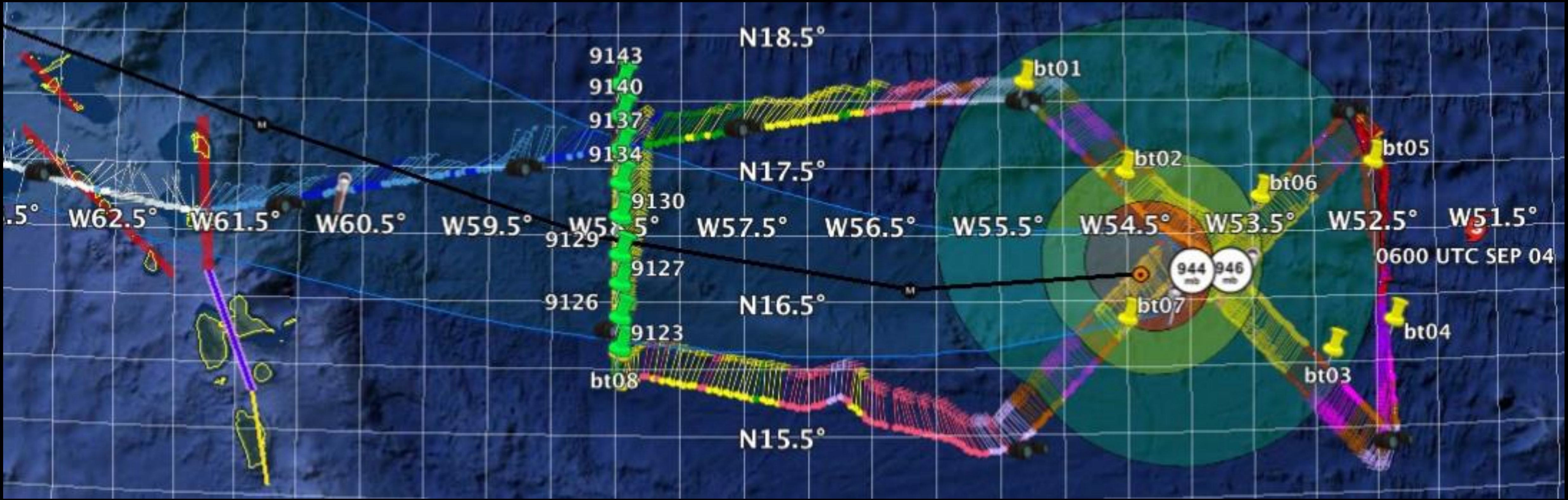
Upper Ocean Data Collection during Operational Hurricane Reconnaissance Missions



Elizabeth R. Sanabia[1] and Steven R. Jayne[2]

[1]United States Naval Academy, [2]Woods Hole Oceanographic Institution

Outline

1) TROPIC
   - ***a)*** ***T***raining and ***R***esearch in ***O***ceanic and atmospheric ***P***rocesses ***I***n tropical ***C***yclones
   - b) Organization and purpose
2) AXBT Demonstration Project: Phases I & II
   - a) Operations
   - b) TROPIC Data Set
   - c) Impact
3) ALAMO float operations
   - a) Introduction
   - b) Ignacio (2015)
   - c) Irma (2017) & Florence (2018)
4) Current work & future plans

The AXBT Demonstration Project (2011-2016; 2017-present)

Overall Objective:

Increase hurricane forecast accuracy by assimilating ocean observations from beneath tropical cyclones into coupled numerical models in near-real time

Incremental Objectives:

① *Collect, process, and transmit AXBT data to coupled modeling centers in near-real time*

② *Assimilate AXBT data into coupled models*

③ *Demonstrate improvement to ocean model initializations and forecasts*

④ *Demonstrate improvement to hurricane track and intensity forecasts*

WC-130J in flight

AXBT Data Path

AXBT Demonstration Project

Deploy → Collect → Process → Transmit

53rd SATCOM Ground Station

Disseminate JJVV

NAVO: RTDHS → NCODA → NCOM

NRL MRY: COAMPS-TC

NDBC: Upload → GTS

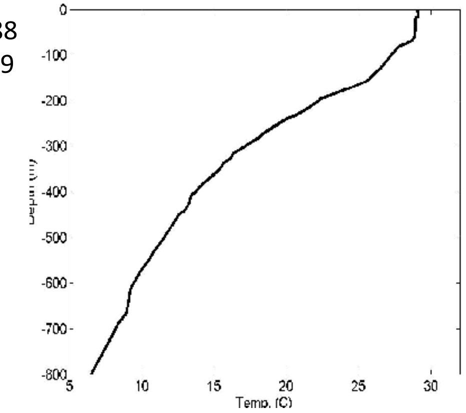
NCEP/EMC: HWRF

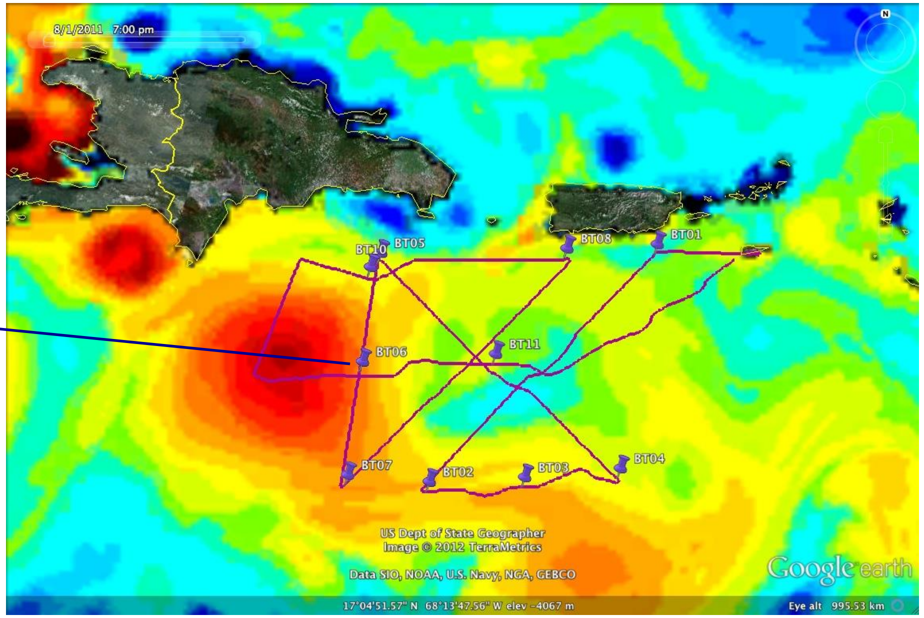
National Hurricane Center

AXBT 06
JJVV Message

JJVV 03081 0741/ 716360 069460 88888
51099 00291 00291 00291 14291 19289
57289 66287 72284 80278 99901
08270 30265 39261 56256 73242
83234 90228 93224 99902 00222
14216 33206 36202 51194 59190
69185 73183 80181 99903 15163
26162 36157 48154 56152 88140
99904 00138 06134 26133 42129
48126 65123 99905 04115 31108
48105 74099 99906 11092 65089
87084 99907 11080 97066 99908
48065 AF306

AXBT 06
Profile



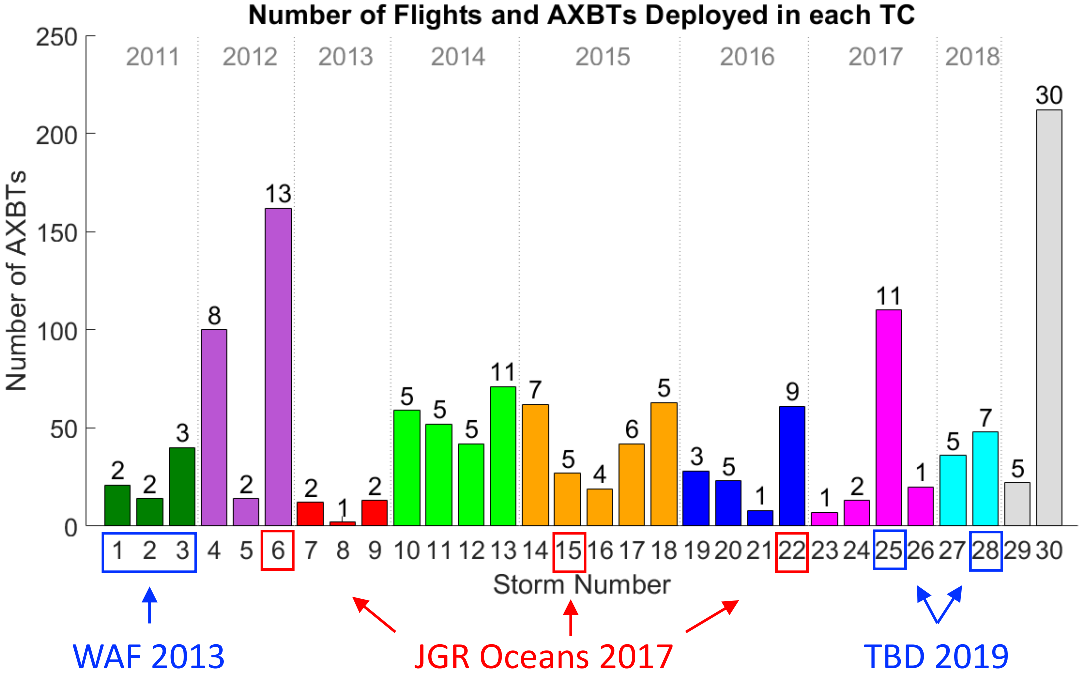


TROPIC data set

- By the numbers
  - **1396 AXBTs deployed** between **2011-2018** by
  - **41** TROPIC team members in
  - **168 flights** with the 53rd WRS, including **109 missions** in
  - **28 named storms,** including **6 major hurricanes** (MH)
  - **5 regions**: Caribbean (11), Central Pacific (6), West Atlantic (6), Gulf of Mexico (4), East Pacific (1)
  - **Various intensities** and stages of the TC life cycle
- Operating constraints
  - Launch altitude <= 10k'
    - new launcher in development (x 6 years)
    - will enable deployment from transit altitudes
  - Temperature only
    - primary instruments are AXBTs that are past their Navy service life
  - Always 2º to atmospheric data collection
    - The floats are launched from the flare tube on the ramp in the tail of the plane & the loadmaster is in the front of the plane buckled in during transits through the eyewall, so most observations are outside the RMW.
  - Timing: Hit or miss – sometimes storms develop, sometimes not.
- Data availability
  - GTS in real time (JJVV with AF3## as the unit identifier)
  - Archive online later this summer (hosted by WHOI)

TROPIC Storms 2011-2018

1.	Don	11.	Iselle	21.	Javier
2.	Emily	12.	Julio	22.	Matthew
3.	Irene	13.	Cristobal	23.	Franklin
4.	Ernesto	14.	Guillermo	24.	Harvey
5.	Helene	15.	Hilda	25.	Irma
6.	Isaac	16.	Danny	26.	Jose
7.	Dorian	17.	Erika	27.	Hector
8.	Fernand	18.	Joaquin	28.	Florence
9.	Gabrielle	19.	Darby	29.	Invest
10.	Bertha	20.	Earl	30.	Training



