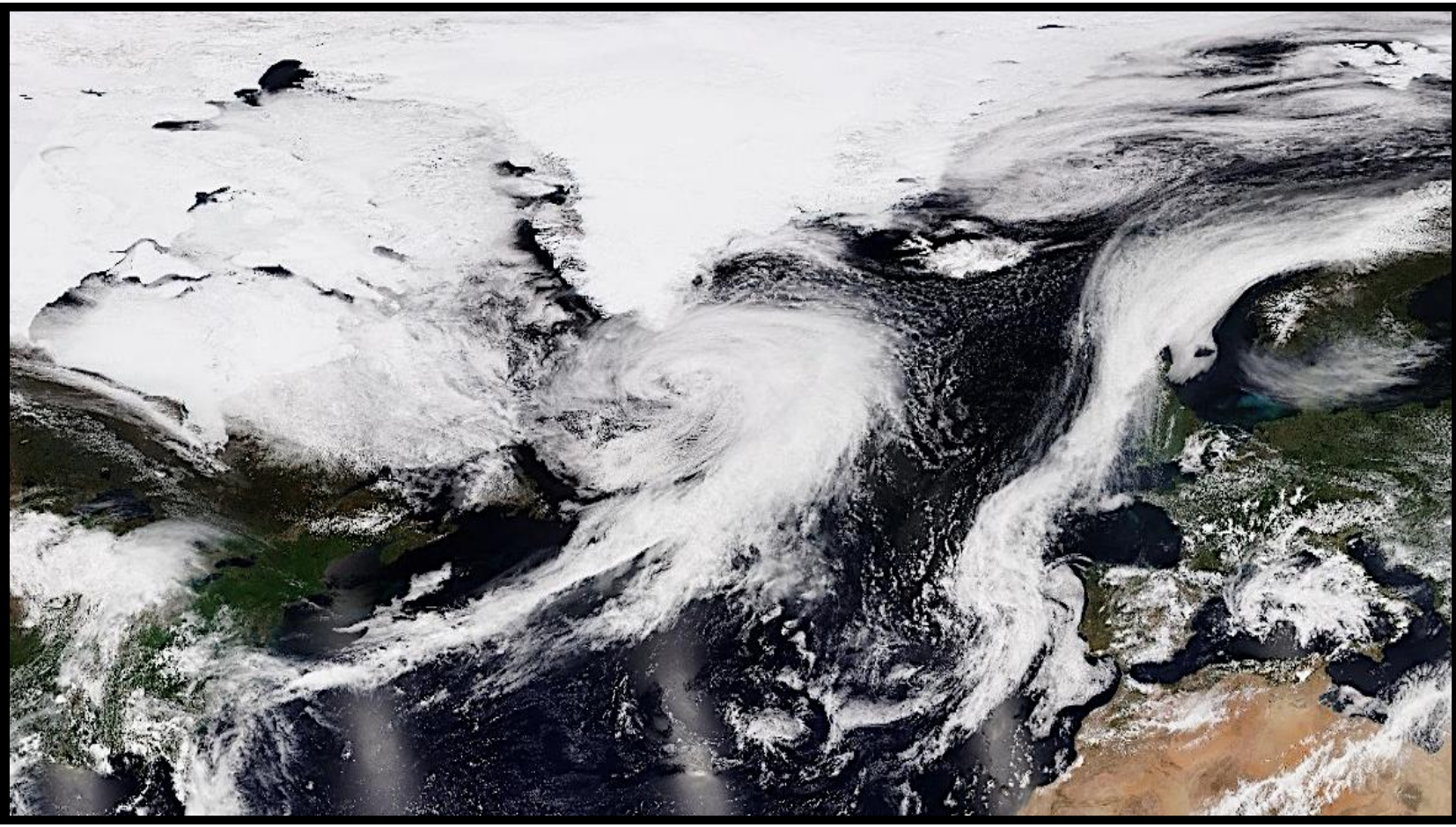
3rd International Workshop on Waves, Storm Surges, and Coastal Hazards

Performance of ERA5 Wind Speed and Significant Wave Height Within Extratropical Cyclones Using Satellite Radar Altimeter and Wave Buoy Measurements



John Lodise, Sophia Merrifield, Clarence O. Collins, James Behrens, and Eric Terrill

Correspondence: jlodise@ucsd.edu

US Army Corps of Engineers ®

CDIP coastal data information program

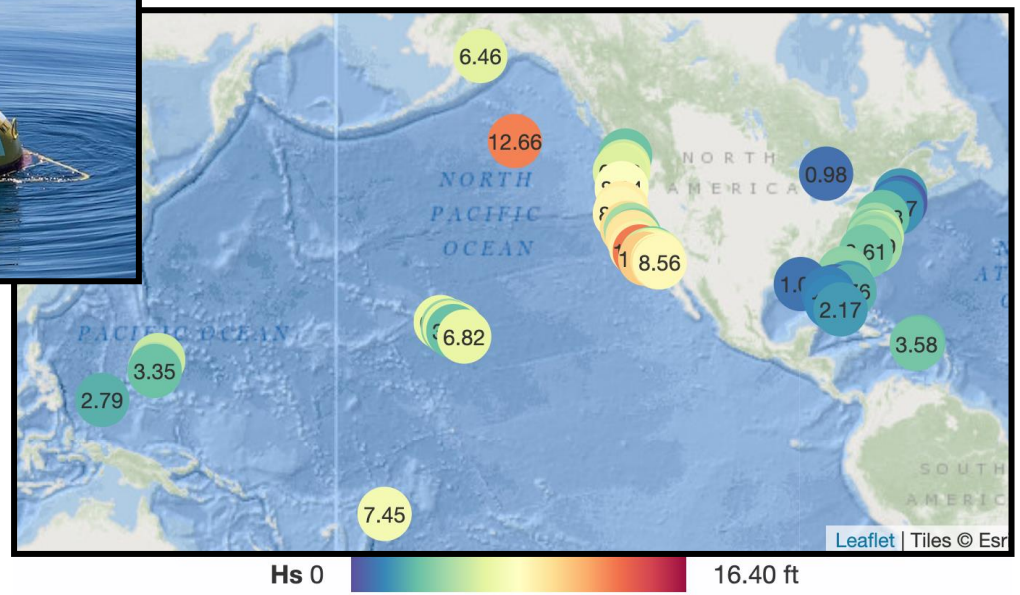
- Postdoctoral Scholar at Scripps Institution of Oceanography

- Coastal Data Information Program (CDIP)
  - High fidelity wave measurements over all US coasts to inform researchers and engineers

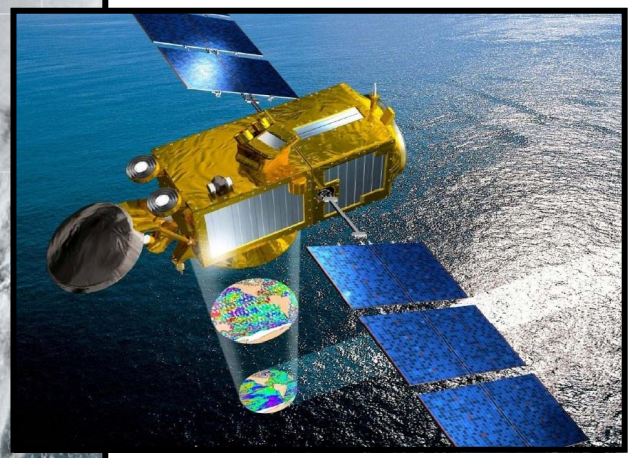
- Current Focus
  - Tracking and studying extreme storm events (Extratropical Cyclones)

  - Comparing wave measurements from remote and in-situ instruments to operational models

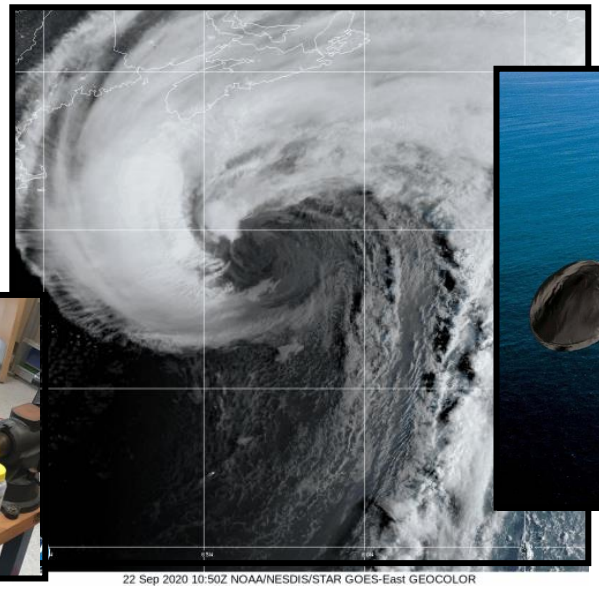
CDIP Wave Buoy Array



Satellite Radar Altimetry



Drifting Wave Buoys



Outline

- **Background/Motivation**
  - **Extratropical Cyclones**
  - **Tendency for wave models to underestimate peak waves during extreme events**

- Data sets
  - ERA5 Reanalysis
  - Global data set of Extratropical Cyclones
  - Satellite Radar Altimeter data

- Results shown in a cyclone centered reference frame
  - Cyclone structure
  - Model Performance

- Summary

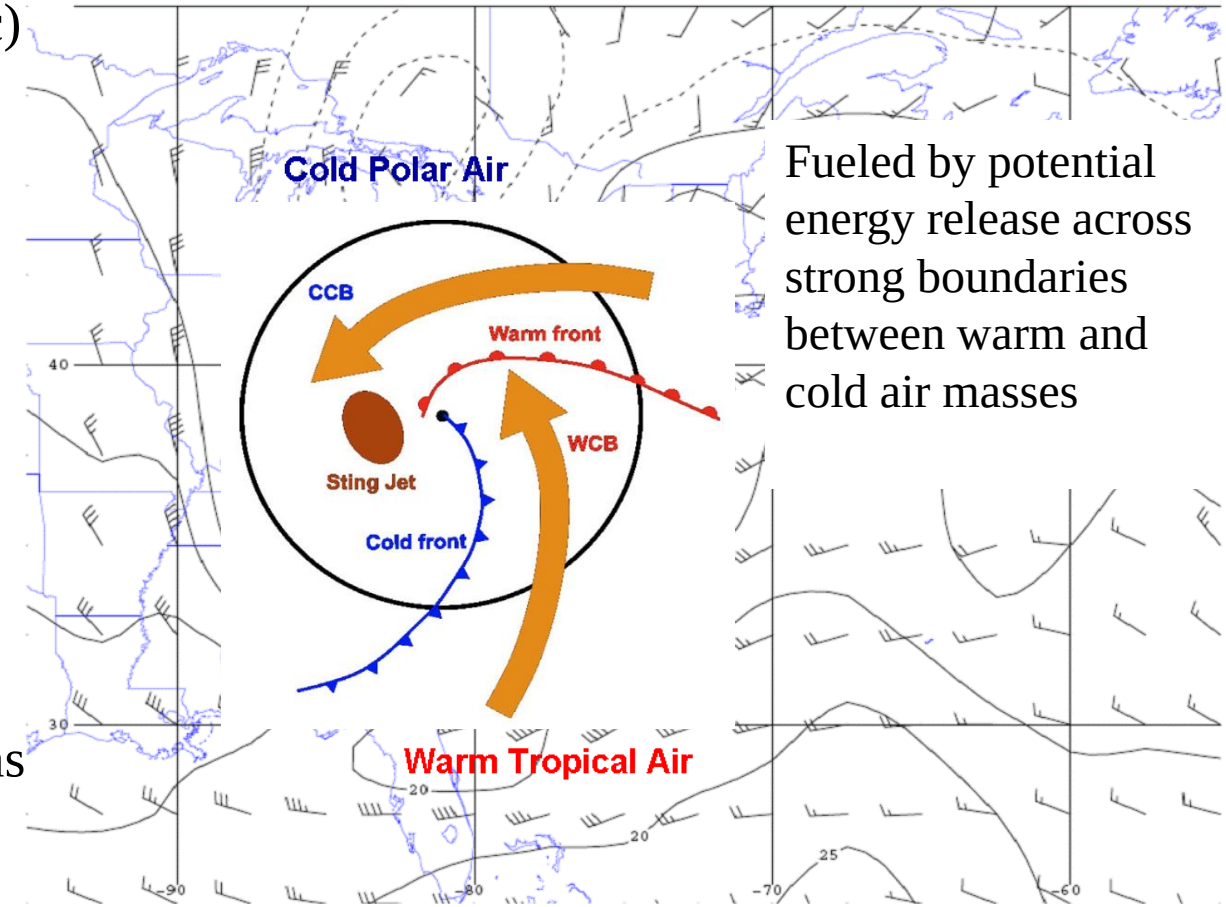
Extratropical Cyclones

- **Extratropical Cyclones** form in mid-high latitudes (>25^{o} N/S)
  - Mixes cold and warm air in Mid-latitudes (Baroclinic)
  - Horizontal Frontal System (warm and cold fronts)

- Examples of extratropical cyclones
  - Blizzards
  - Nor'easters
  - Mid-latitude cyclones

- Dominate wave climatology in mid-high latitudes
  - Strong winds and large fetch O(1000km)
  - Extreme sea states and swell that travels across oceans
  - Coastal erosion and inundation
  - Cause large upper ocean mixing event

Extratropical Cyclone



Fueled by potential energy release across strong boundaries between warm and cold air masses

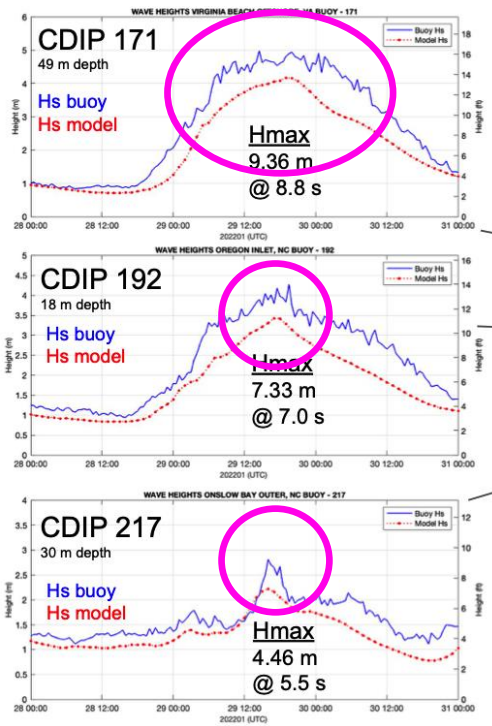
Ponce de Leon et al (2021)

