# TC Ocean Observations:

# Current State and Future Outlook

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In collaboration with the
Ocean Modeling Impact Tiger Team and Others

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13 March 2018

# What do we need to resolve?

## Initial Conditions

**1) Background state**

- Resolve regional features and processes
  - GOMEX: Loop Current, Eddies
    - **Katrina vs. Nate**
  - MIDATL: Seasonal Cold Pool, Gulf Stream
    - **Irene vs. Sandy**
  - CARIB: Amazon Outflow Region
    - **Frequent RI**
- Critical to condition the model so the pre-storm observations can be assimilated and nudge the model

**2) Pre-TC conditions**

- Update background state prior to TC arrival

## Physical Processes

**1) Observations in & around TC**

- Air-sea exchanges
  - Enthalpy and momentum fluxes
  - Drag coefficient
- Upper ocean mixing
  - Wave and shear-driven
  - Buoyancy
  - Upwelling
  - Tidal (WPAC)
- Waves
  - Energy distribution
  - Langmuir circulation
  - Stokes drift
  - Sea spray

**2) Post-TC conditions**

- Understand magnitude and duration of ocean response following TC passage

# Key Considerations

"Experiments have shown that coupling the ocean and the atmosphere in the forecast model leads to better predictions of tropical cyclone intensity."
ECMWF news 11 Jan 2018

## Observations

1) Variables
2) Location
3) Resolution
4) Frequency

## Data

1) Available in near real-time?
2) Assimilated into ocean / coupled models?

# Instrument Capabilities

| | Aircraft - A-sized launch tube | | | | Aircraft - Ramp Deployed | | P-3 | Ship | Satellite / Ship / Shore Background | | | Emerging Technologies ( Air-launched A-sized or smaller) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AXBT | AXCP | AXCTD | ALAMO | Minimets | EM-APEX | WSRA | GLIDER | Satellite | ARGO | Coastal HF | COYOTE | ADWB | IR SONDE | MASED |
| Temperature ($T$) | * | * | * | * | SST | * | | * | SST | * | | | | SST | * |
| Salinity ($S$) | | | * | * | | * | | * | SSS | * | | | | | |
| Pressure ($P$) | | | | * | | * | | * | | * | | | | | |
| Current ($u,v$) | | * | | possible | | * | | * | surface | * | * | | | | |
| Wave field | | | | possible | * | | * | possible | * | * | * | | * | | |
| Near-surface Winds | | | | | * | | | | * | | | * | | * | * |
| Profiles | single | single | single | multi | time series | multi | multi | multi | multi | multi | multi | multi | multi | single | up to 5 |
| Comm Link | VHF | VHF | VHF | IRIDIUM | IRIDIUM | IRIDIUM | SAT/FTP | IRIDIUM | | IRIDIUM | | VHF | IRIDIUM | VHF | IRIDIUM |
| Avail Real Time? | yes | T only | T only | yes | yes | yes | yes | yes | yes | ys | yes | in progress | | | |
| Assim (NCODA) | yes | T only | T only | yes | part | yes | no | part | part | yes | no | not yet | | | |

# Active TC Ocean Observing Programs

## AIR-DEPLOYED

- **NOAA AOC**
  - **AXBT, AXCP, AXCTD**
    - Non-tasked missions
    - Uploaded to GTS / NOTAL
  - **WSRA** -- wave spectra
    - P-3 for half the 2018 season
    - Transmitted to NHC in NRT (not GTS)
  - Coordinated with HRD and CARCAH
- **USAF 53rd WRS**
  - **AXBT** and **ALAMO** floats
    - During tasked missions on a not-to-interfere basis
    - Uploaded to GTS via NDBC and AOML
  - **EM-APEX** and **Minimet** drifters
    - Via Buoy Tasking Order
    - Coordinated with CARCAH and 53rd WRS – typically on a separate line

## SHIP/SHORE/SATELLITE

- **Argo Profiling Floats**
  - Worldwide; geographically dispersed
  - 1 observation to ~2000m / 10 days
  - *T, S, P, (u,v)* data uploaded to GTS
- **Gliders**
  - Mid-Atlantic Bight, Western Caribbean
  - Non-tasked
  - Variety of sensors
  - Data often uploaded to GTS
- **Coastal HF**
  - Coastal U.S. (2-200km offshore)
  - Non-tasked (IOOS)
  - Nearshore surface currents *(u,v)*, waves
  - Not assimilated
- **Satellite Observations**
  - *SST, SSH*, Significant wave height
  - Temporal and spatial resolution varies
  - Routinely assimilated into NCODA
  - *SSS* available, not assimilated

| A/C: A-sized | Single profile |
|---|---|

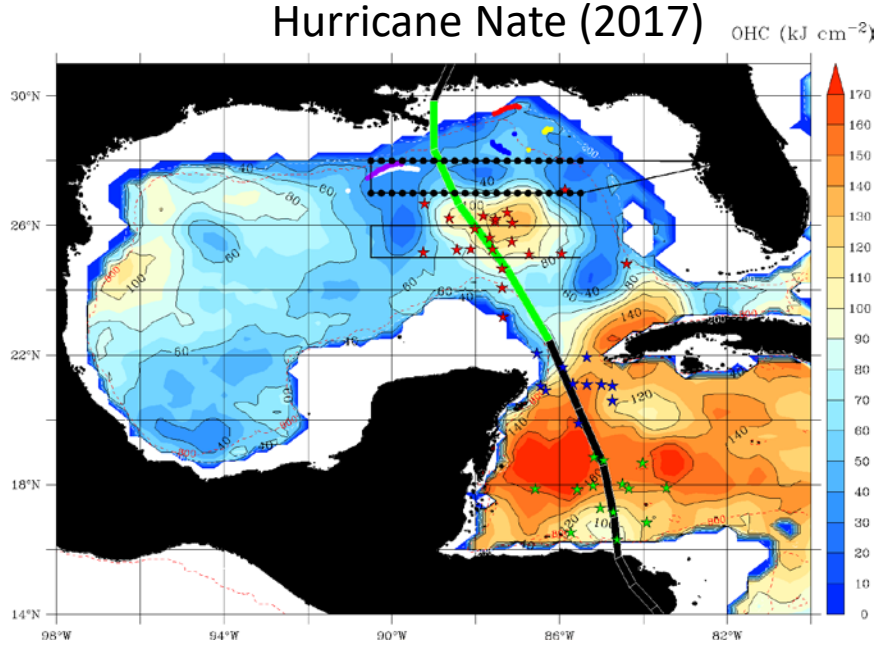
# AXBT / AXCP / AXCTD

- ***A***irborne e***X***pendable:
  - ***B***athy***T***hermograph (AXBT)
  - ***C***urrent ***P***rofiler (AXCP)
  - ***C***onductivity, ***T***emperature, ***D***epth (AXCTD)

- Deployed in 2 ways
  - Pre- & post-TC surveys
    - NOAA P-3
    - Shown to be impactful (OSSE)
  - In & around TC
    - USAF 53rd WRS WC-130J
    - P-3 as feasible (e.g. Nate at right)
    - Shown to be impactful (adjoint)

- Impacts
  - Improved Initial Conditions
  - Improved Physics

Hurricane Nate (2017)




In-storm AXBT Flights

| Flight | Parameters | Deployed | Transmitted Data | Success Rate |
|---|---|---|---|---|
| 201706H1 | T | 14 | 14 | 100% |
| 201706H2 | T | 11 | 9 | 82% |
| 201707H1 | T | 21 | 11 | 52% |
| **Overall** | | **47** | **34** | **72%** |

Post-storm Flight

| Probe Type | Parameters | Deployed | Transmitted Data | Success Rate |
|---|---|---|---|---|
| AXBT | T | 20 | 19 | 95% |
| AXCP | T, u, v | 16 | 13 | 81% |
| AXCTD | T, S | 5 | 5 | 100% |
| **Overall** | | **41** | **37** | **90%** |