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  - Always 2° to atmospheric data collection
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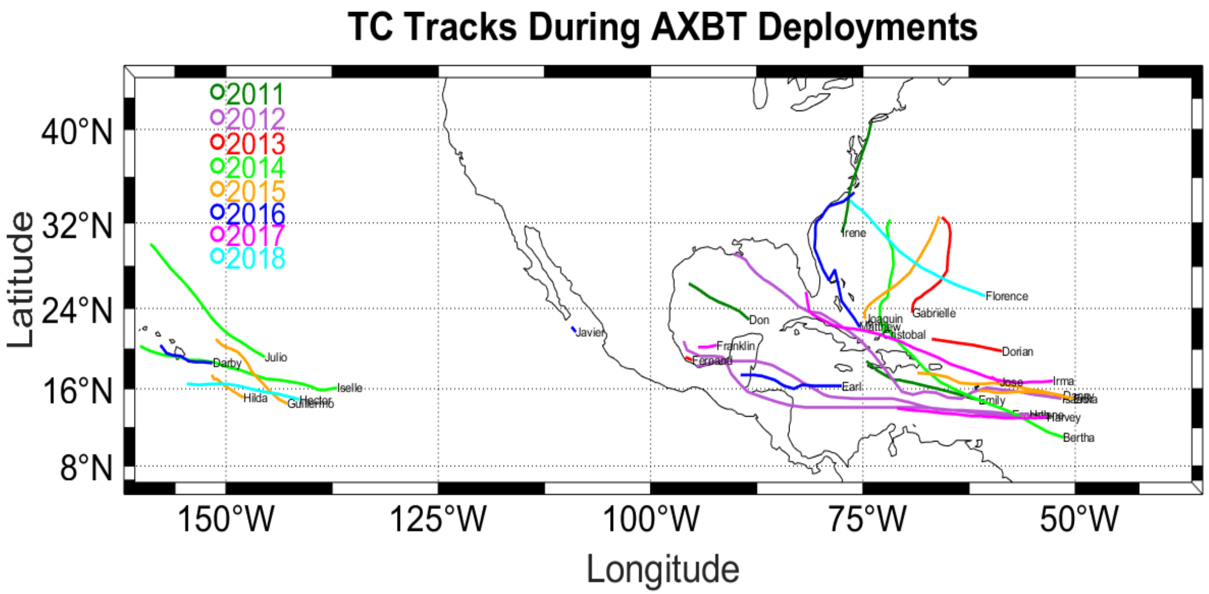
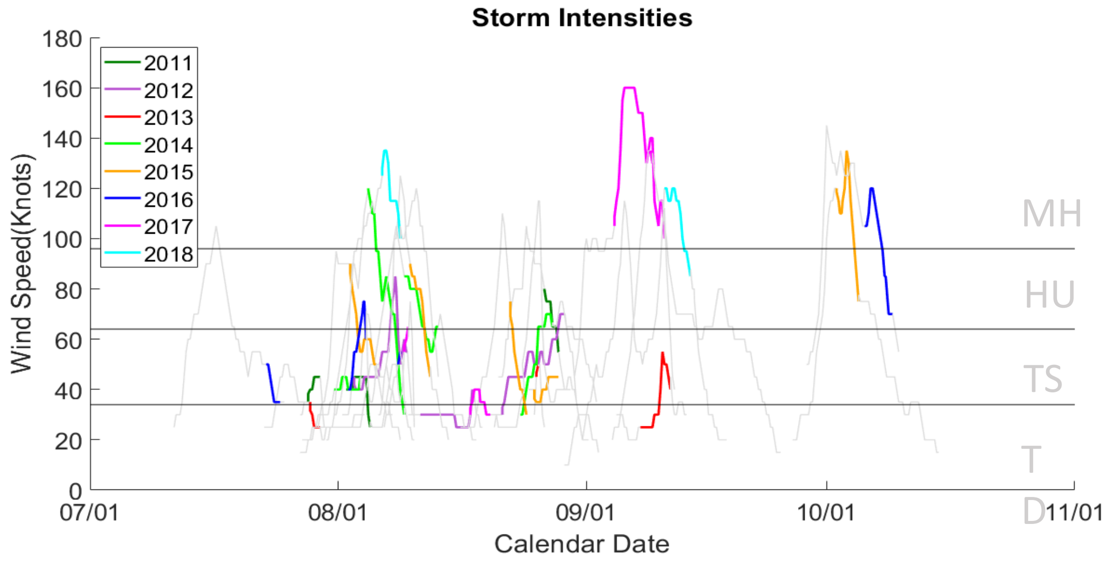
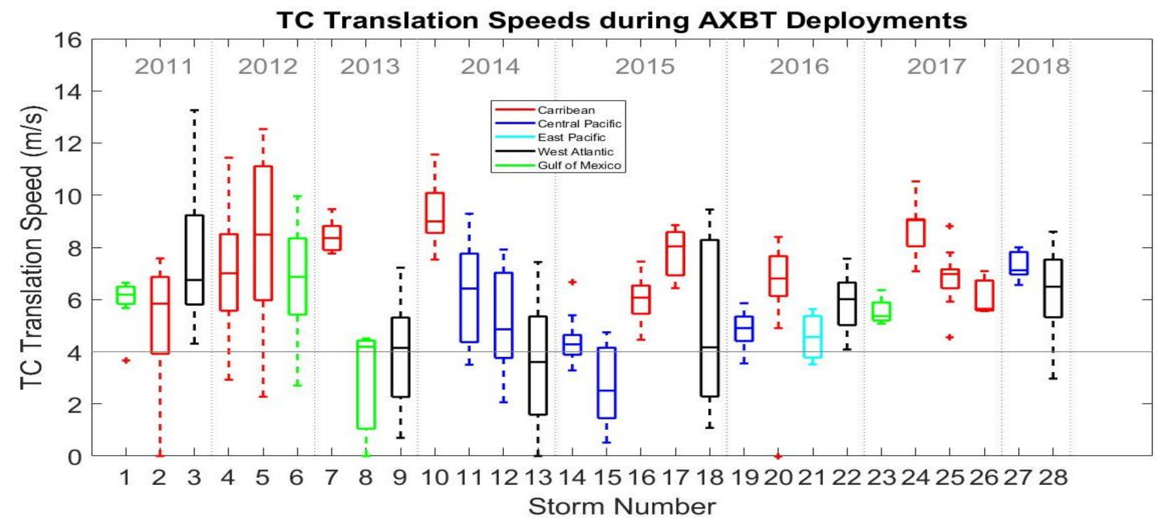
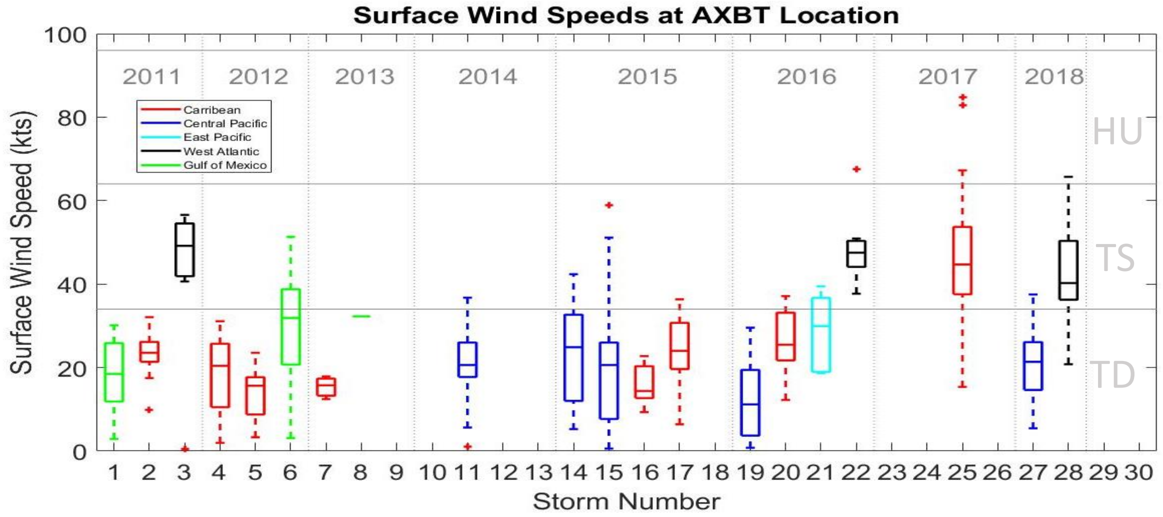






TC Translation Speed

- **Key Value**: 4 m s^{-1}
  - Entrainment due to upwelling is significantly increased for speeds < 4 m s^{-1} (Price 1981)
- **Overall**: Translation speeds average 6-8 m s^{-1}
  - Most TC speeds did not favor entrainment
  - Cristobal (#13; 2014) and Hilda (#15; 2015) moved most often at speeds that did favor entrainment
- **Basin**: TCs moved *fastest* in the ***Caribbean***
- **Greatest Variability**: TS Helene (2012) 2.5-12.5 m s^{-1}



Surface Wind Speeds

- **Key Value**: Higher surface wind speeds (SWS) result in greater extraction of heat from the ocean surface
- **Overall**: Low SWS during AXBT deployments
  - Most AXBTs were deployed at locations where surface wind speeds were < TS intensity (34 kts)
  - AXBTs rarely deployed in TC eyewalls (safety reasons)
- **Basin**: ***W. Atlantic*** AXBTs were deployed in *highest* SWS
- **Greatest Variability**: HU Irma (2017) from 15-90 kt SWS
- Note: n=500 (a few corrupt/missing SFMR files; continuing this)