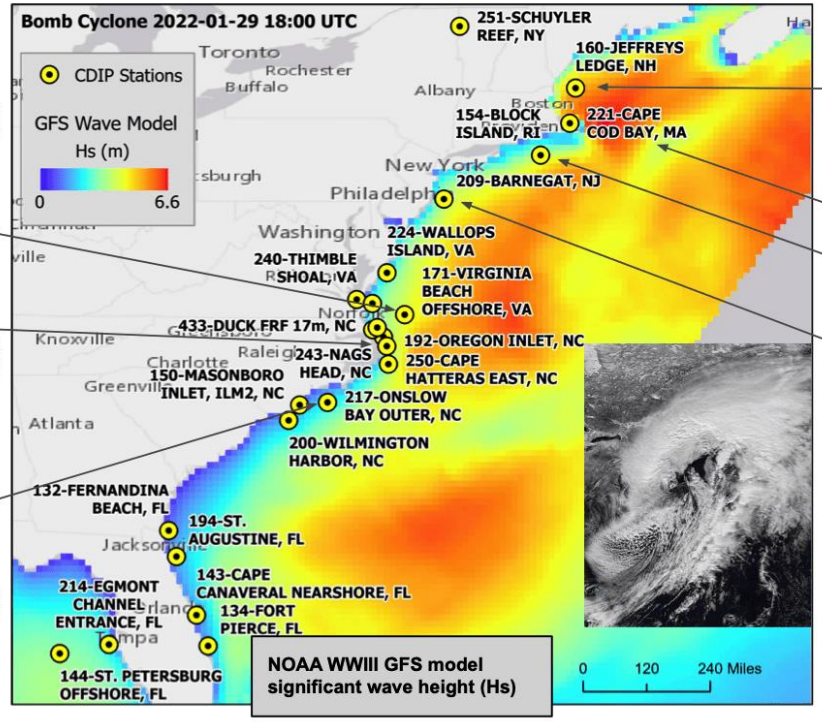
(MIT Dep. Earth, Atmosphere, and planetary Sciences)

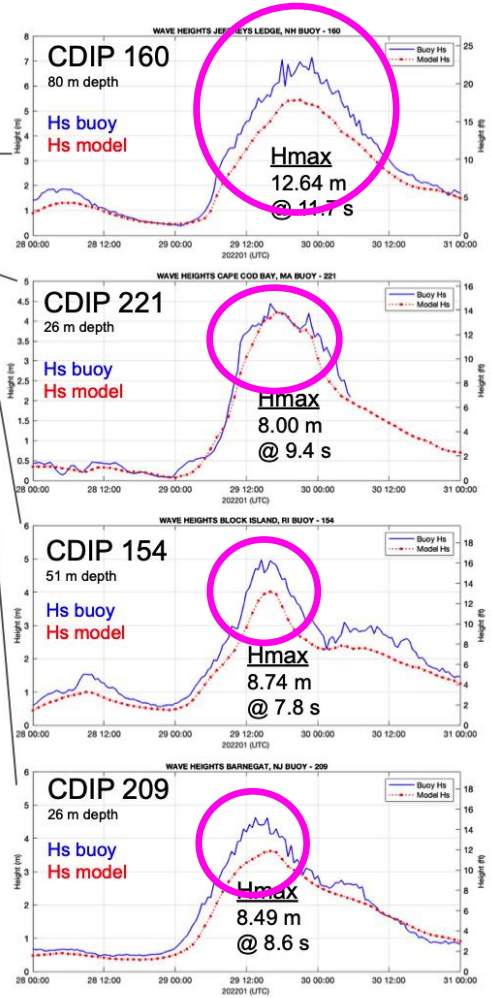
CDIP
coastal data information program
cdip.ucsd.edu

CDIP Wave Observations:
Bomb Cyclone Nor'easter
January 29-30, 2022

US Army Corps of Engineers ®







- A bomb cyclone nor'easter set snowfall records in the Northeast, with gale force winds driving coastal flooding and erosion, in addition to the blizzard conditions on shore.
- Wind gusts at Cape Cod were equal to that of a Category 2 hurricane.
- CDIP buoy stations from North Carolina to New Hampshire measured powerful storm waves, with relatively short peak periods of ~ 8 sec.
- The storm underwent rapid intensification, reaching a central low of 968 mb.
- Complete data set is available at cdip.ucsd.edu

CDIP hurricane and storm reports:
cdip.ucsd.edu/themes/cdip?d2=p13

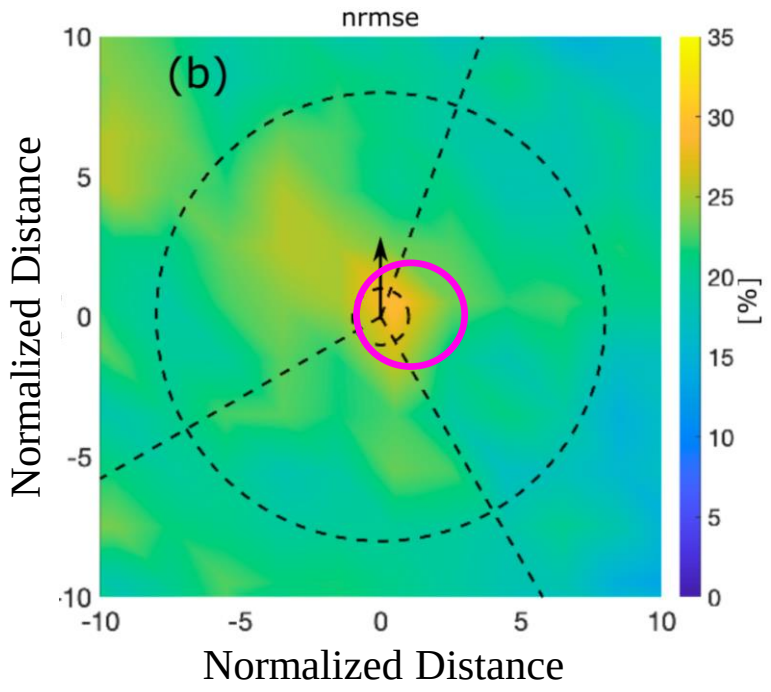
Model misses peak wave heights all along US east coast

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

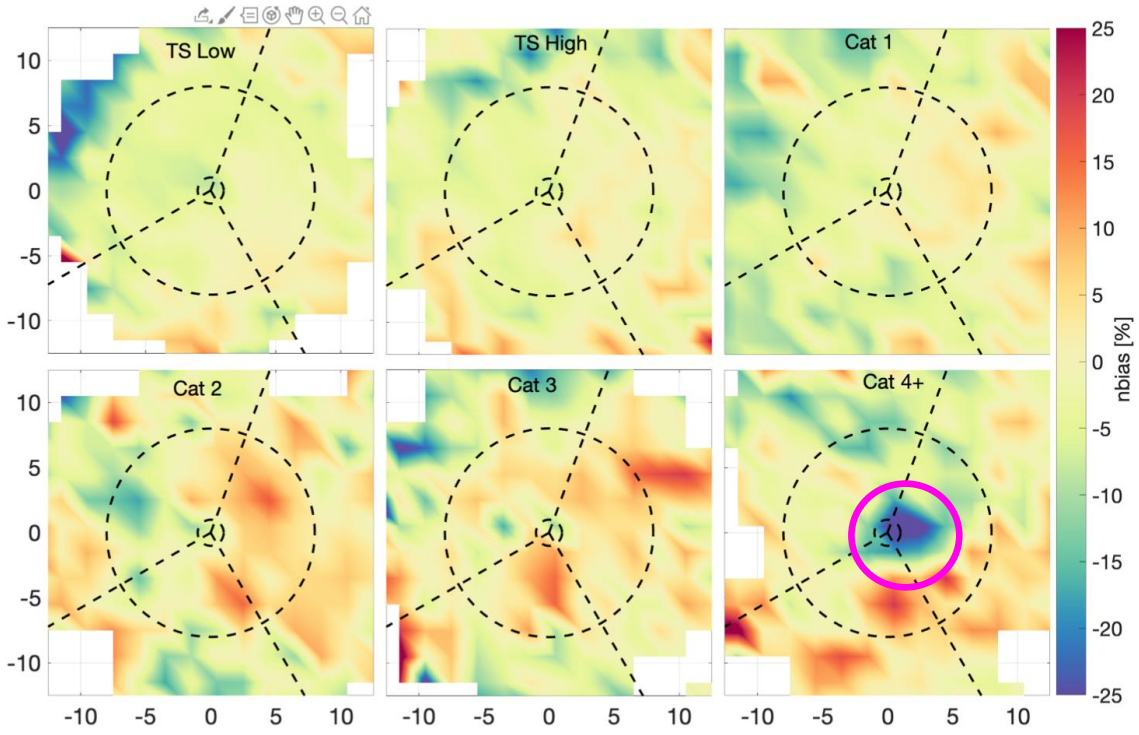
Models Miss Extreme Waves in Tropical Cyclones

- Highlight challenges of modeling waves under rapidly evolving/extreme conditions
- Strong dependence on cyclone region, speed, strength

Composites of Satellite Hs in TC reference frame



Bias from Operational Wave Hindcast (*Ifremer Global)*



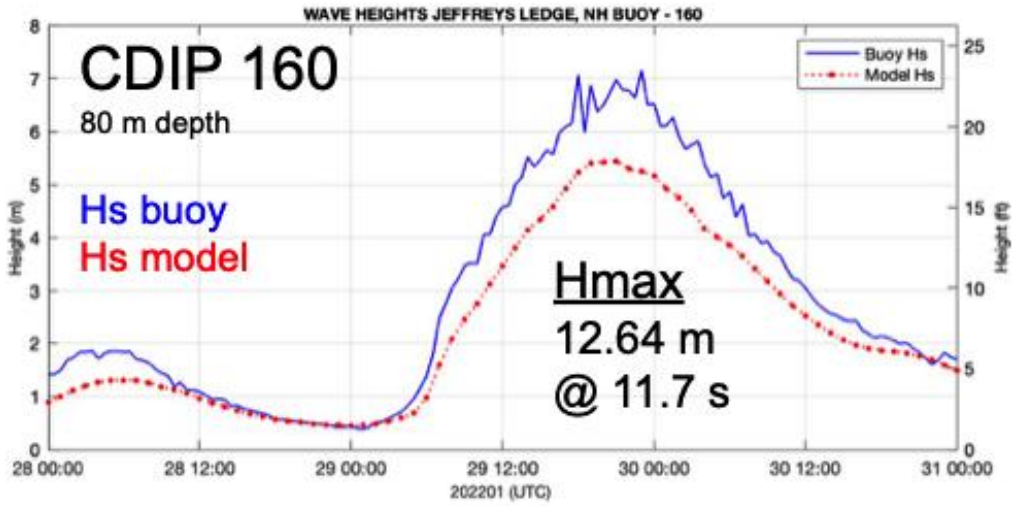
Collins et al. (2021)

Suspected Causes of Wave Model Underestimation

- Errors in wind forcing
- Missing physics in extreme regimes
- Lack of temporal and spatial resolution => smoothed fields and lower variance

Objectives of this Work:

- Investigate cause of this wave bias in Extratropical Cyclones
- Use wind and wave measurements to assess model performance
- Link suspected causes to wave height errors



Outline

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- **Data sets**
  - **ERA5 Reanalysis**
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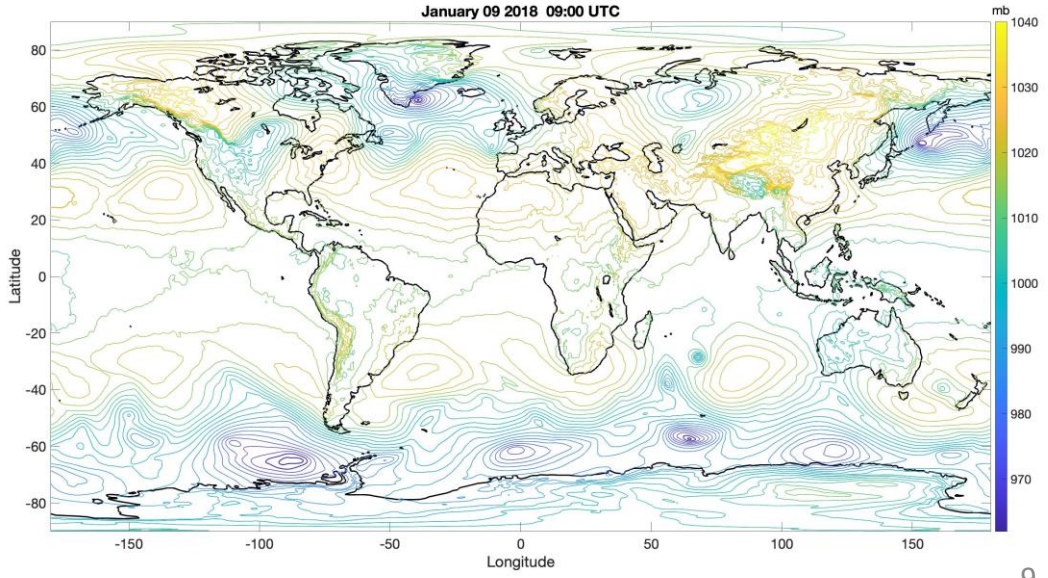
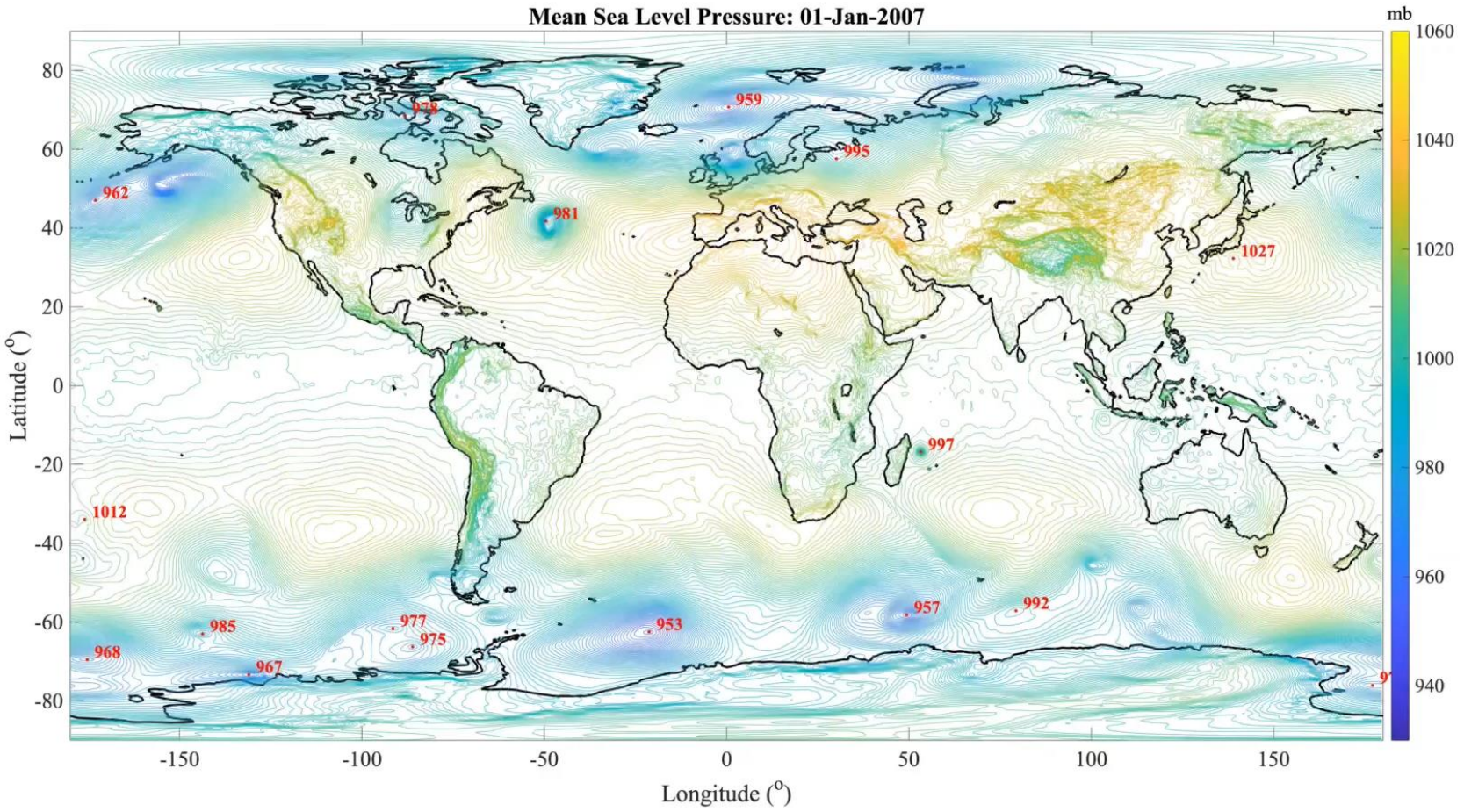
ERA5 Reanalysis