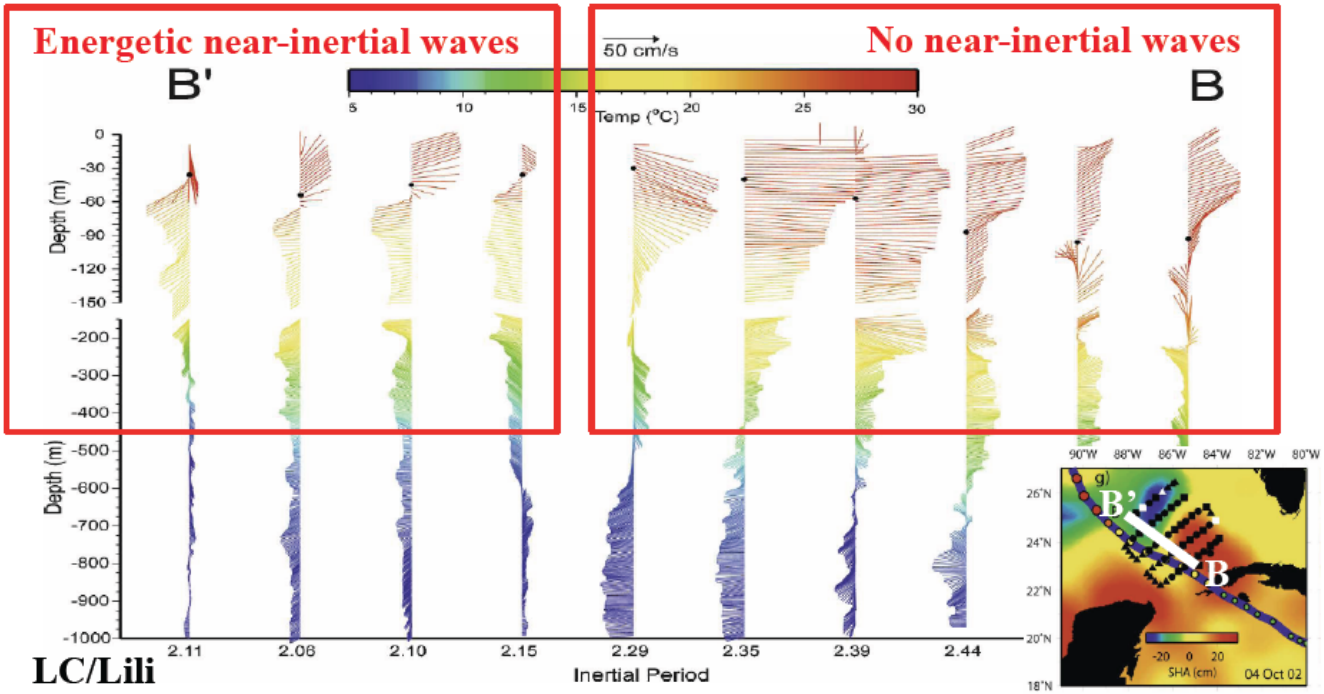
N. Shay

# Vertical Structure of Near-inertial Currents From AXCPs

**Loop Current (LC) near-inertial response to Hurricane Lili of 2002:**

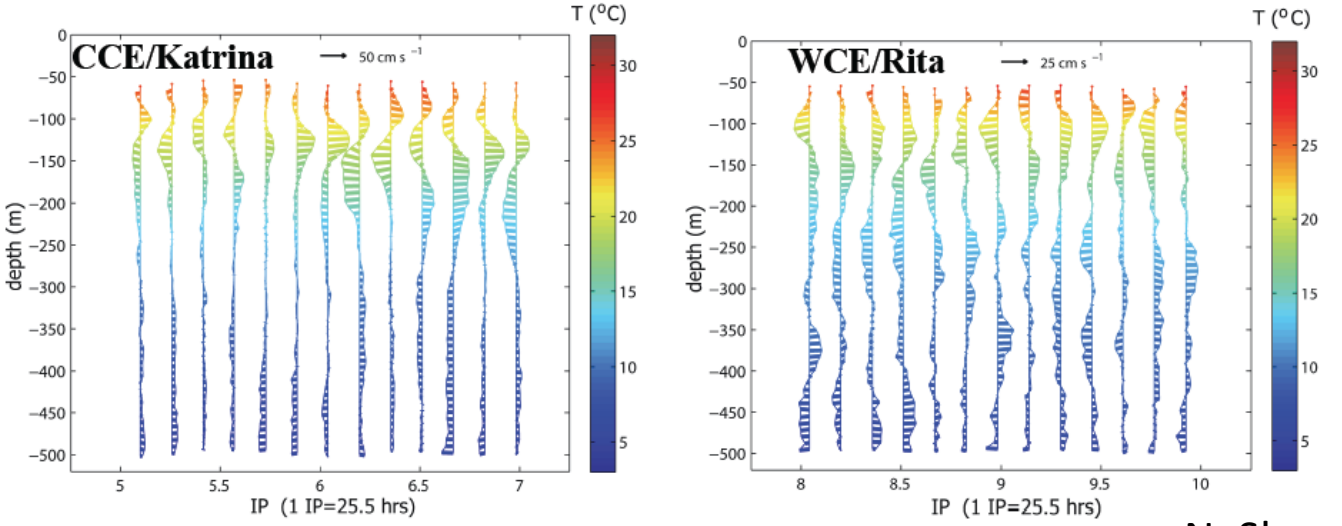
- **Energetic near-inertial response outside the LC.**
- **Weak near-inertial response inside the LC.**

The near-inertial response is important because it leads to vertical mixing.




**Near-inertial response to Hurricanes Katrina and Rita of 2005:**

- **CCE: energetic near-inertial response to hurricane Katrina.**
- **WCE: weak near-inertial response to hurricane Rita.**