1. Don
2. Emily
3. Irene
4. Ernesto
5. Helene
6. Isaac
7. Dorian
8. Fernand
9. Gabrielle
10. Bertha
11. Iselle
12. Julio
13. Cristobal
14. Guillermo
15. Hilda
16. Danny
17. Erika
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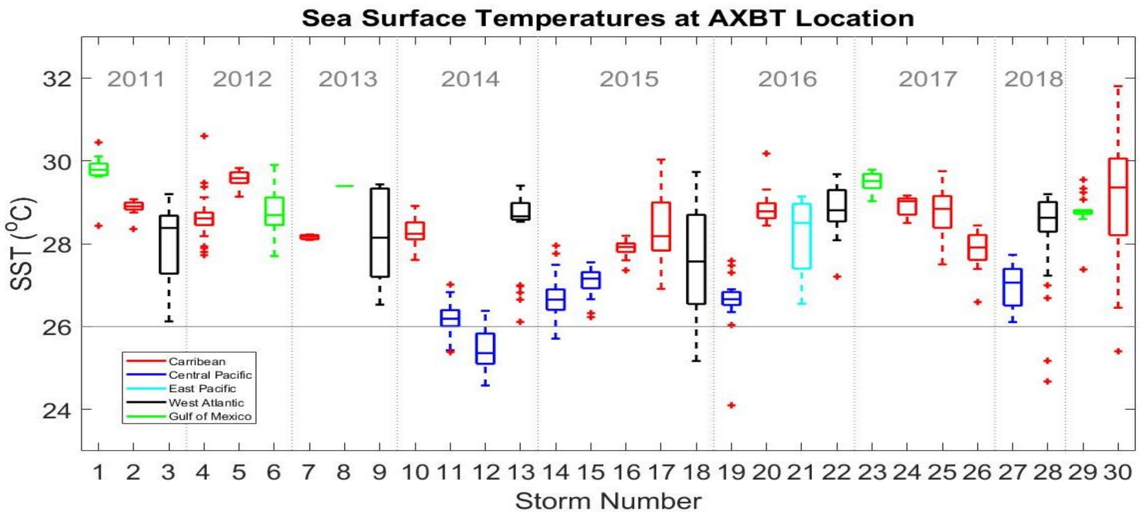
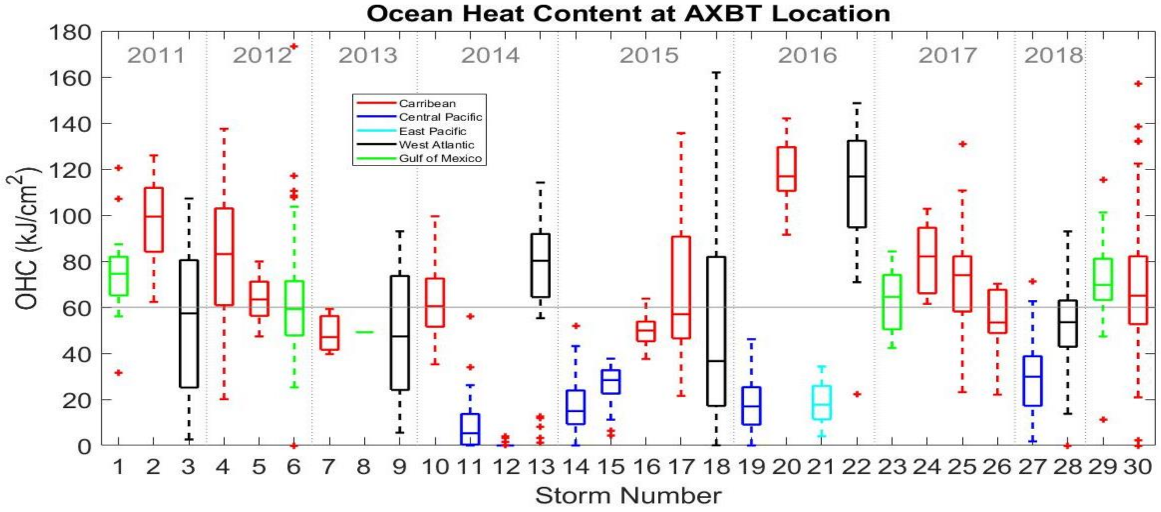


Sea Surface Temperatures

- **Key Value**: 26°C
  - Most TCs form in areas with SSTs > 26°C (Gray 1968)
- **Overall**: Average SST values are between 26-30°C
  - Most often AXBTs were deployed in regions that favored TC formation
  - The SSTs measured in HU Julio (2014) were the coldest of all 28 TCs
- **Basin**: SSTs were *coldest* in the ***Central Pacific***
- **Greatest Variability**: HU Joaquin (2015) from 26.5-29°C
- Note: n=995; (a few did not have measurements near the surface)



Ocean Heat Content

- **Key Value**: 60 kJ cm^{-2}
  - Predictor for TC intensification (Mainelli et al. 2008)
- **Overall**: Average OHC between 30-60 kJ cm^{-2}
  - Most TCs transit regions below the OHC key value
  - In 58 cases, OHC = 0 due to SSTs > 26°C
- **Basin**: *Lowest OHC* values were in the ***Central Pacific***
- **Greatest Variability**: HU Joaquin (2015) transited ocean regions with OHC values that spanned 30-80 kJ cm^{-2}

1. Don
2. Emily
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23. Franklin
24. Harvey
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27. Hector
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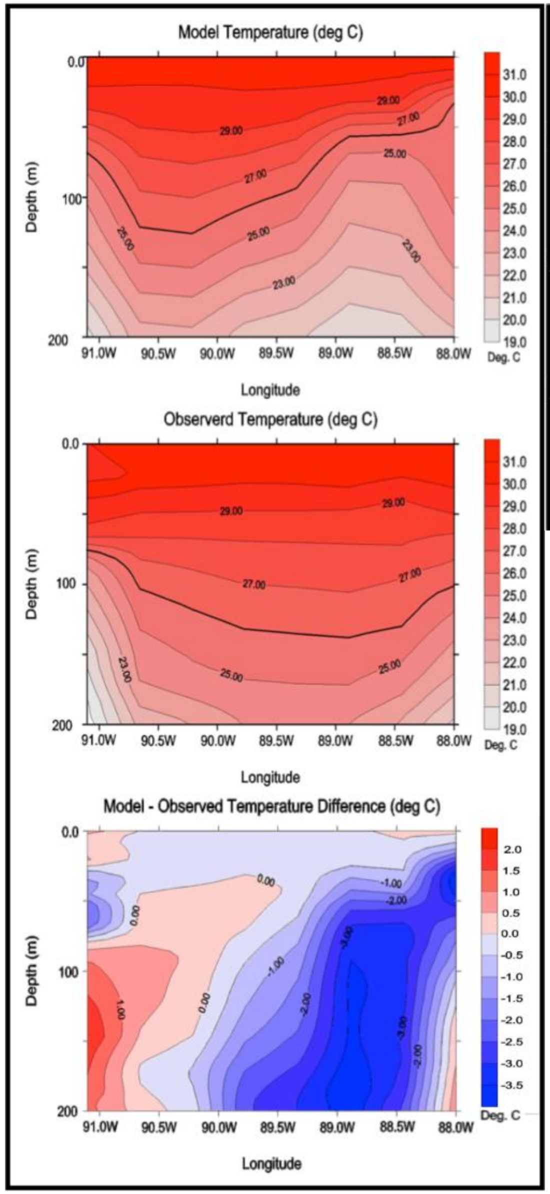
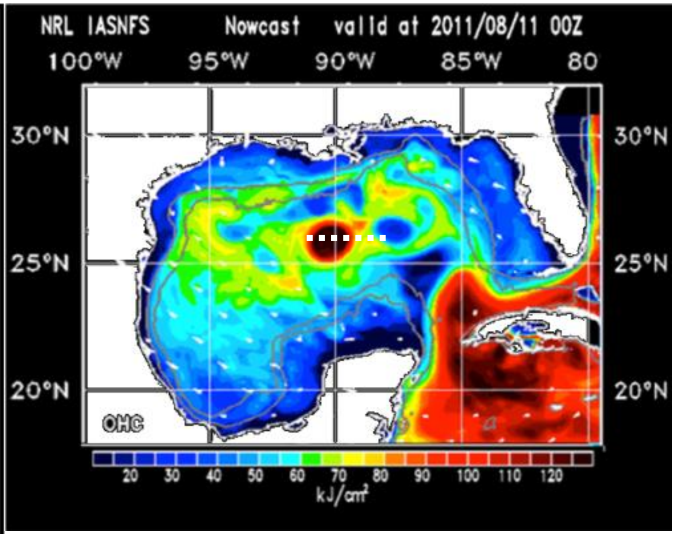
29. Invest
30. Training

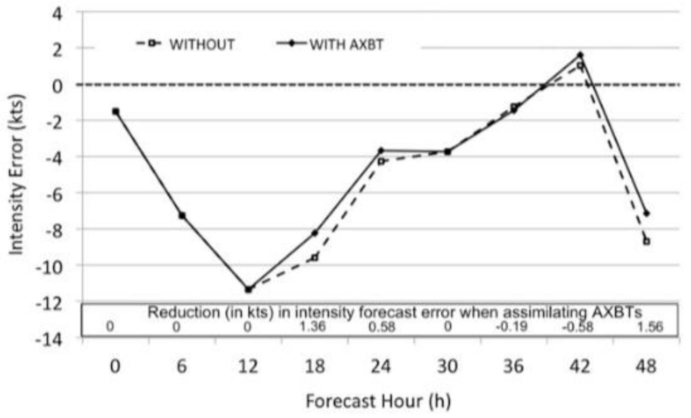
Model Impacts





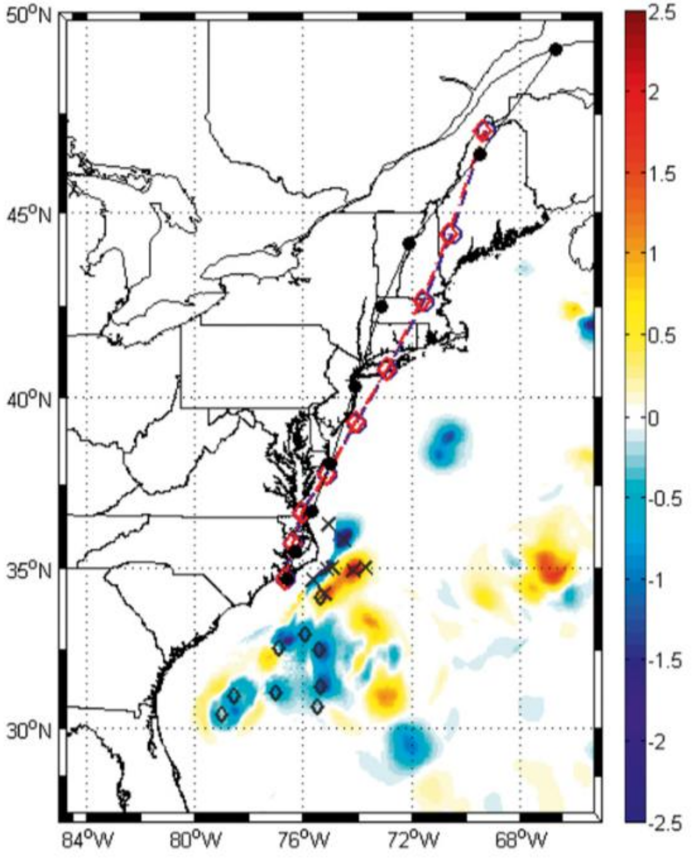
Regional Ocean Model

- IntraAmericas Seas Nowcast Forecast System (IASNFS) model evaluation (courtesy of D. Ko).
- Dashed line indicates AXBT positions across a warm core eddy (and in vertical cross sections)
- WCE is deeper and extends farther east than in the model.
- Fig. 4 (Sanabia et al. 2013)

