Uncrewed Surface Vehicles developed for GOOS:
A success story of Public-Private Partnership of NOAA Research and Saildrone

NOAA/PMEL and CICOES/UW: *Dongxiao Zhang, Chidong Zhang, Meghan Cronin, Adrienne Sutton, Calvin Mordy, Jessica Cross, Noah Lawrence-Slavas, Andy Chiodi, Edward Cokelet, Eugene Burger, Kevin O'Brien, Phyllis Stabeno;*

DOE/PNNL: *Chris Meinig;*

NOAA/AOML and CIMAS/UM: *Greg Foltz, Jun Zhang, Gustavo Goni;*

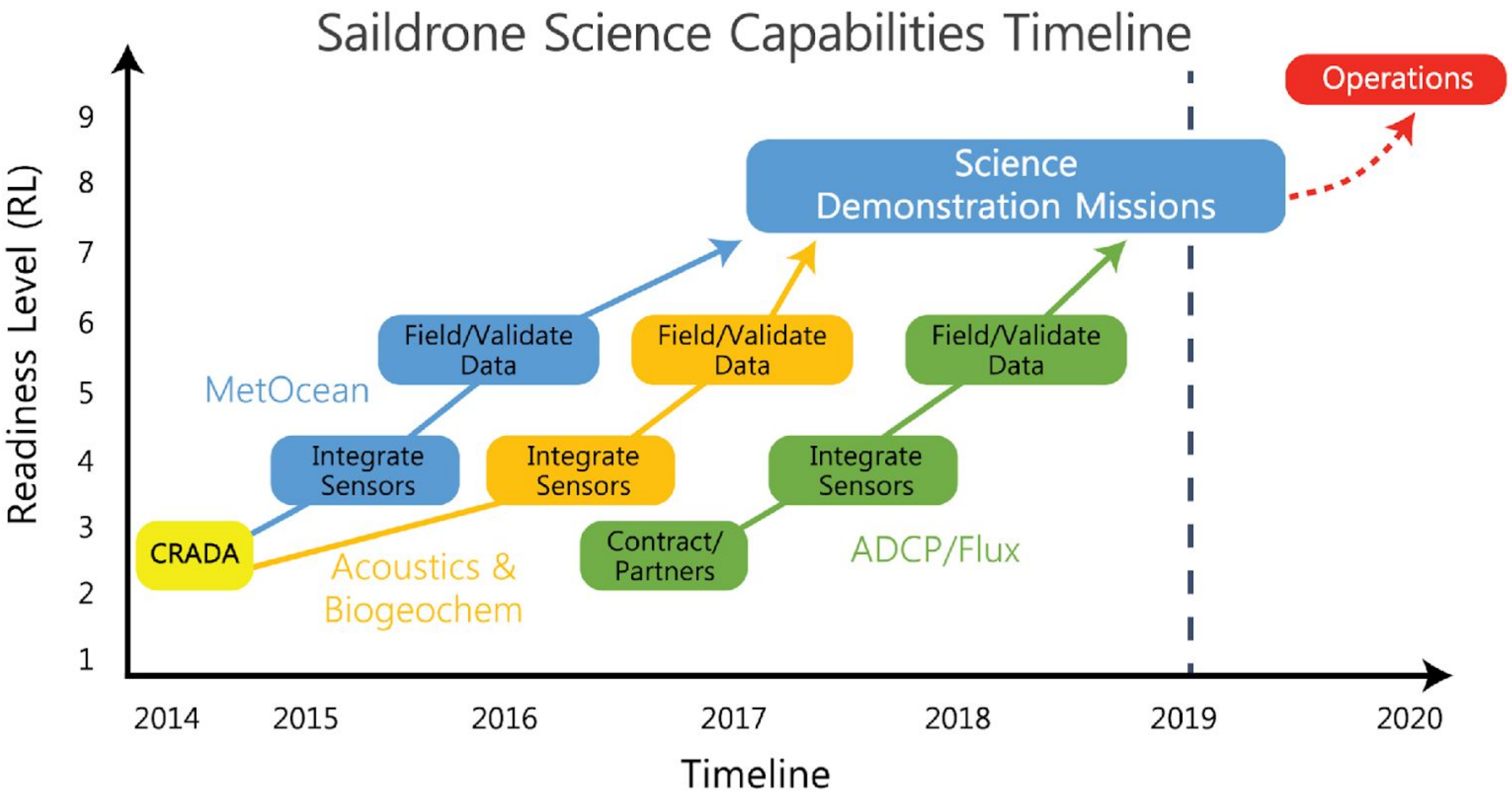
NOAA/PSL: *Elizabeth Thompson, Chris Fairall;*

Saildrone, Inc.: *Richard Jenkins, et al.*

Picture by saildrone inside Hurricane Sam recorded significant wave height 14.6 meters 9/30/2021

Acknowledge support from GOMO, OMAO, OER, WPO, and CVP

Saildrones: Global Class Autonomous Surface Vehicles for Air-Sea Interaction Observation



Fast development, production and application cycle, Public-Private Partnership.
Meinig et al. 2019 OceanObs'19

- ***2015-16: PMEL Innovative Technology for Arctic Exploration and AFSC Bering Sea fish biomass surveys with off-the-shelf surface Met/ocean sensors and echosounder -- Saildrone time through CRADA***

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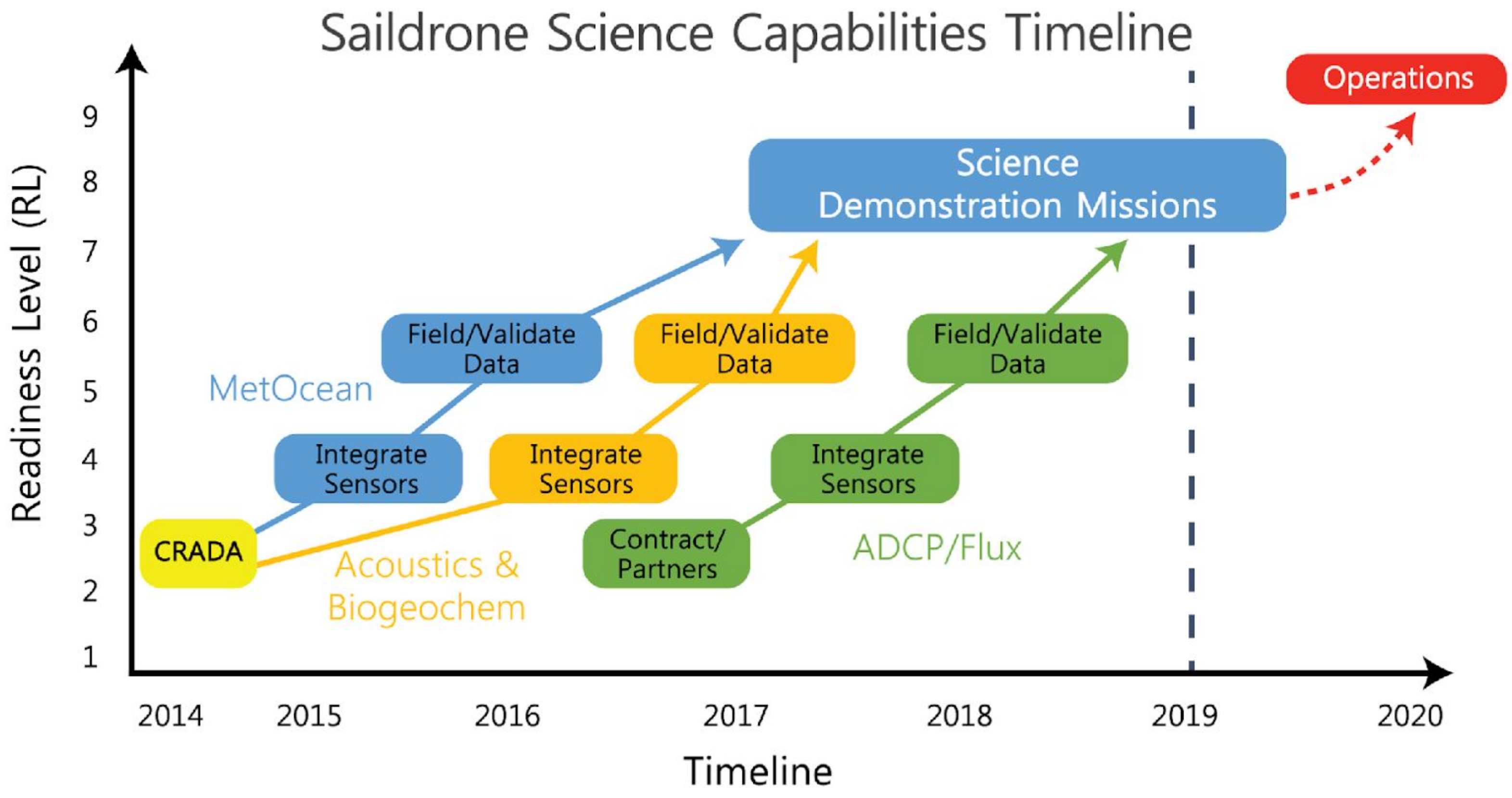

