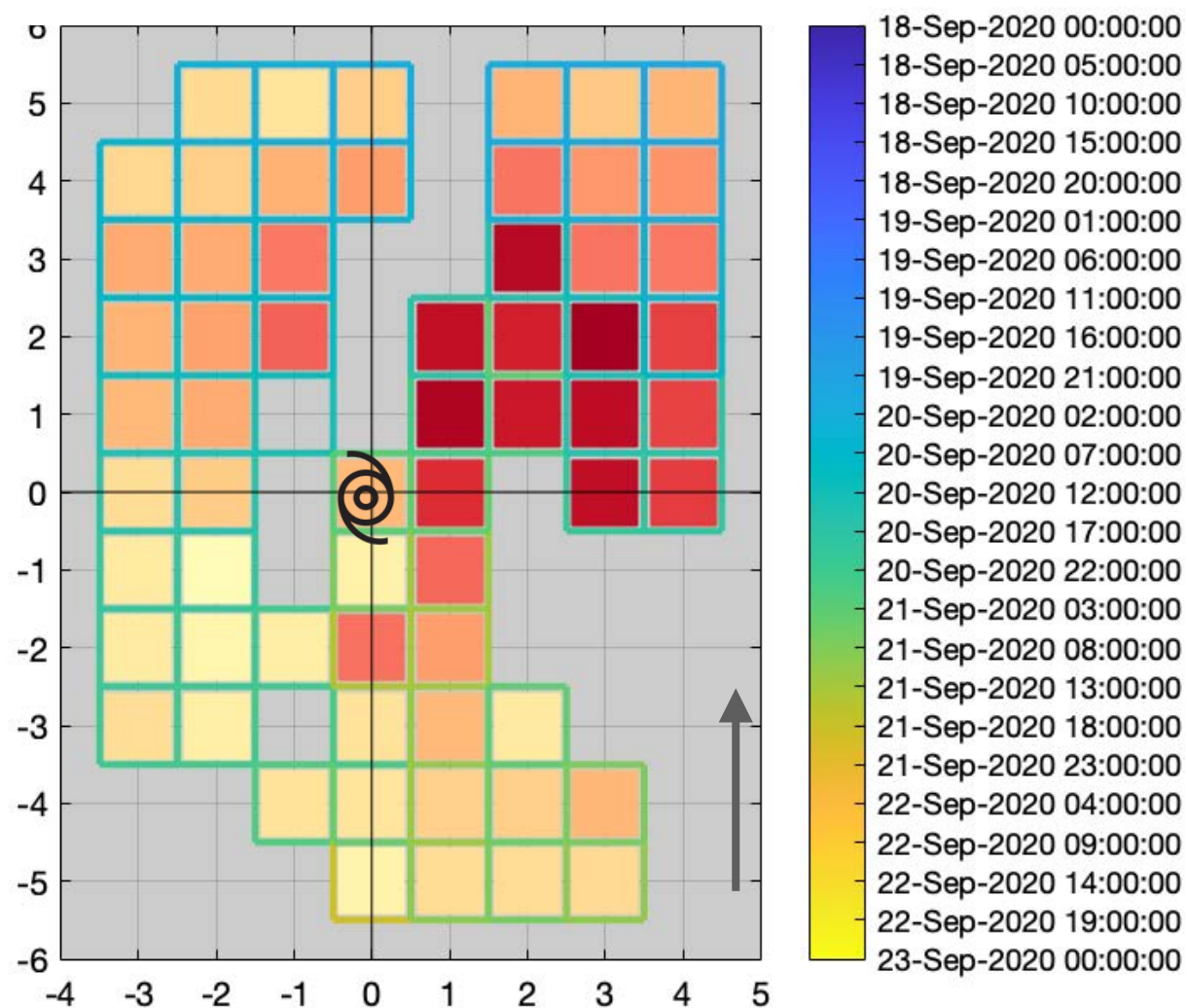
Deployment two days ahead of storm

Deployment during RECON flights

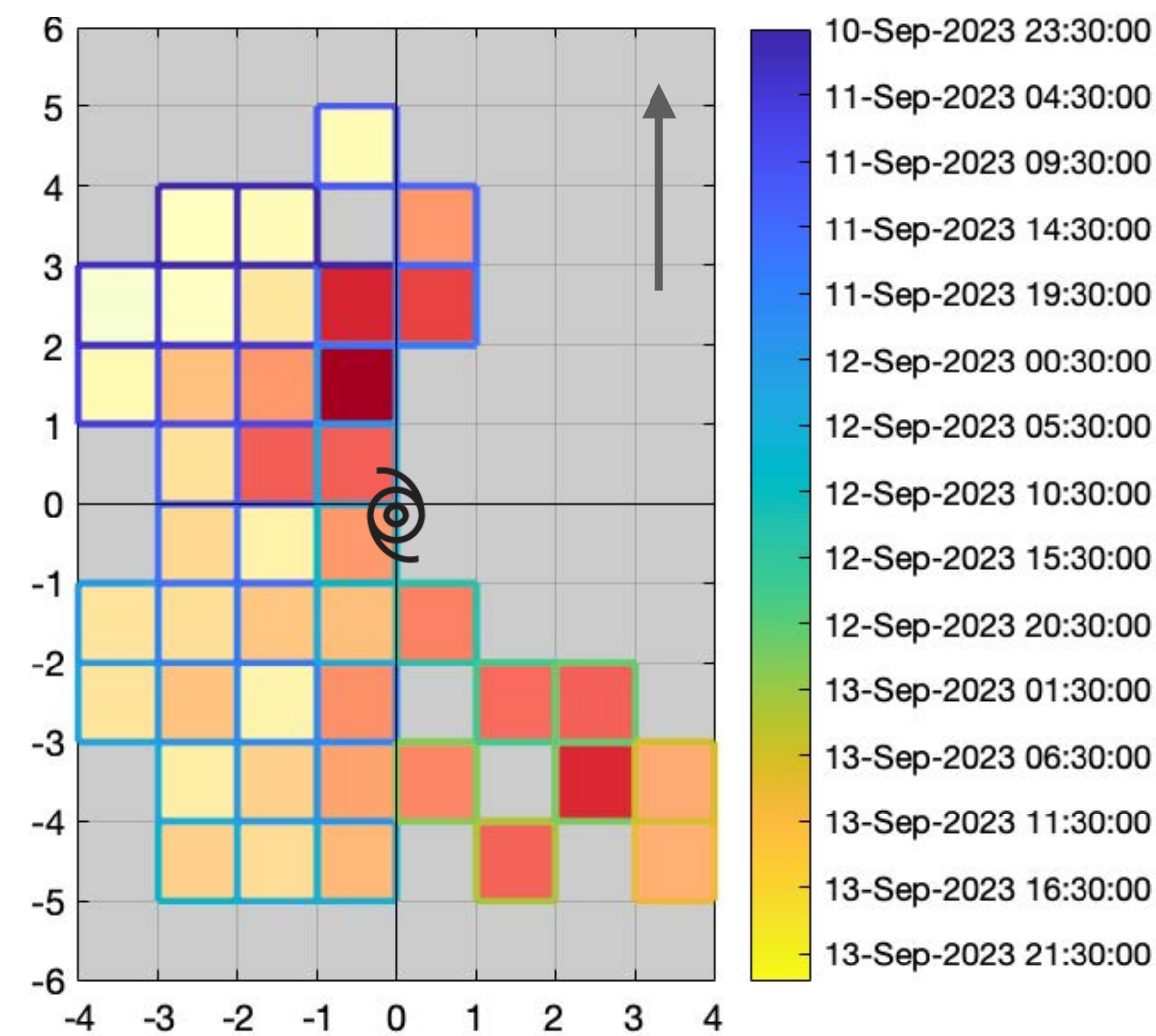
**Targeted DWSD/DWSBD/ADWSD in...**

- Hurricane Michael (2018)
- Hurricane Isaias, Hurricane Teddy (2020)
- Hurricane Ian (2022)
- Hurricane Lee, Hurricane Idalia (2023)
- Hurricane Francine, Hurricane Helene, Hurricane Milton, Hurricane Raphael (2024)
- Hurricane Erin and Hurricane Gabrielle (2025)