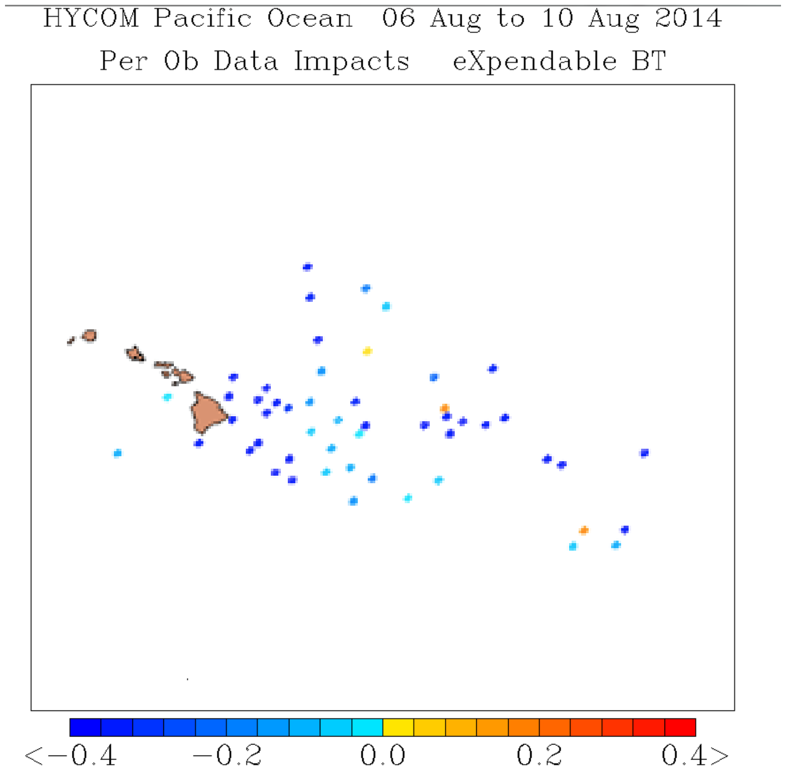


COAMPS-TC Forecast Model

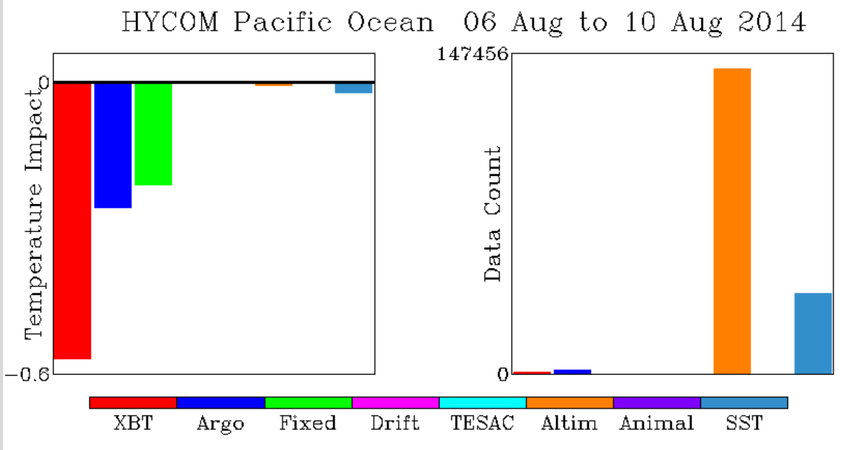
- Data denial following the assimilation of 18 AXBTs from 2 flights
- Little change in TC track forecast
- Intensity improvements are small (2 kts or less at 3 time steps), but present
- Figs. 11 & 13 (Sanabia et al. 2013)

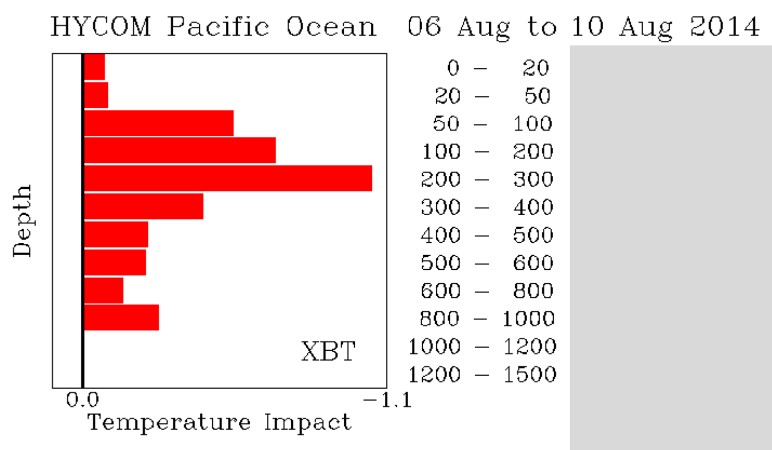


2014: HYCOM AXBT Data Impacts (Hurricanes Iselle & Julio)



The AXBT impact to HYCOM 48-h sea temperature forecast between 06-10 August 2014. A negative value (cool color) is a beneficial impact (reduced the 48 hr forecast error in deg C according to the color). A positive value (warm color) means assimilation of the AXBT increased forecast error.





Success: AXBTs had the ***greatest impact*** on reducing HYCOM model error during Hurricanes Iselle & Julio.

2017: Targeting Ocean Observations

- Adjoint approach used to evaluate impact of ocean observations on Hurricanes Isaac (2012 – GOM), Hilda (2015 – CPAC), and Matthew (2016 – WATL)
- Targeting application developed to identify ocean locations where observations will best benefit a given air-sea coupled TC model forecast

AGU PUBLICATIONS JGR

Journal of Geophysical Research: Oceans

INTRODUCTION TO A SPECIAL SECTION

10.1002/2017JC012727

Special Section:
Oceanic Responses and

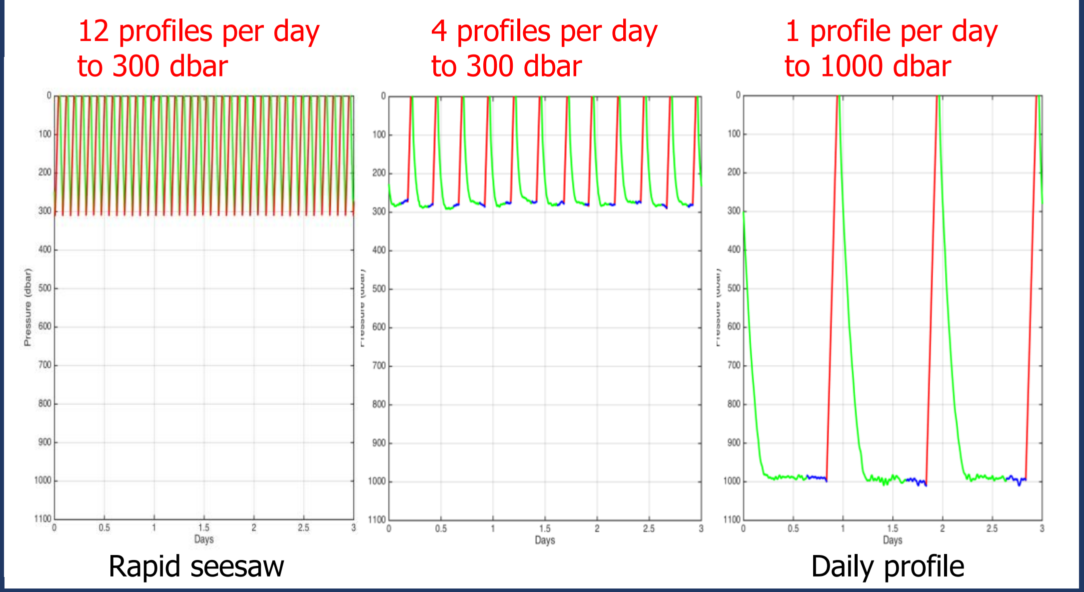
Targeted ocean sampling guidance for tropical cyclones

Sue Chen[1], James A. Cummings[2], Jerome M. Schmidt[1], Elizabeth R. Sanabia[3], and Steven R. Jayne[4]

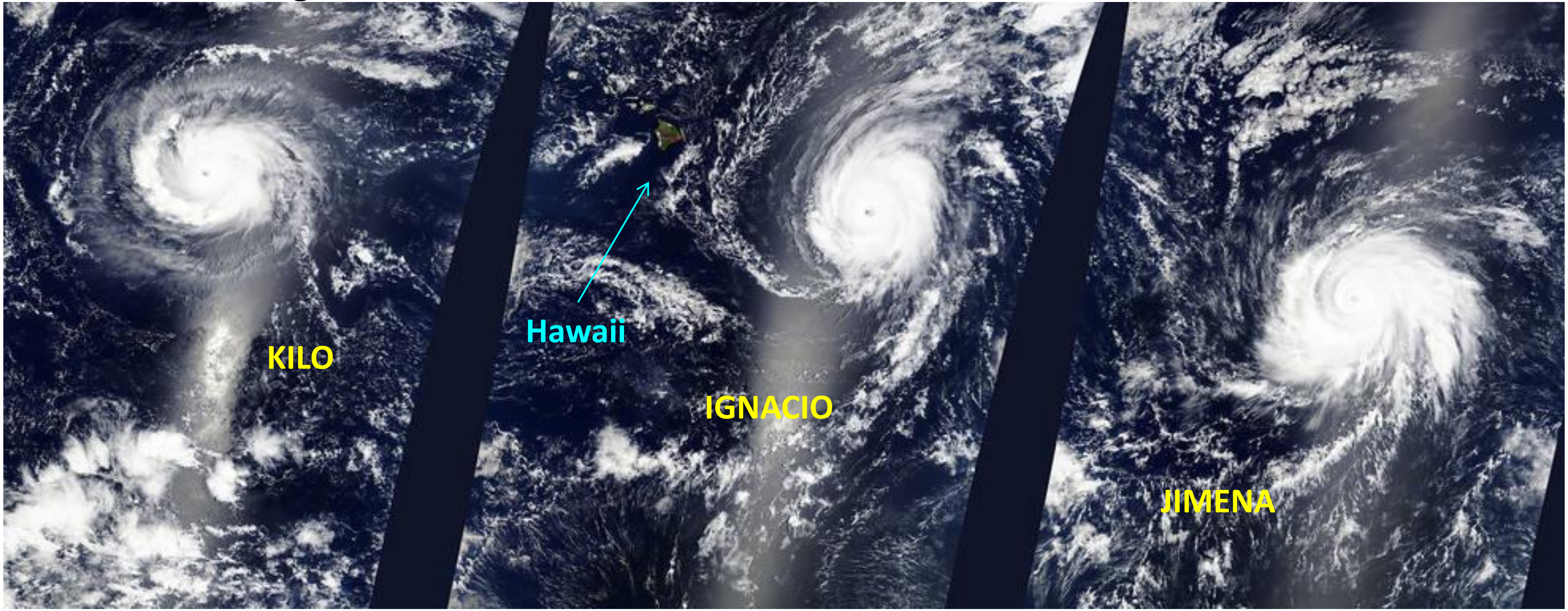
ALAMO Float Introduction

- ***A***ir-***L***aunched ***A***utonomous ***M***icro-***O***bserver
- Advantages over other profiling floats:
  - A-sized; enables deployment without opening ramp
- Advantages over AXBT:
  - multiple profiles
  - more sensors (pressure, salinity, & accelerometer for surface waves)
  - no VHF receiver equipment on planes
- The float profiles on its way to the surface, transmits its data, and then sinks back to its programmed parking depth according to its schedule
- Location, profile and engineering data sent by Iridium SBD (Short Burst Data) packets and received by email
- WHOI decodes telemetry, updates local database, makes data files and figures
- WHOI FTPs data file to NOAA/AOML in previously defined Argo PHY format. AOML reformats data and submits to GTS for transmission to operational centers
- Data and plots available at http://argo.whoi.edu/alamo/

Depth-time plots of sampling scenarios



2225 UTC 29 August 2015

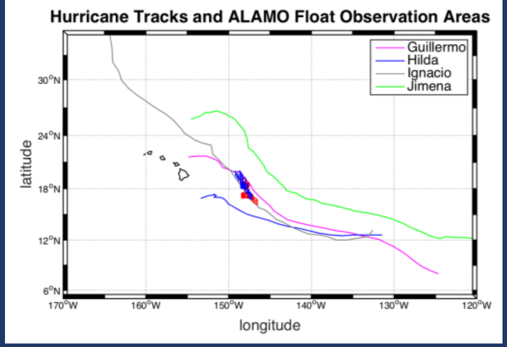


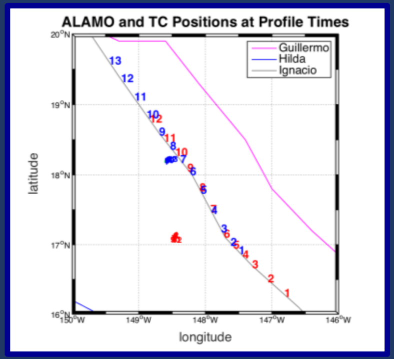
Imagery of three Category Four hurricanes in the Central and Eastern Pacific Ocean at 2225 UTC 29 August 2015 from the NASA Terra satellite. In this image, the maximum winds in Hurricane Ignacio are 120 kts near the TC center, and the outer winds are beginning to affect ALAMO float 9077. Eyewall winds reach ALAMO 9077 14 hours later and impact the water beneath the buoy for several days (Fig. 4a). Image courtesy NASA.