- European Centre for Medium-range Weather Forecasts (ECMWF)'s ERA-5 Reanalysis
  - State of the art, data assimilating reanalysis
  - High resolution => Hourly & 0.25^{o} x 0.25^{o} (~31 km)
  - MSLP used for tracking Extratropical Cyclones
  - U10 winds and significant wave height (H_s) used for comparison to observations

Mean Sea Level Pressure (MSLP)



Extratropical Cyclone Database

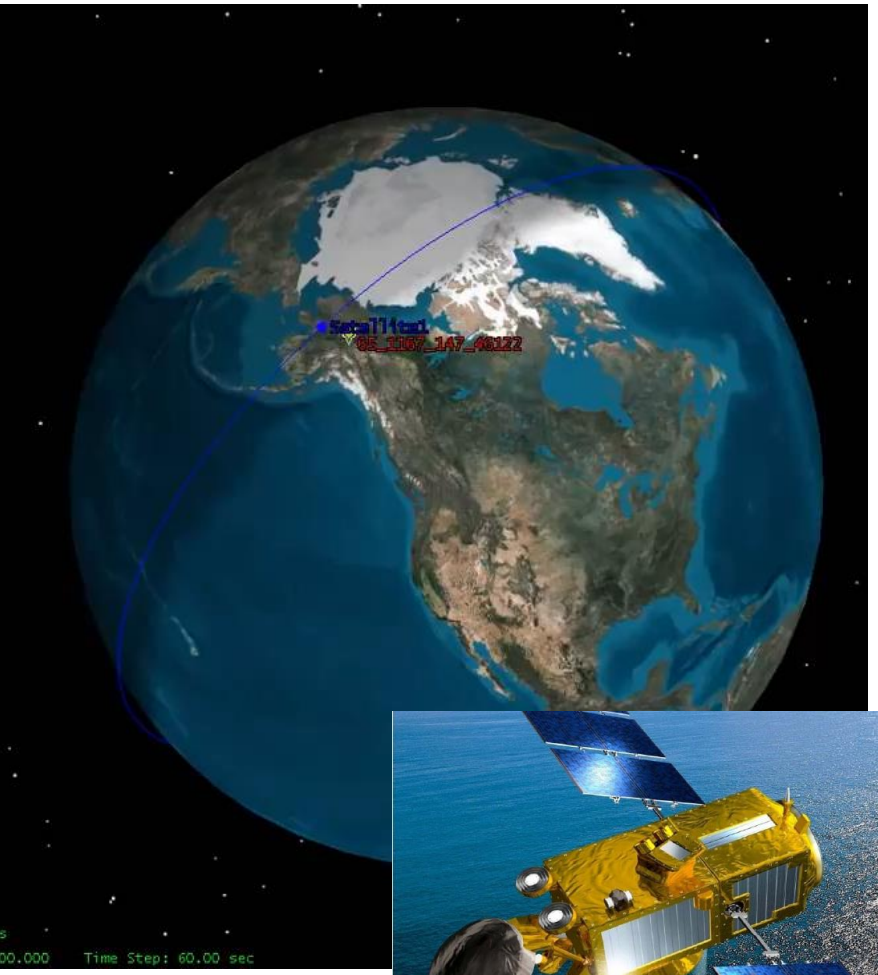


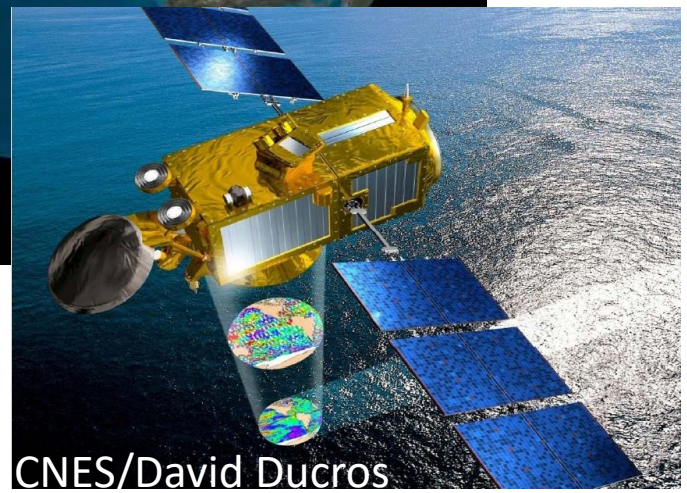
- Uses fields of mean sea level pressure (MSLP) from ERA-5
- 1979-2020 (42 years)
- **North Atlantic, North Pacific**, and Southern Ocean
- Contains over 100,000 Extratropical Cyclone tracks

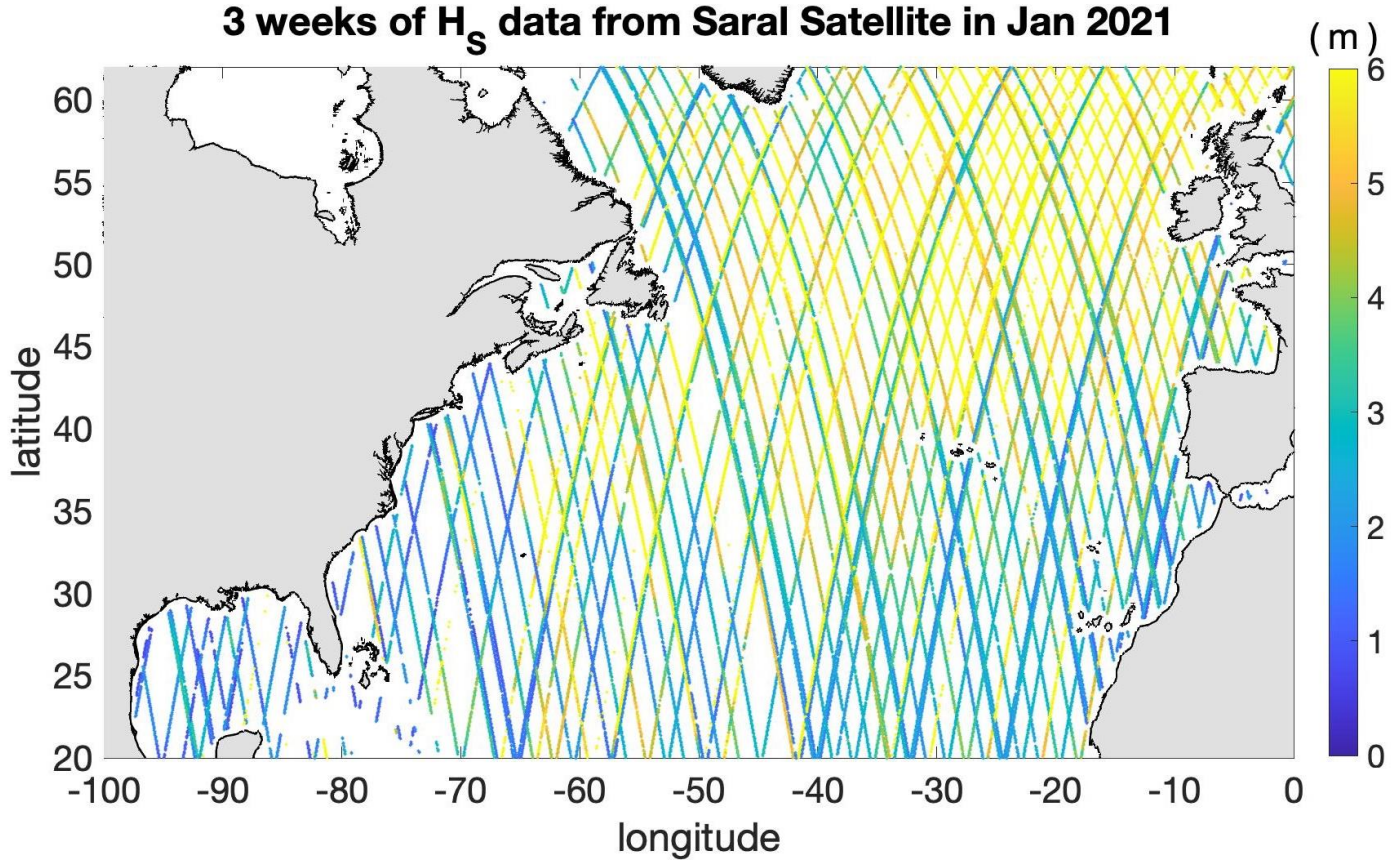
Lodise, J., Merrifield, S. T., Collins, C., Rogowski, P., Behrens, & J., Terrill, E, (2022). Global Climatology of Extratropical Cyclones From a New Tracking Approach and Associated Wave Heights from Satellite Radar Altimeter. ***Journal of Geophysical Research: Oceans***

***Storm tracks available on github**

Satellite Radar Altimeter Measurements





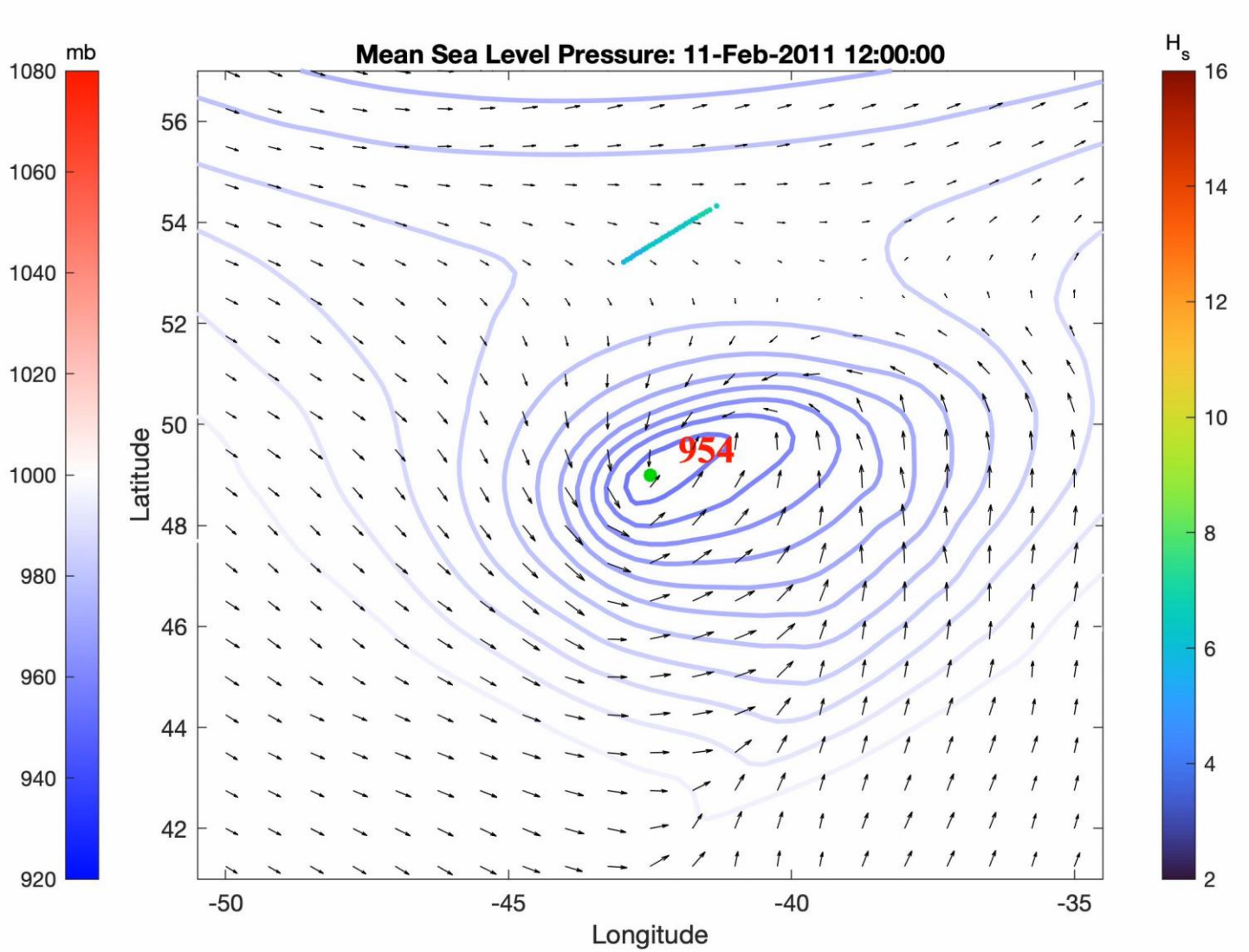


- Global coverage but low repeat resolution (1 week - 1 month)
- High along track resolution (7km at 1 Hz)
- Can Empirically derive **Hs** and **wind speed** measurements