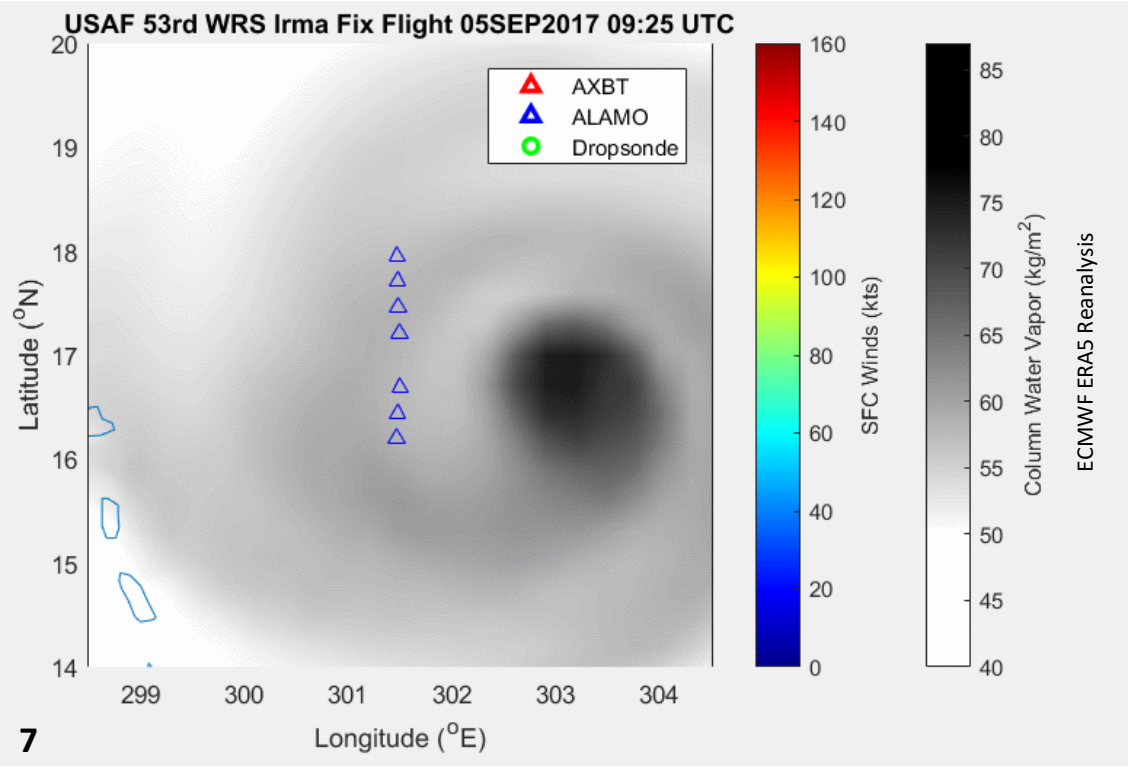



N. Shay

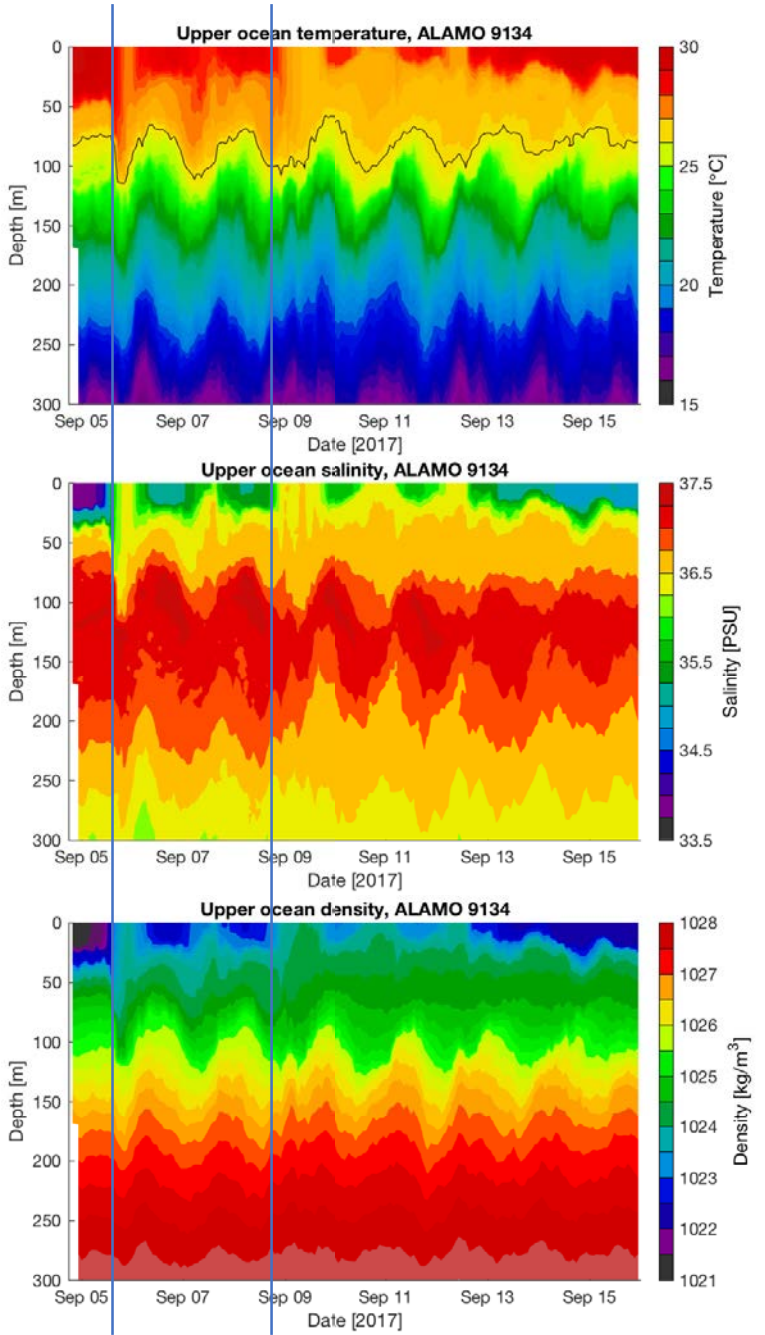
| A/C: A-sized floats | Many profiles |
|---|---|

# ALAMO

- *Deployment Coordination*: 53rd WRS
- *Variables*: $T, S, P$ $(+2D\ wave\ spectra\ in\ 2019)$
- *Data Path*: Iridium
- *Spatial Resolution:* sfc to 1000m
- *Temporal Resolution:* sfc to 300m at 2-h intervals
- *Duration*: ~6 months




## Hurricane Irma (2017)

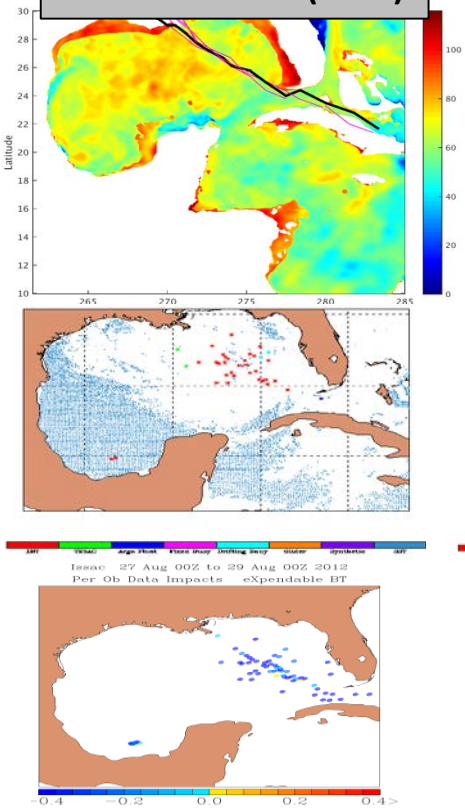


# Data Impacts: *Improvement to TC Forecast*

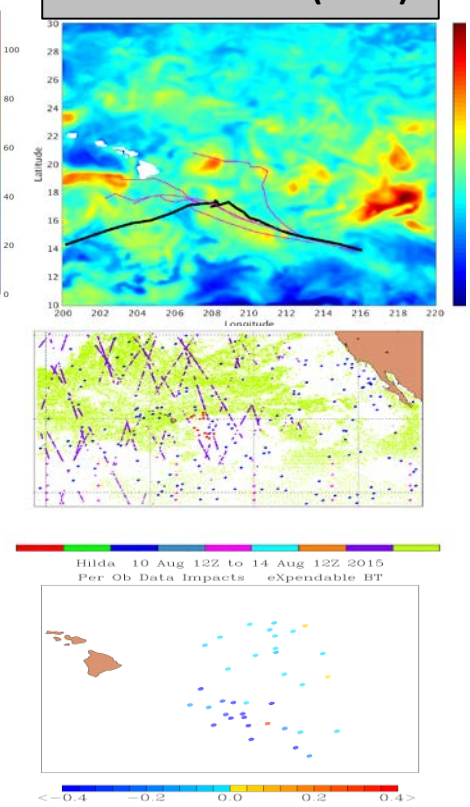
Ocean Data Assimilation (Adjoint / Data Denial Study):

- Improved the NCOM 12-24 forecast of SST and ocean heat content
- Improved both the track and intensity forecast