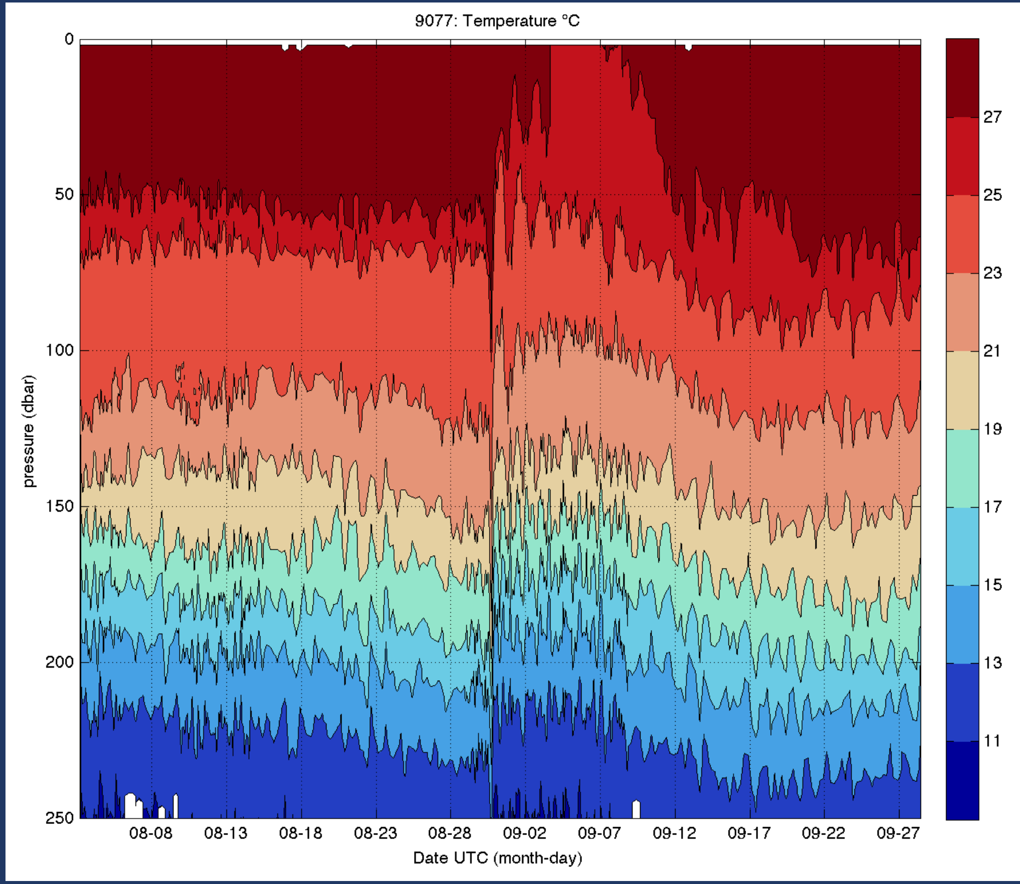
Ignacio (2015) – ALAMO 9077

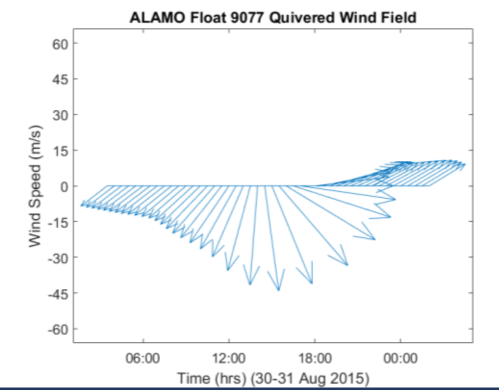
- Pressure & Temperature only
- 13 profiles ≤ 200km of TC center
- Max wind: 85 kts

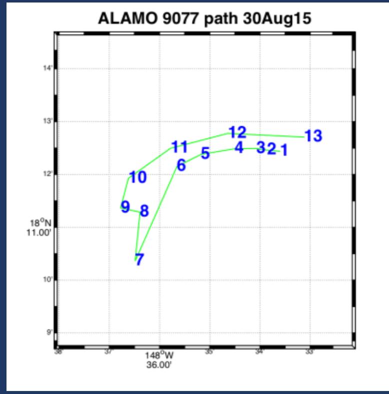
- Closest observations: 2 at 25 km
  - Eye radius was 18.5 km (vortex message)
  - 1400-1600 UTC 30 August 2015

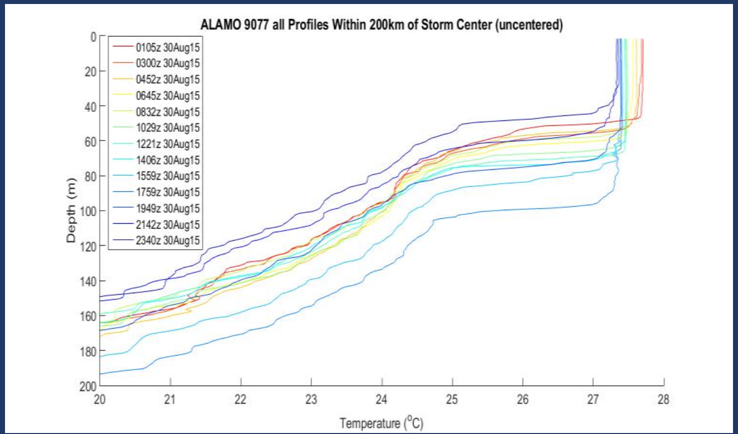












Ignacio: Upper Ocean Temperature Response

- 3D Price-Weller-Pinkel mixed layer model (Price et al., JPO, 1994) accurately replicates the phase and magnitude of the response – *after* the initial forcing

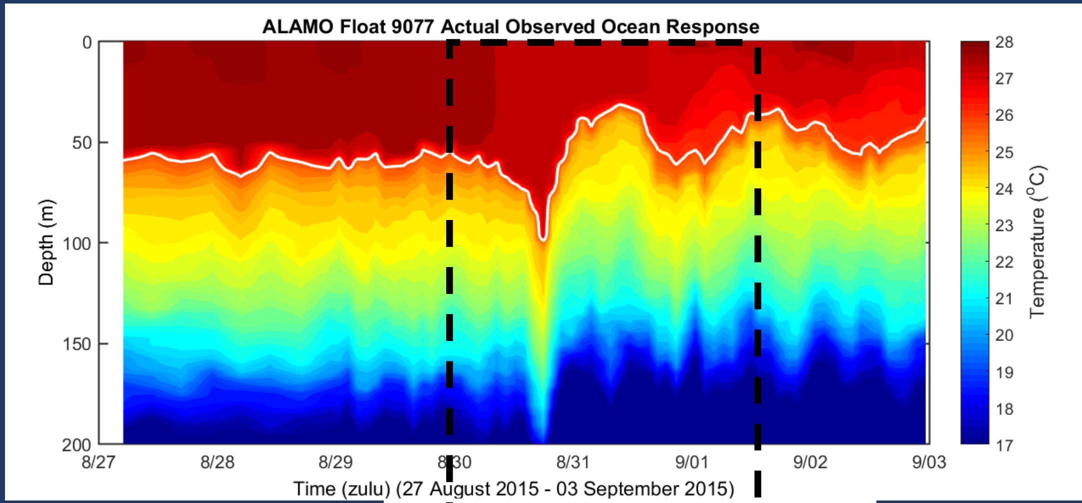
- Due to the translation speed of the tropical cyclone, there is an asymmetry in the wind speeds between the left and right sides of the storm, with enhanced wind on the right hand side of the storm

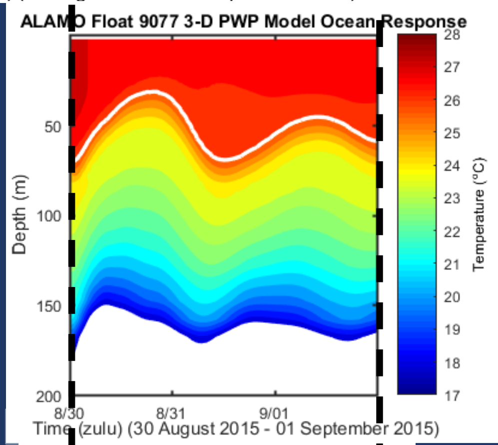
  - Wind (interfacial) stress ~ u*2
  - Stokes transport ~ u*3   (McWilliams and Restrepo, JPO, 1999)
  - Sea spray stress ~ u*4 (Andreas and Emanuel, JAS, 2001)

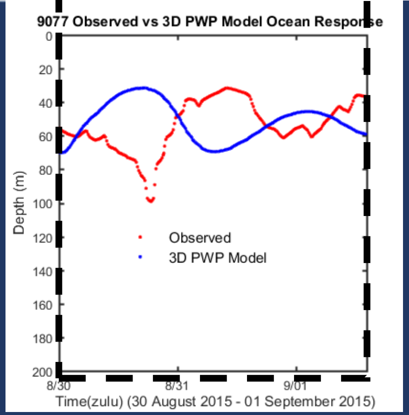
- Plan to add sea spray stress and Stokes transport for 3D PWP

- Presence of a strong downwelling ahead of the storms may be caused by the asymmetry in the surface layer mass flux, driven by either Stokes transport or the sea spray stress.

- Points to the need for coupled ocean – wave models to understand the ocean response.