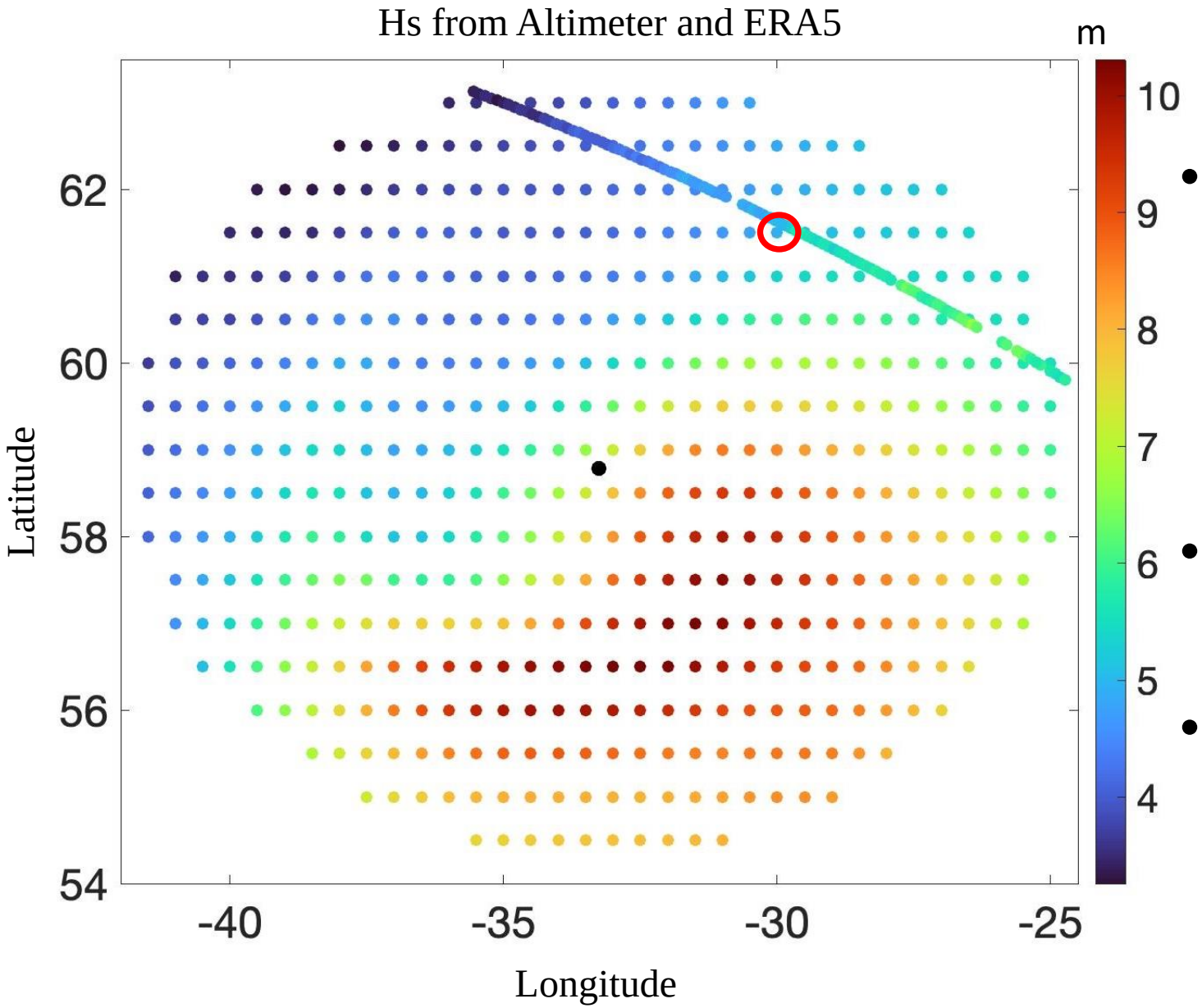
Altimeter Hs Along Extratropical Cyclone Tracks

- Satellite Altimeter Observations (Ribal and Young, 2019)
  - 36 years of calibrated significant wave height (Hs)
  - 14 satellite missions dating back to 1985

- Pull observations along storm track
  - Within 500km and 0.5hr of cyclone center



Altimeter- ERA5 Pairing



- All points within 25 km and 0.5hr are averaged (weighted by distance) and assigned to grid point in ERA5
- ◯ 25km neighborhood
- Minimum of 5 altimeter data points per ERA5 grid point

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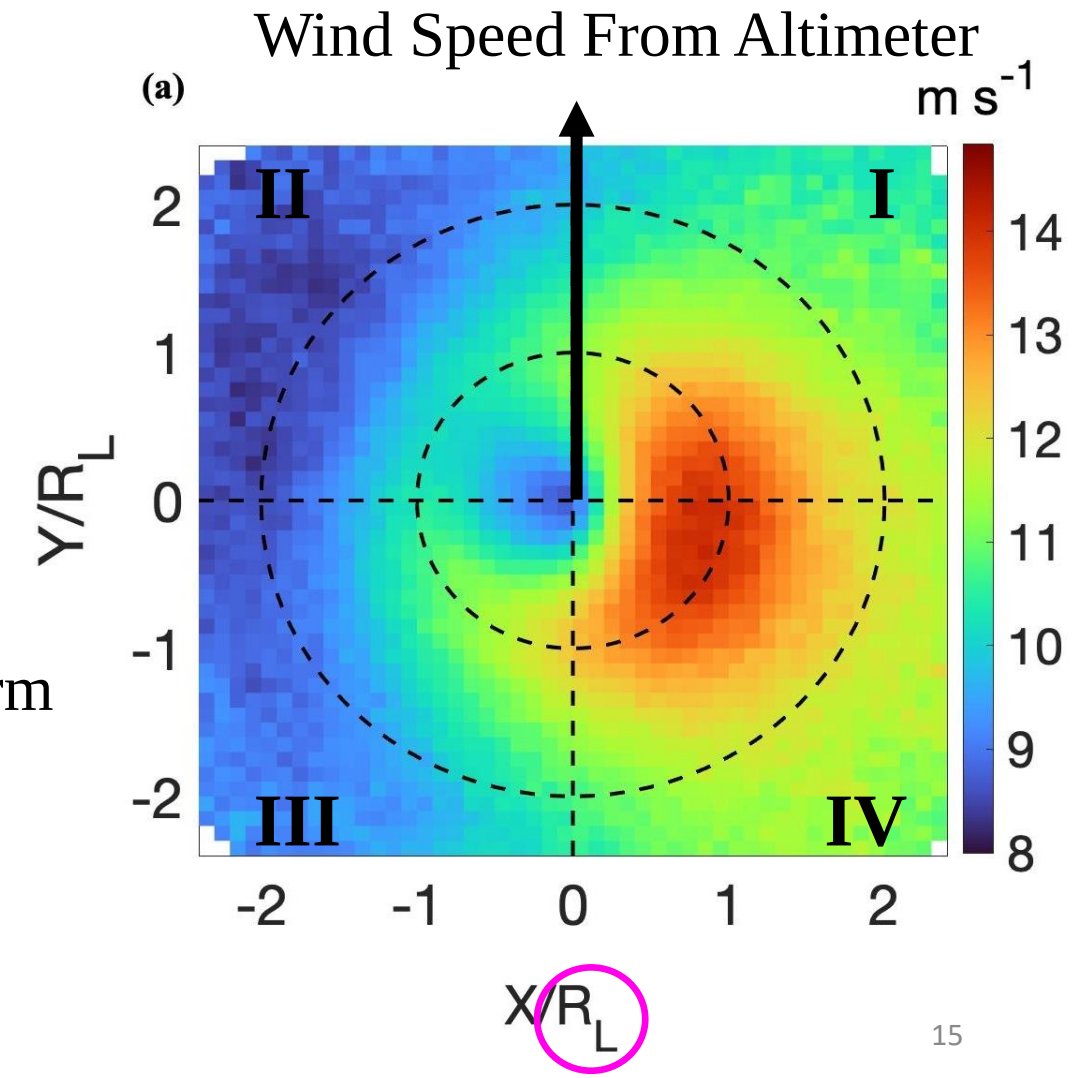
- **Results shown in a cyclone centered reference frame**
  - **Cyclone structure**
  - **Model performance**

- Ongoing work/Summary

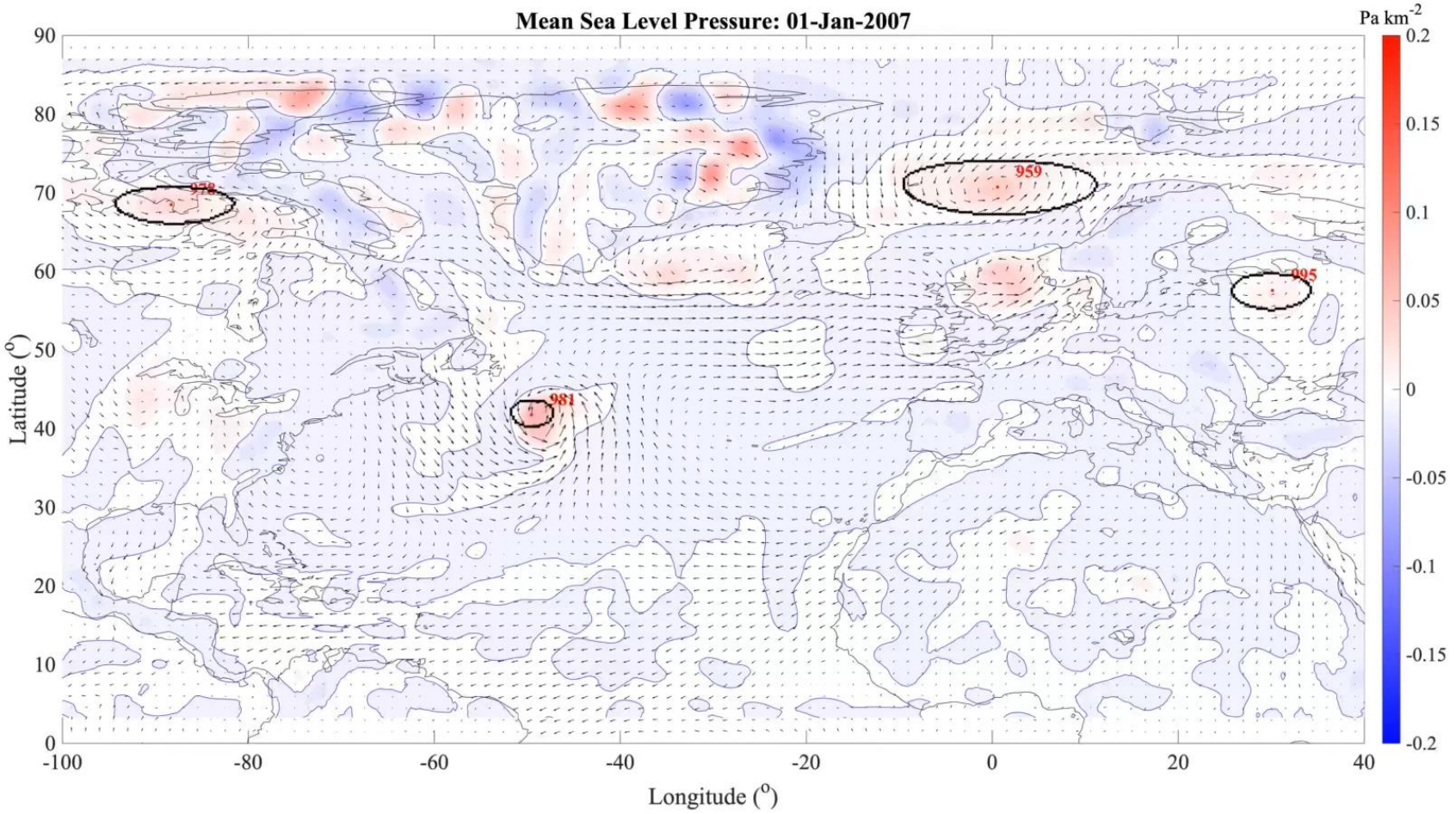
Satellite Altimeter Data in a Cyclone Reference Frame

- At each time step along every Extratropical Cyclone track
    - Origin is defined as Cyclone center
    - Data is rotated to align all storm directions
    - Binned and averaged spatially
- Results highlight the alignment of wind and storm direction on right side of cyclones



Characteristic Radius (R_L)

Laplace of MSLP

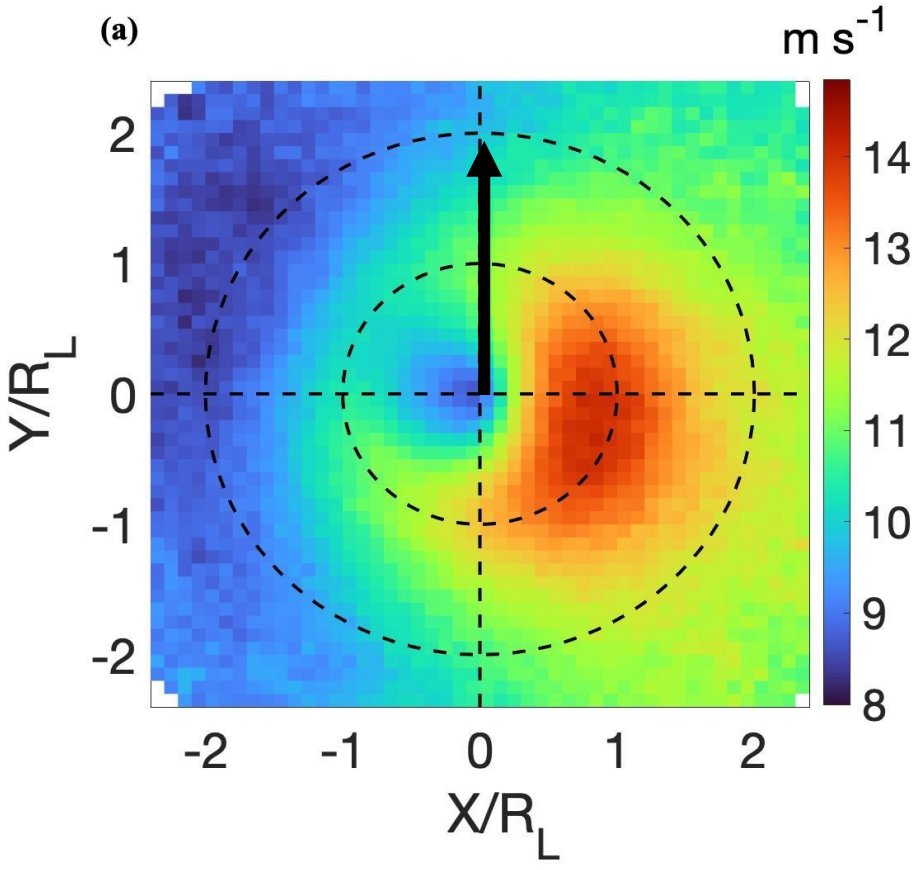


R_L

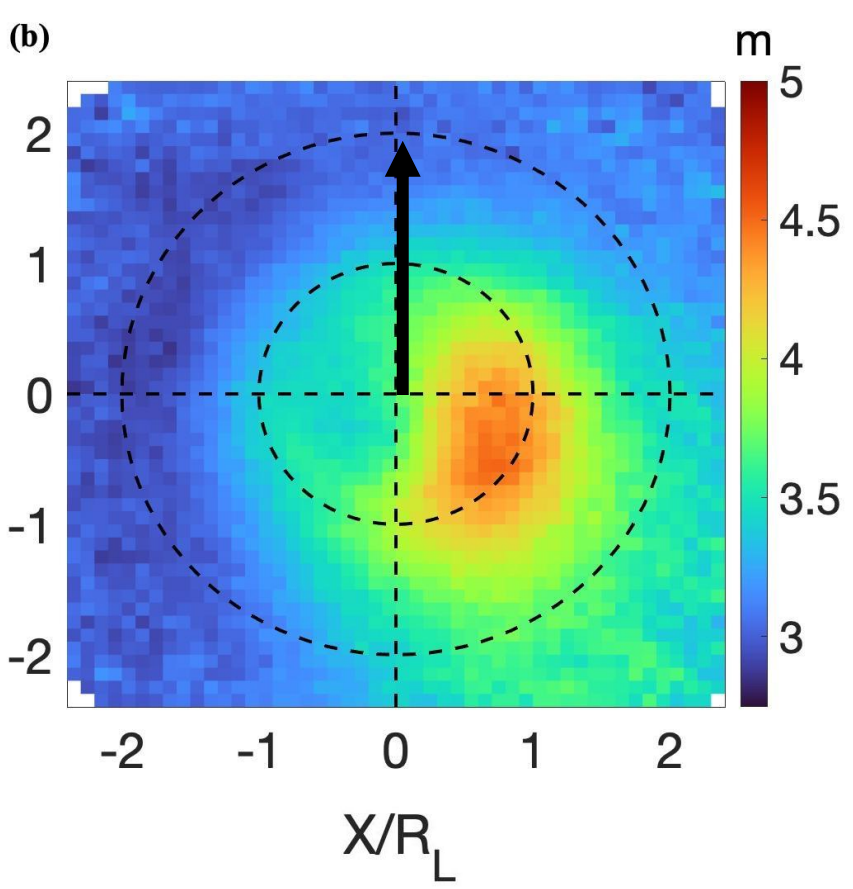
- Defined as distance to closet inflection point in MSLP field from each cyclone center
- Found by calculating the Laplace of MSLP
- Used to normalized storm size