Fast development, production and application cycle, Public-Private Partnership.
Meinig et al. 2019 OceanObs'19

One of the GOMO TPOS-2020 pilot projects

- ***2016-19: Tropical Pacific Observing System (TPOS) and NOAA Tech. Development (Air-sea heat, momentum and CO_2 fluxes, ADCP upper ocean currents) -- 3 TPOS Saildrone Misssions***
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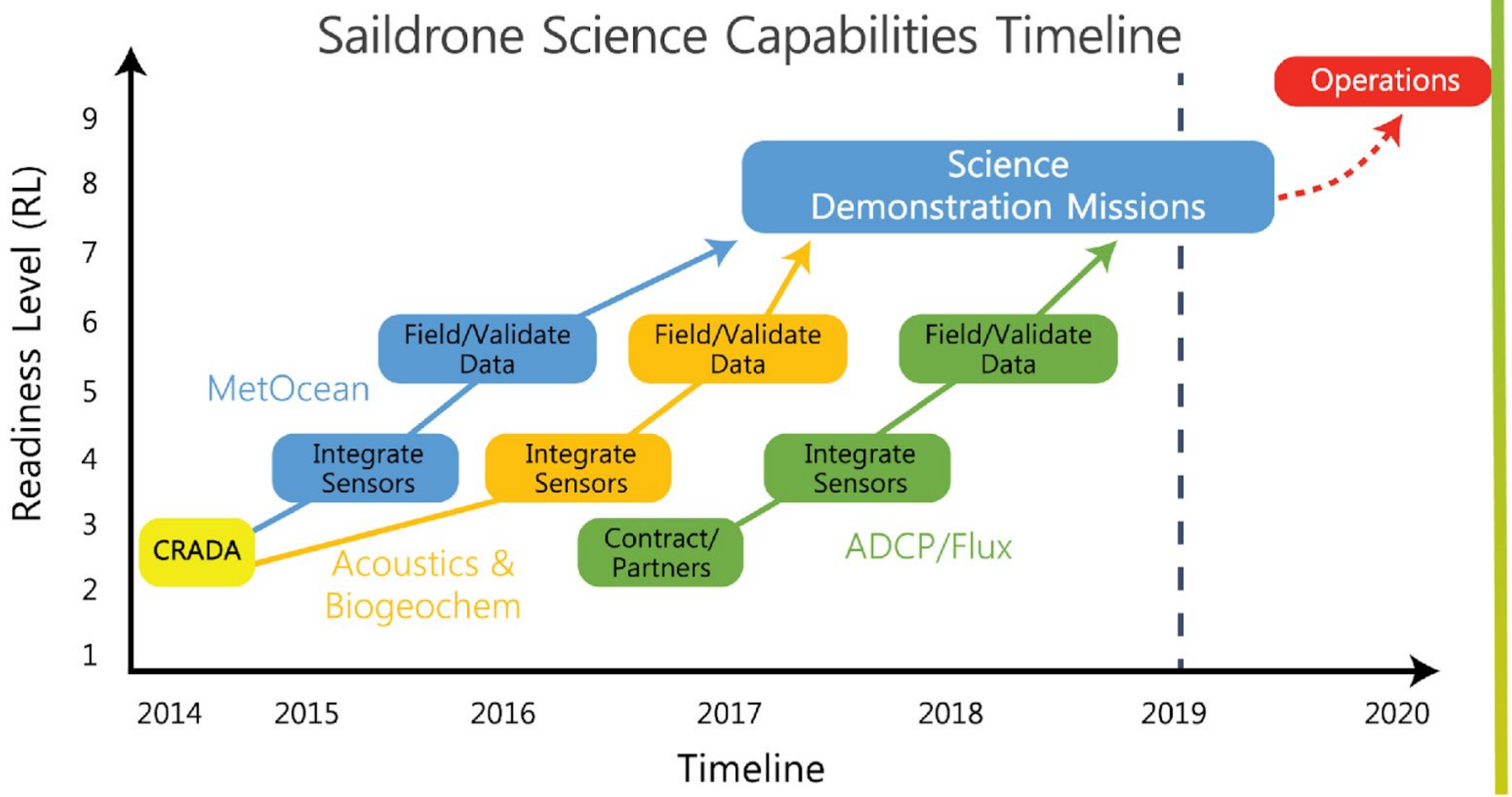

Fast development, production and application cycle, Public-Private Partnership.
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- ***2023: Hurricane Mission 3***
- ***2023: Tropical Pacific Observing System Integration (TPOS Mission 6)***
- ***2022: Hurricane Mission 2***
- ***2022: TPOS Mission 5***
- ***2021-22: Eastern Tropical Pacific Hurricane Genesis and Cold Tongue Upwelling (TPOS Mission 4)***
- ***2021: Tropical Atlantic Hurricane Intensification (Hurricane Mission 1)***
- ***2020: NOAA ATOMIC Field Campaign in the Tropical Atlantic***
- ***2019: PMEL Air-Sea Flux Measurements Following Rapid Arctic Ice Retreat***
- ***2016-19: Tropical Pacific Observing System (TPOS) and NOAA Tech. Development (Air-sea heat, momentum and CO_2 fluxes, ADCP upper ocean currents) -- 3 TPOS Saildrone Misssions***
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Autonomous Surface Vessels as Low-Cost TPOS Platforms for Observing the Planetary Boundary Layer and Surface Biogeochemistry