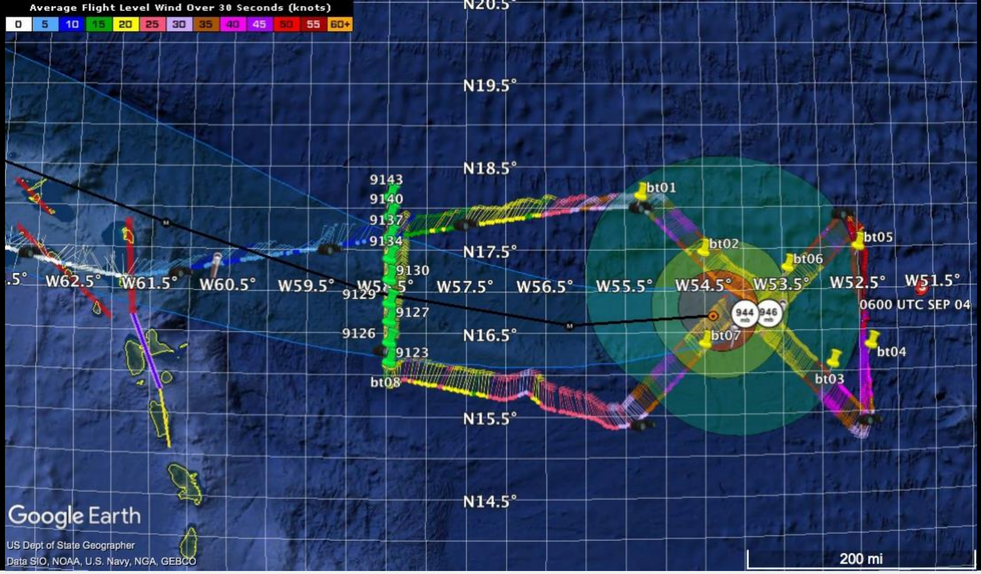


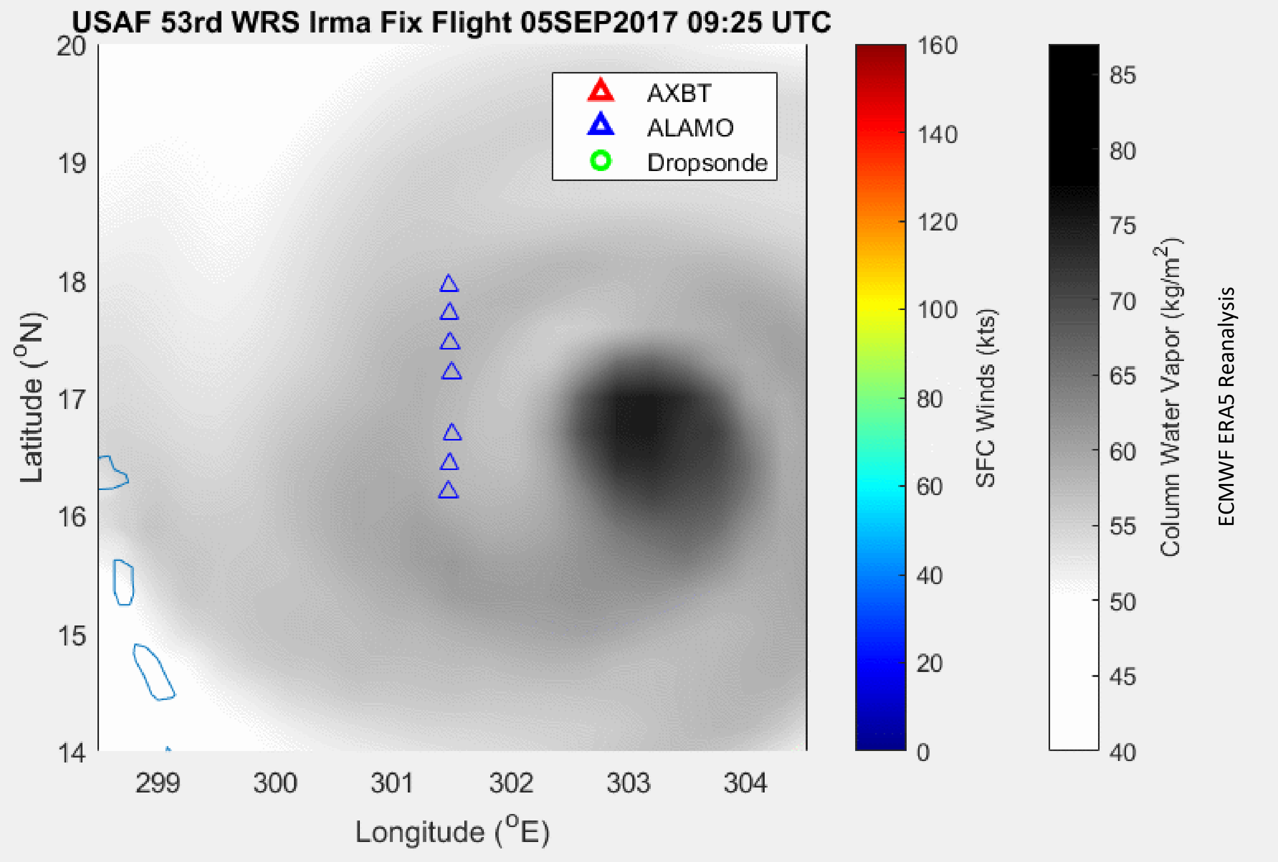




Hurricane Irma

- Hurricane Irma
  - Category 5 NATL 30 Aug – 11 Sep 2017
  - Period of Interest: 4-6 Sep 2017
    - Rapid Intensification
      - 115 kts at 1800 UTC 04 Sep 17
      - 160 kts at 1800 UTC 05 Sep 17
    - Crossed ALAMO array at 1500 UTC 05 Sep 17
- ALAMO Float Deployment
  - 9 floats along 58.5W (USAF 53rd WRS)
  - 0.25° resolution between 16-18N
    - 2 non-functional (16N, 17N)
    - 1 deployed in the wake (17N)
- Aircraft Reconnaissance
  - USAF 53rd WRS WC-130J and NOAA P-3 aircraft
  - 4 flights and 11 center passes within 200km of floats
  - SFMR surface winds and dropsonde observations





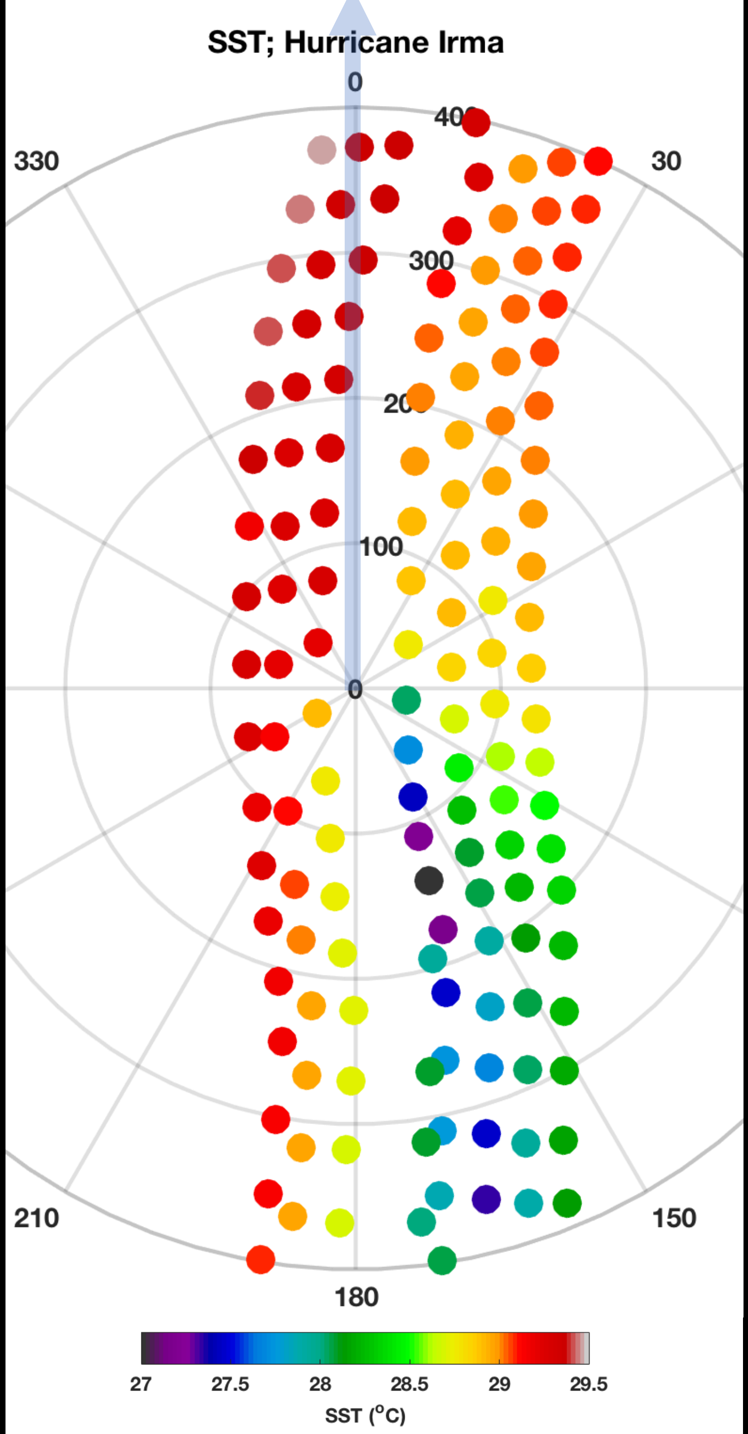
SST

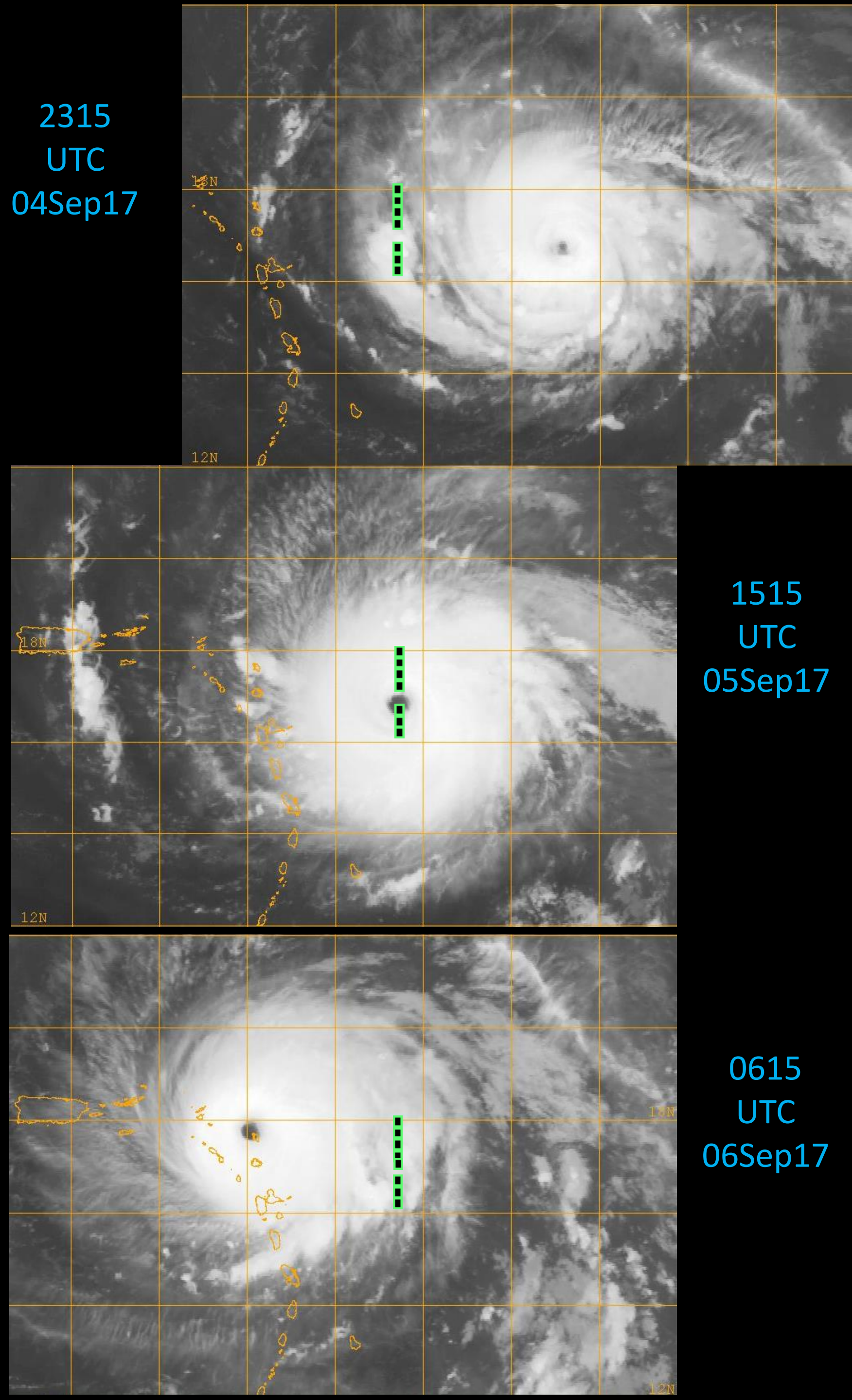
- Profiled to 300m at ~2-h intervals
  - 139 profiles within 400 km of Irma
  - 65 profiles within 200 km of Irma
  - 4 profiles within 50km of Irma