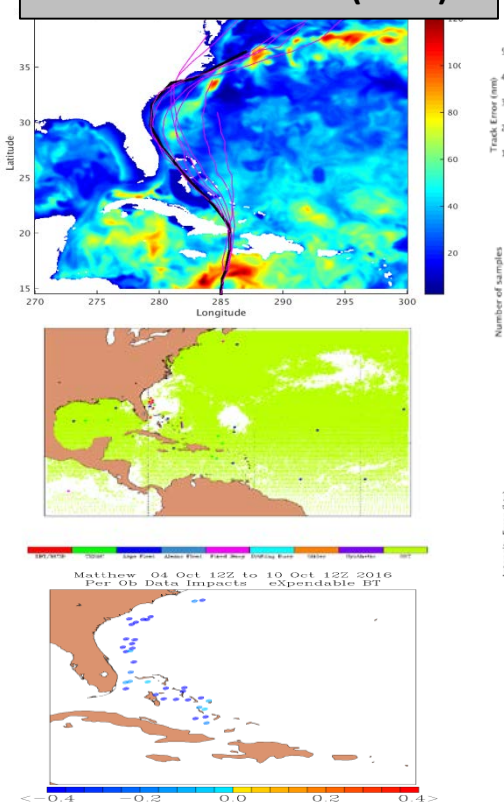
**Hurricane Isaac (2012)**



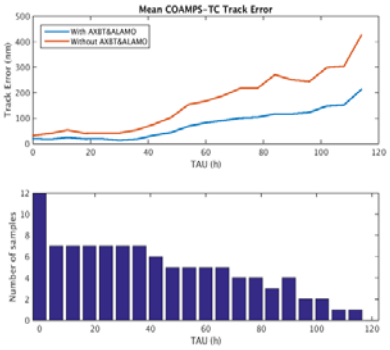

**Hurricane Hilda (2015)**



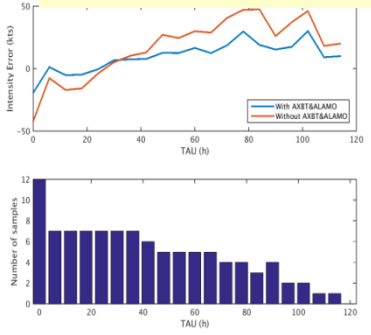

**Hurricane Matthew (2016)**




**Intensity Error**




**Track Error**

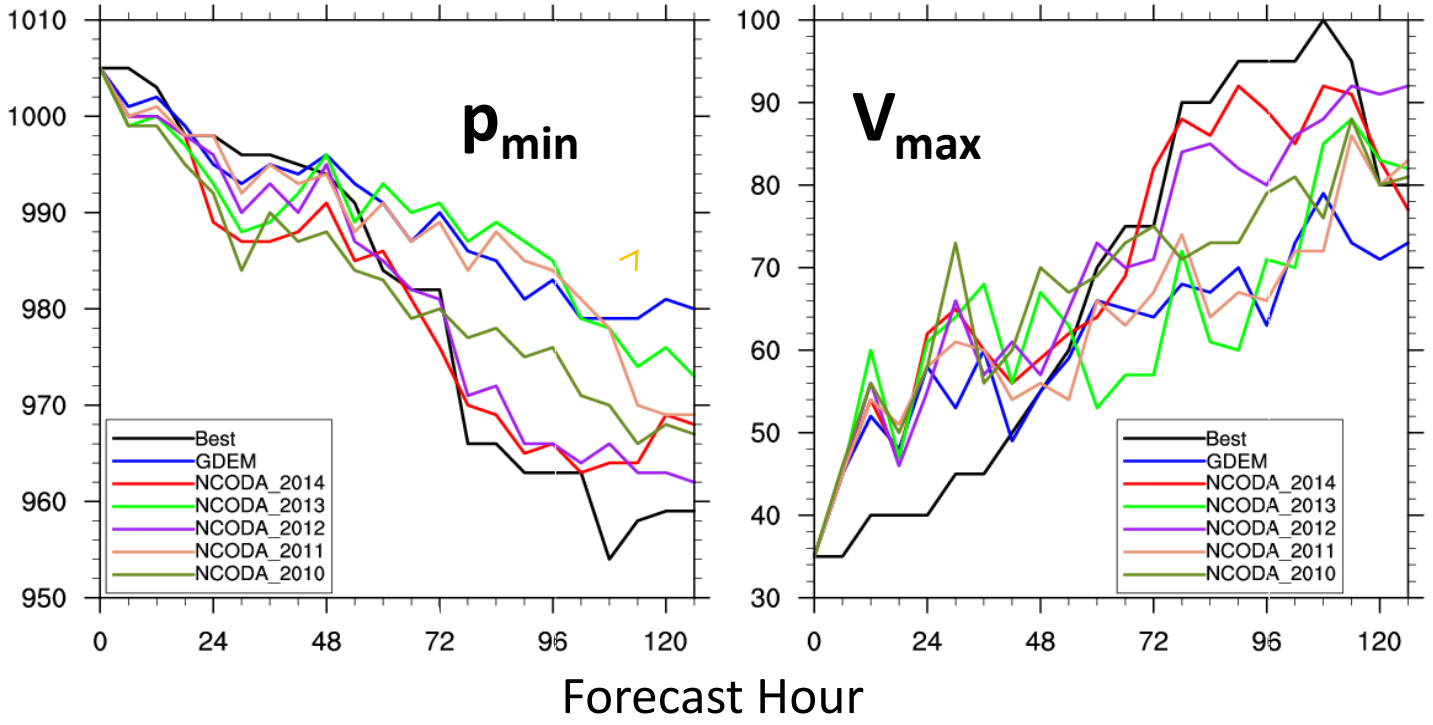





S. Chen

# Data Impacts: *Sensitivity of Intensity to Ocean Initialization*

Hurricane Edouard (2014)




HYCOM-HWRF initialized from GDEM climatology and Navy Global HYCOM analyses from 5 different years (2010-2014, performed by J. Dong).

Interannual differences in upper-ocean conditions have a large influence on predicted intensity (maximum spread: 22 hPa and 30 knots).

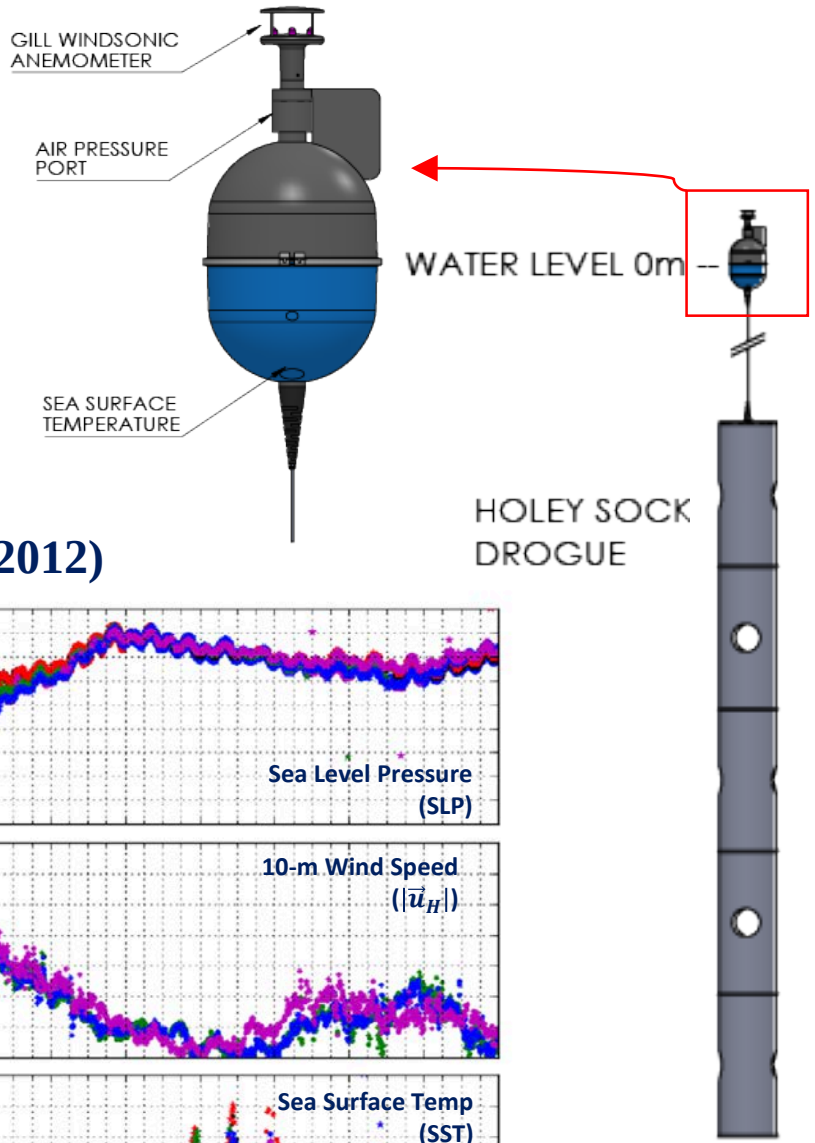
Accurate ocean model initialization is necessary.