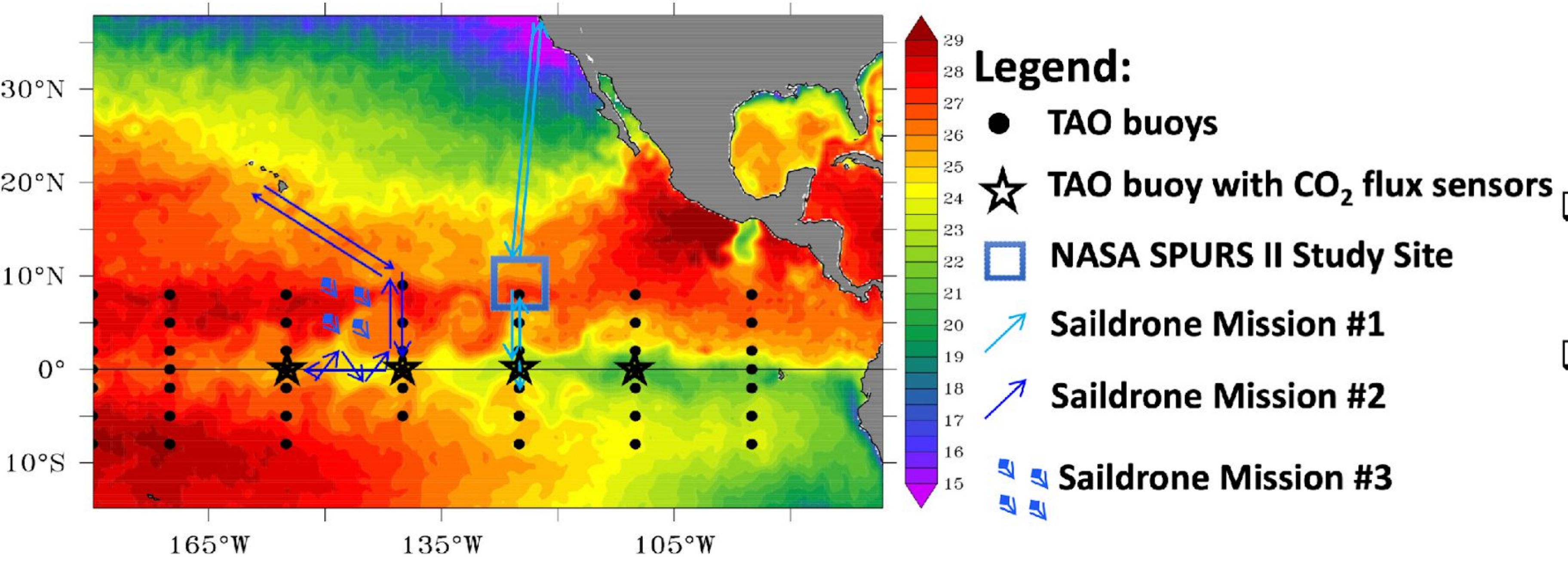
Co-PIs: M. Cronin, D. Zhang, A. Sutton, C. Meinig
Postdocs: Samantha Wills, Jack Reeves Eyre

Goal: Testing the ability of Saildrone to make ***climate-quality*** *measurements in the Tropics*

Funded by GOMO, supplemented by OMAO

Three 6-month missions:

1) NASA salinity study (SPURS II) and 125°W section (Sept.2017)
2) Equatorial sections 140°W, with and against currents (Oct. 2018)
3) Cluster of 4 drones, adaptive sampling around 140°W (June 2019)



- ❑ Climate quality measurements (Zhang et al. 2019), with excellent resolution of sharp fronts and rapid variability (Cronin et al. 2023).
- ❑ Precise navigation is challenging in cold tongue region due to weak winds and strong ocean currents
- ❑ Each mission has led to changes to the platform and its use… and new understanding (Wills et al. 2021, 2023; Reeves Eyre et al. 2023)

Saildrone Explorer

Extreme Weather Saildrone

Off-the-shelf Sensors:

- Air Temperature and Relative Humidity
- Air Pressure
- SST (@-0.5m), SST and SSS (@-1.5m)

Wind and Wind Stress (Bulk and eddy covariance)

ADCP currents (upper 100m) or **Echosounder fish biomass**

Air-sea heat fluxes (LW and SW radiation, bulk latent heat and sensible heat)

Waves (significant wave height, period, and direction)

Cameras (ice and cloud images)

BGC Suite

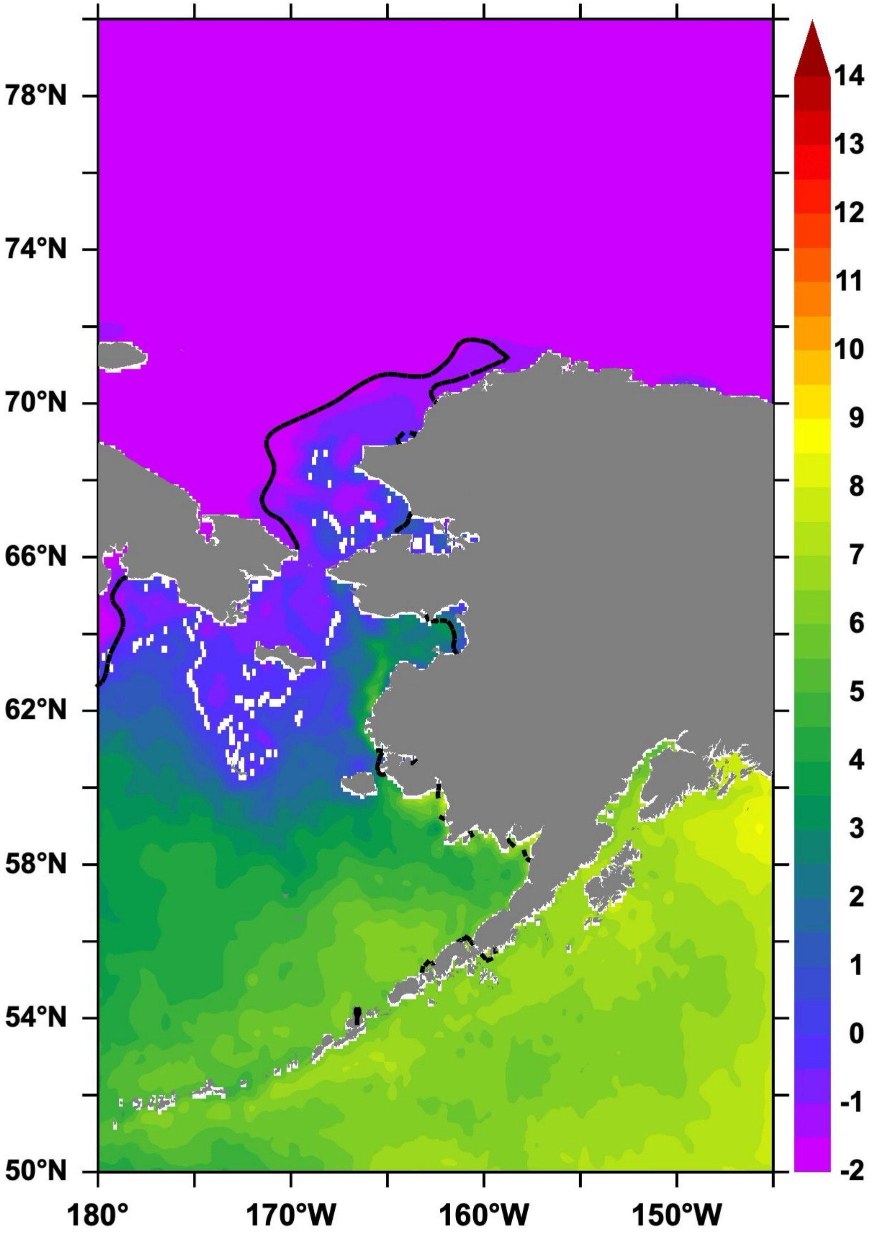
- Air pCO2, Sea surface pCO2, bulk air-sea CO2 flux
- Dissolved Oxygen, Chla