	Mean (°C)	Range (°C)
400 km (~ 24 h) prior	29.2	0.5
~ 6 h after TC	28.4	2.2

- Cooling dominant right of TC track

- Within 200km
  - Most cooling: 1.8°C in 9134
    - Closest right of track (ob w/in 36 km)
  - Least cooling: 0.16°C in 9126
    - Farthest left of track (ob w/in 77 km)

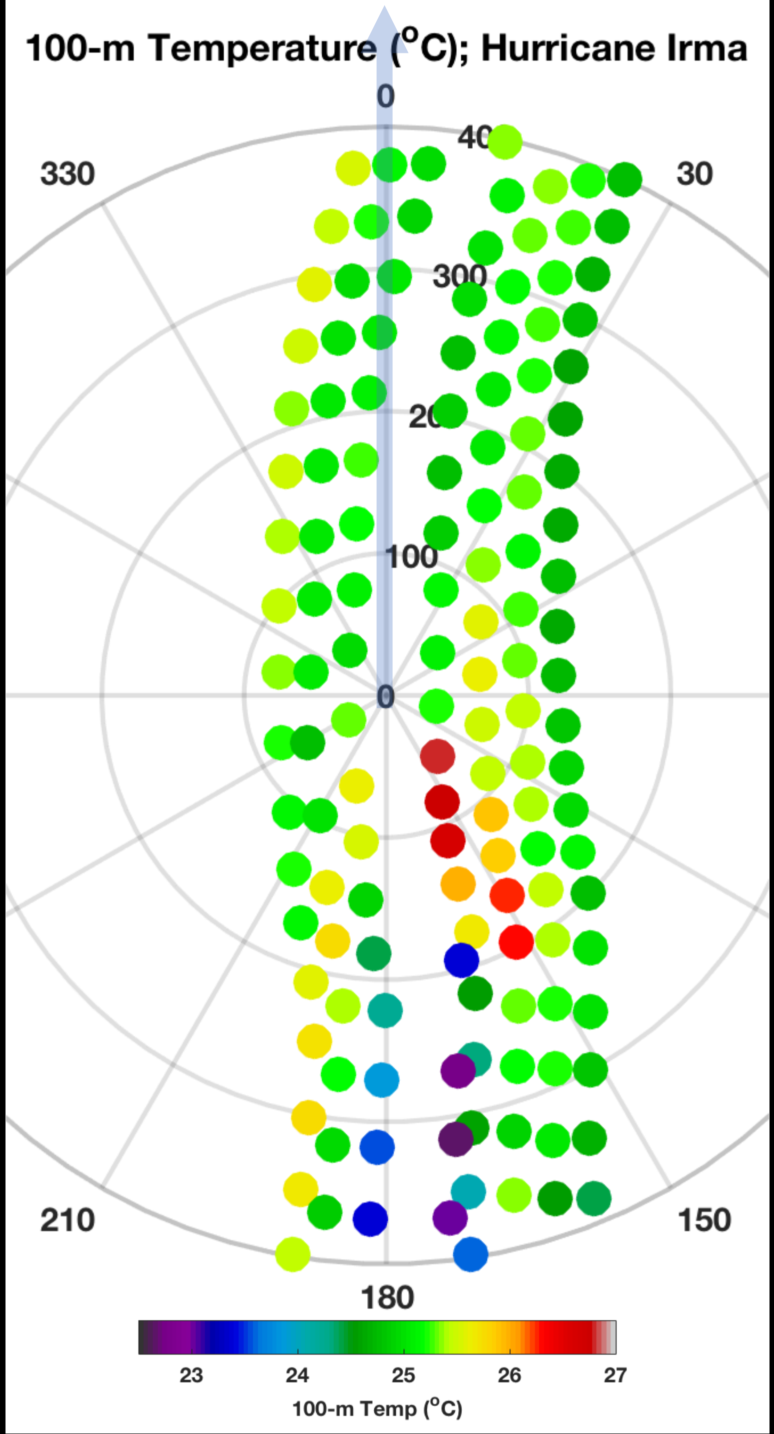




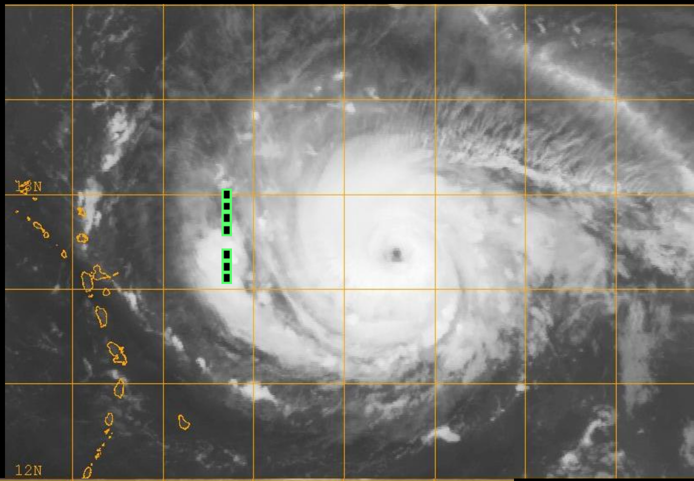
100-m Temperature

	Mean (°C)	Range (°C)
400 km (~ 24 h) prior	25.2	0.8
~ 6 h after TC	25.7	1.9

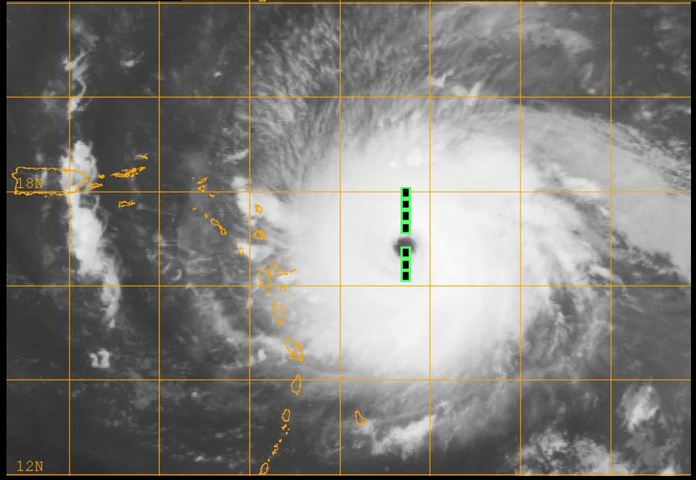
- Increases across the array as TC passed
- Greater change right of track
- **Downwelling** is evident in a wedge of maximum warming
- Response began later and was weaker farther from TC track
- Continues after eyewall passage