Assimilation of ocean observations is critically important for improving initialization.

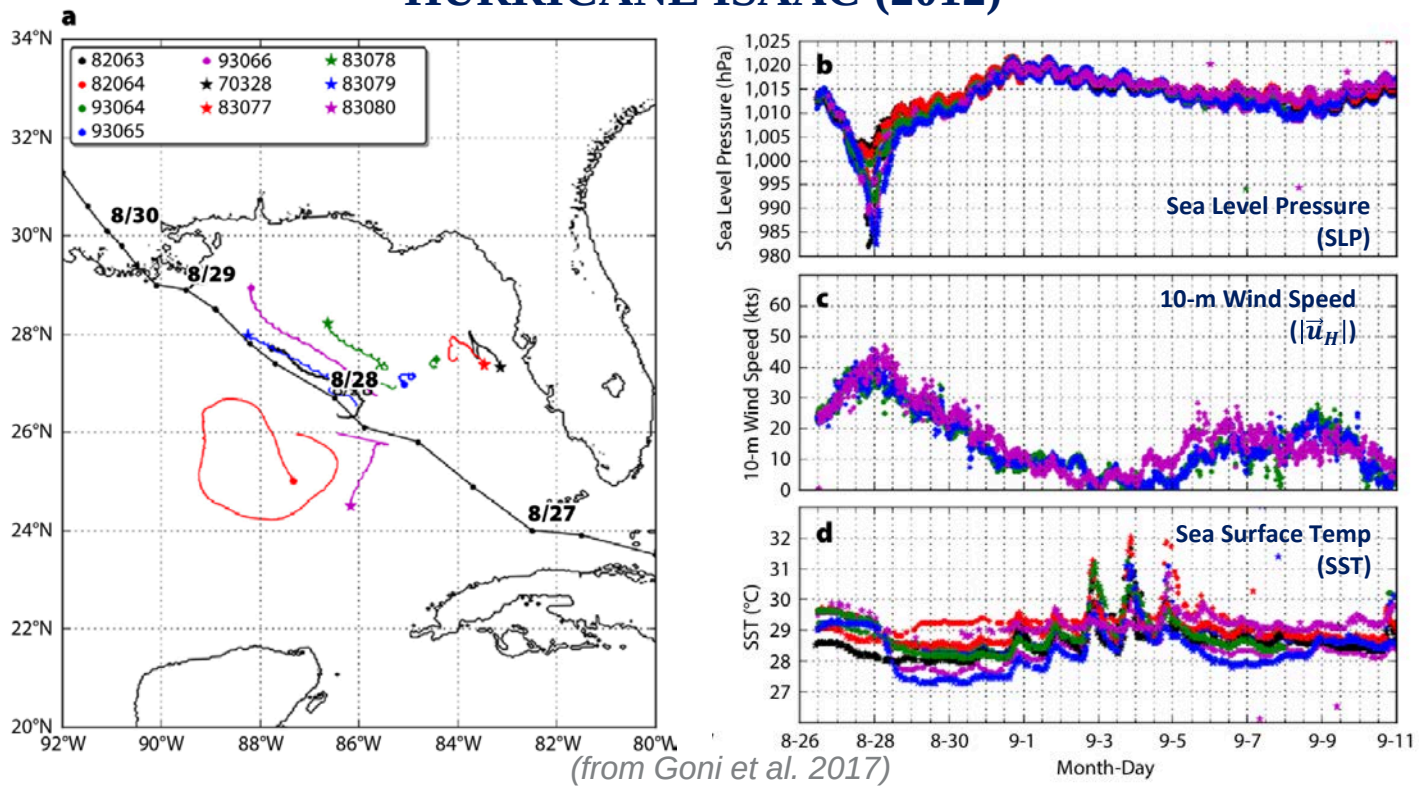
G. Halliwell

# Minimet

- **Global Drifter Program**
- *Deployment Coordination*: CARCAH and 53rd WRS
- *Variables*: *SST, SLP, 10-m wind speed* ($|\vec{u}_H|$)
- *Data Path*: Iridium
- *Temporal Resolution:* variable down to 5 min




## HURRICANE ISAAC (2012)




(from Goni et al. 2017)

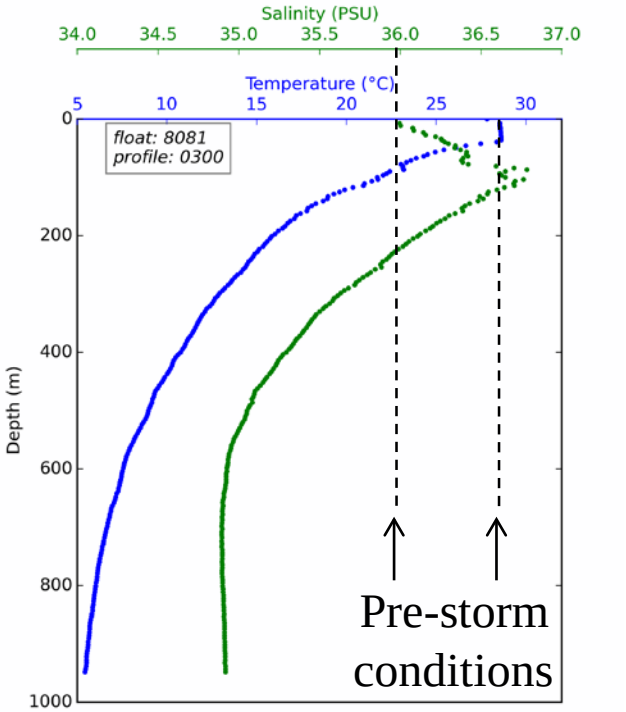
Minimet drawing courtesy: http://gdp.ucsd.edu/ldl_drifter/instruments/minimet.html

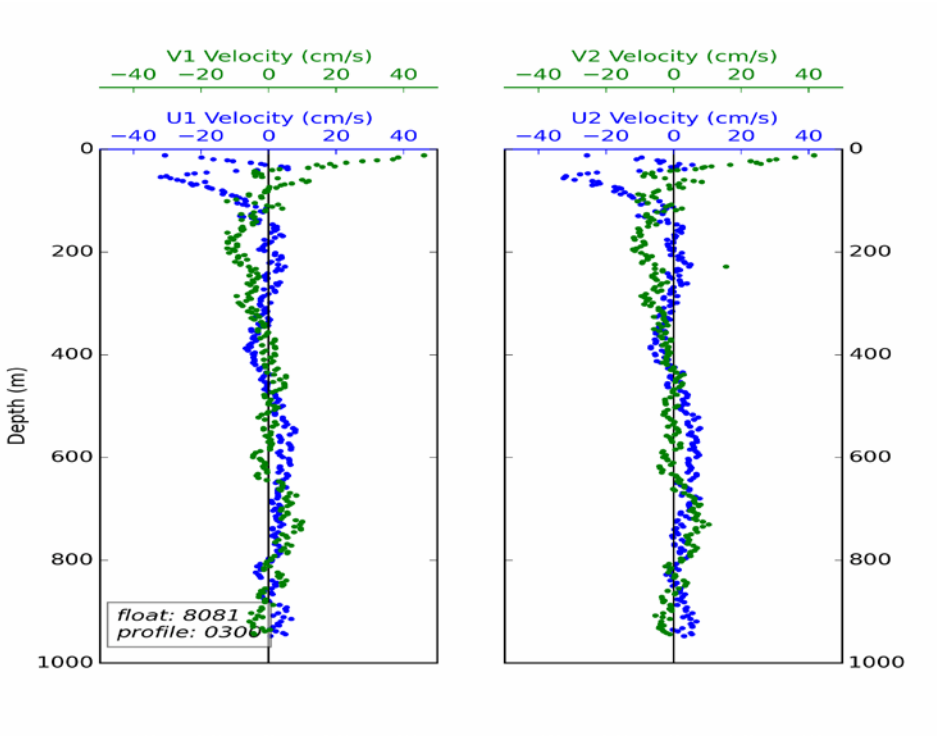
A/C: Ramp-deployed | Many profiles

# EM-APEX

***E***lectro***m***agnetic ***A***utonomous ***P***rofiling ***Ex***plorer

- *Deployment Coord*: CARCAH and 53rd WRS
- *Variables*: *T, S, P,* $u, v$
- *Data Path*: Iridium
- *Spatial Resolution:* variable (to 2000m)
- *Temporal Resolution:* variable