Air-sea Fluxes Following the Unusual Summer Ice Retreats

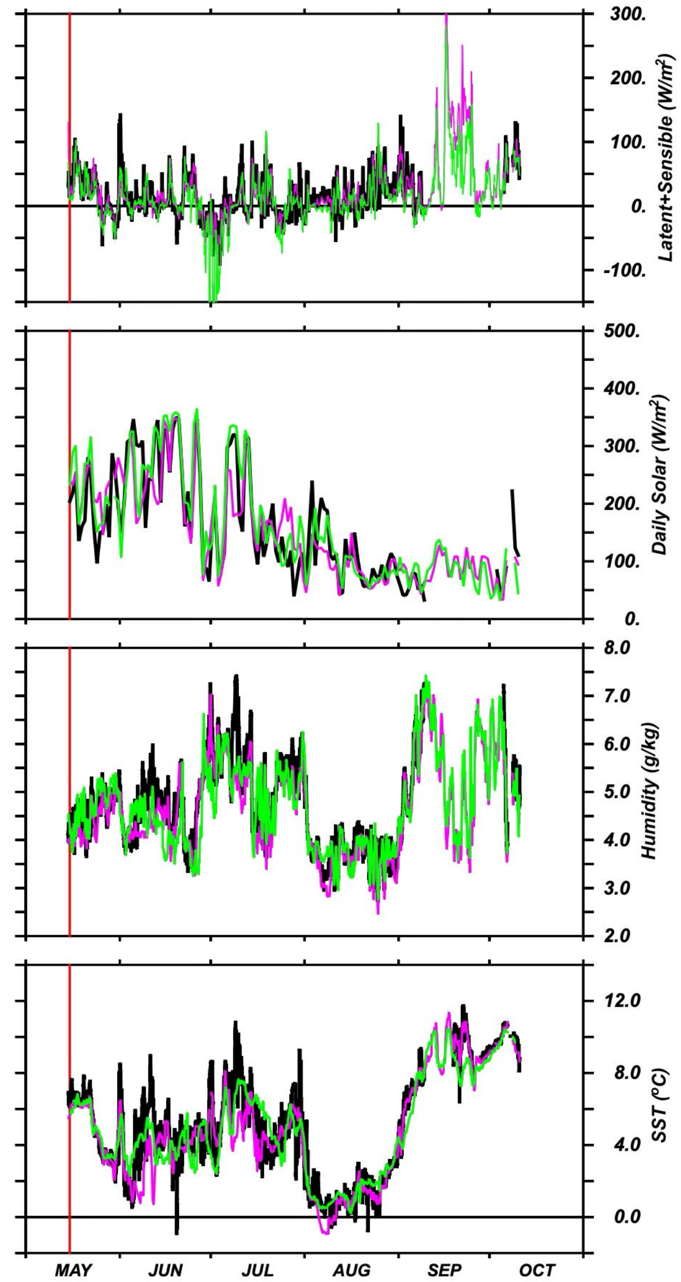
PIs: *Chidong Zhang, J. Cross (NOAA/PMEL)*
C. Mordy, D. Zhang (CICOES/PMEL)
A. De Robertis (NOAA/AFSC)
C. Gentemann (Farallon Institute, now NASA)

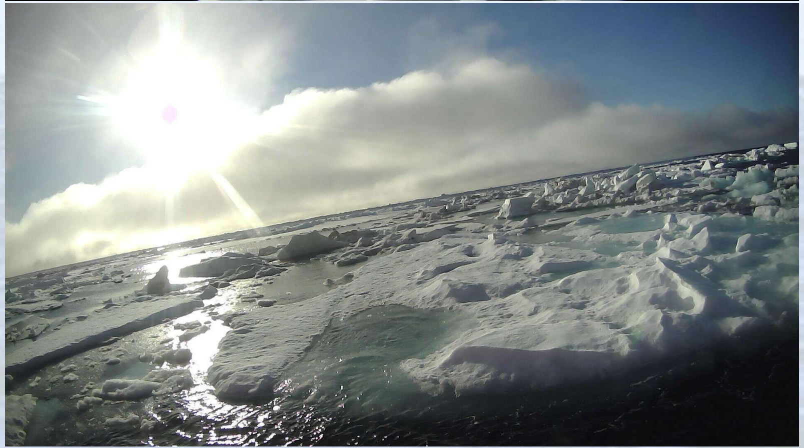
Funded by
NOAA: PMEL, GOMO/Arctic, OMAO, CPO/COM
NASA/NOPP