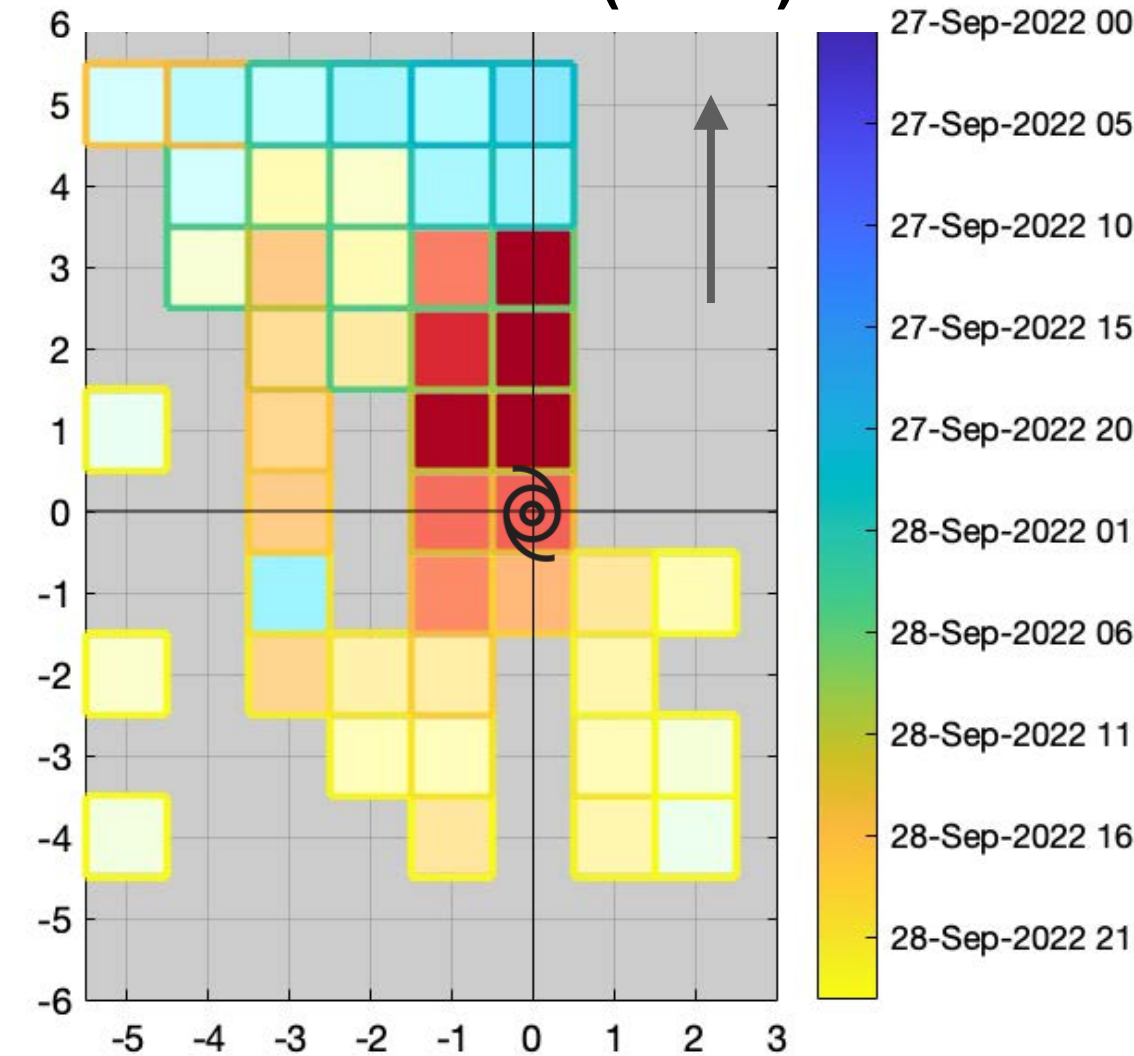
**Hurricane Teddy (2020)**



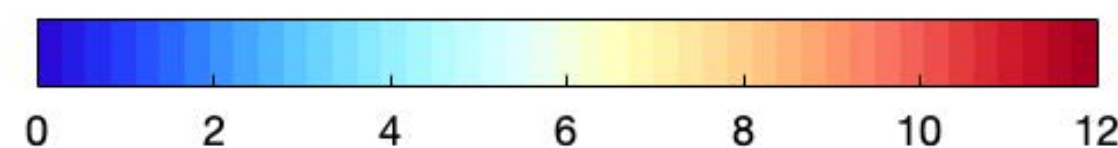
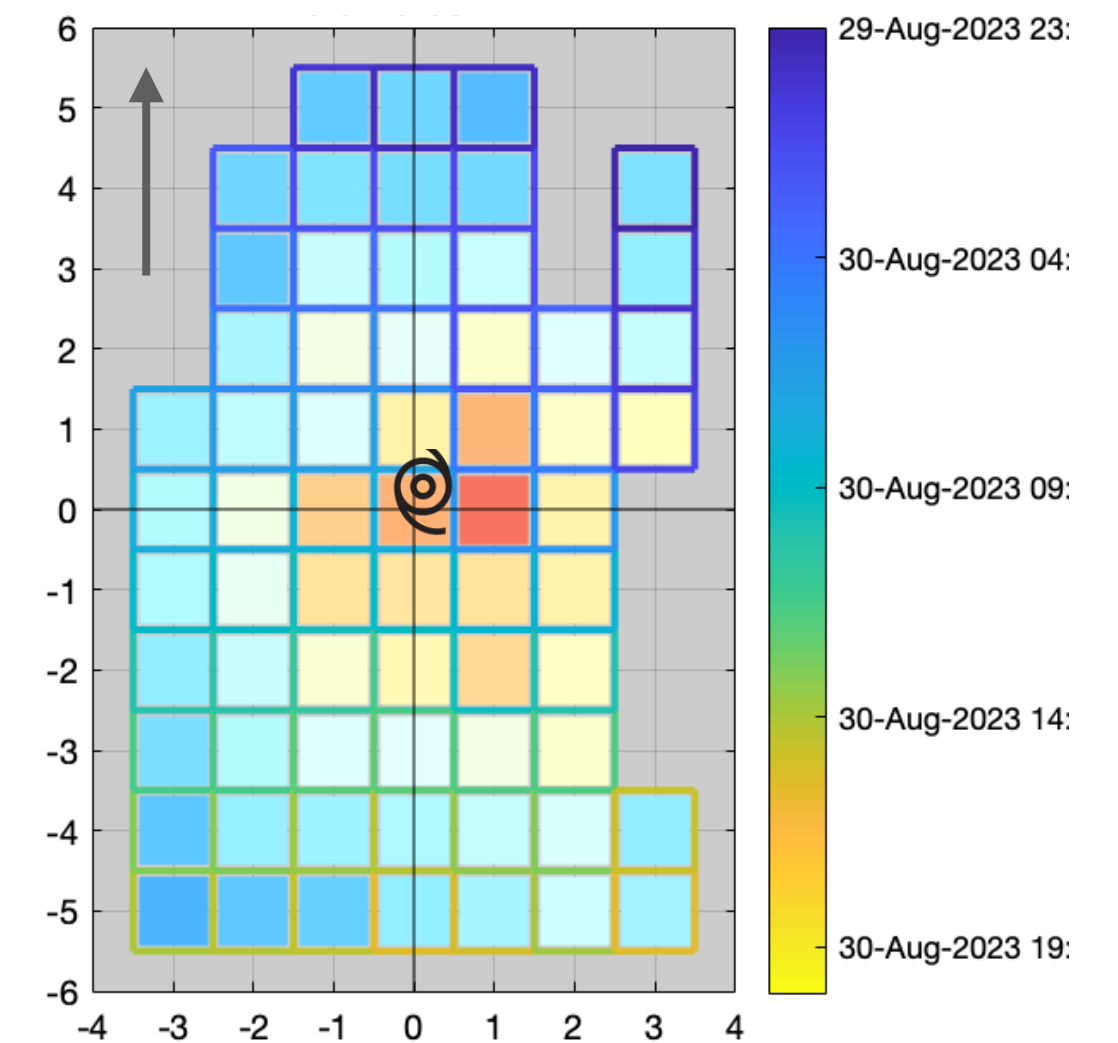
**Hurricane Lee (2023)**