Satellite Altimeter Data in a Cyclone Reference Frame

Wind Speed



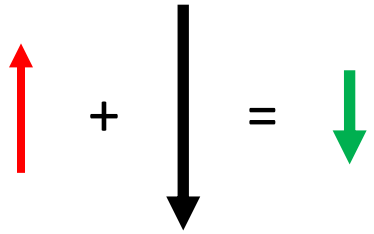
Significant Wave Height

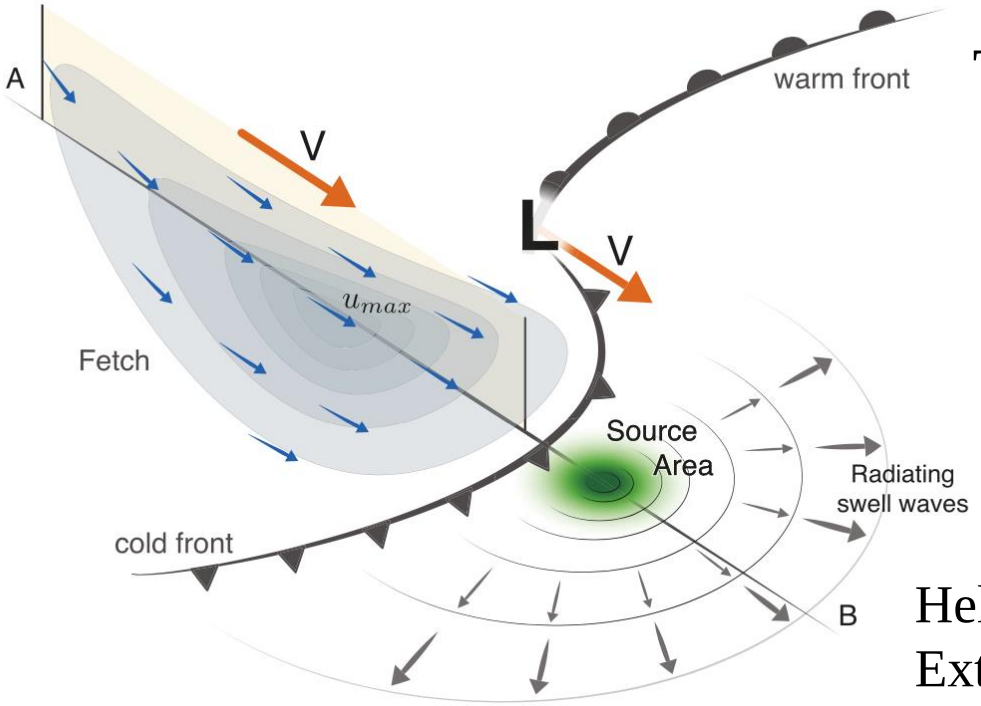


Asymmetry of Wind Speed in Extratropical Cyclones

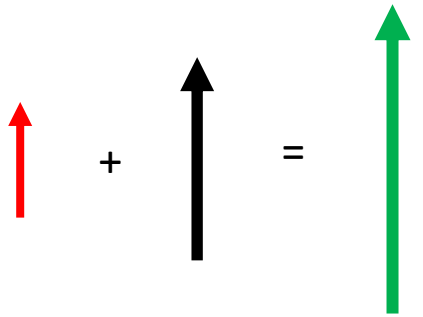
Storm Speed + Wind Speed = Total Effective Wind Speed

Total Wind Speed on Left





Total Wind Speed on Right

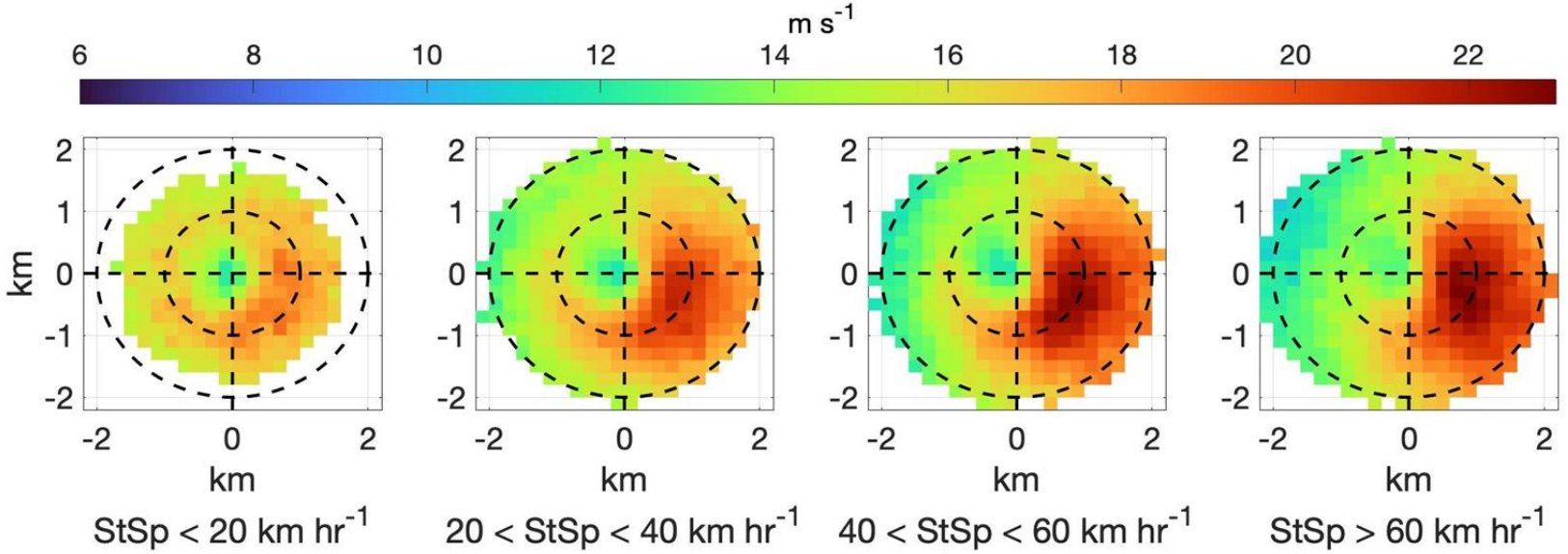


Hell et al. (2021) Swell Generation in Extratropical Cyclones

- Extended Fetch: Waves on the right propagate in storm direction => Increased momentum input
- Resonant effects when incident waves travel at the same velocity as Cyclones
- Young and Vinoth (2013) => Showed Extended Fetch in Hurricanes

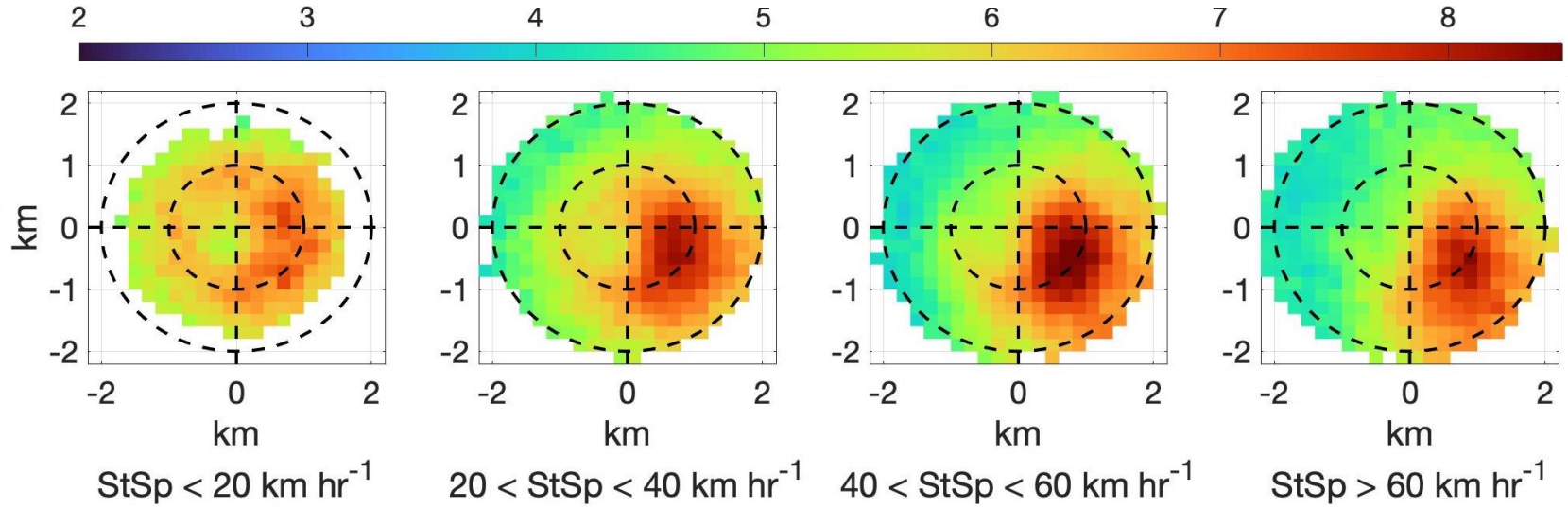
Organization of Wind and Waves with Cyclone Translational Speed

Wind Speed (m/s)



Organization of wind speed and wave heights as storm speed increases

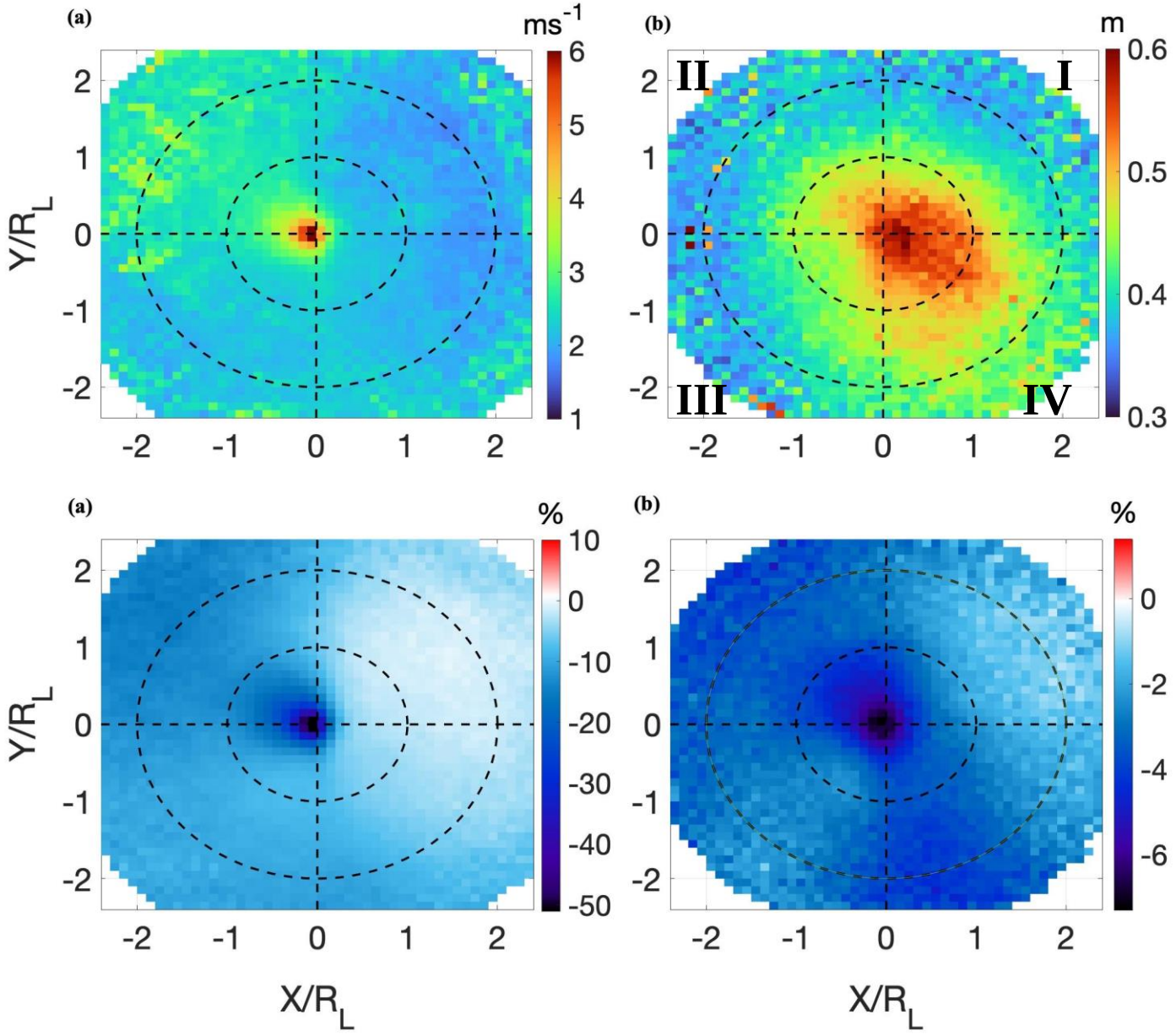
Significant Wave Height (m)



Effects of Extended Fetch

- Largest waves in Cyclones speeds from 40-60 km/hr
- Deep water waves with 14-21s Periods travel at same speed
- Faster Cyclones out run the waves they create