7-day Saildrone Tracks over Satellite SST 15-MAY-2019

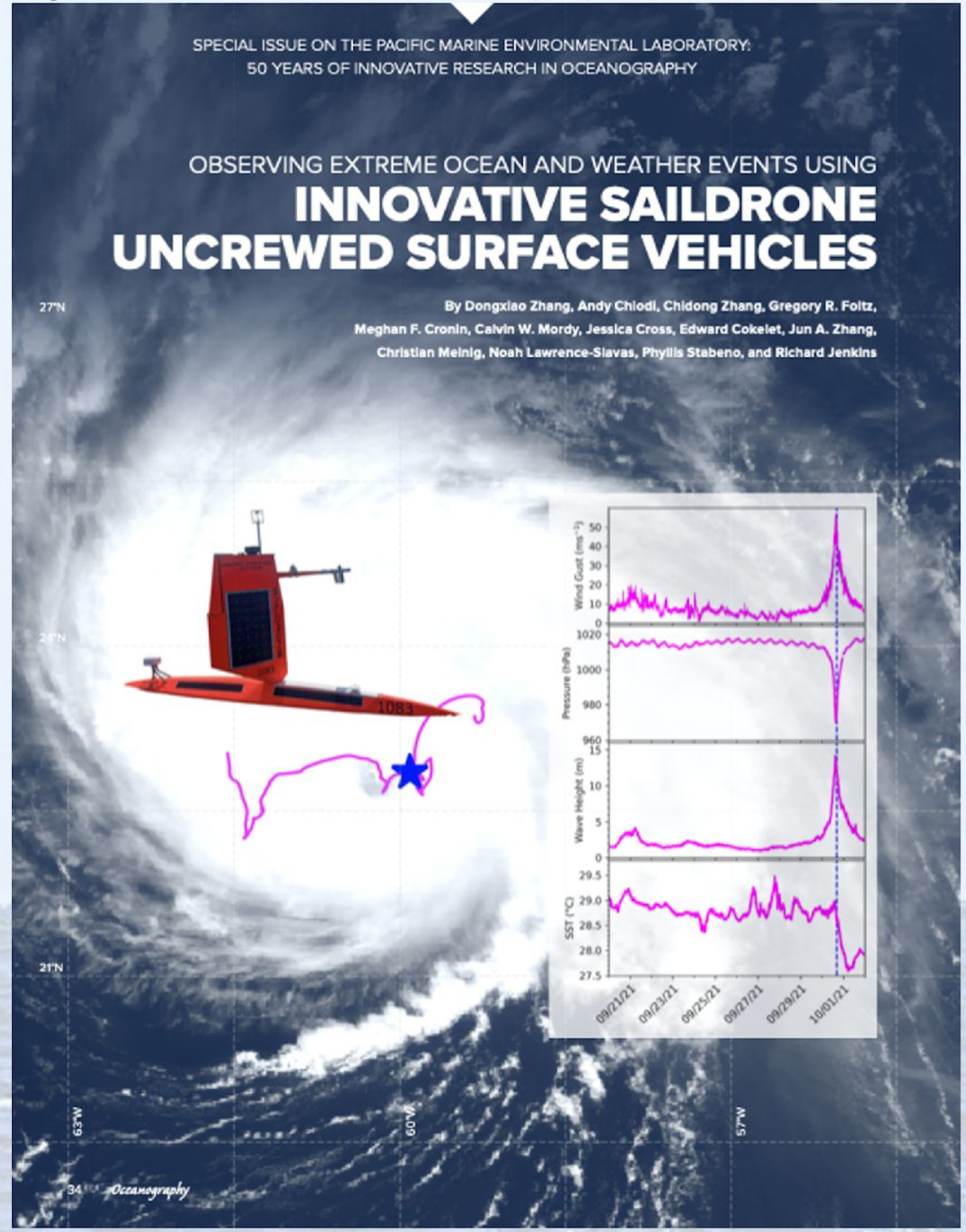


Saildrone1034 *vs.* ECMWF ERA5 and NOAA CFSR

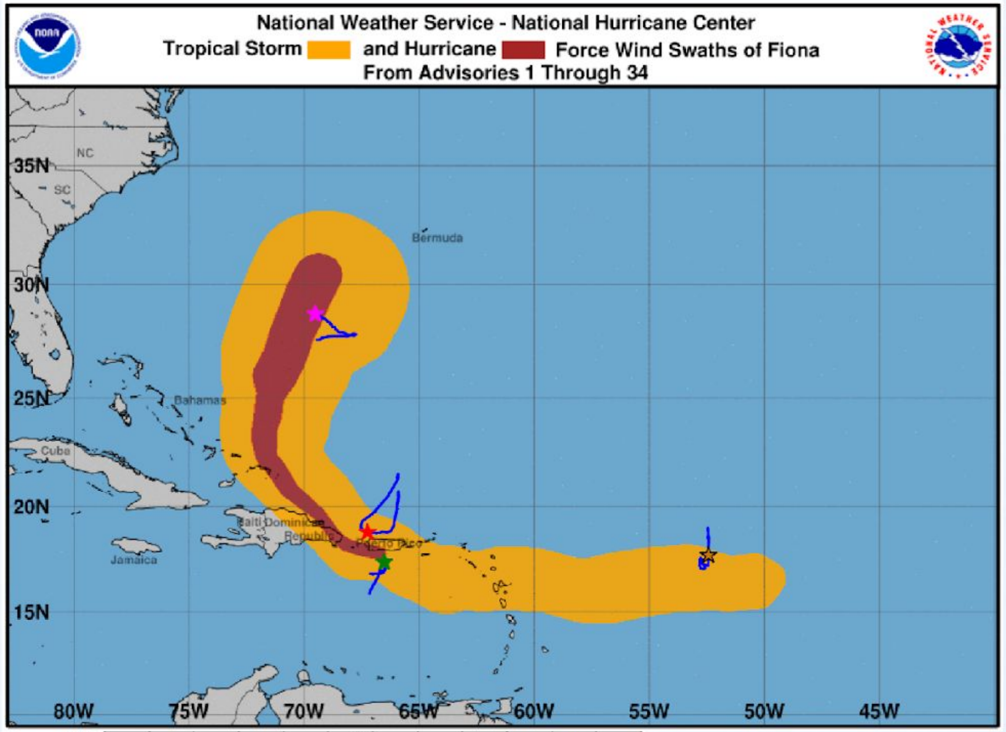


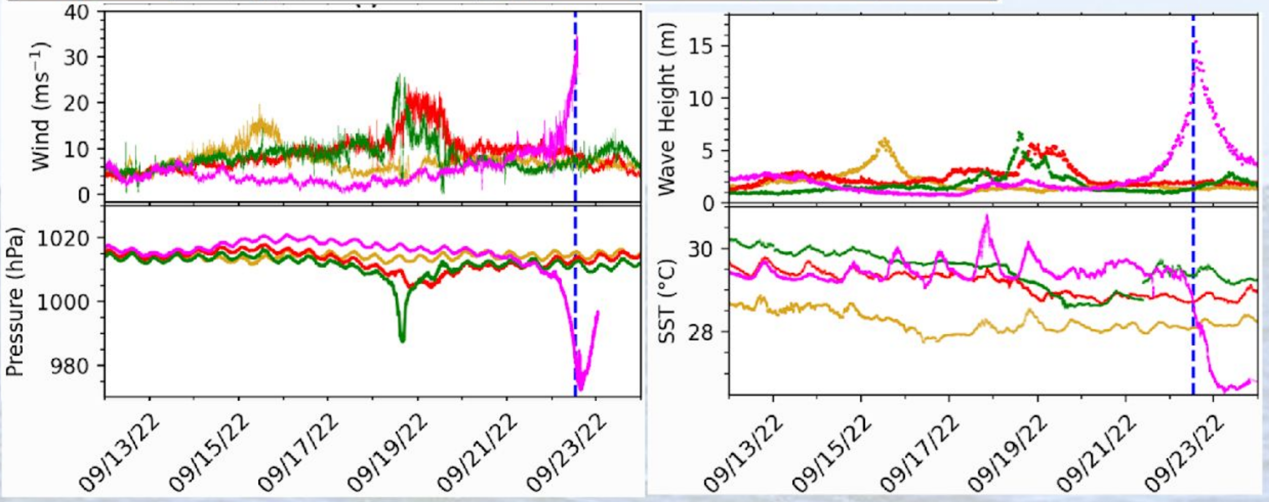


Zhang et al. 2023 **Observation of Category 4 Hurricane Sam 2021**



4 Saildrones observed Hurricane Fiona during its development from tropical storm to Category 4 hurricane 2022





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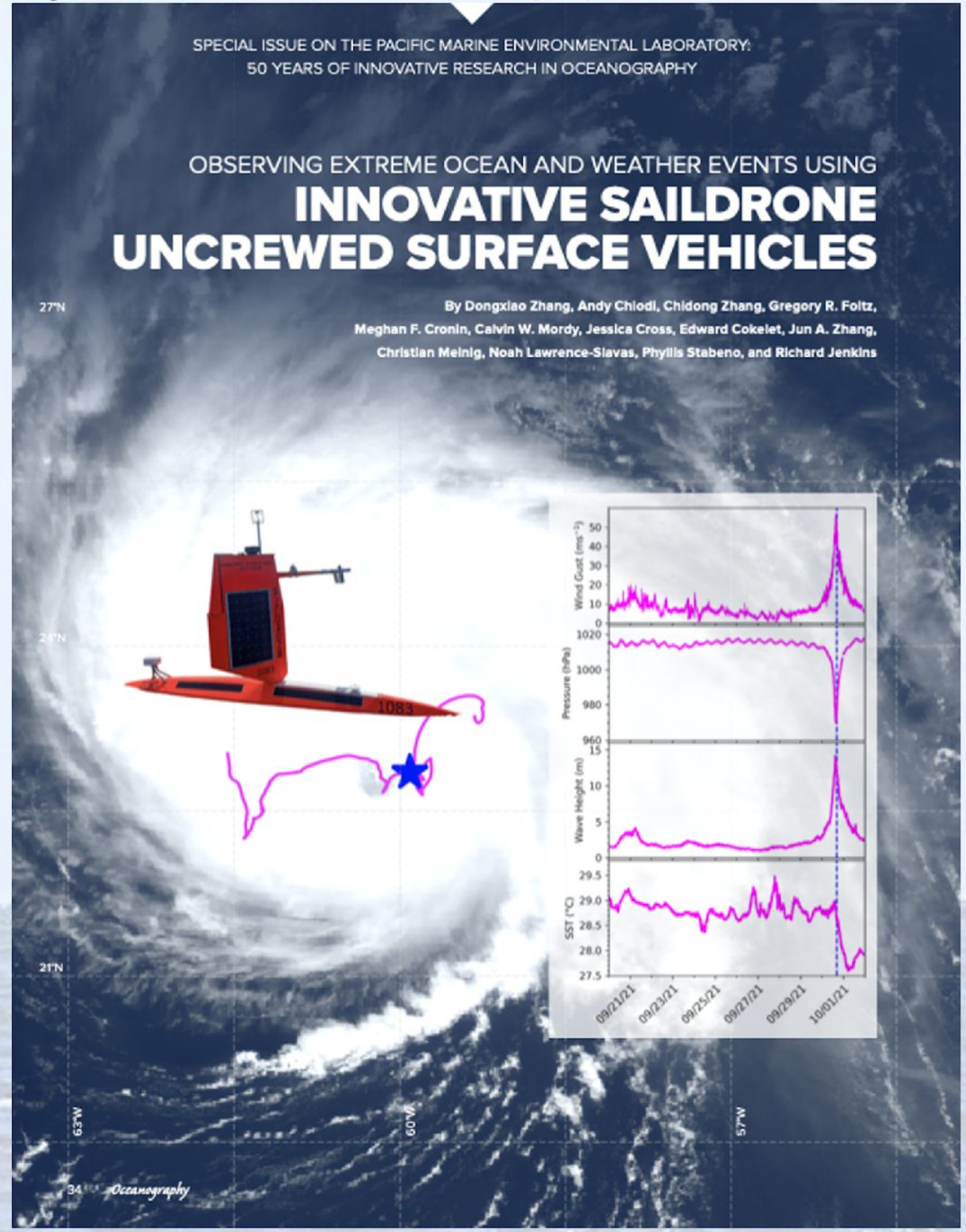