**Hurricane Ian (2022)**



**Hurricane Idalia (2023)**

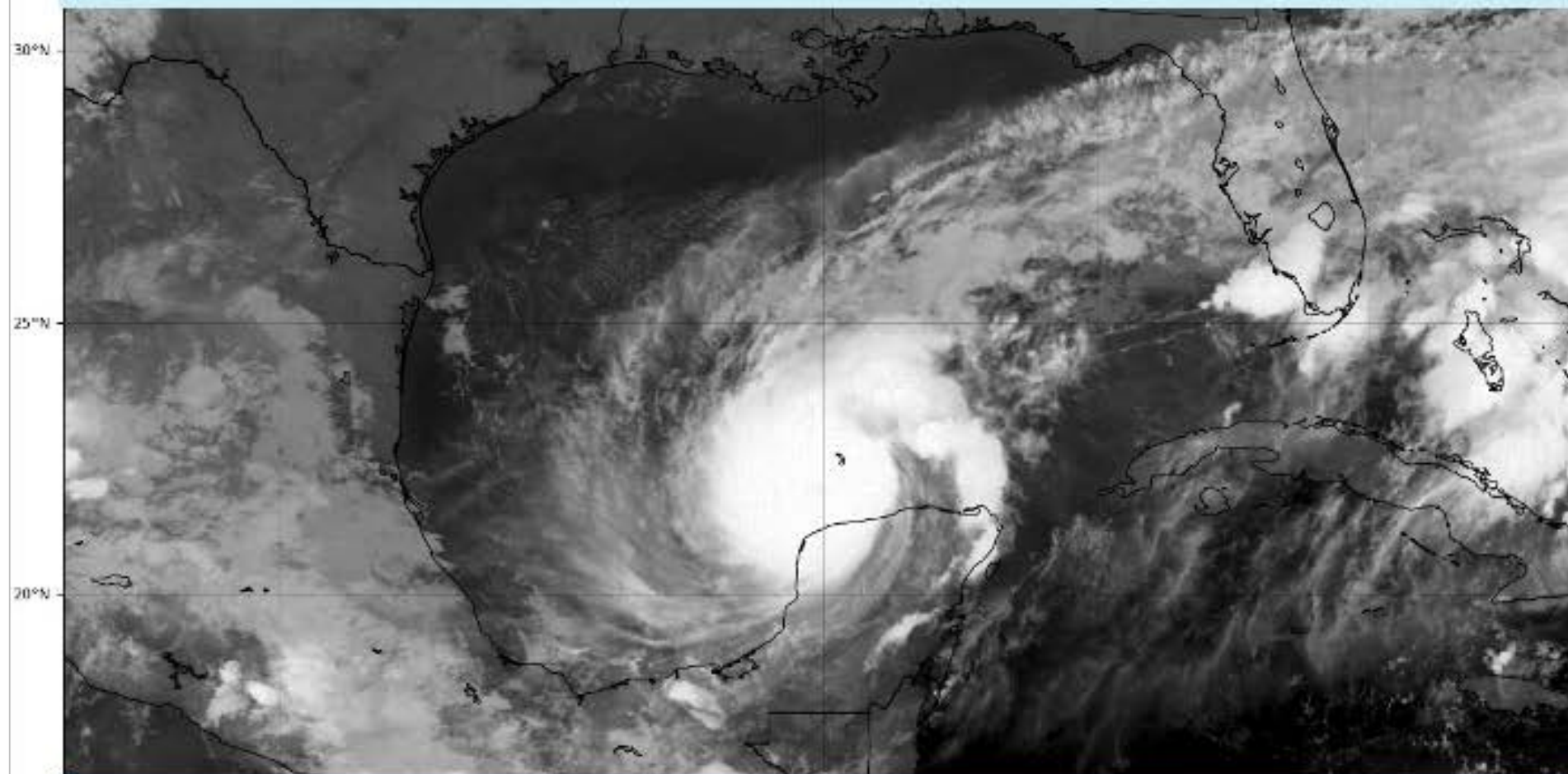


**Significant Wave Height (m)**

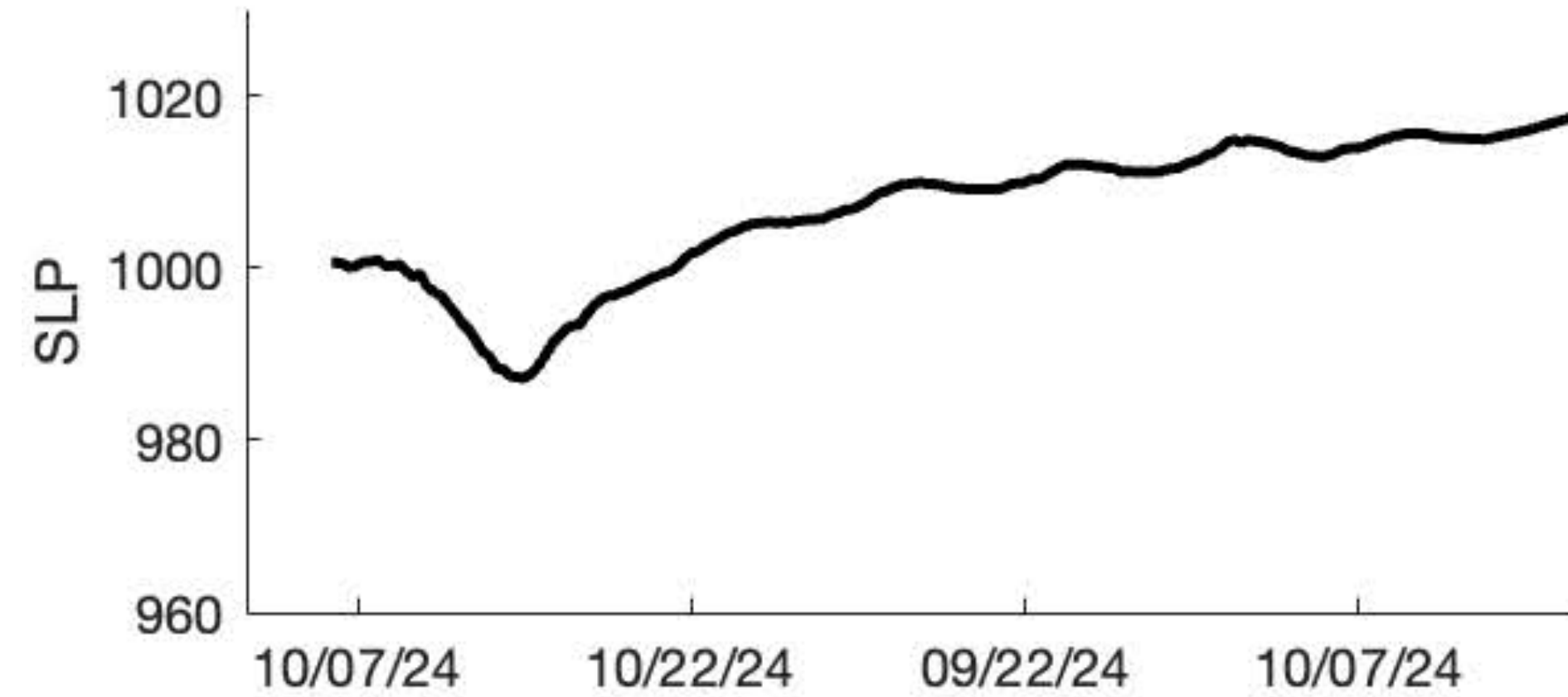
\*50 km bin

# Hurricane Milton (2024): 4 ADWSBD

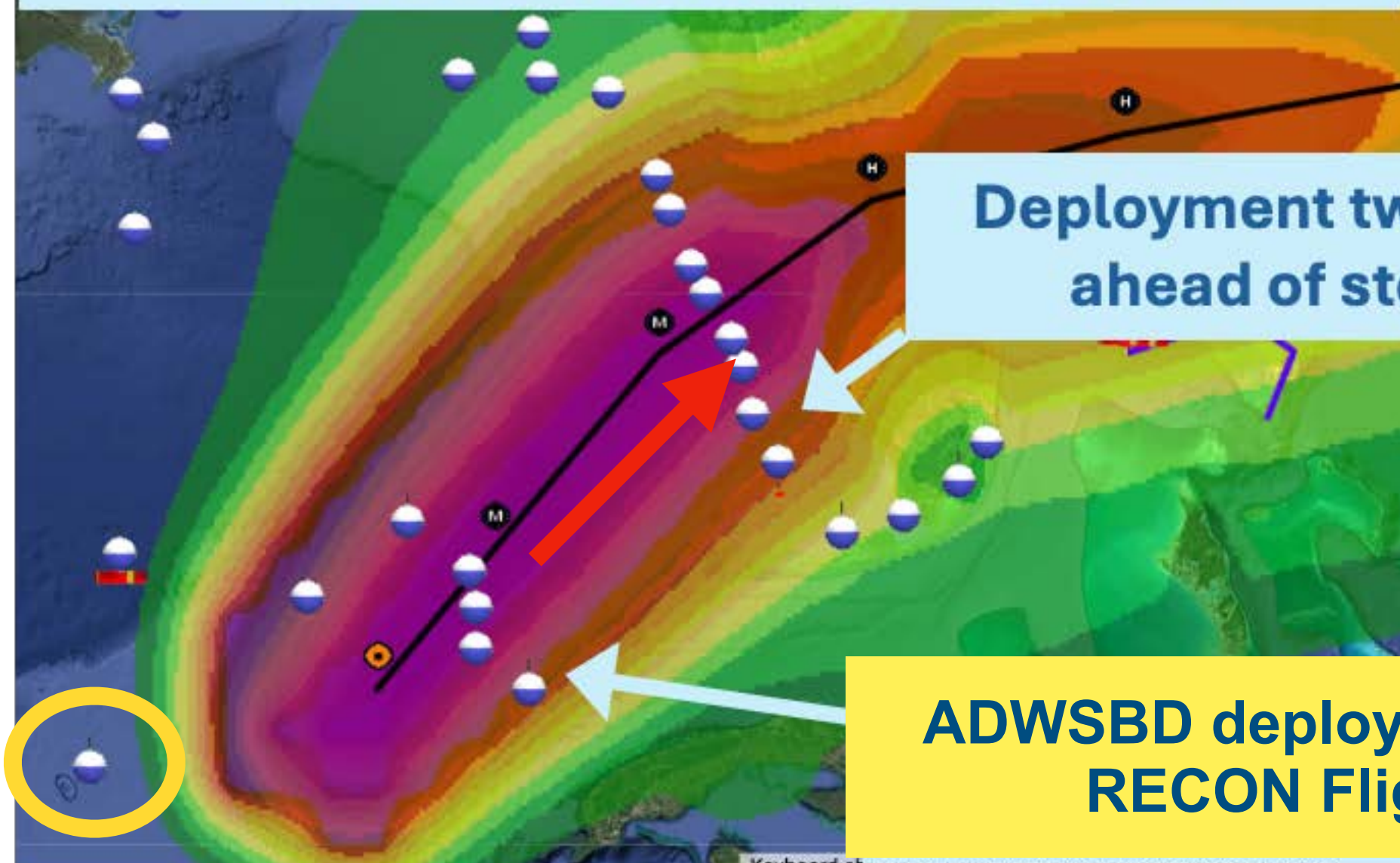
**Hurricane Milton  
GOES16; 8OCT2024; 0200Z**



**Sea Level Pressure (mb)**



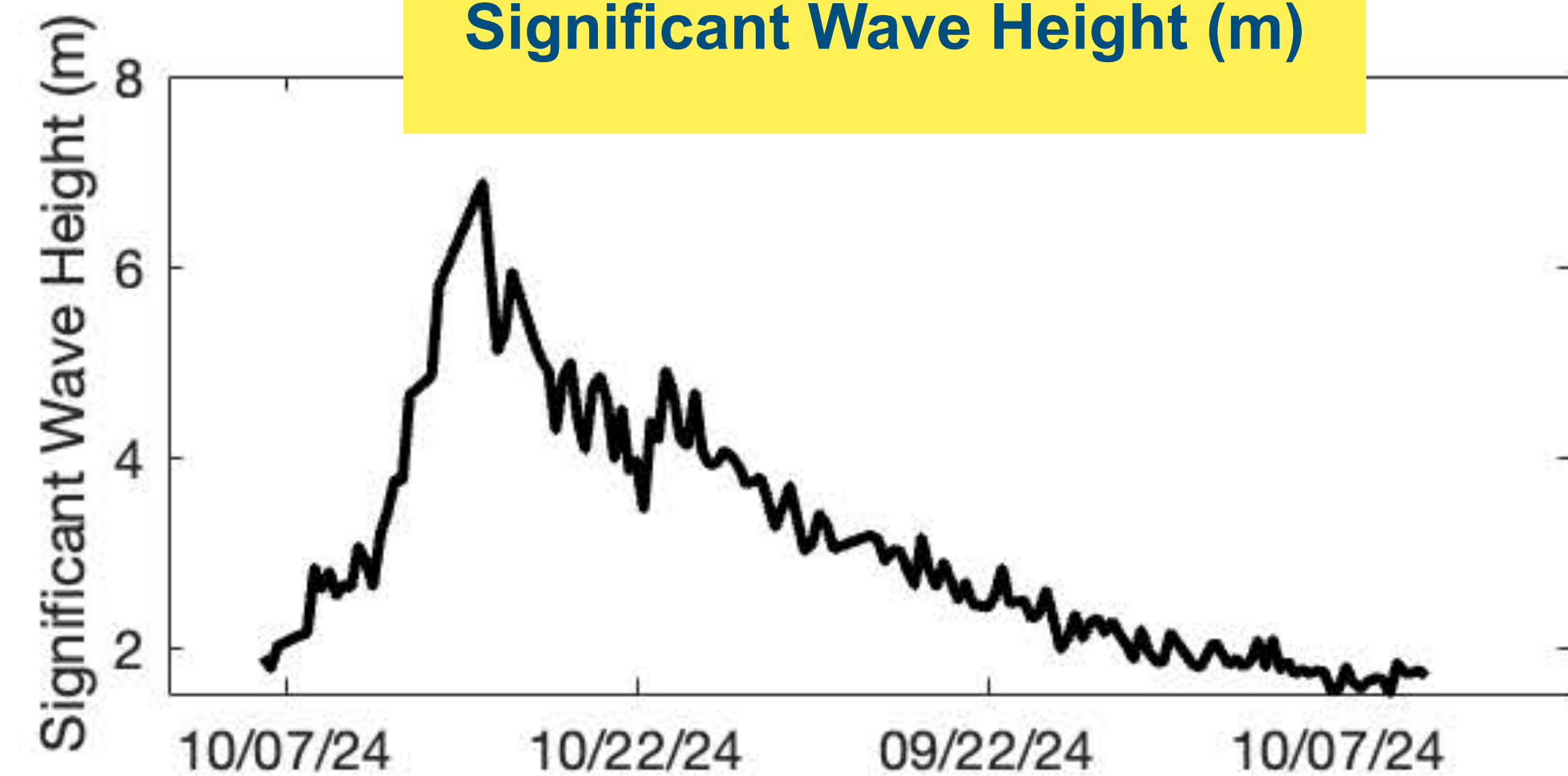
**ADWSD/ADWSBD Array 9OCT 0500z**



**Deployment two days  
ahead of storm**

**ADWSBD deployed during  
RECON Flights**

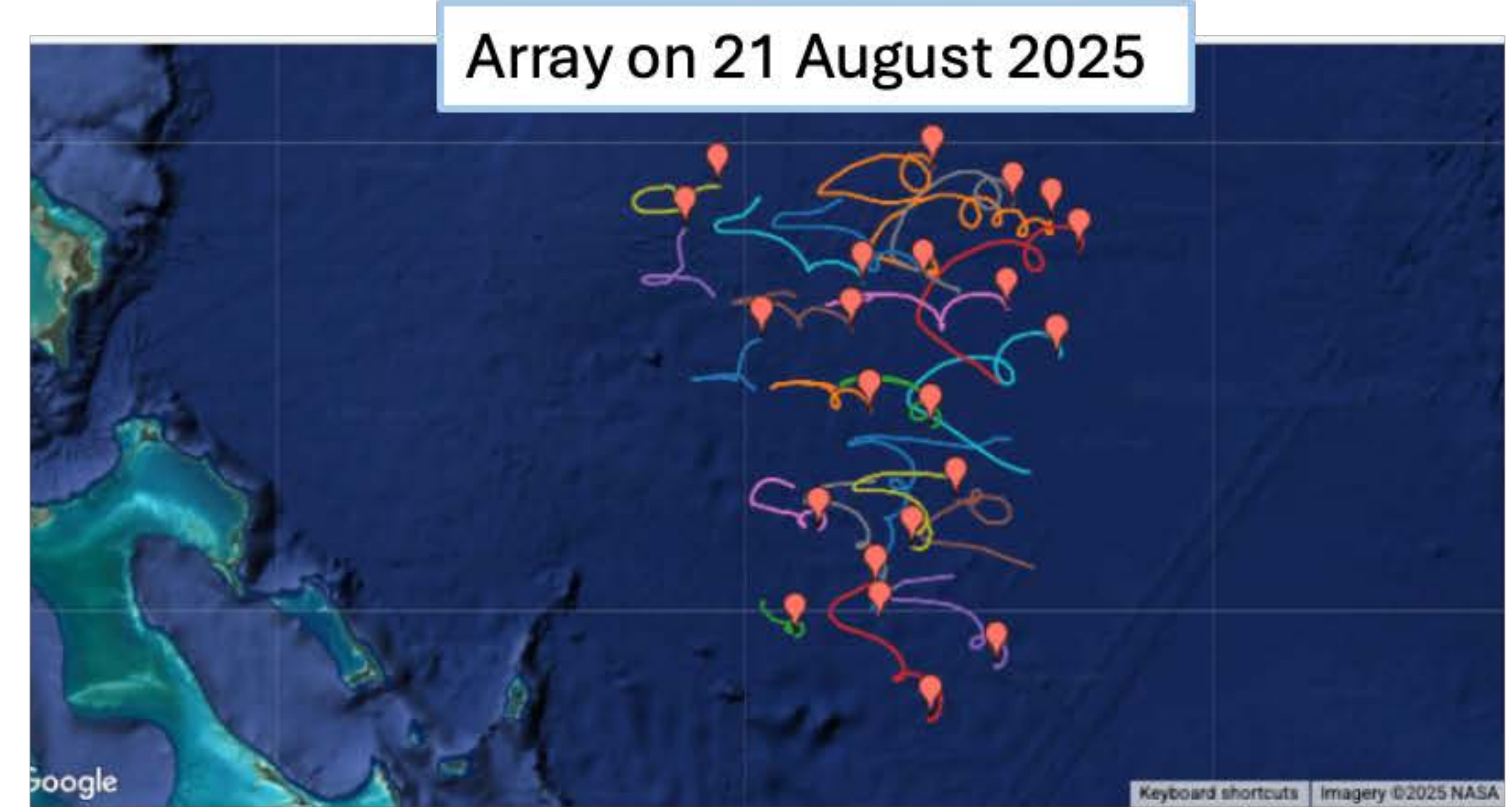
**Significant Wave Height (m)**



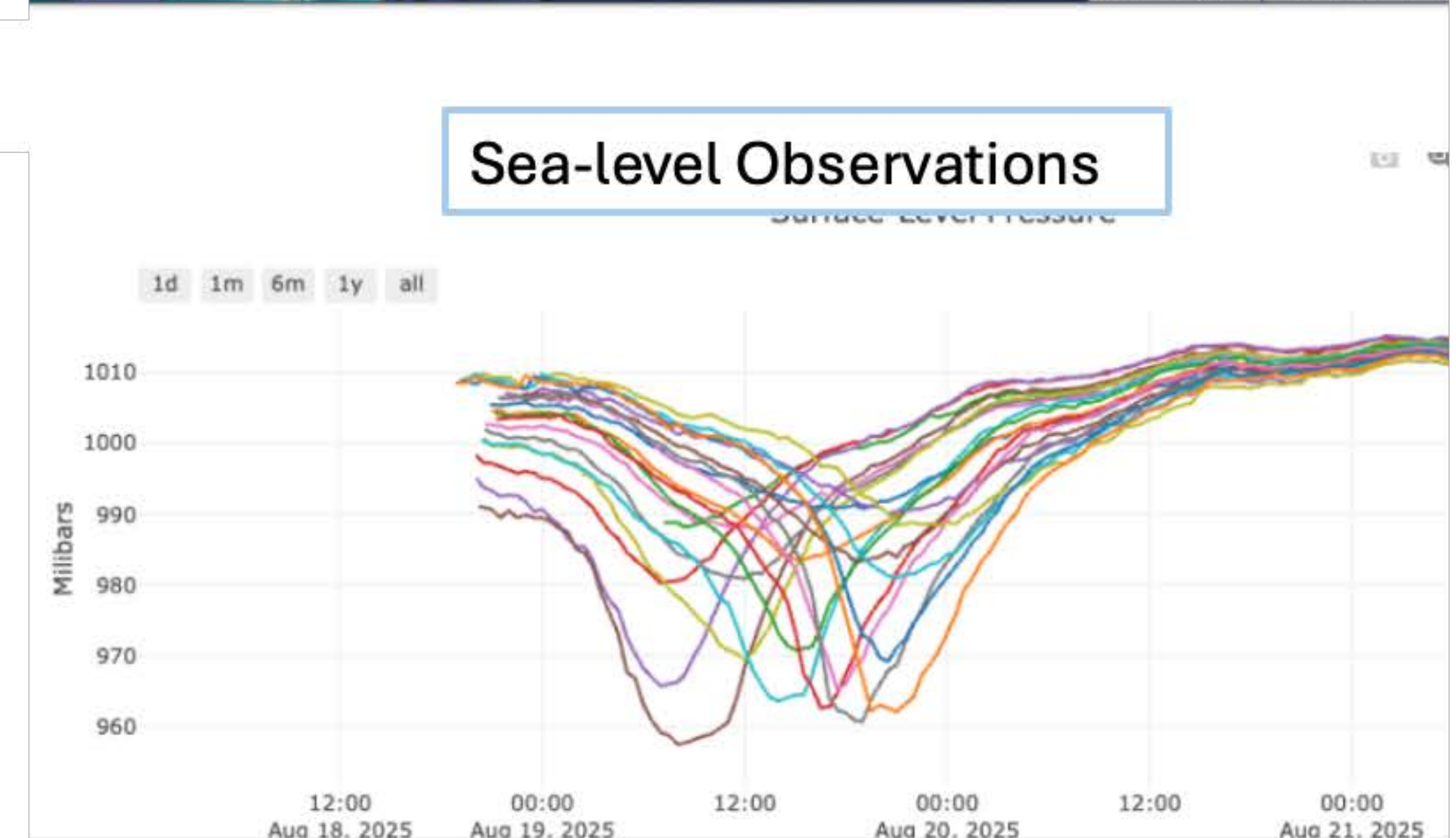
# Targeting with ADWSBD: Hurricane Erin (2025)