Wind Speed Hs

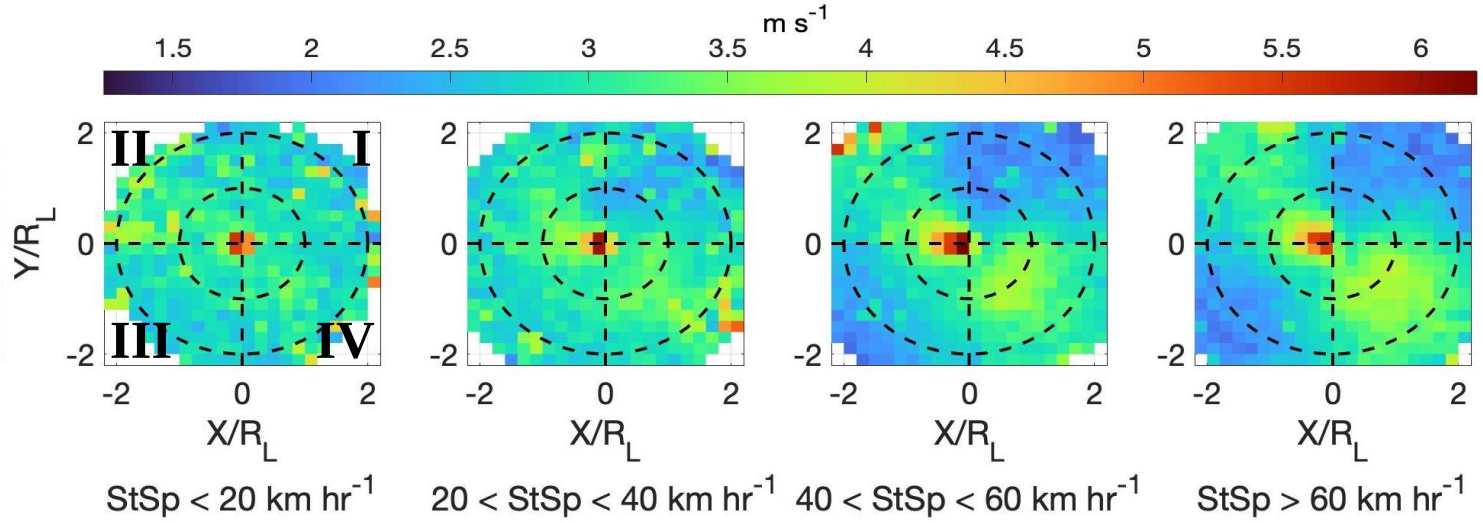


$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_{mod_i} - X_{obs_i})^2}$$

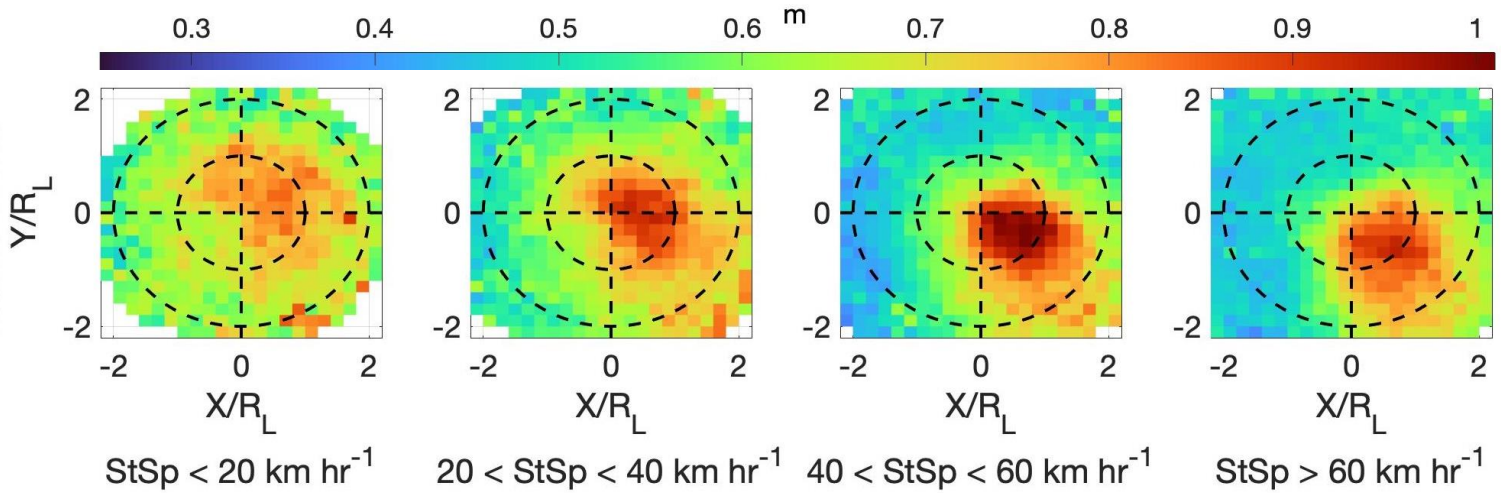
$$\%Bias = \frac{100}{n}\sum_{i=1}^{n}\frac{(X_{mod_i} - X_{obs_i})}{X_{obs_i}}$$

RMSE and Cyclone Speed

Wind Speed



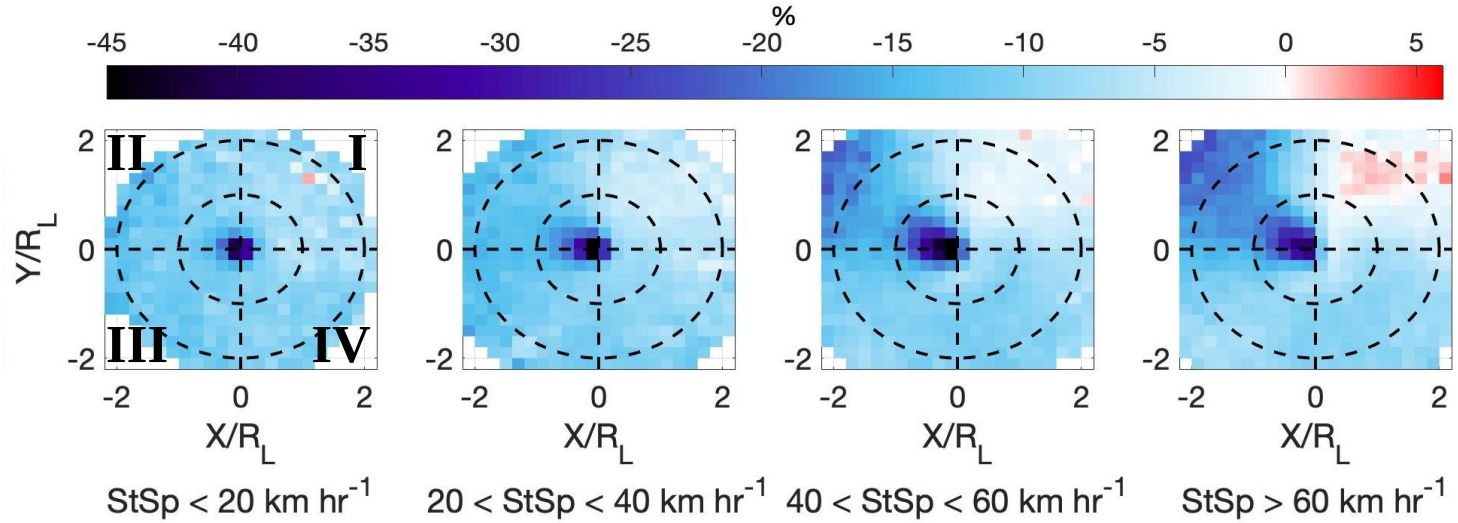
Significant Wave Height



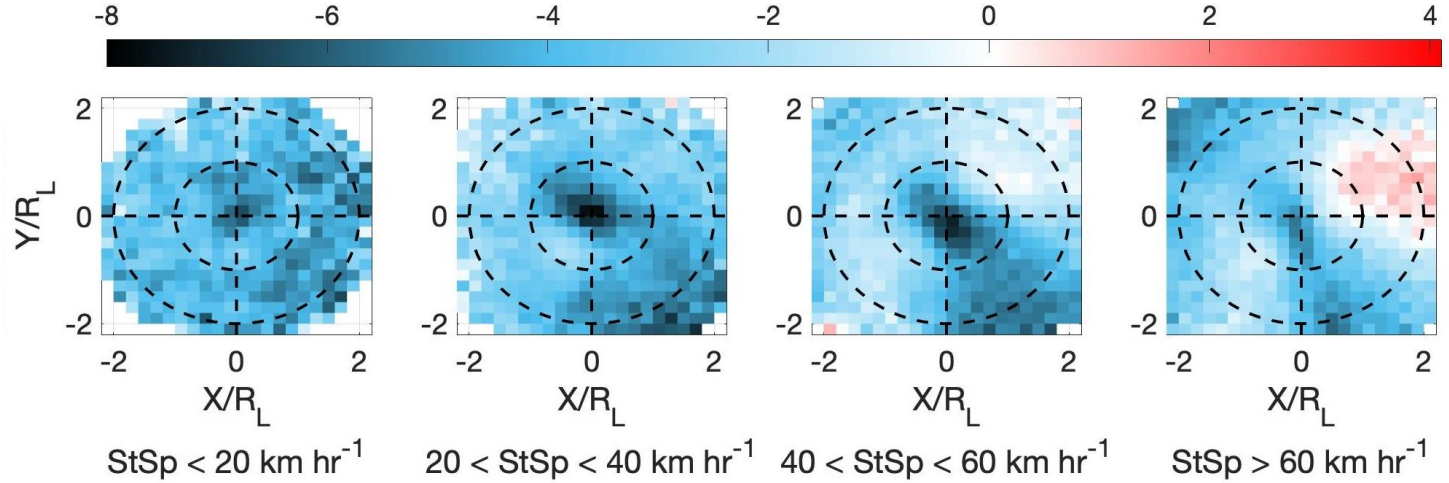
- Large RMSE in Cyclone Center
- Organization of error (wind speed and H_s) with increasing storm speed
- We see largest error for cyclones traveling 40-60 km/hr
- Errors within extended fetch compounded as forcing travels with waves

%Bias and Cyclone Speed

Wind Speed

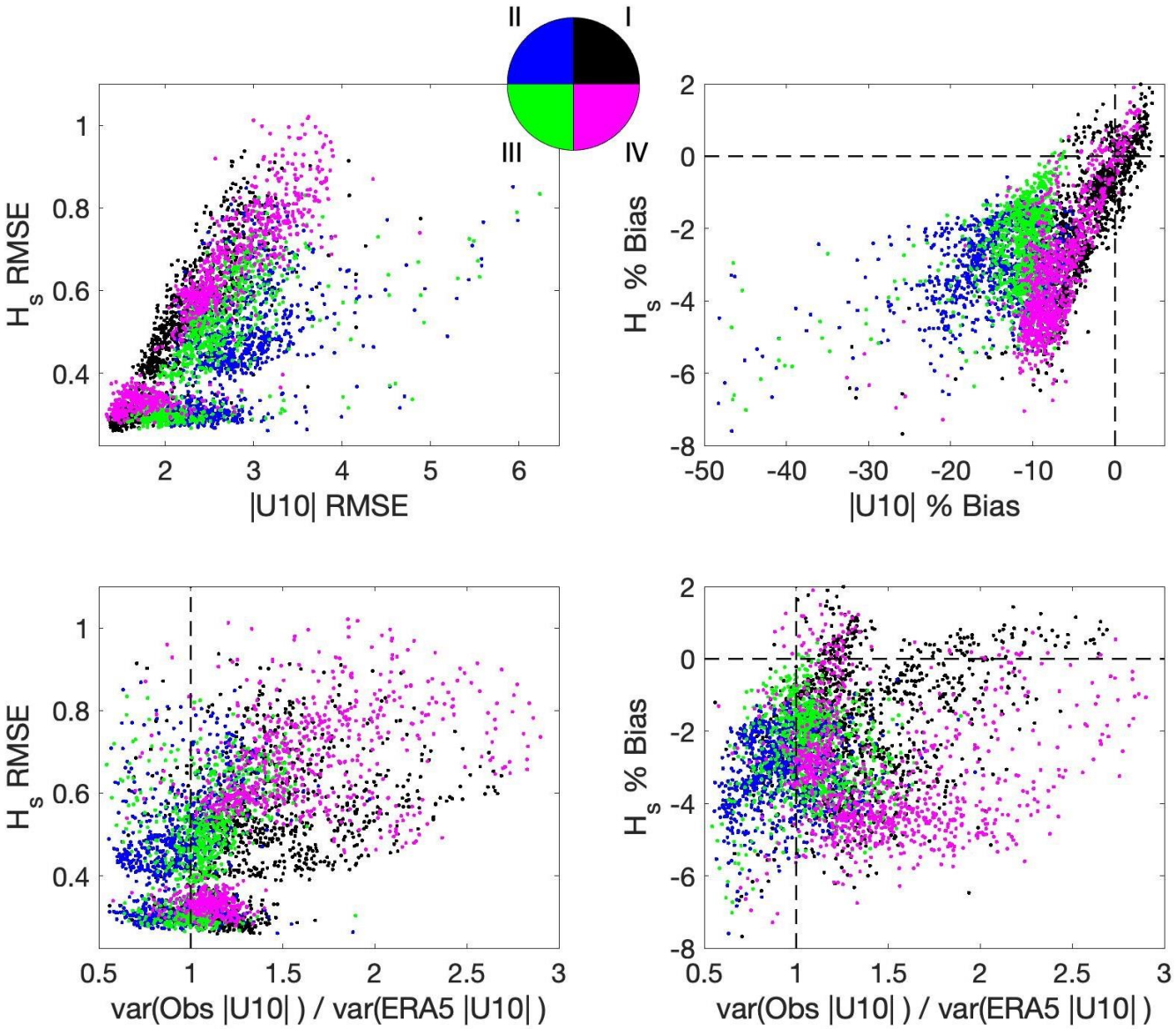


Significant Wave Height



- Large underestimation in Cyclone center
- Organization of bias (wind speed and H_s) with increasing storm speed
- Largest bias for cyclones traveling 40-60 km/hr