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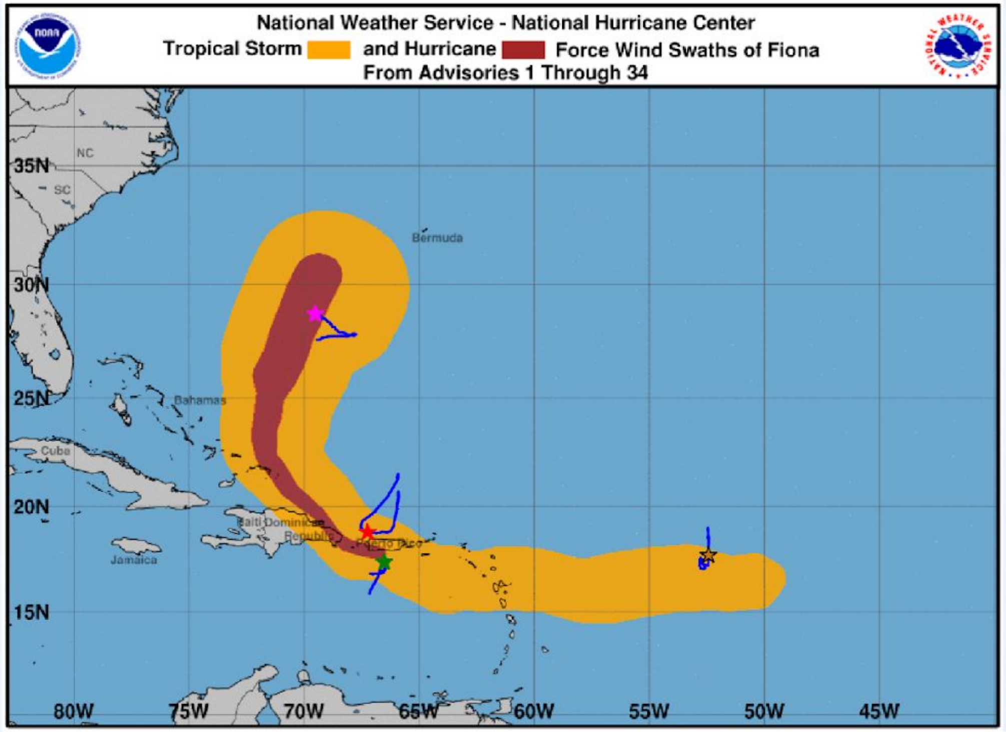

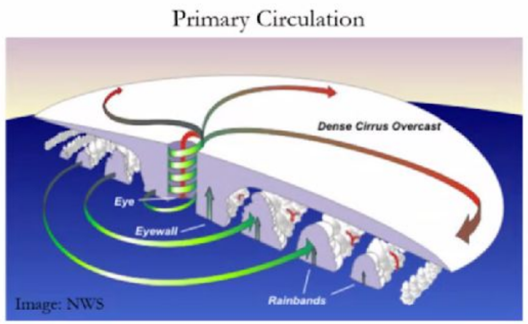

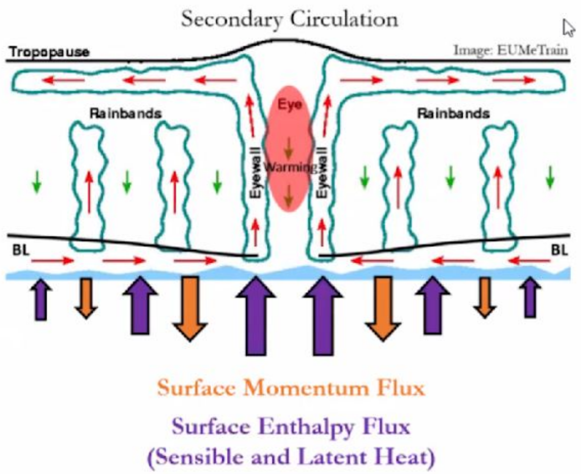

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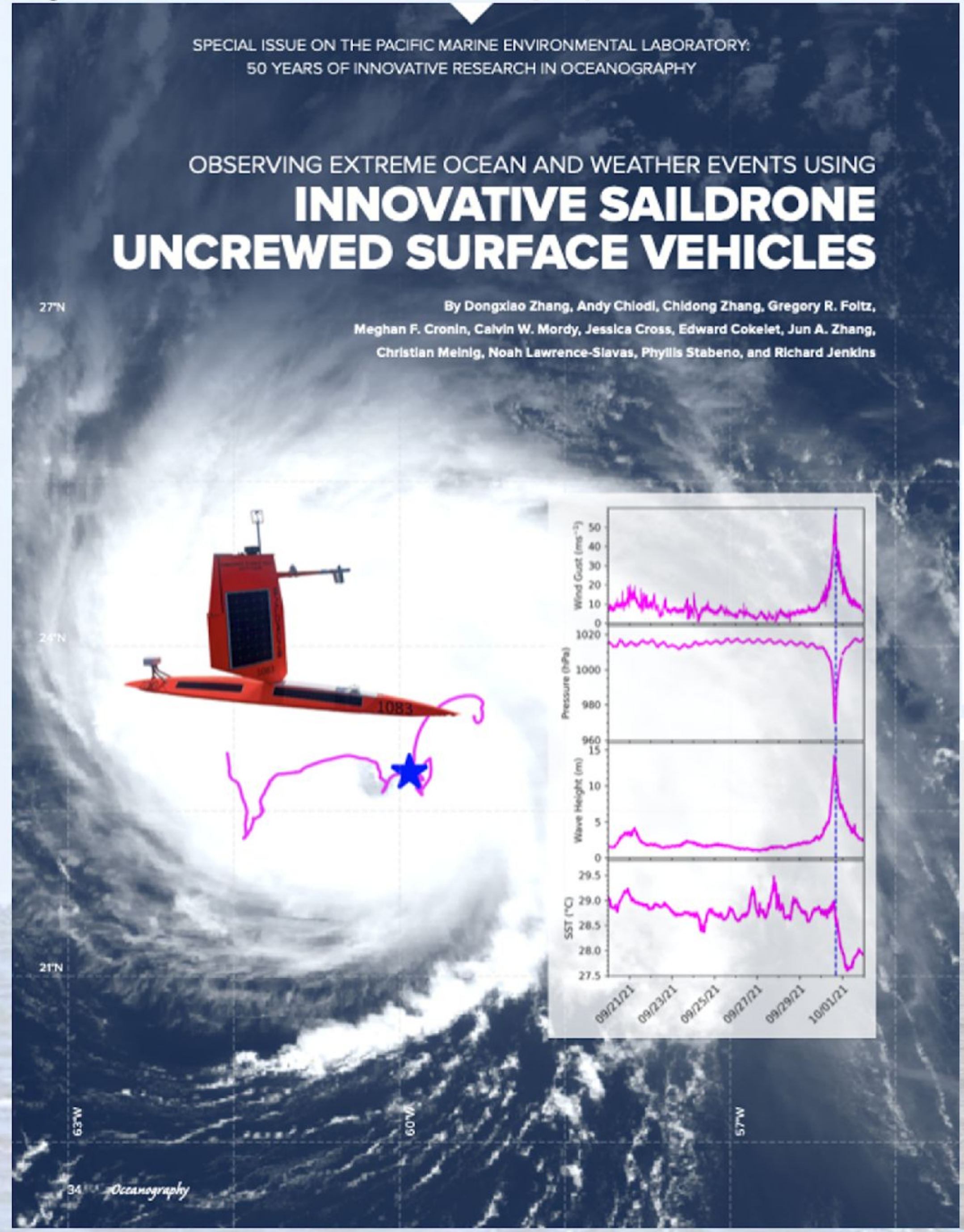
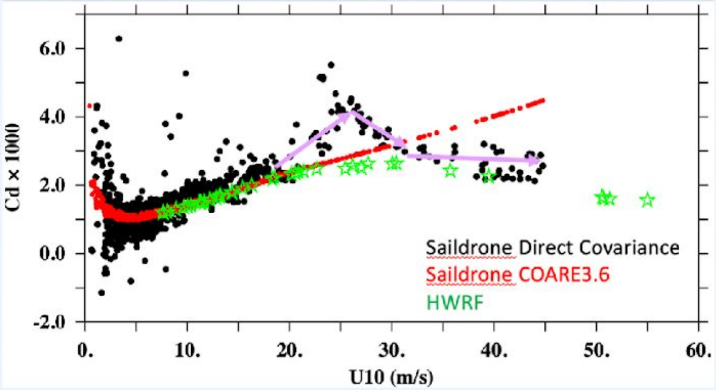