\* ONR SASWATCH PROJECT\*

- 20 A-size Directional Wave Spectra Barometer Drifters (ADWSBDs) were air-deployed roughly 16 hours before Hurricane Erin

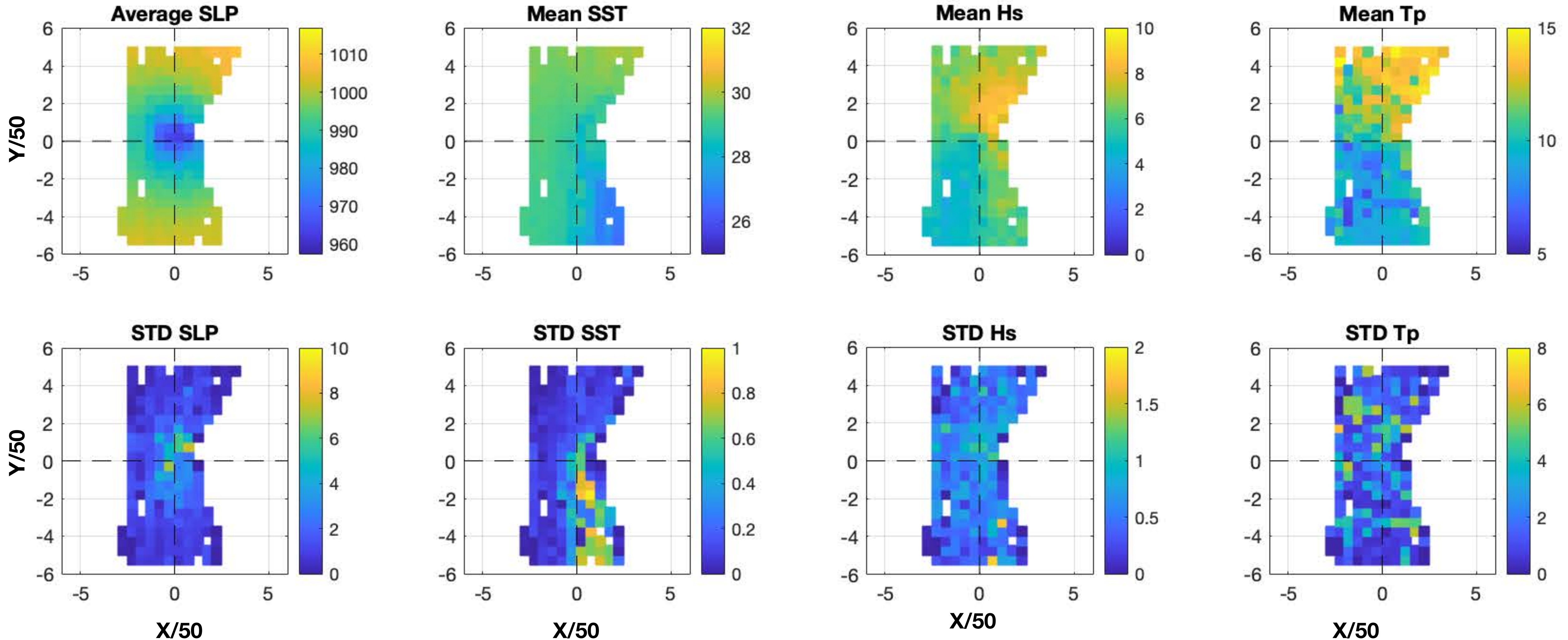


- Drifters observed wave energy and direction, sea-level pressure and temperature as the Hurricane transited over the array as a Category 3 storm



# Hurricane Erin (2025)

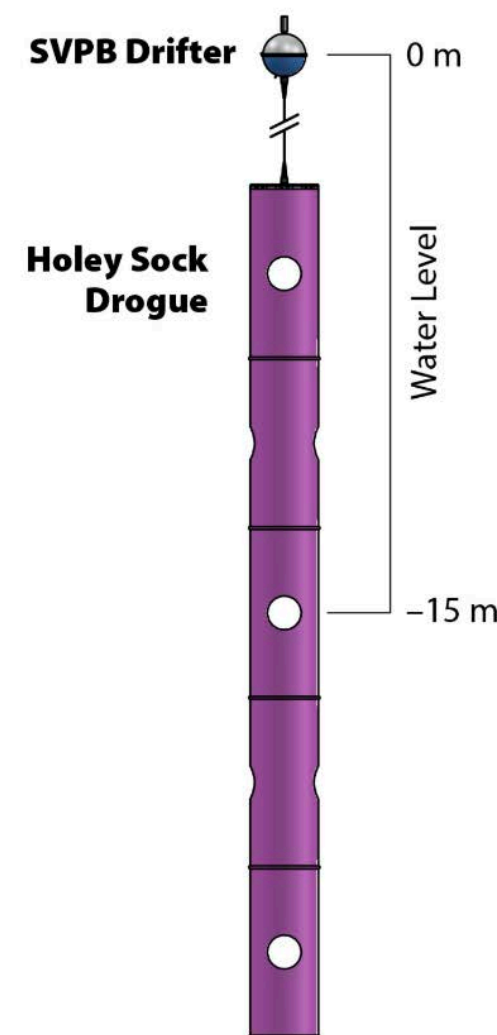
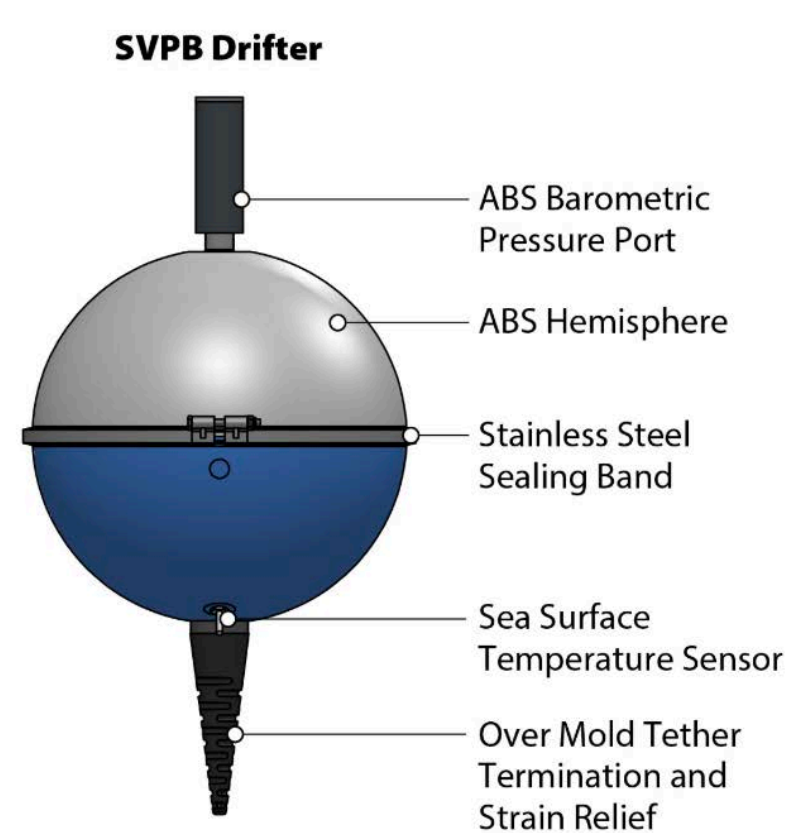
## Storm Centered and Averaged in 25 x 25 km Bins



# Drifter Types: SVPB, DWSBD AND ... wind

## Surface Velocity Program Drifter (SVPBD)

- Sea-Surface Temperature (SST), SLP and currents
- **Drogued:** Measures ocean currents ~15 m