Wind Forcing Error and Hs Error by Quadrant

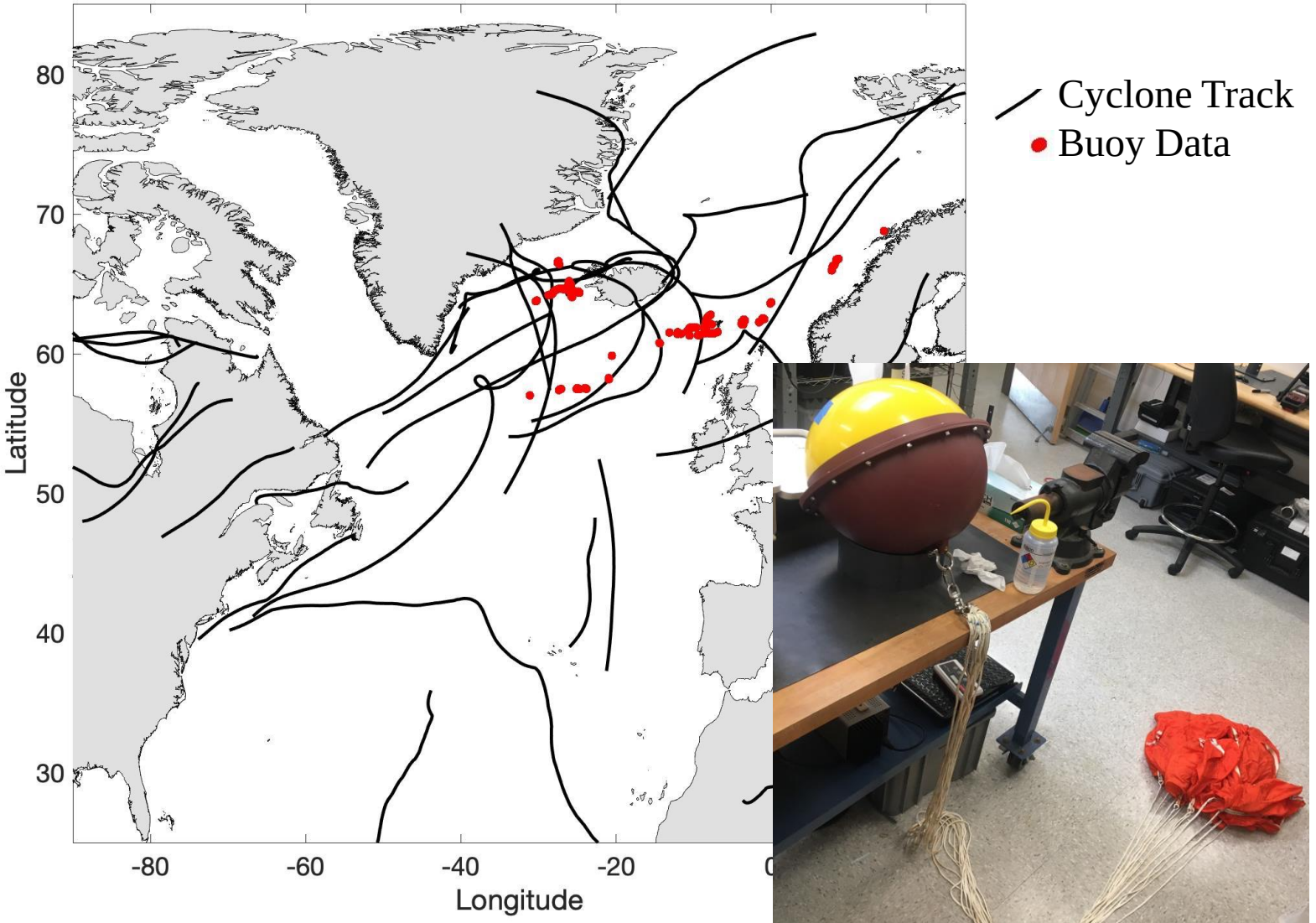


- Clear regime changes from left side to right side of cyclones
- Hs on right side of cyclones show increased sensitivity to errors in wind speed
  - Likely due to extended fetch
- Large outliers from cyclone centers where strong gradients exist
- Lack of variance in the wind fields are associated with larger errors in wave fields

Lodise, J., Merrifield, S. T., Collins, C., Behrens, & J., Terrill, E, (In Review). Performance of ERA5 Wind Speed and Significant Wave Height Within Extratropical Cyclones Using Collocated Satellite Radar Altimeter Measurements. ***Coastal Engineering Journal: Progress of Ocean Wave Measurements***

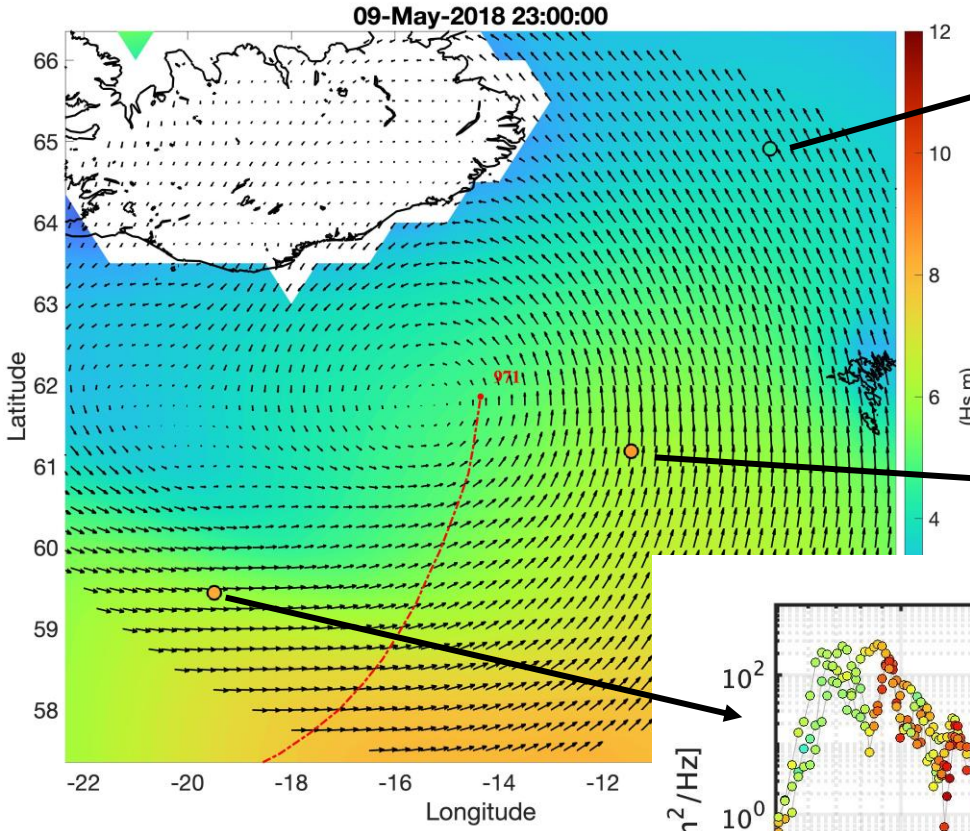
Ongoing work with drifting wave buoy array

Buoy-Storm Track Pairing



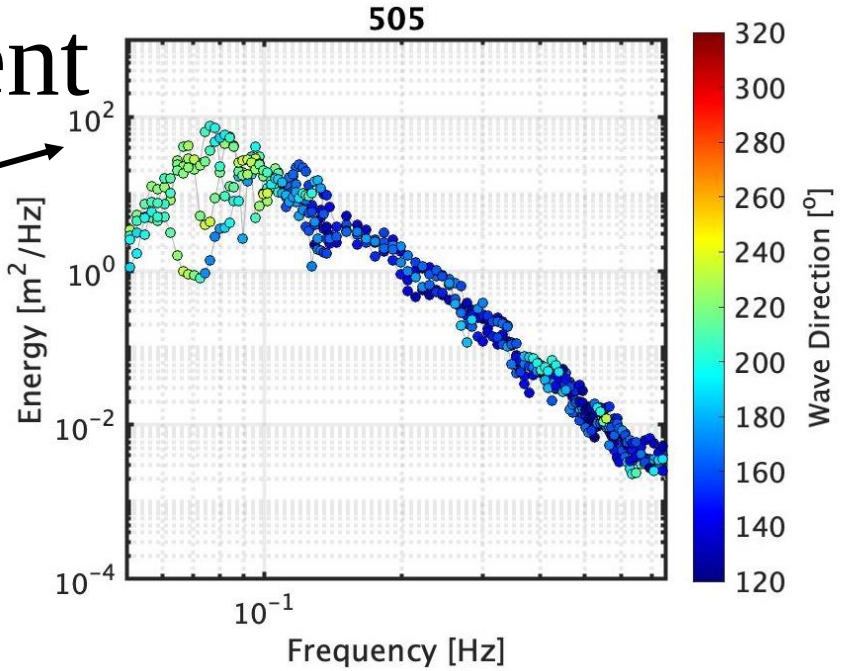
- Pair Mini Wave buoy data with Extratropical Cyclones
- Pair data within 500km and 0.5 hrs of cyclone centers

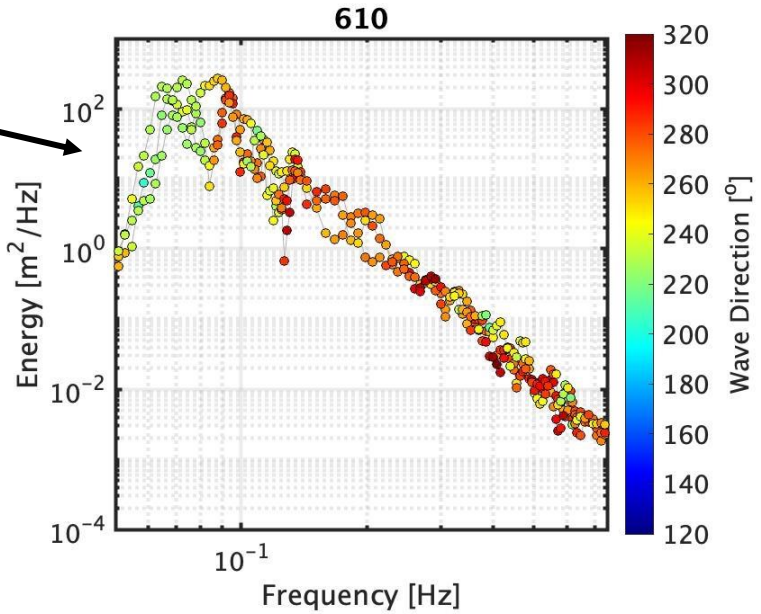
Directional Wave Spectra in Different Storm Regions

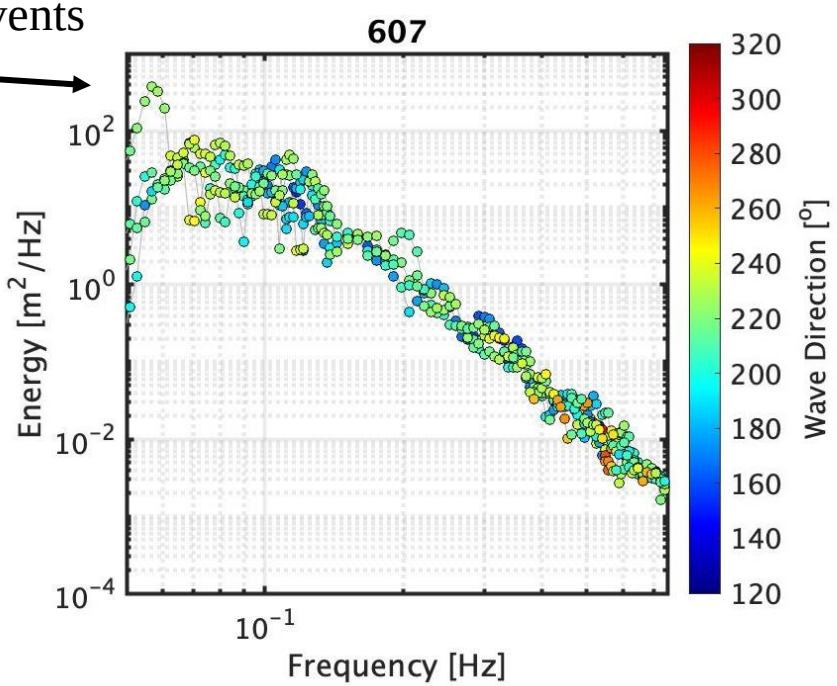


Working towards characterizing Swell/Wind seas in Cyclone Regions

More detailed insight to wave bias in extreme events







In Summary

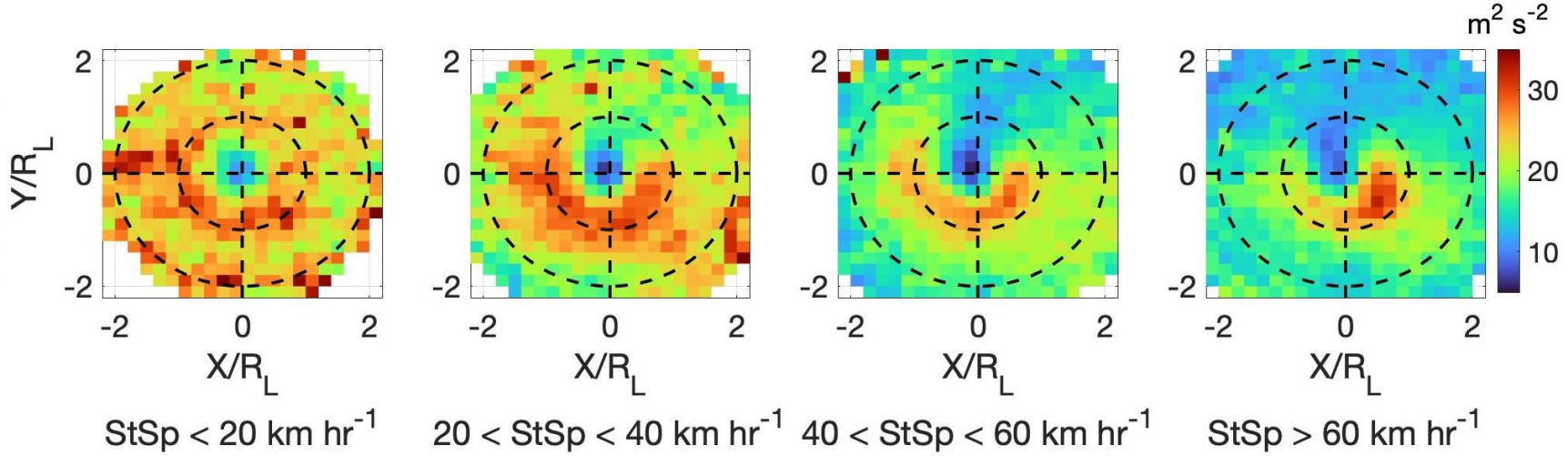
Questions?