SPECIAL ISSUE ON THE PACIFIC MARINE ENVIRONMENTAL LABORATORY: 50 YEARS OF INNOVATIVE RESEARCH IN OCEANOGRAPHY

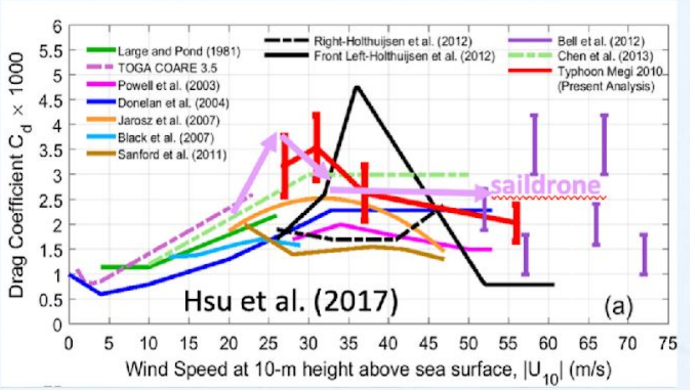
OBSERVING EXTREME OCEAN AND WEATHER EVENTS USING

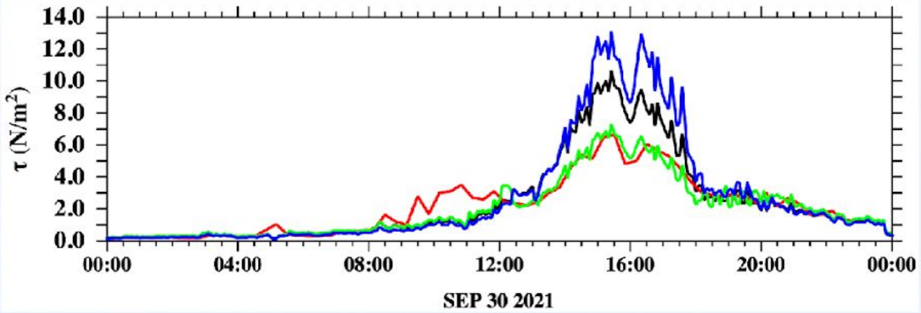
INNOVATIVE SAILDRONE UNCREWED SURFACE VEHICLES

By Dongxiao Zhang, Andy Chiodi, Chidong Zhang, Gregory R. Foltz, Meghan F. Cronin, Calvin W. Mordy, Jessica Cross, Edward Cokelet, Jun A. Zhang, Christian Meinig, Noah Lawrence-Slavas, Phyllis Stabeno, and Richard Jenkins

Saildrone Direct Eddy Covariance Momentum Flux vs. Bulk Fluxes to improve COARE bulk algorithm







Saildrone Direct Covariance

COARE3.6: Wind Dependent

Charnock coefficient saturates > 19m/s

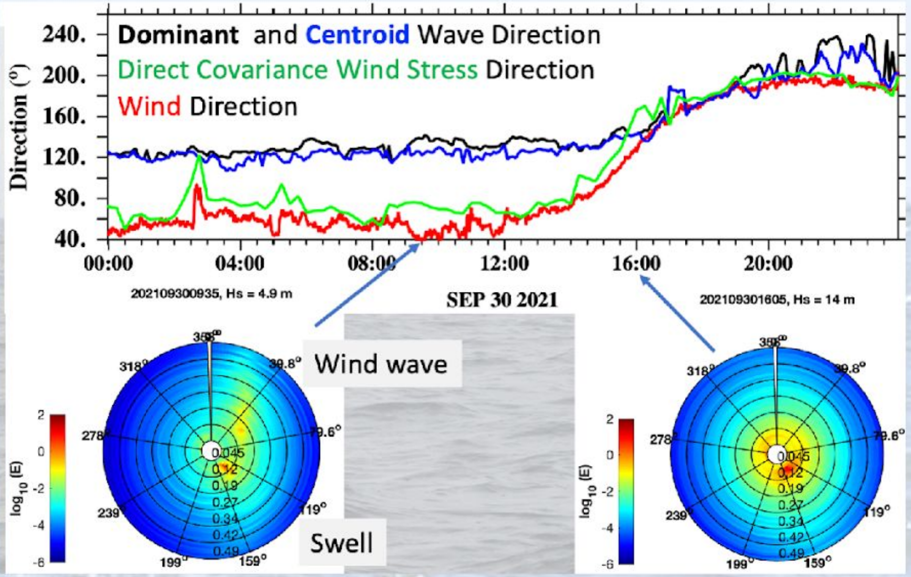
COARE3.6: Wave Dependent

Steepness (Significant H, Dominant period)

COARE modified:

Reduced Charnock > 28m/s

Steepness (Significant H, Centroid period)