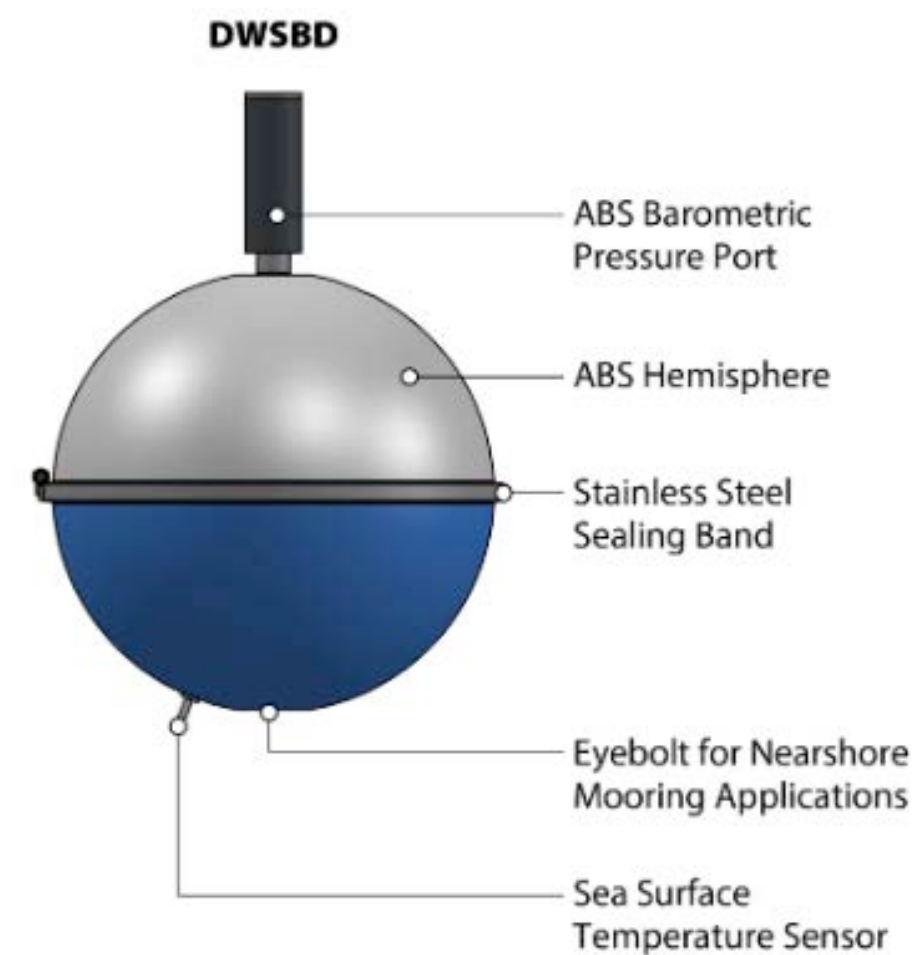


- Equipped with 2-way Iridium satellite communications



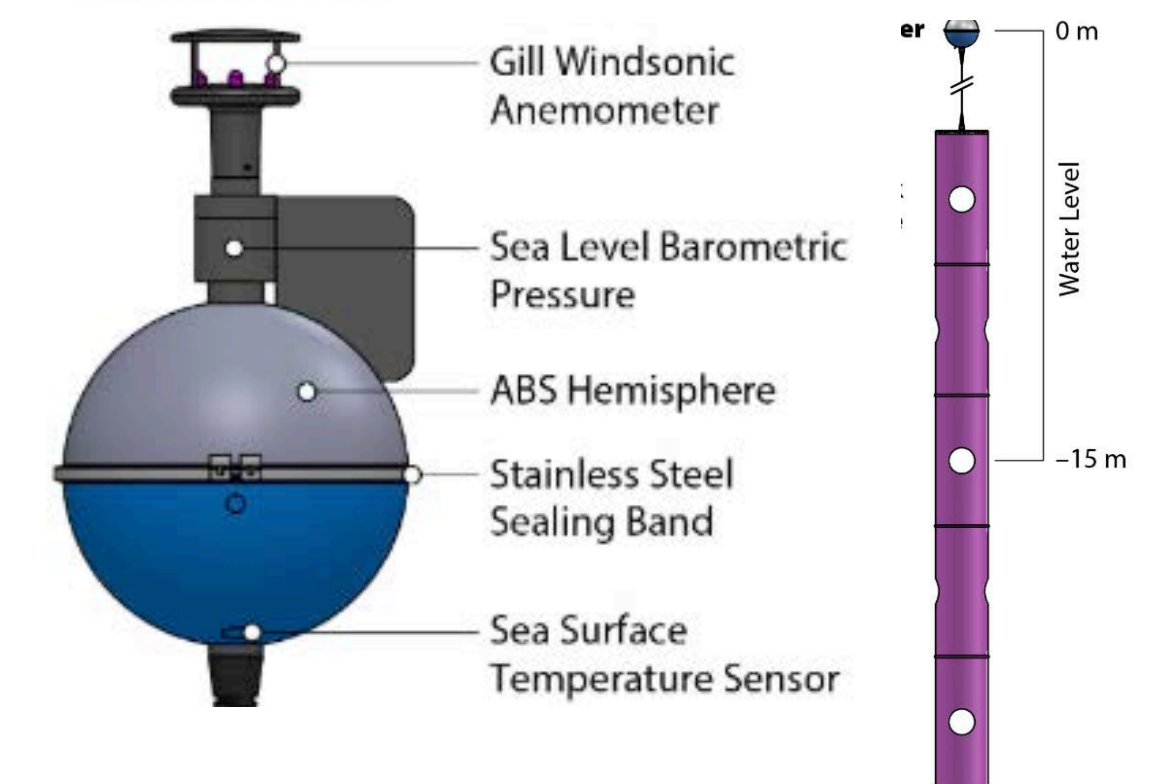
## Directional Wave Spectra Drifter (DWSBD)<sup>TM</sup>

- Measures wave energy and direction using GPS technology, delivering "First-Five"
- Measures SST, SLP
- **Undrogued:** Follows surface

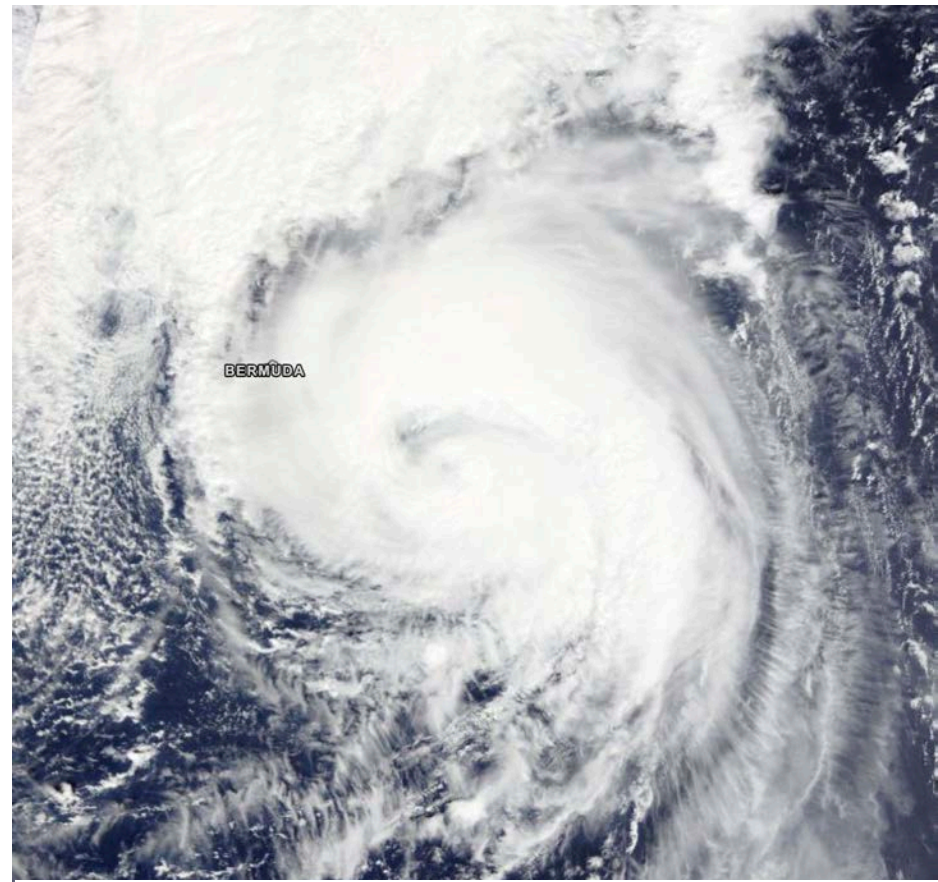


## MiniMet (SVPBWD) and Directional Wave Spectra Barometer-Wind Drifter (DWSBWD)<sup>TM</sup>

- 2 D directional wind, SST and SLP
- Measures currents (drogued) **OR** wave energy and direction using GPS technology
- **Drogued (MiniMet - SVPBWD) or Undrogued (DWSBWD)**



# Example of Wind-Wave Direction: Hurricane Teddy

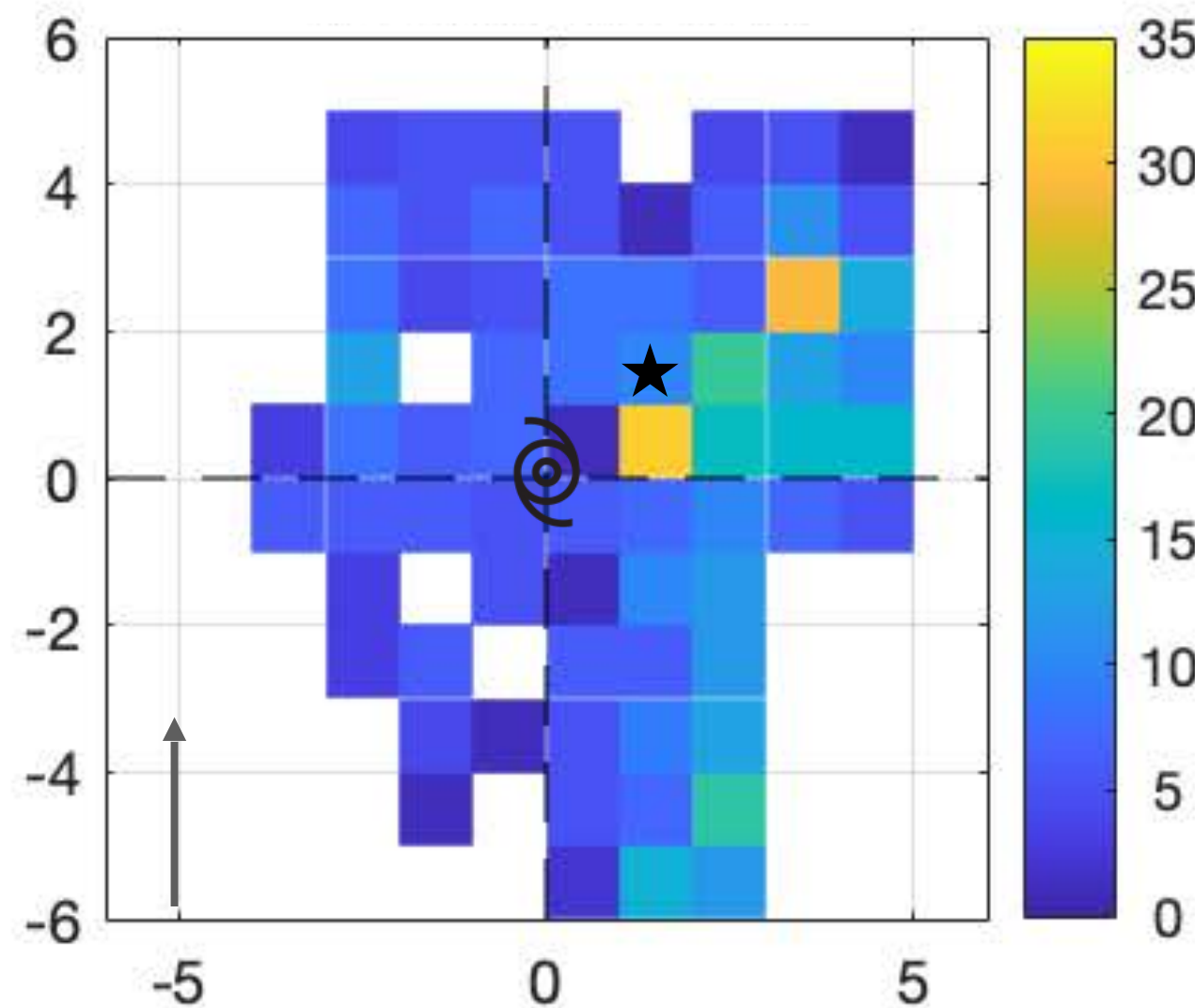


<https://worldview.earthdata.nasa.gov/>  
Terra/Modis

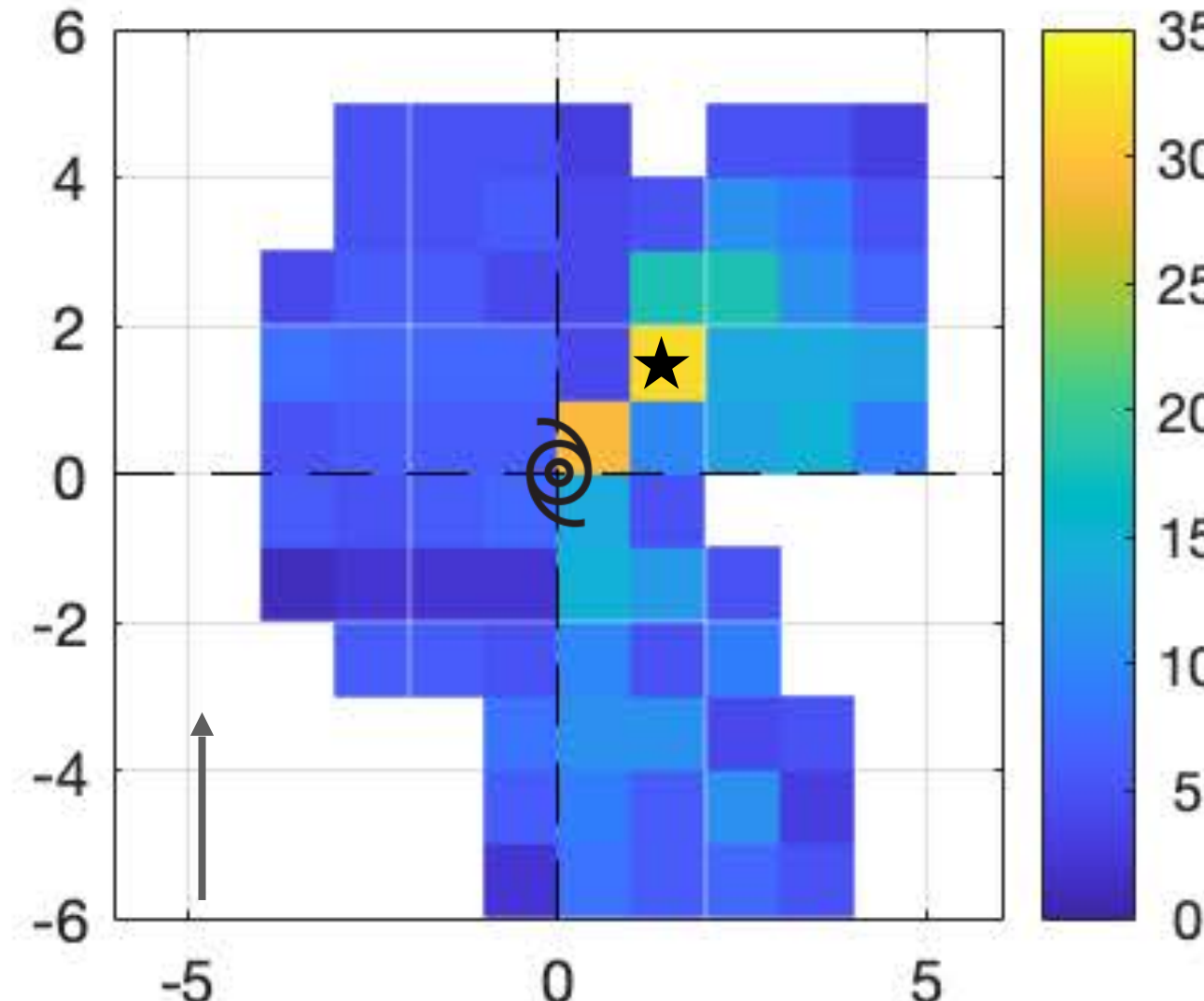
- Hurricane Teddy formed SE of Bermuda and achieved a Category 4 status before dissipating in the subtropics.