**HURRICANE NATE (2017)**

| A/C: P-3 Fuselage mounted | Many observations |
|---|---|

# WSRA

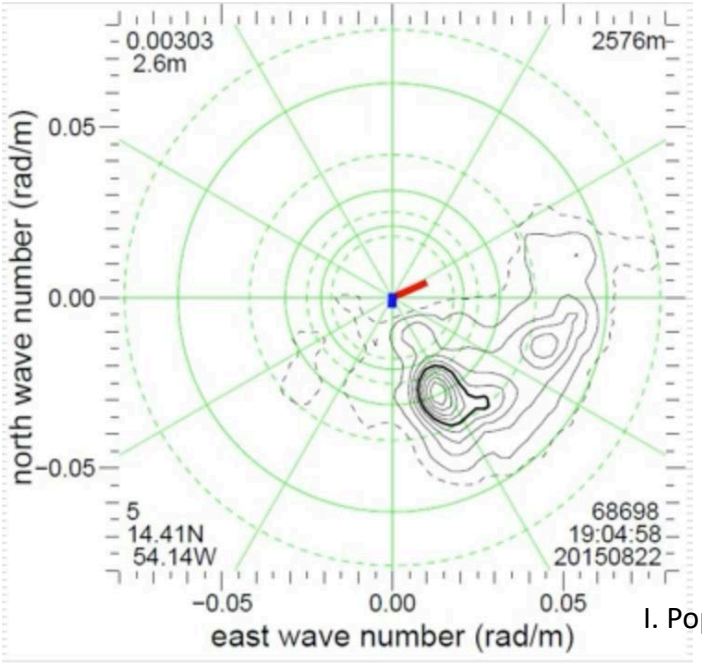
- **W**ide **S**wath **R**adar **A**ltimeter
- NOAA P-3 fuselage – ½ season

- Measures
  1) ocean directional wave spectra
  2) significant wave height
  3) rain rate
  4) mean square slope of the ocean surface

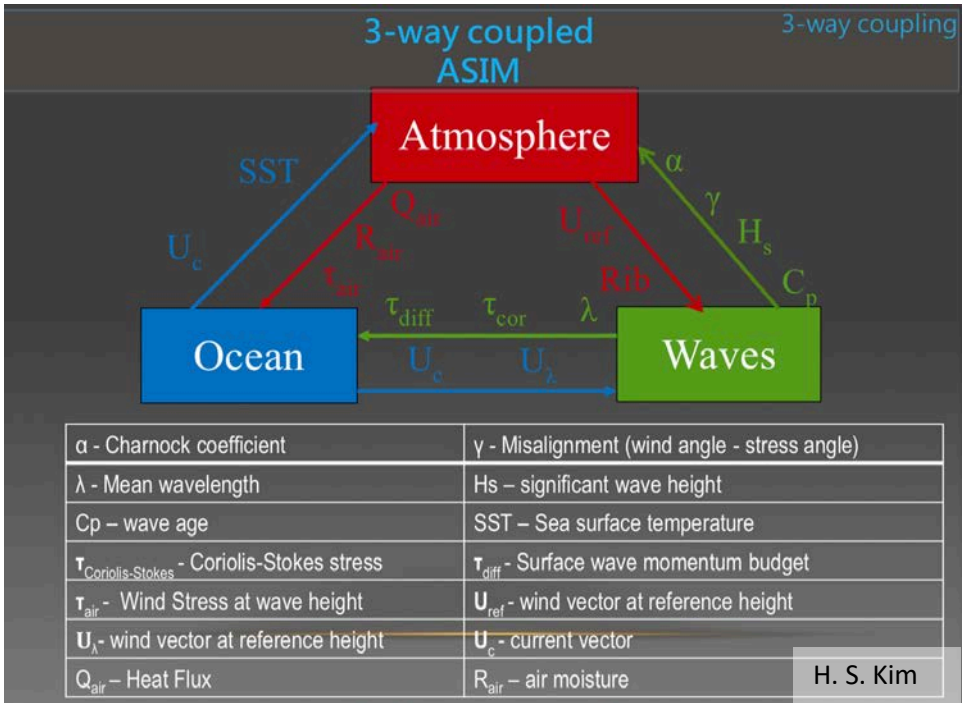
- Resolution
  - Spatial: ~3.5-km cross track
  - Temporal: ~5 min

- Data Availability
  - To NHC In REAL TIME
  - Not to GTS

## HURRICANE DANNY (2015)




I. PopStefanija



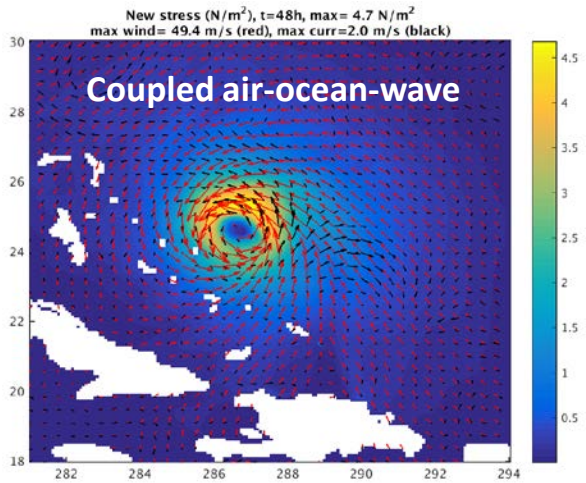

| | |
|---|---|
| α - Charnock coefficient | γ - Misalignment (wind angle - stress angle) |
| λ - Mean wavelength | Hs – significant wave height |
| Cp – wave age | SST – Sea surface temperature |
| $\tau_{Coriolis\text{-}Stokes}$ - Coriolis-Stokes stress | $\tau_{diff}$ - Surface wave momentum budget |
| $\tau_{air}$ - Wind Stress at wave height | $U_{ref}$ - wind vector at reference height |
| $U_\lambda$ - wind vector at reference height | $U_c$ - current vector |
| $Q_{air}$ – Heat Flux | $R_{air}$ – air moisture |

H. S. Kim

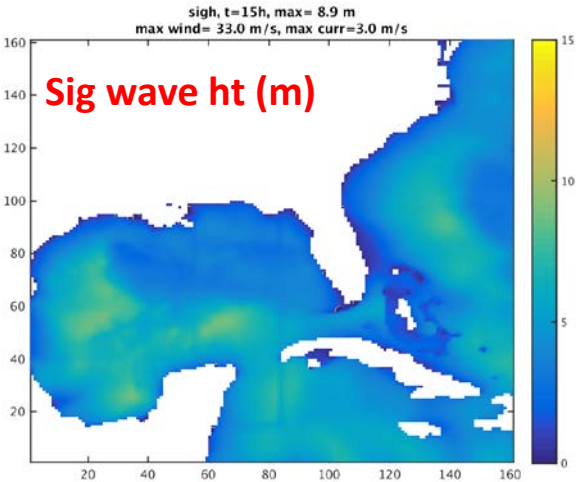
# Wave Coupling Tests

## COAMPS-TC / NCOM / SWAN

- **Wave coupling reduces the momentum stress to ocean by ~11%**




Hurricane Frances (2004)