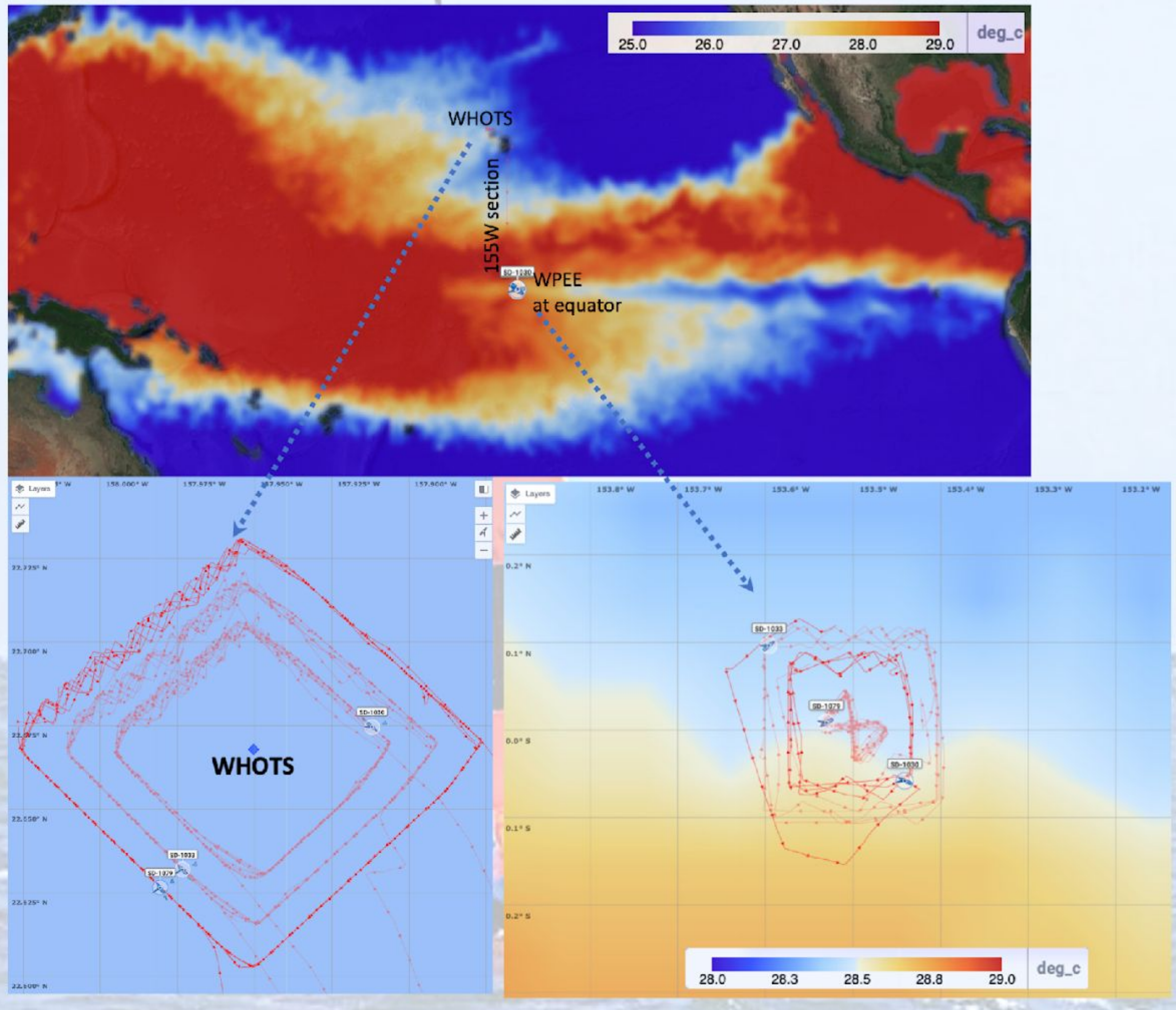


- **Wind stress is sensitive to waves**
- **Misaligned waves tend to turn wind stress toward the waves away from wind direction; Enhancing the wind stress (?)**
- **COARE3.6 wave dependent parameterization worth further investigation**

NOAA Saildrone Missions to Watch 2023

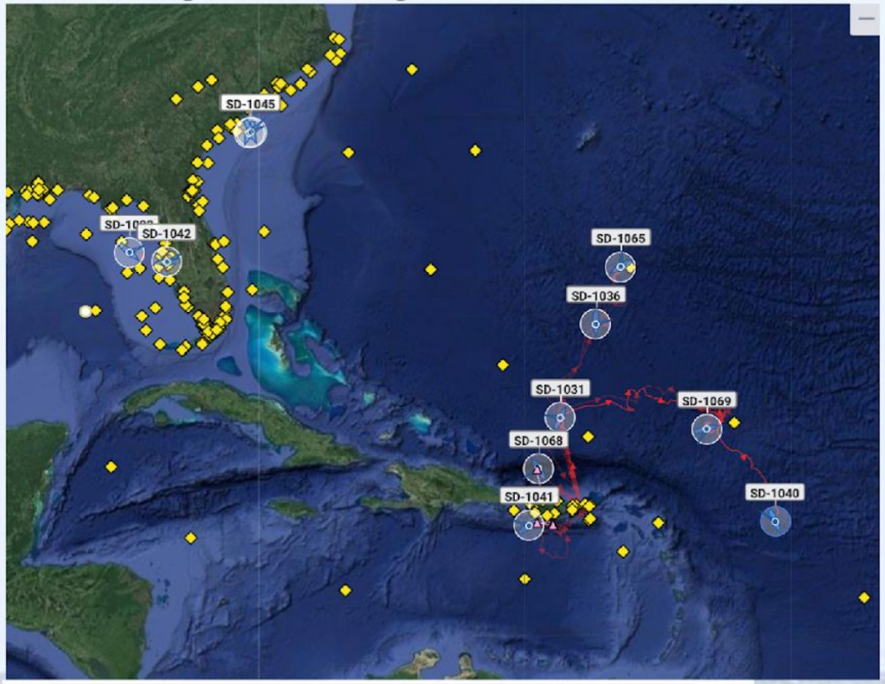
TPOS Mission 6: 120-day, started on June 22, 2023; **Lead PI:** Meghan Cronin
Partners: NOAA OAR/PMEL, NMFS/PIFSC, NWS/NCEP/CPC, NWS/NDBC, and UW/CICOES

- Integrating USVs in TPOS;
- GO-USV sections of air-sea fluxes and biomass (2 ADCP USVs, 1 echosounder USV);
- Observing the developing El Nino (weakened upwelling, migration of the Warm Pool Eastern Edge (WPEE) and relaxation of CO_2 outgassing).

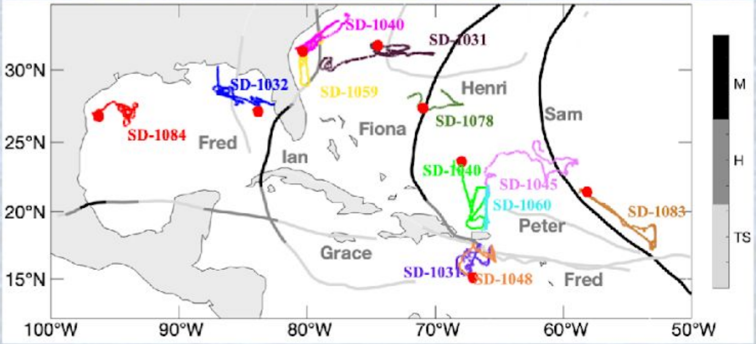


Hurricane Mission 3: 90-day, starting date August 1, 2023**; Lead PI:** Greg Foltz
Partners: NOAA OAR/AOML, OAR/PMEL, NWS/NHC, NWS/NCEP/EMC, NWS/OPC, NWS/NDBC, NOS/IOOS, and UW CICOES, UM/CIMAS

- 10 USVs ready for intercepting tropical storms and hurricanes;
- Improving situational awareness for NHC and OPC forecasters;
- Providing data to EMC for initial condition in forecast models;
- Advancing understanding of hurricane intensification and model physics.



10 saildrones prepositioning themselves to intercept hurricanes in 2023; 1 (SD-1042) stationed on land for rapid deployment to observe landfalling hurricanes.



Tracks of 5 tropical storms and 3 hurricanes that the saildrones were steered into in 2021 and 2022. Two saildrones sailed into the eyewall of category 4 Hurricane Sam and Fiona, two into the eyewall of Fiona and Ian when they were category 1 hurricanes.

Summary

1. NOAA's early engagement with Saildrone, Inc. ensures the fast development, production and application cycle of the USVs that fit NOAA's needs and benefits the success of the startup company.
2. Saildrone USVs successfully demonstrated their potential as an ideal air-sea interaction observing platform for being integrated into the Tropical Pacific Observing System, for observing the Arctic marginal ice zone during the rapid seasonal ice retreat and for observing the extreme ocean and weather conditions inside major hurricanes.
3. The saildrones' capability for adaptive sampling and actively coordinating with other observing platforms will greatly expand the current Global Ocean Observing System's geographic extent and capacity for monitoring multiscale, multi-process air-sea interaction processes.
4. Continued Public-Private Partnership is required for the use of Saildrone USVs to obtain high quality data within GOOS since data are collected on a "pay-for-service" or "data-buy" basis: the platform and most of its sensors are owned, operated, and maintained by Saildrone Inc., and scientists are responsible for designing the sampling scheme that dictates where, when, and how measurements are made.
5. The "pay-for-service" eliminates cost of ownership and maintenance, and the fixed daily rate allows for a science mission with predictable costs, which is particularly important for observing extreme ocean and weather events. The risks of loss and potential damage to the platform and sensors are not taken by scientists or NOAA.
6. PMEL has developed an efficient workflow to serve the saildrones' near real time data via GTS and public ERDDAP servers. Automatic QCs are in development based on statistics and Machine Learning. However further QCs based on process-oriented diagnostics are needed, especially for extreme "outlier" events that have not been observed before.
7. Saildrone USV observations provide the opportunity for inspiring and educating the next generation ocean and atmospheric scientists. Over the past three years, 20 NOAA Hollings Scholars and Lapenta Interns have chosen to work with PMEL scientists on saildrone data.