- Temporal variability can be resolved within the storm

Number of Wind Observations

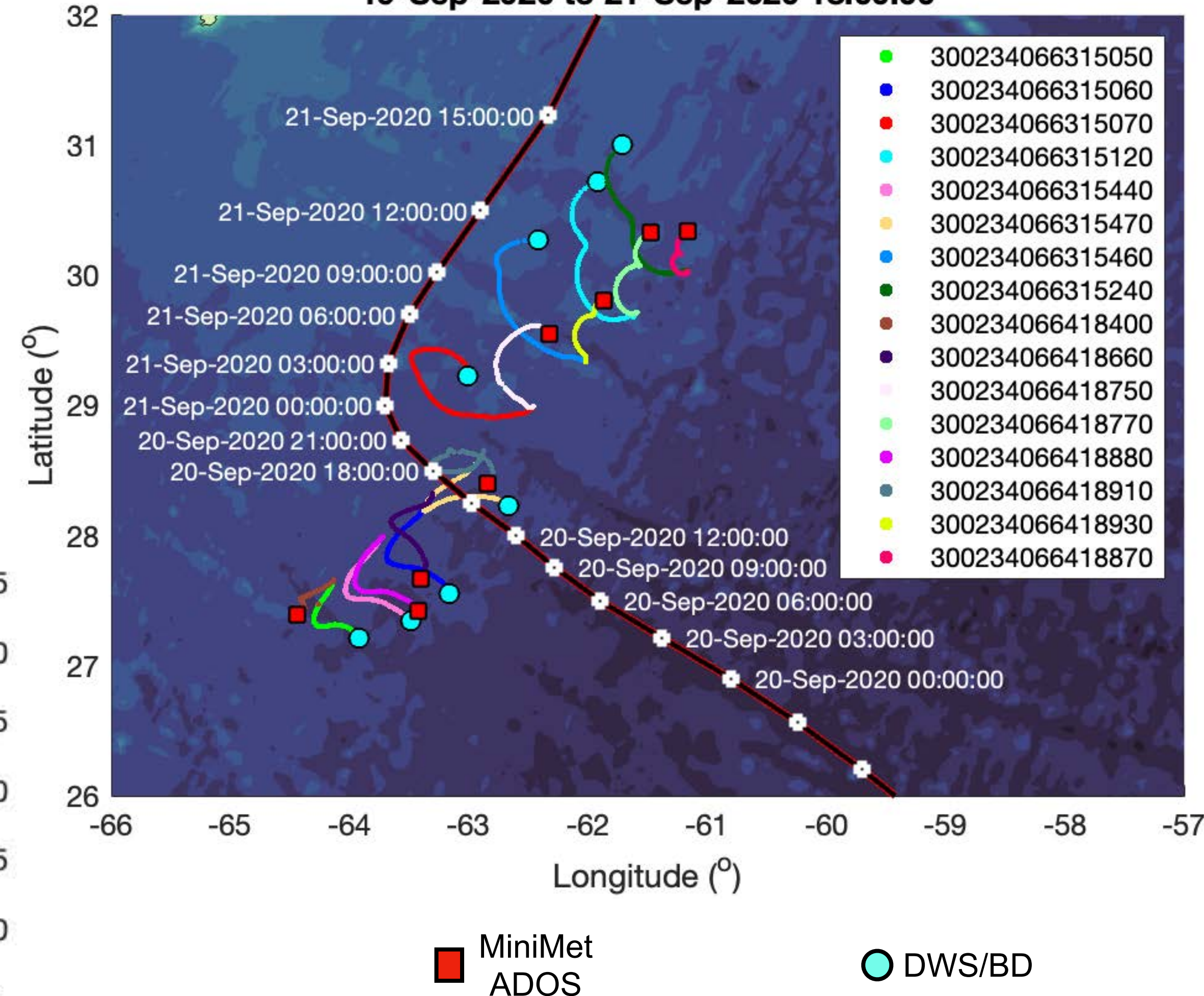


Number of Wave Observations



## Hurricane Teddy (2020)

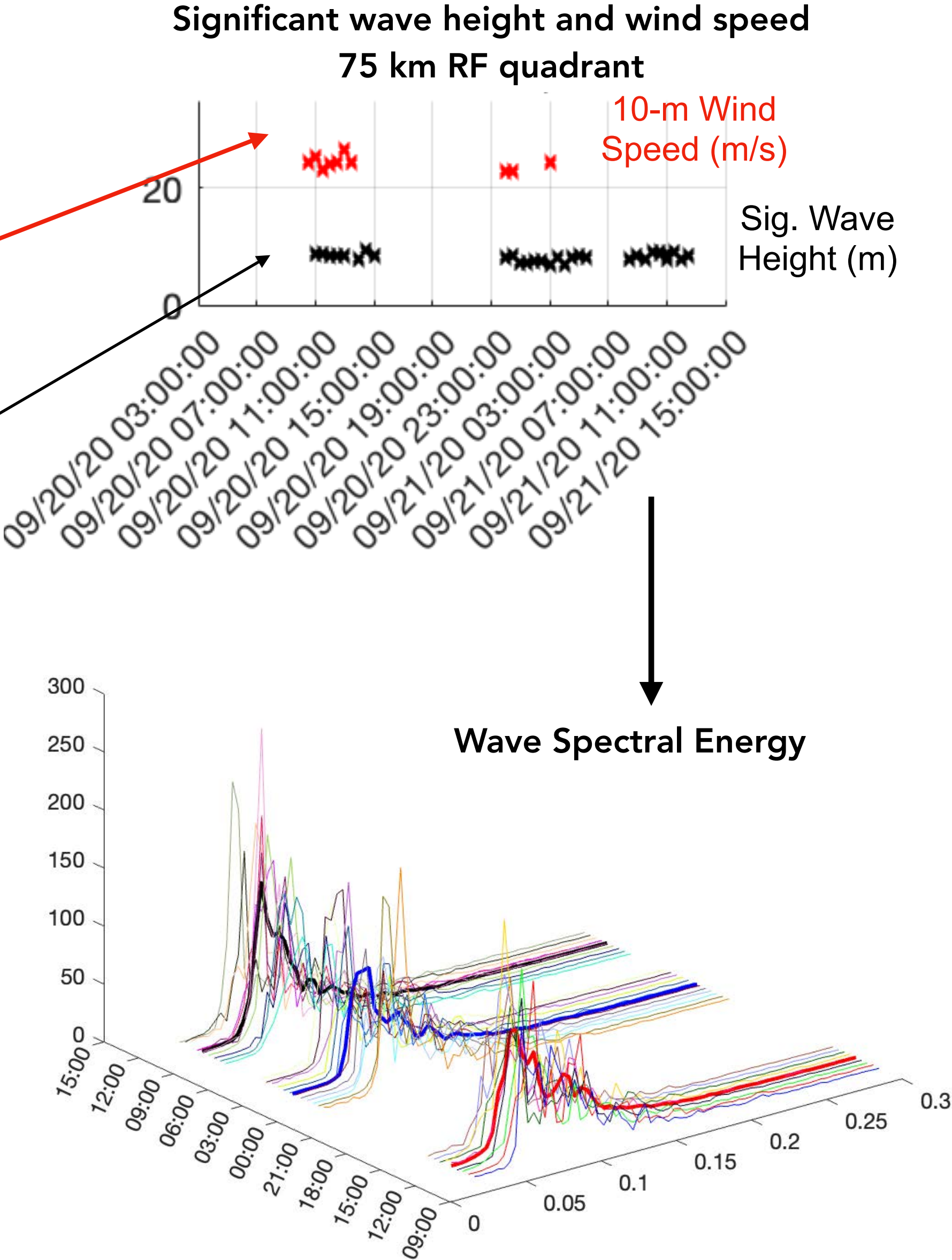
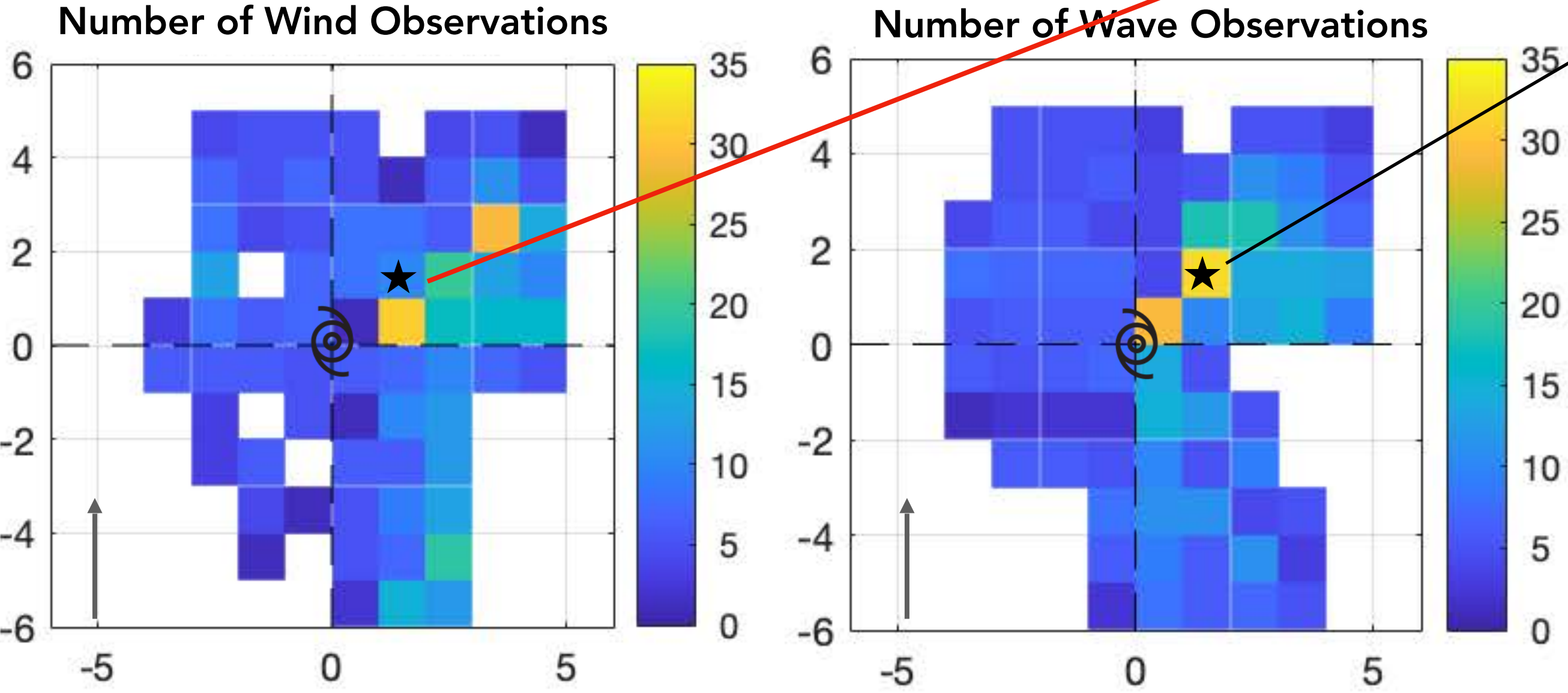
19-Sep-2020 to 21-Sep-2020 18:00:00