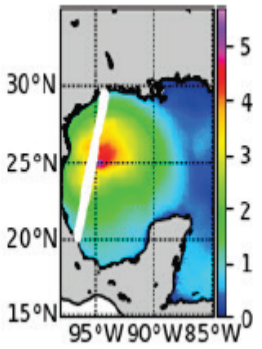


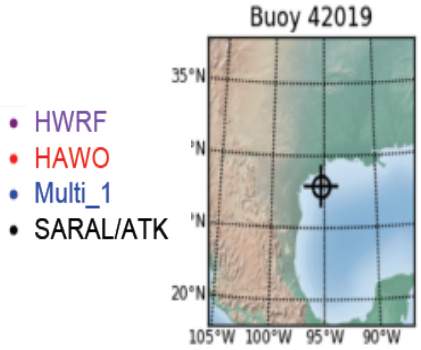

Hurricane Harvey (2017)

## HWRF / HYCOM / WWIII

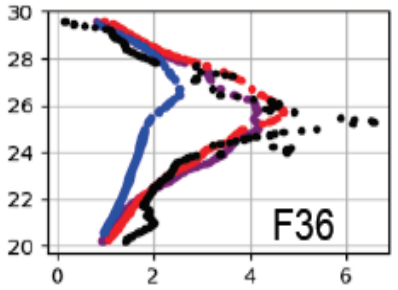
Hurricane Harvey (2017)

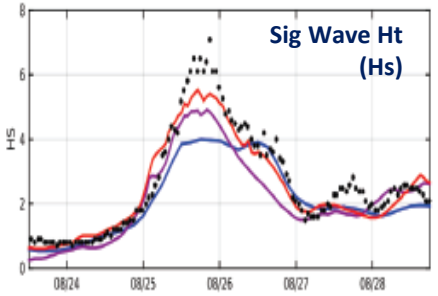
- Altimeter vs. Buoy

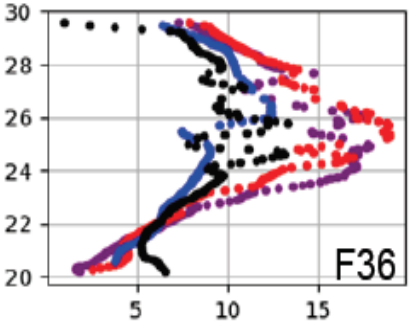


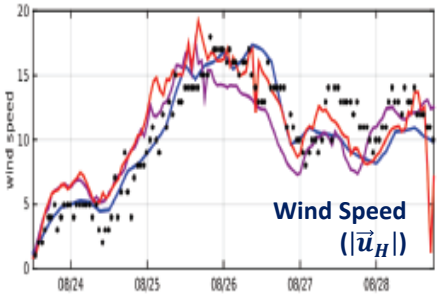




HWRF
HAWO
Multi_1
SARAL/ATK



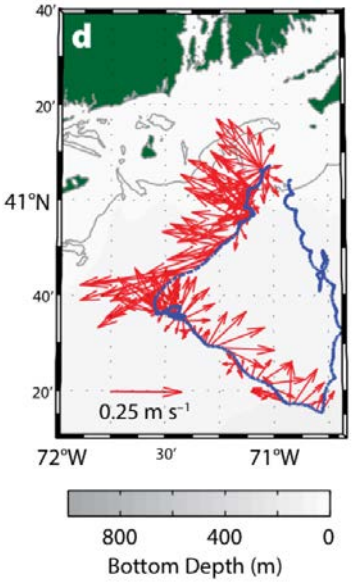



Ship / shore-deployed

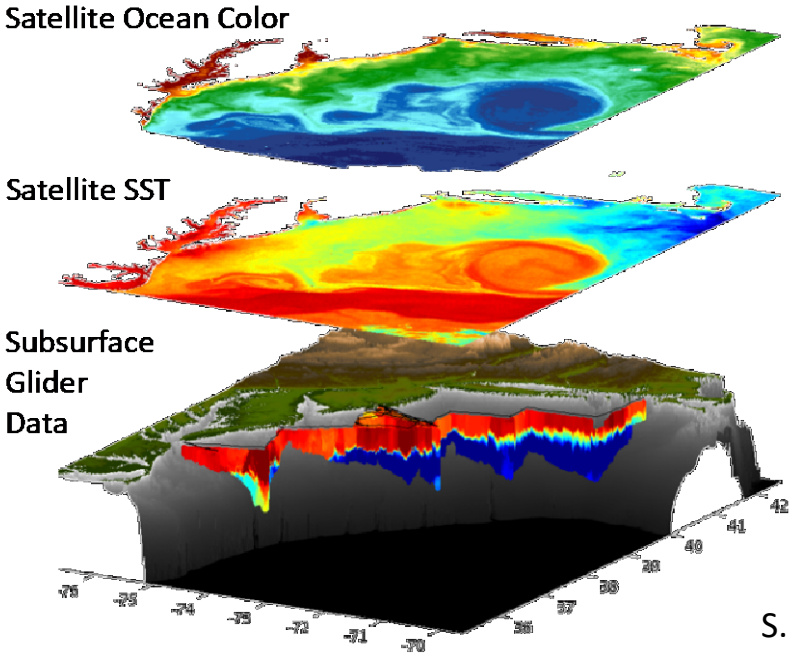
# Gliders

- Variables: *T,S,P,* $\vec{u}$ *(+many others)*
- Operating depths: from ~5-1200 m
- Pre-storm surveys
  - Critical gap-filling platform, particularly in shelf regions where altimetry is not assimilated
  - Observations often uploaded to GTS
- Results
  - **Initial Conditions:** Captures spatial and temporal variability of pre-storm state
  - **Physics:** Changes in drag coefficient at high wind speeds
- Groups
  - **Mid-Atlantic** (IOOS – NSF funded)
    - *Rutgers* Scott Glenn
      - Sandy (2012), Gonzolo and Fay (2014)
    - *WHOI* Robert Todd
      - Arthur (2014), Hermine (2016)
  - **Western Caribbean**
    - *AOML* Gustavo Goni

## HURRICANE HERMINE (2016)


*(from Goni et al. 2017)*

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## Satellite (surface)

- **Sea surface temperature (SST)**
  - NCODA: NOAA 18,19, METOP A,B, MSG, and NPP VIRRS
    - Himawari-8 in testing at NAVO
  - NOAA: AMSR-2
- **Sea surface heights (SSH)**
  - Geostrophic Currents
- **Sea surface salinity (SSS)**
  - NASA: Soil Moisture Active Passive (SMAP)
  - ESA: Soil Moisture Ocean Salinity (SMOS)
  - Available, but not assimilated
- **Significant wave height (Hs)**
  - Various altimeters
  - Assimilated into Wavewatch III
    - FNMOC only, not NAVO
- Characteristics
  - High resolution
  - Often impacted by cloud cover in areas of interest