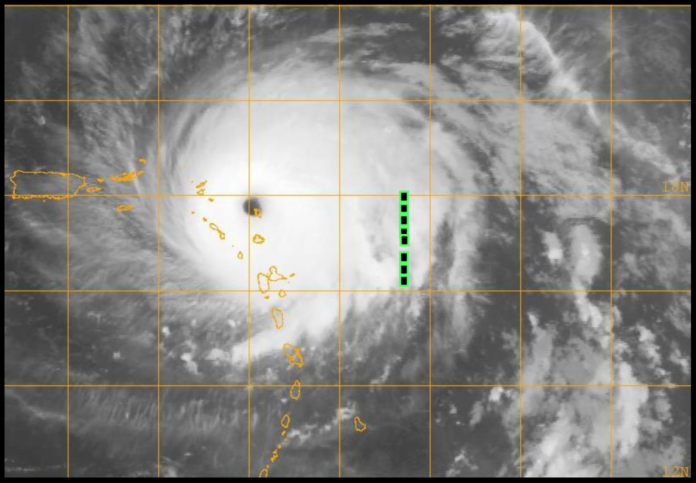
2315 UTC 04Sep17



1515 UTC 05Sep17

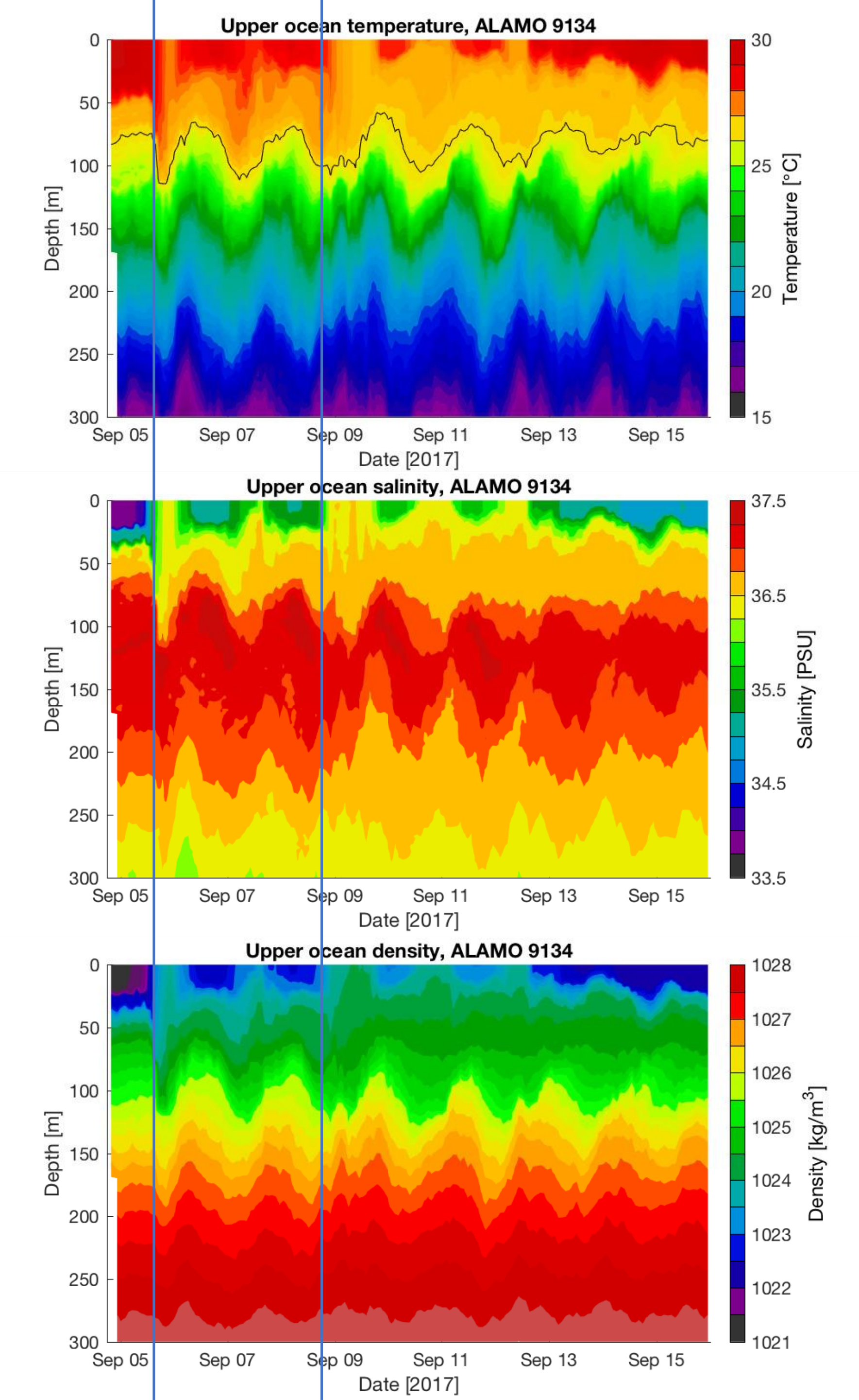


0615 UTC 06Sep17



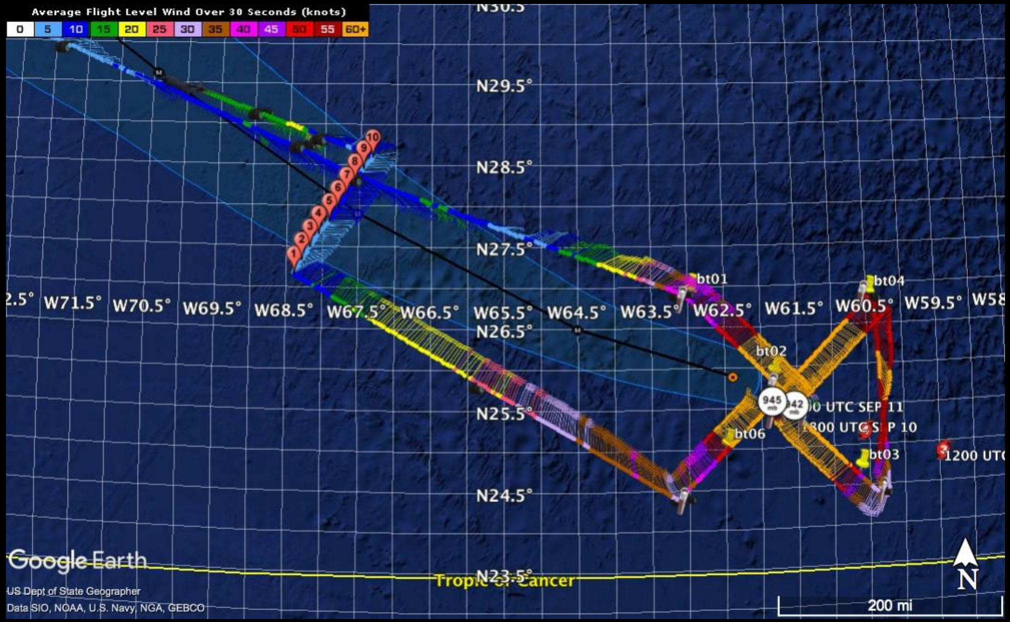
ALAMO Float 9134

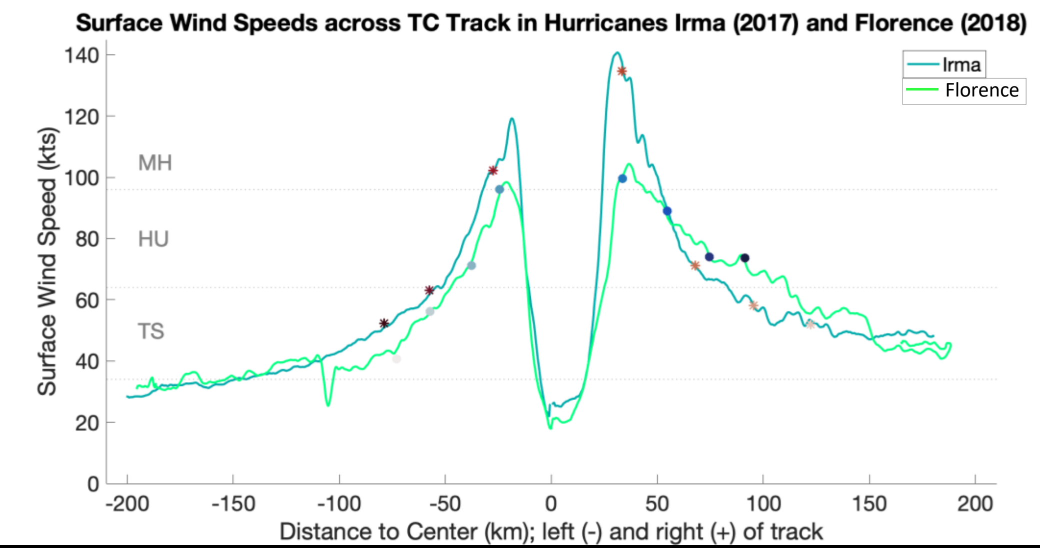
- Largest response of the 7 original floats
  - Post-TC profiles in 9138 corroborate 9134 magnitude
- Heaving of the column through 300m
  - Oscillations continue through 10 days at near-inertial periods
  - Passage of Jose
- Waves and mixing
  - Rigid lid
  - Wave propagation with the storm



Florence (2018)

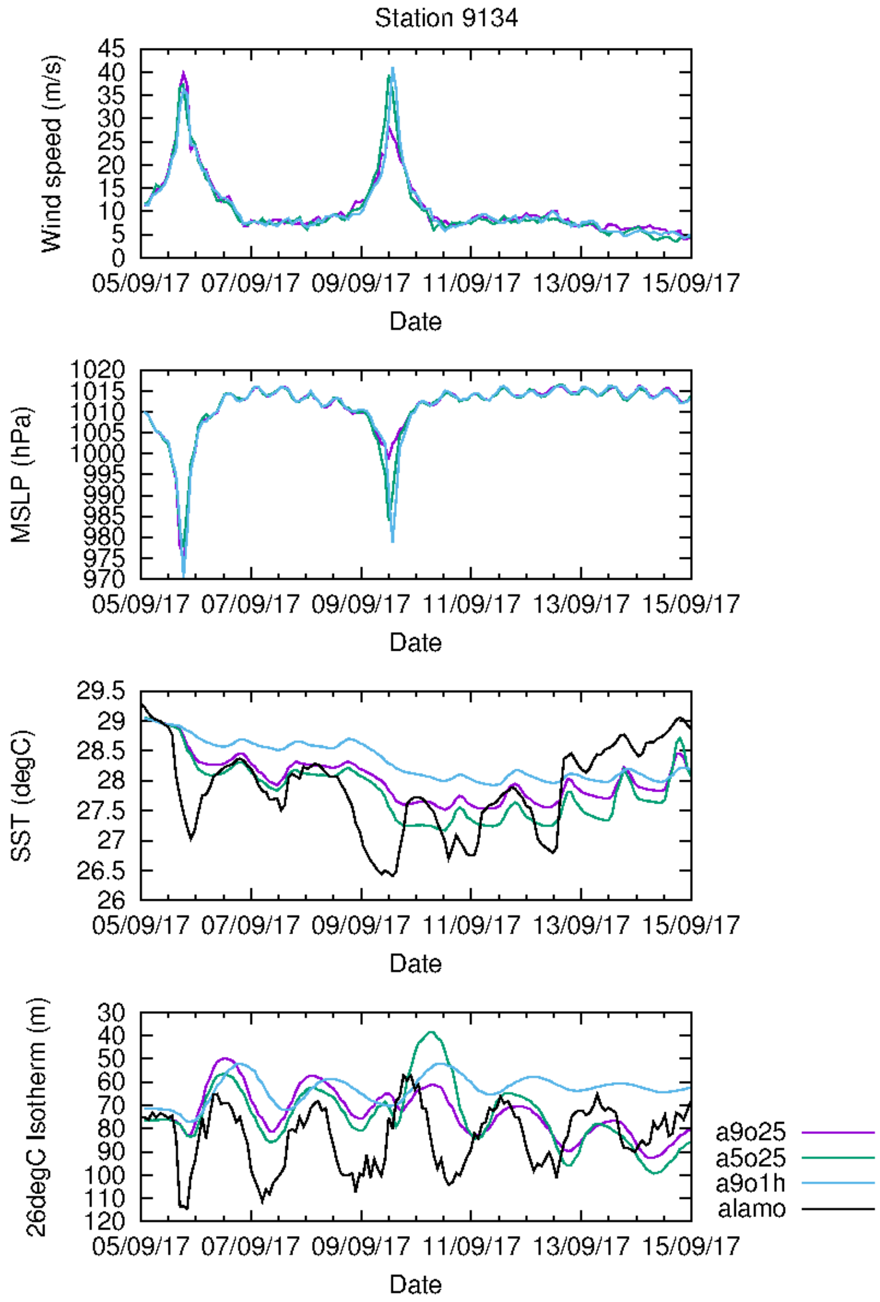
- Characteristics
  - Category 4 NATL 31 Aug – 17 Sep 2018
  - Period of Interest: 11-12 Sep 2018
    - Crossed ALAMO array at ~2345 UTC 11 Sep 18
- ALAMO Float Deployment
  - 10 floats SW-NE at the 00z 12 Sep 18 forecast position (USAF 53rd WRS)
    - 1 non-functional (southwestern-most float)
    - Center float stopped reporting at RMW
  - 0.20° resolution





Current work & future plans

- Research
  - Irma & Florence analysis
    - Mixing
    - Internal wave characteristics
  - Model Verification Studies
    - COAMPS-TC – Irma
    - ECMWF – Irma & Florence
  - ALAMO v2
    - 2D surface wave spectra
    - Passive acoustic receiver
- Operations
  - Software: Shift toward automated processing
  - Hardware: Upgrade equipment
  - Deployment strategy:
    - Sensor distribution
    - Fine tune targeting for deployments near the storm environment
- Engagement & Collaboration
  - Funding is year-to-year
  - Data available
    - ALAMO http://argo.whoi.edu/alamo/
    - TROPIC AXBT archive end of summer 2019
  - If we can show the data are useful, it is much easier to continue to the observation program



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