- Underprediction of Hs by wave models is seen in Extratropical Cyclones
  - Underestimated wind forcing (Right half of storms, compounded by extended Fetch)
  - Inability to represent strong gradients around cyclone centers
  - Difficulty representing spatial and temporal variance on discrete grids

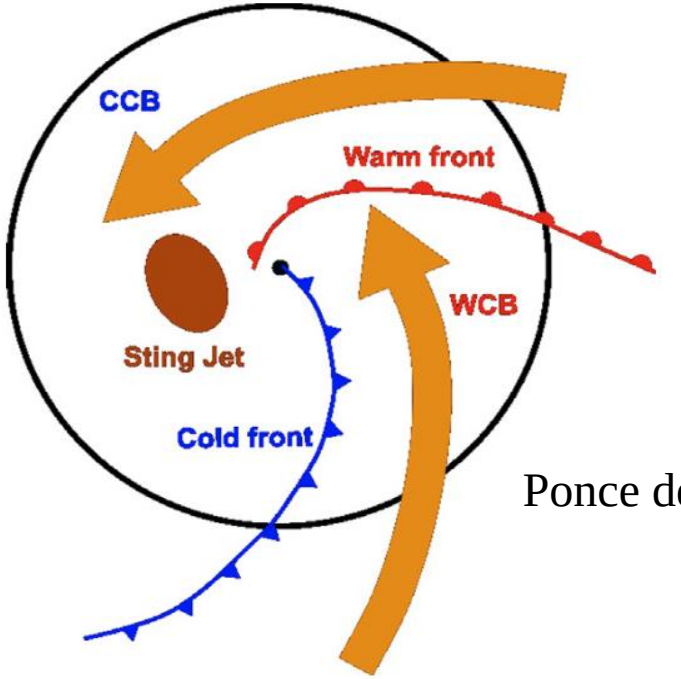
- Implications of missing Peak Wave Height
  - Underestimated real-time forecasts of shoreline impacts and marine hazards
  - Added error to modeling wave propagation across long distances
  - Mixing in the upper ocean modeled incorrectly

Extras

Variance of Wind Speed and the Sting Jet



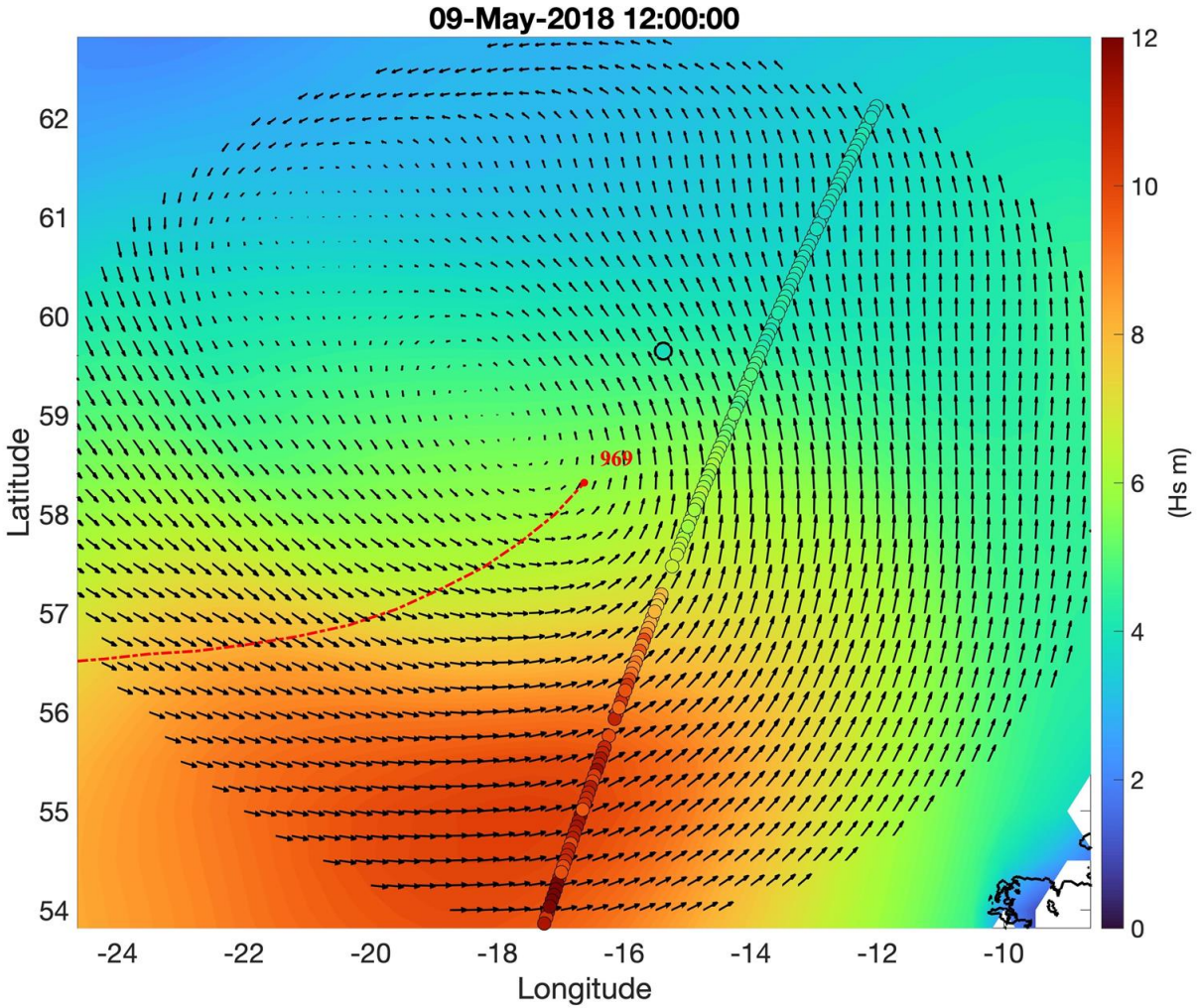
- Intense jet of winds following behind cold front
- Sting Jet occurs during strong intensification
- Does not occur in all storms and intermittent when it does



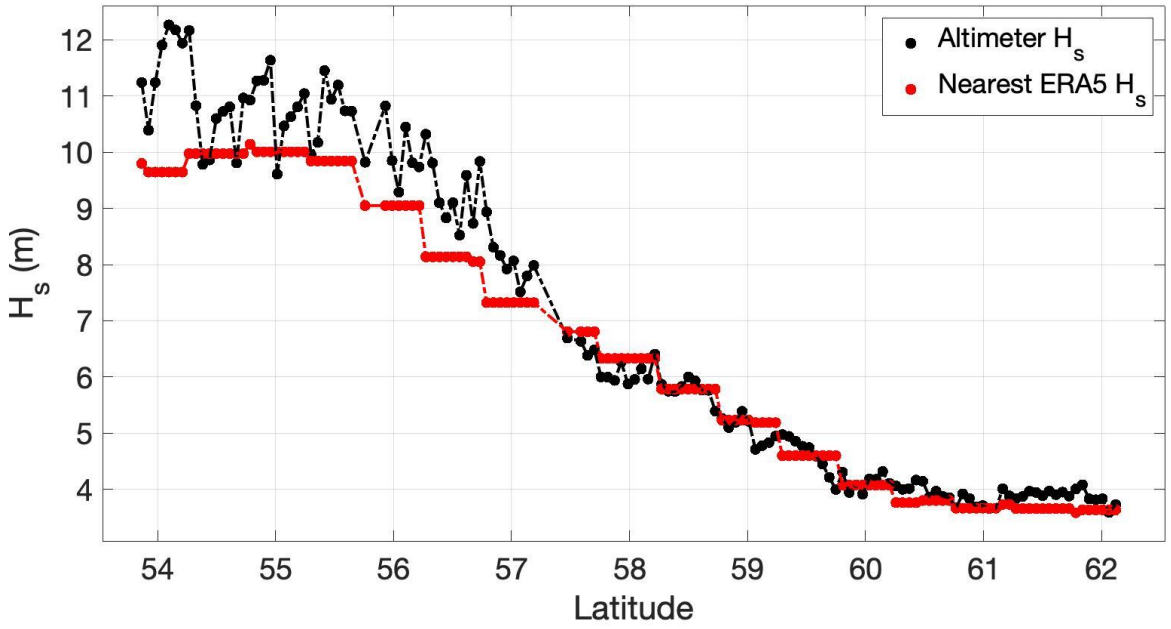
Ponce de Leon et al (2021)

Cyclone Observations and ERA5 Hs

ERA5 Hs Field and U10 Vectors



- Variance of Altimeter Hs is much higher than smoothed modeled field



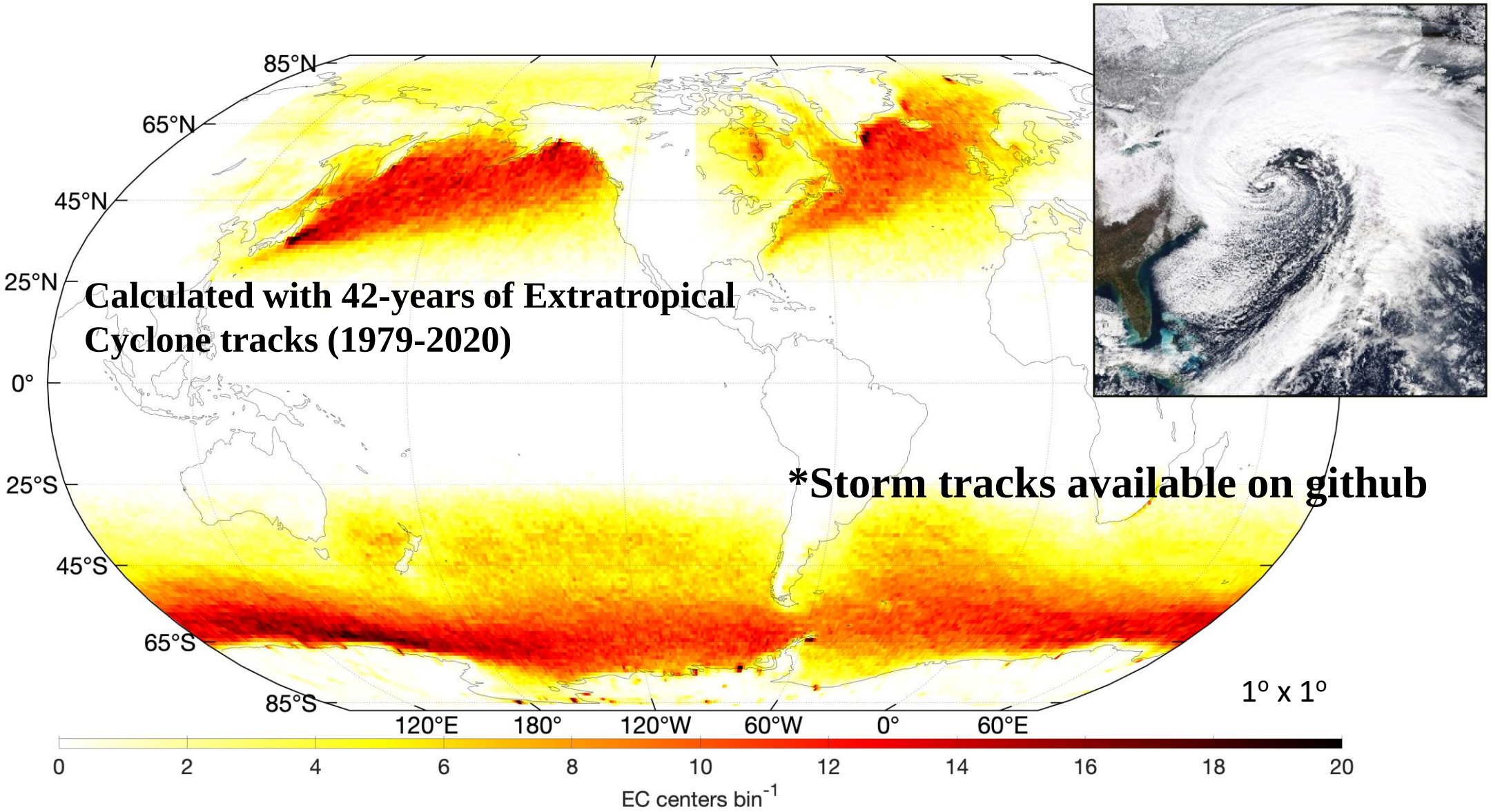
GPS-Based Wave Buoy

- The CORDC Miniature Wave Buoy (MWB) records 3-axis GPS velocity measurements (North, East, Down)
  - Velocity data is integrated into wave displacement data
    - bulk statistics (Hs, Tp, Dp..)
    - Directional wave spectra

- Satellite communications
  - Real time data availability
  - Enable prolonged, unattended operations worldwide
  - Ability to up sample/down sample measurements
  - Save Battery life for most interesting events

- Other measurements:
  - UTC time, lat/lon, course and speed over ground, sea surface temperature, and battery voltage.

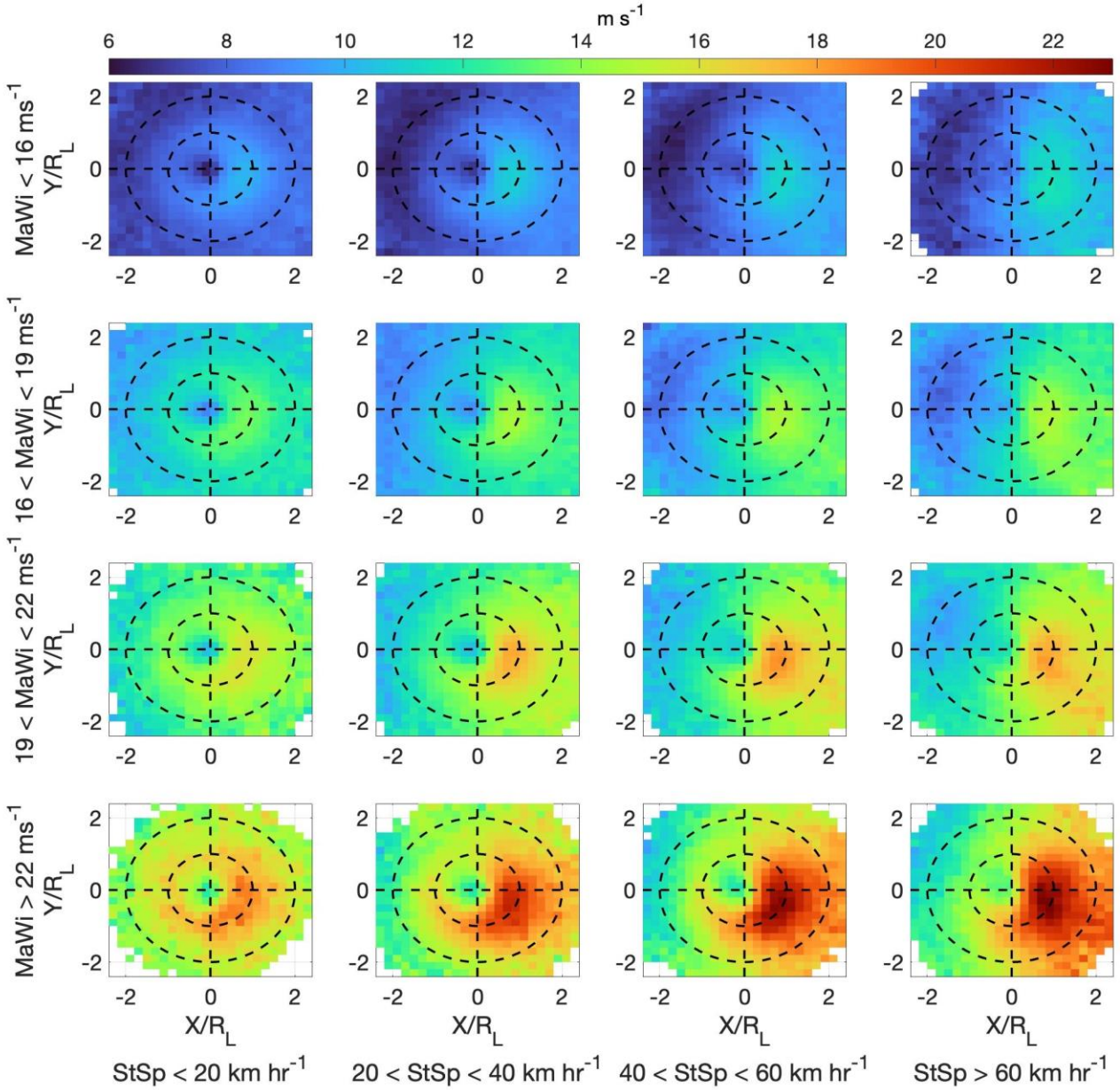
Annual Average Cyclone Center Density



Calculated with 42-years of Extratropical Cyclone tracks (1979-2020)

***Storm tracks available on github**

Wind Speeds and Wave Heights Across Storm Conditions



Wind Speeds and Wave Heights Across Storm Conditions