# Hurricane Teddy: Wave and Wind Evolution

- Time series from a given location in the storm can be made for wind and waves

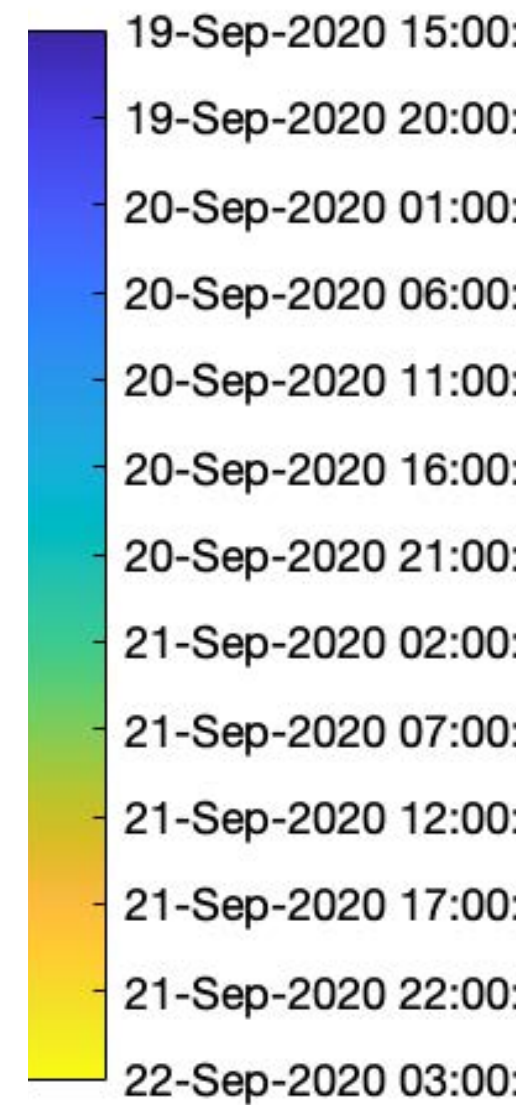
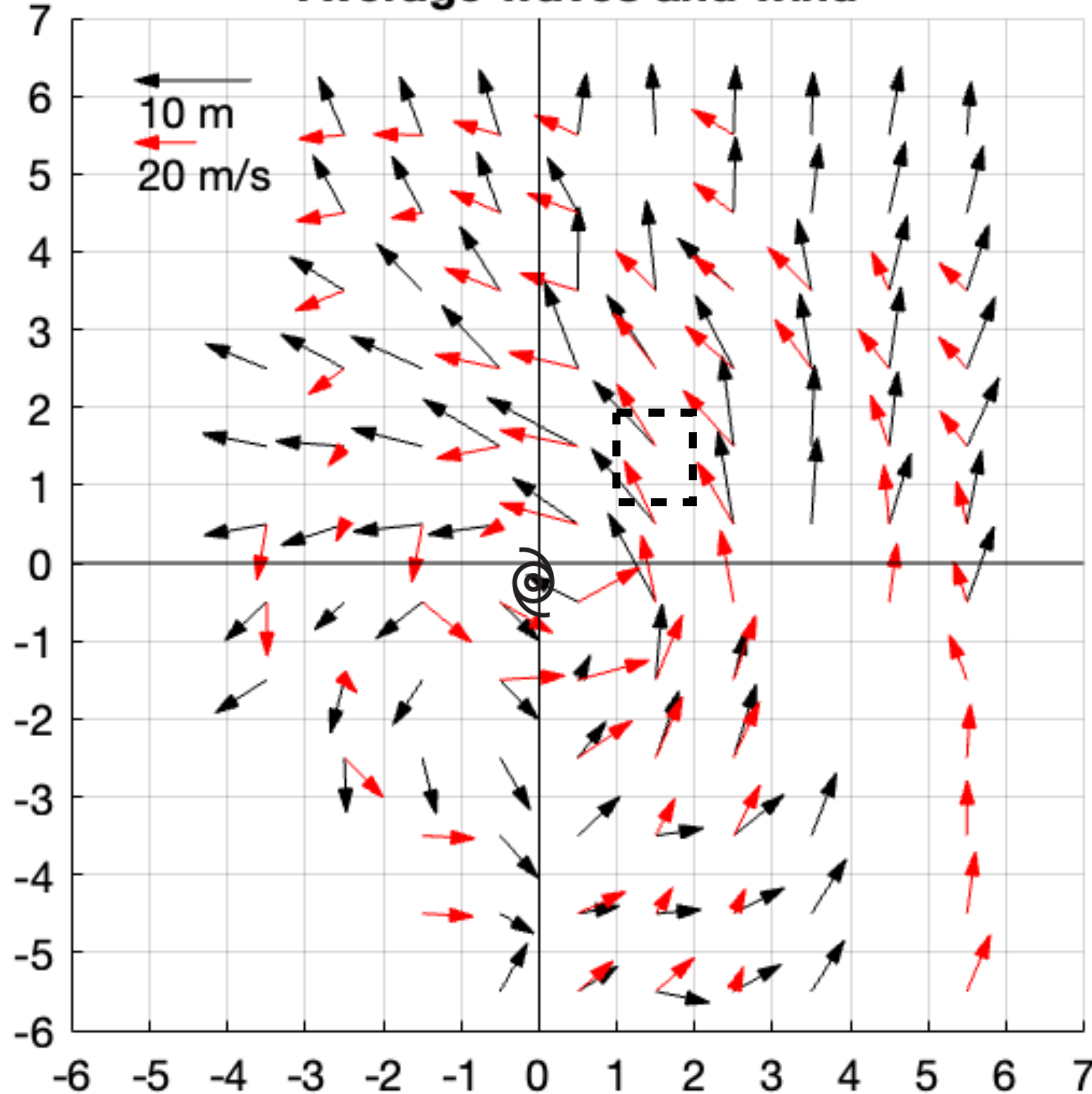
## Hurricane Teddy (2020)



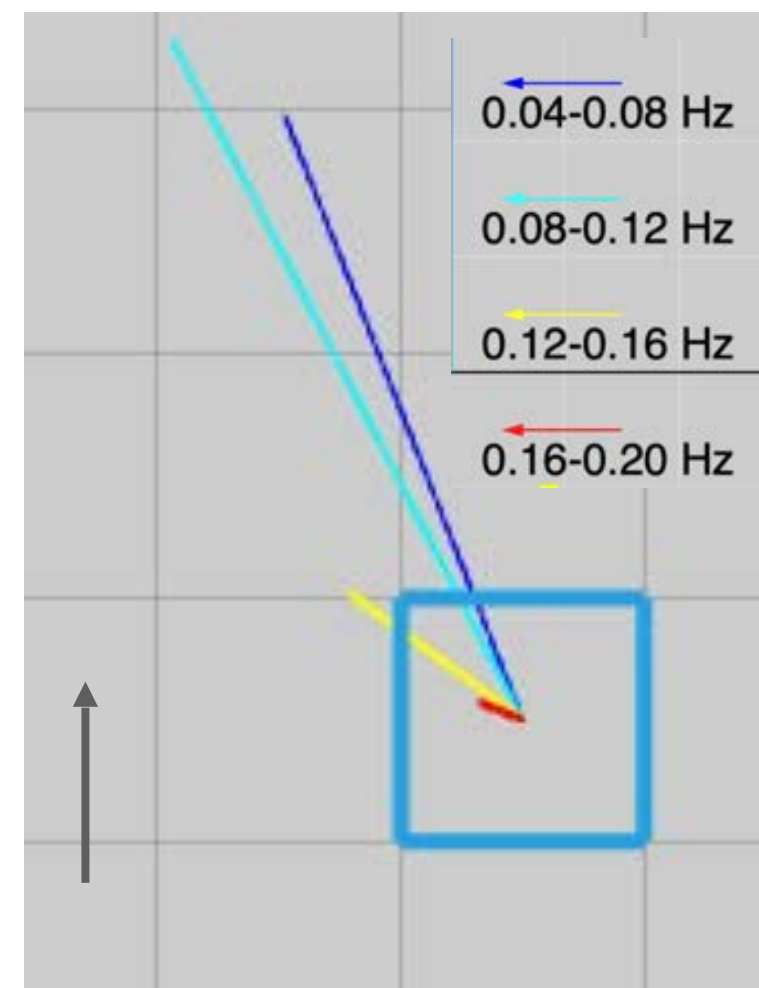
# Hurricane Teddy: Wave and Wind Alignment

## Hurricane Teddy (2020)

### Average waves and wind



20 Sep 13:00  
Before turn



21 Sep 2:45  
During turn



21 Sep 10:42  
After turn



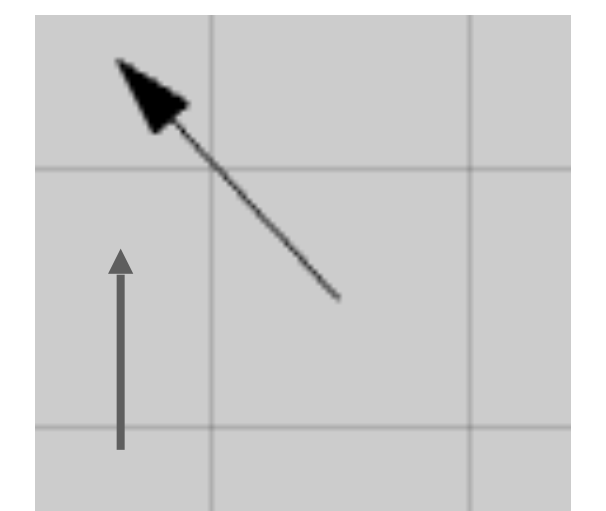
20 Sep 13:00



21 Sep 2:45



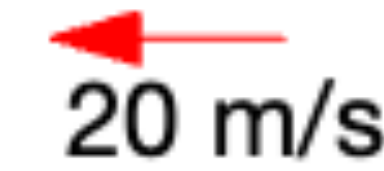
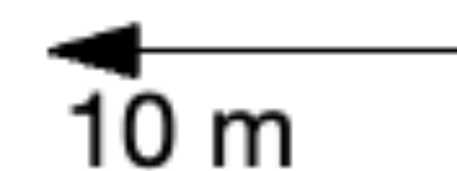
21 Sep 10:42



• Average of wind/  
waves during the  
same period

• Evolution of directional wave energy as storm turns show the adjustment of the waves become at different angle with wind