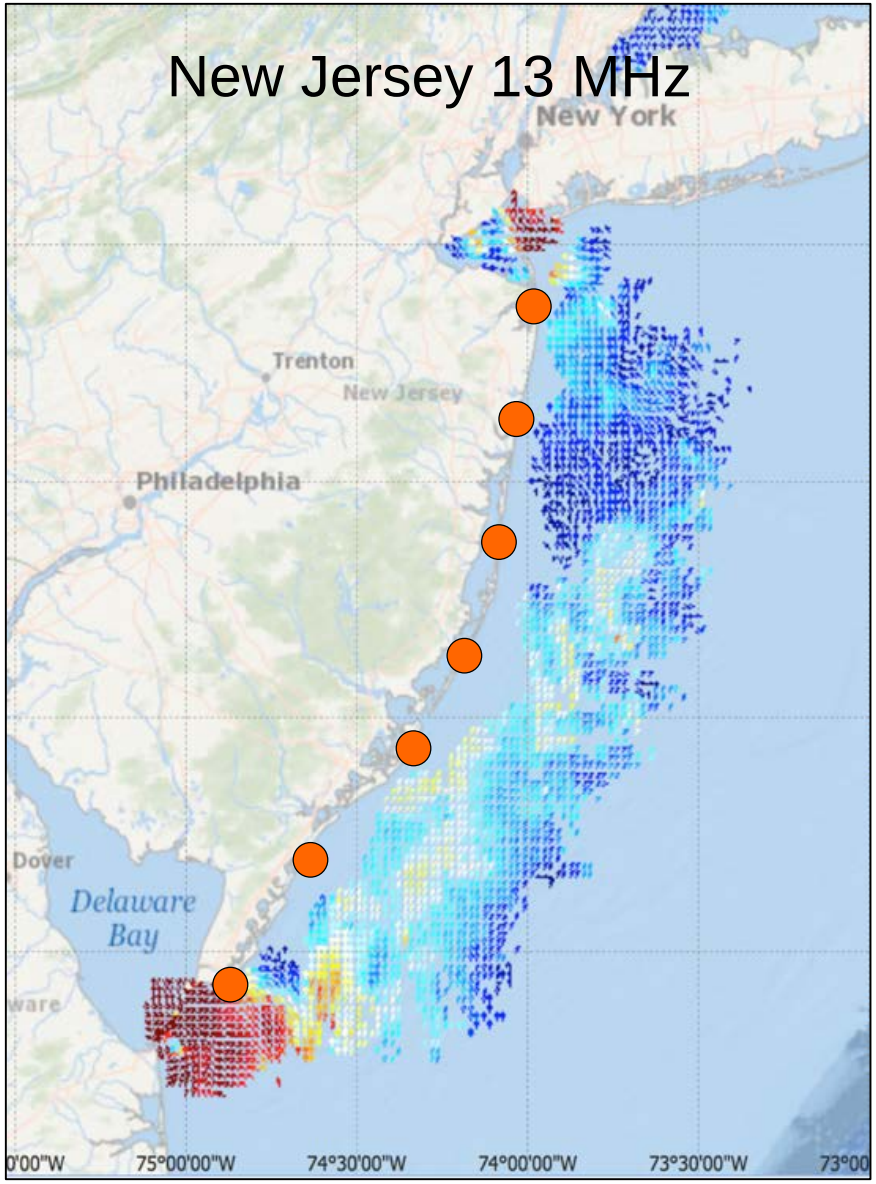
## Argo (upper 2000m)

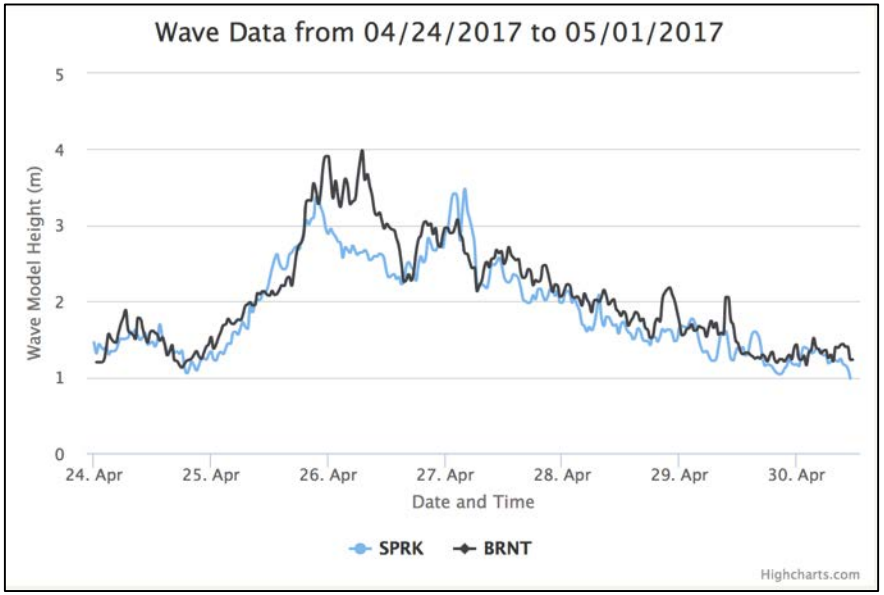
- Global network of profiling floats
- **Variables: *T,S,P (at times u,v)***
- Resolution:
  - Space: Worldwide, irregular
  - Time: 1 x/ 10 days
- Regular improvement to model background

## HF Radar (surface)

- Coastal Observing Network
- **Variables: *Sea surface currents (u,v) and wave data***
- Coverage: 2-200km offshore
- Resolution:
  - Space: 500m – 6km (frequency dep)
  - Time: Averaged hourly
- Available, but not assimilated

# Medium Range HF Radar Network – Nearshore Waves




- **Variables: *surface wind, waves***
- Coverage: Coastal U.S.

  2-200km offshore
- Resolution:
  - Space: 500m – 6km (freq. dep.)
  - Time: averaged hourly
- Available, not assimilated

IOOS | Integrated Ocean Observing System



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# Emerging Technologies

## 1) Coyote UAS

- Boundary layer atmospheric data
- A-sized; deployed from P-3
- Duration: Mission dependent

## 2) Air-Deployed Wave Buoy (ADWB)

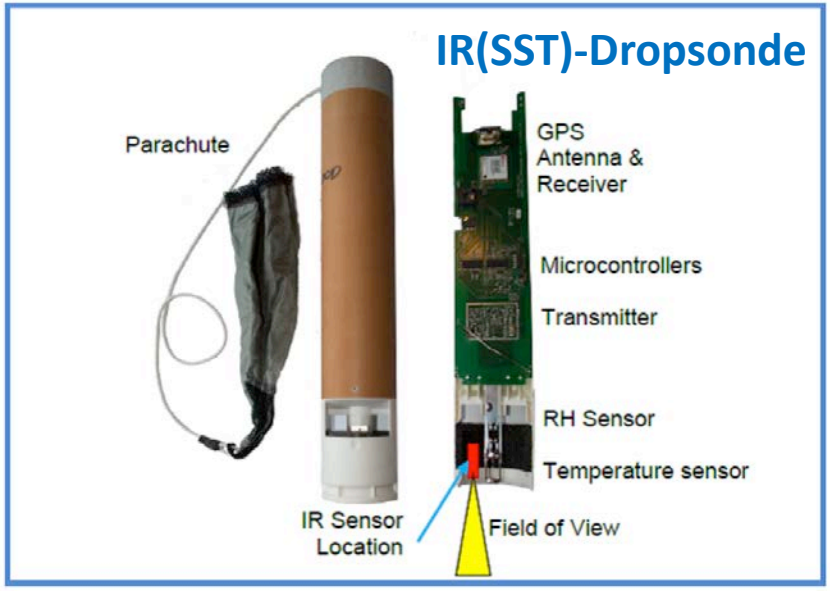
- 2D wave spectra
- A-sized, C-130/P-3 deployable
- Data Path: Iridium
- Duration: 6-mo at 3-hourly obs
- Scripps

## 3) IR(SST)-Dropsonde

- Aircraft track
- Melenix Infrared Thermometer and Infrared sensor

## 4) MASED - Combo Air-Ocean Sonde

- Multi-Purpose Above Surface/Below Surface Expendable Dropsonde
- A-sized
- Boston Engineering through NOAA SBIR




J. Cione

# Hurricane Ocean Sensing Strategy

- **Goal:** Improve TC Forecasts

- **Objectives**
  1) Improve initial conditions (*T, S, P,* $\vec{u}$)
  2) Improve parameterizations (*T, S, P,* $\vec{u}$*, wave spectra*)
  3) Wave coupling
  4) Coupled model validation

- **What's Needed**
  1) Coordinated comprehensive sensing strategy
  2) Commitment to funding

- **One Way Forward**
  1) Observation Pattern
     a) *Background:* Satellite, ARGO / Moorings, Glider, HF Radar
     b) *Pre-TC:* AXCP, ALAMO, (AXBT), Minimet, EM-APEX, (ADWB)
     c) *In & Around TC:* AXCP, ALAMO, (AXBT, AXCTD), WSRA, Coyote
     d) *Post-TC:* AXCP, (AXBT, AXCTD), Glider
  2) Ensure observations are transmitted in NRT and assimilated
  3) Consistent model testing and evaluation

# References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# Helpful Websites

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- Boston Engineering: https://www.prnewswire.com/news-releases/boston-engineering-advances-hurricane-forecasting-with-noaa-300515566.html
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