**Sig. Wave Height/  
Dominant Direction**

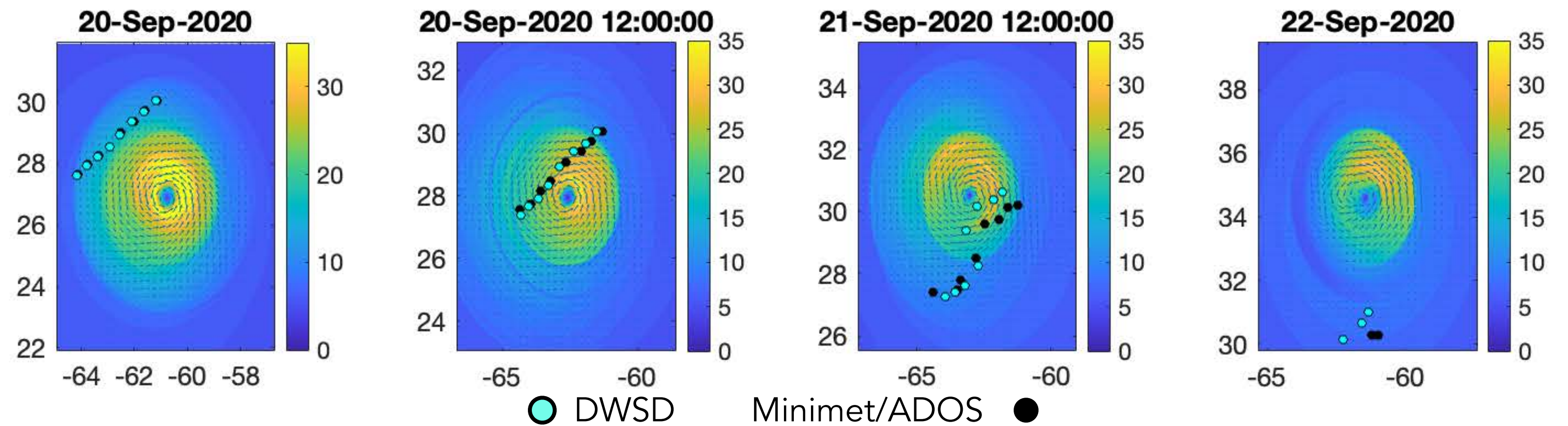


**Wind Speed/  
Direction**

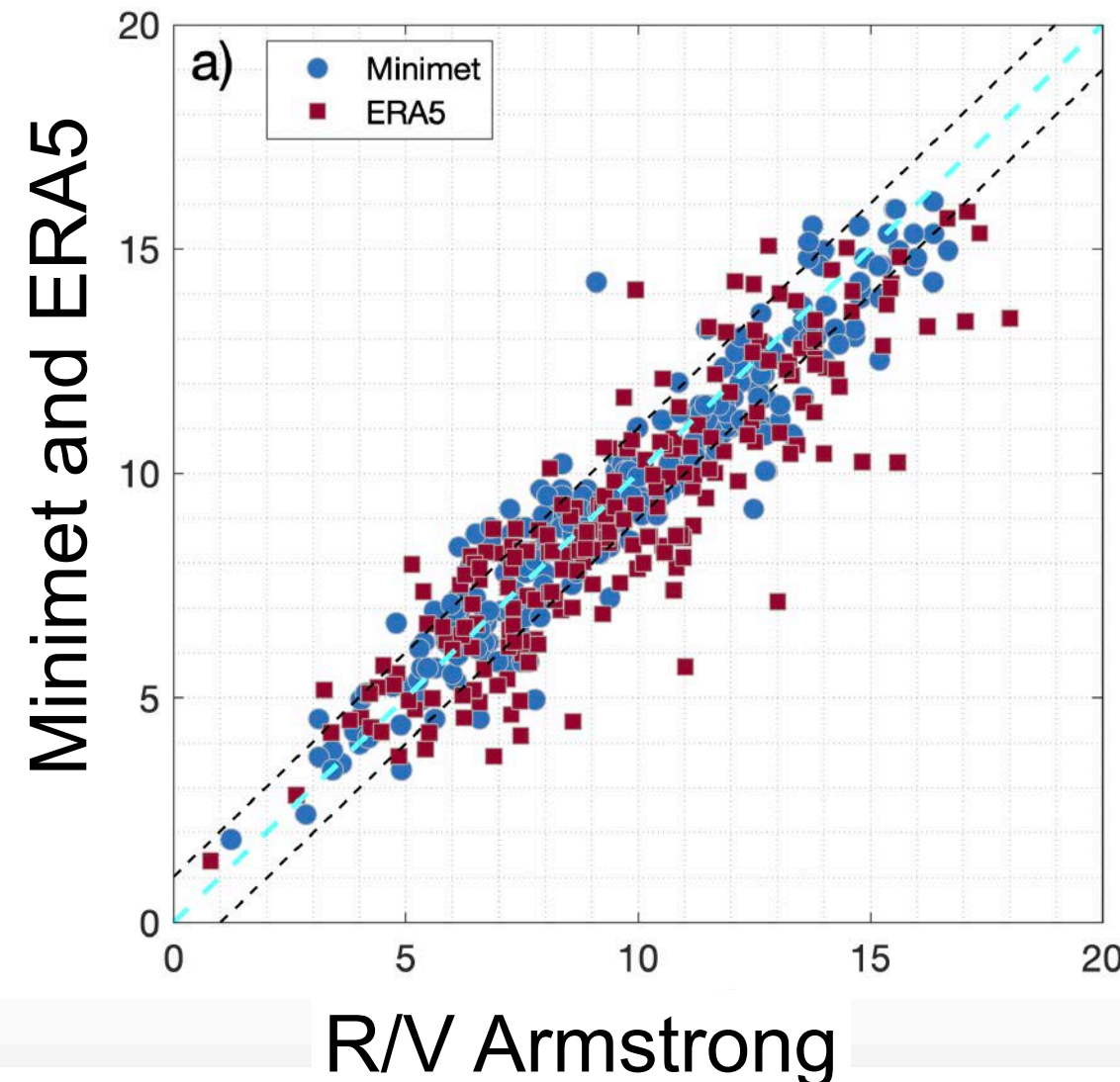
# Surface Wind Measurement (and Modeling)

- Previous results show good agreement between Minimet wind speed and direction with ERA5 and shipboard observations. In hurricanes, these observations show that some products and models may differ at high wind speed.

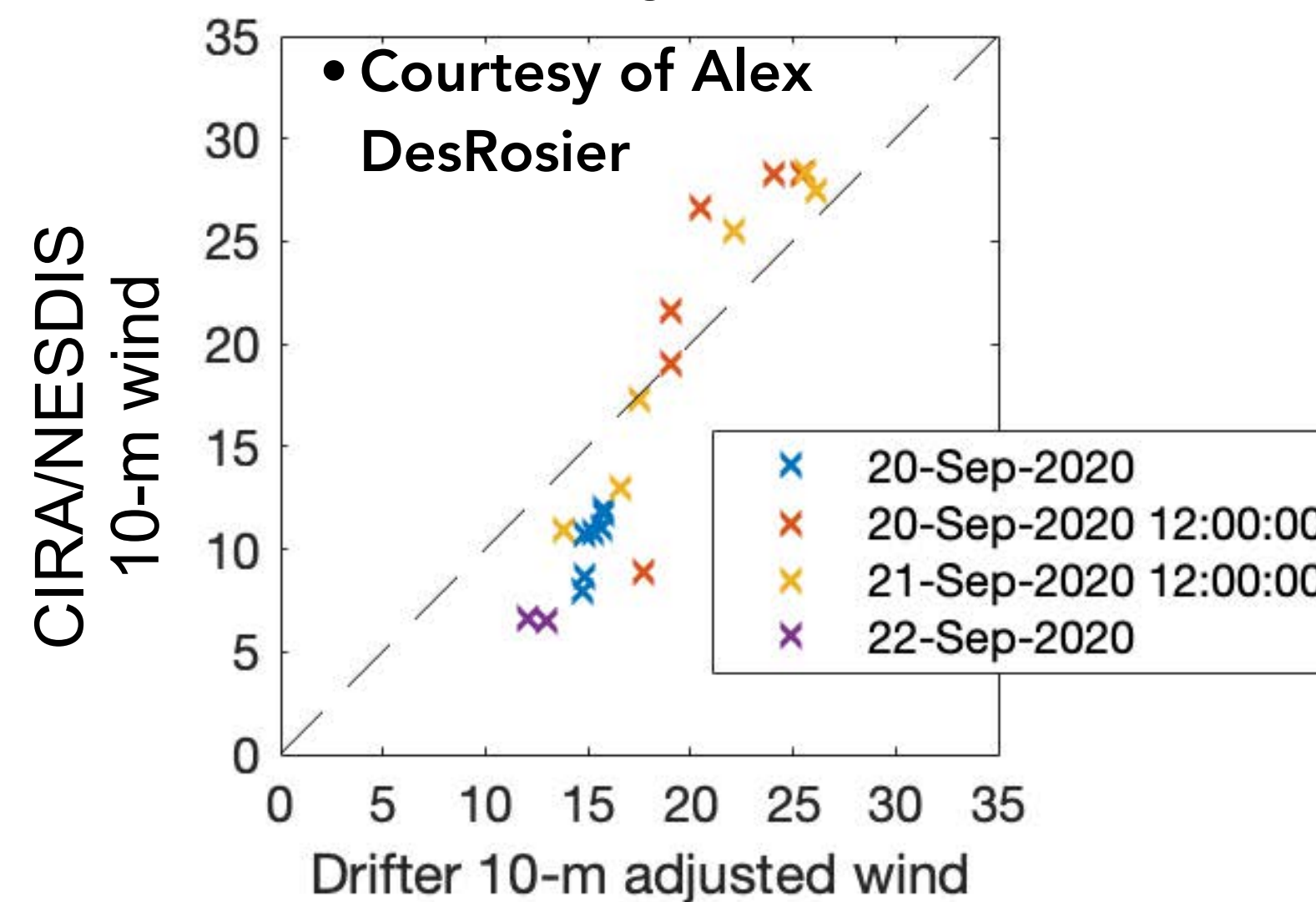
- **CIRA/NESDIS Wind Analysis** combines airborne and satellite data courtesy of Alex DesRosiers (CIRA-CSU) and John Knaff (NESDIS-STAR)



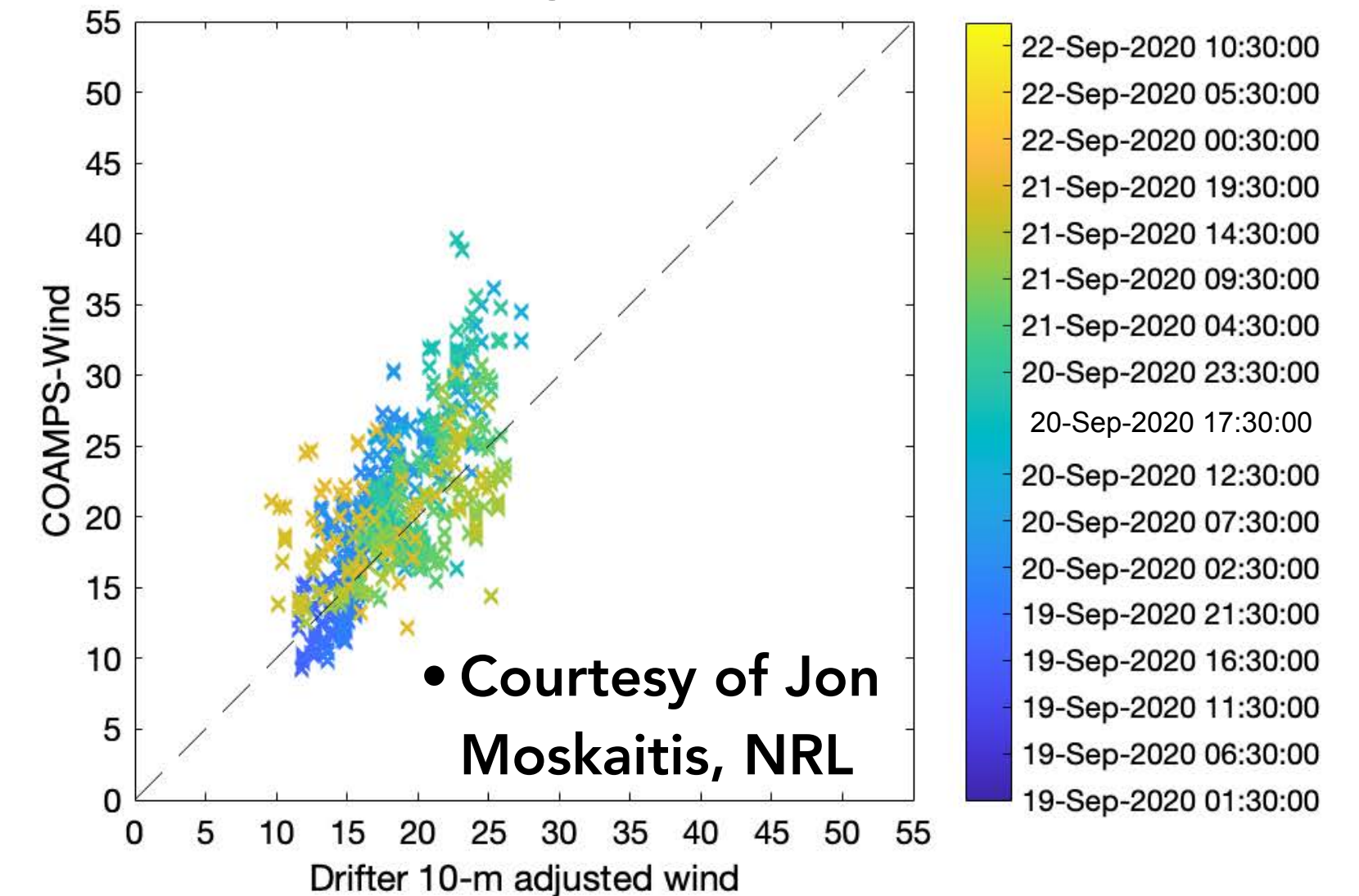
## Comparison to Shipboard observations: Klenz et al. 2022



## Hurricane Teddy: CIRA/NESDIS



## Hurricane Teddy: COAMPS-TC



# Summary

- **CW3E** and the **GDP** have partnered to increase the number of **SLP** observations in the N. Pacific. Waves, near-surface currents and SST are also measured.
- SLP from drifter data have had **beneficial impacts** on numerical weather prediction in the AR Region, extending to **250 hPa**, and out to **5 days**.
- There have been **~4.5 million** observations of SLP by GDP drifters with AR Recon barometer upgrades since 2019.
- Recent studies (e.g., Lavers et al., 2025) have shown that the **greatest impact** of SLP observations on NWP is in the regions of **high SLP gradient**
- Targeting of extreme events with **barometer-equipped wave drifters (A-DWSBDs)** shows the feasibility to resolve SLP at **~25 km** horizontal resolution across high gradient regions

