MTrack: Determining Tropical Cyclone Center Location from Satellite Wind Speed Data

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02/26/2020

Part I
Introduction to MTrack

Parametric Wind Model

$$V(r,\phi) = \left[\frac{2r\left(R_m V_m + .5 f R_m^2\right)}{R_m^2 + a r^b} - \frac{fr}{2}\right][1 - A\cos(\phi - \phi_{max})]$$

Tunable Parameters:

Vm: maximum wind speed

Rm: radius of maximum wind speed

A: ratio of Vmax at 0 deg to Vmax at 180 deg

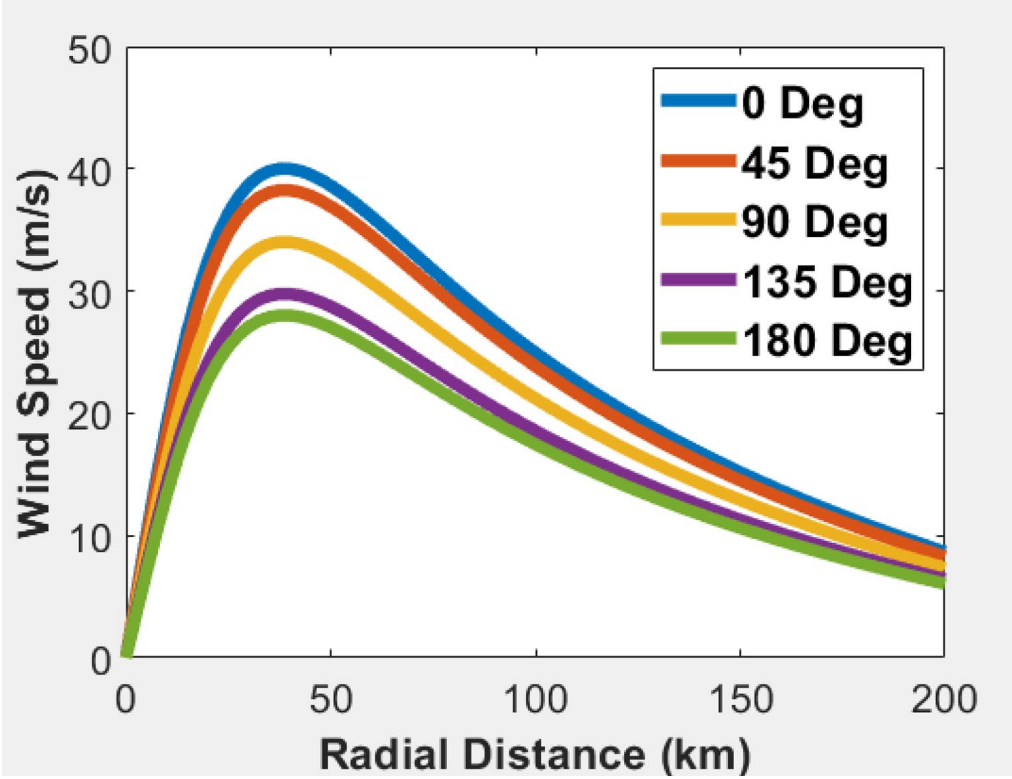
ϕ_{max}: angle of Vmax

a,b: wind speed roll-off rate from Vmax

Other Inputs:

f: Coriolis parameter

r, ϕ: distance and angle from assumed storm center

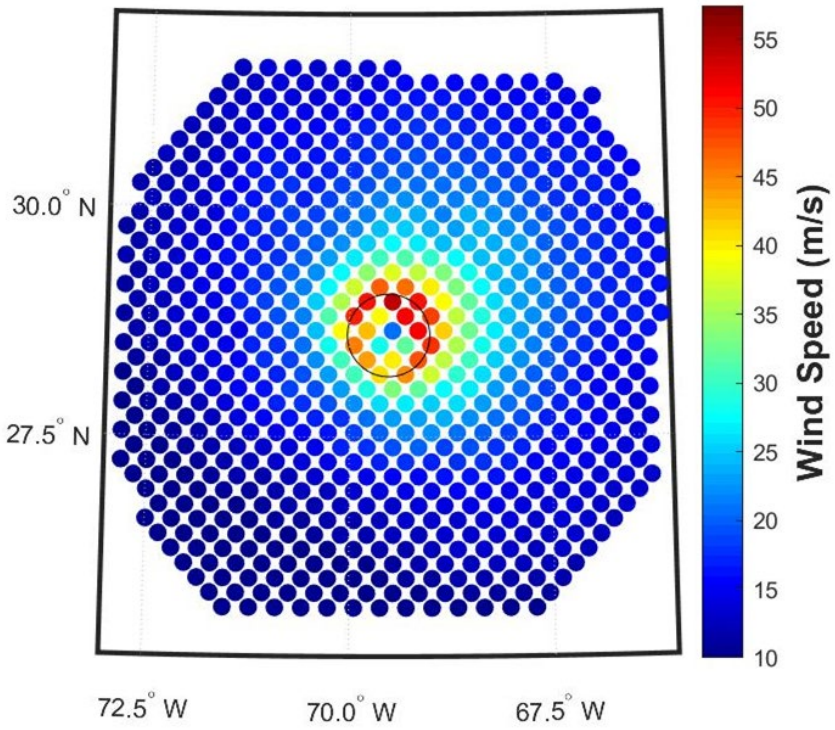


Azimuthal slices where 45 deg means 45 deg from the angle of Vmax

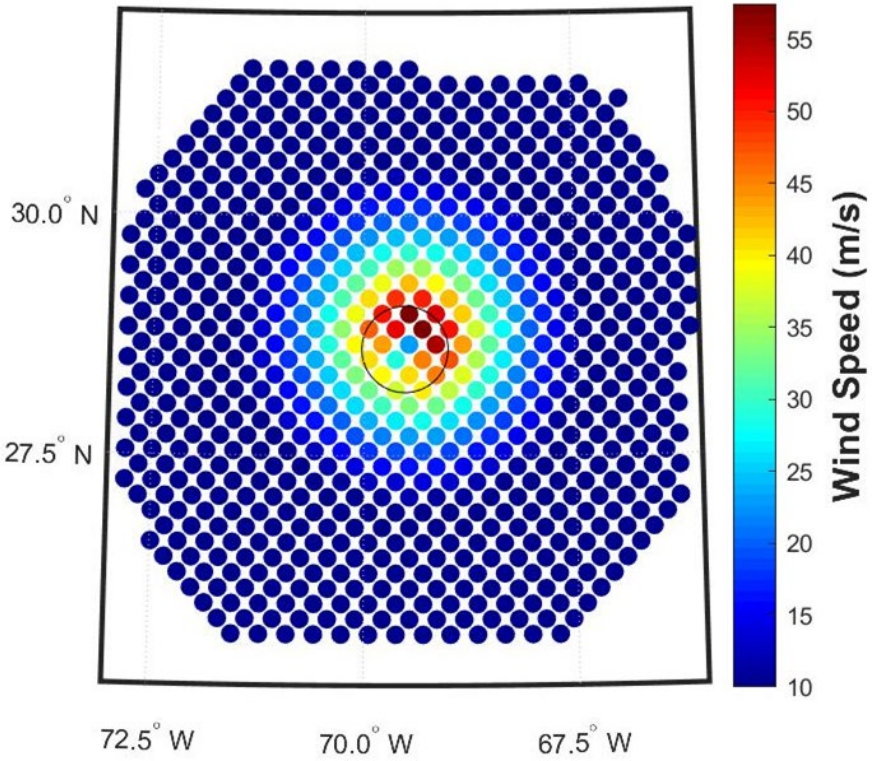
Morris, M. and C.S. Ruf, 2017: Determining Tropical Cyclone Surface Wind Speed Structure and Intensity with the CYGNSS Satellite Constellation. *J. Appl. Meteor. Climatol.*, **56**, 1847–1865, https://doi.org/10.1175/JAMC-D-16-0375.1

Wind Model (Ideal Case)

Real Wind Field



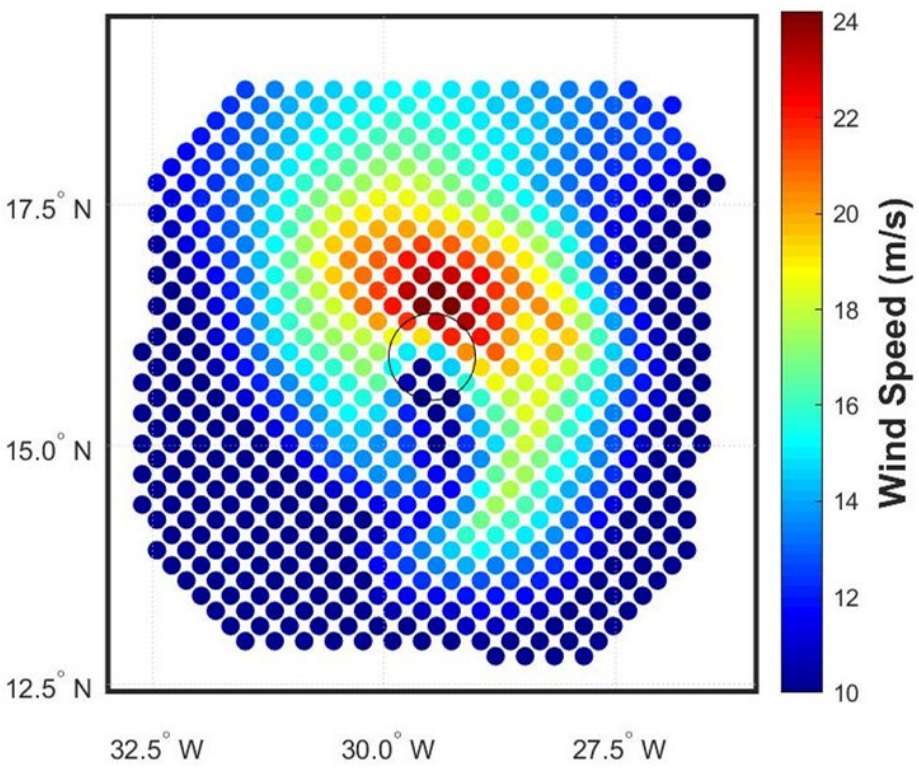
Best-Fit Wind Field



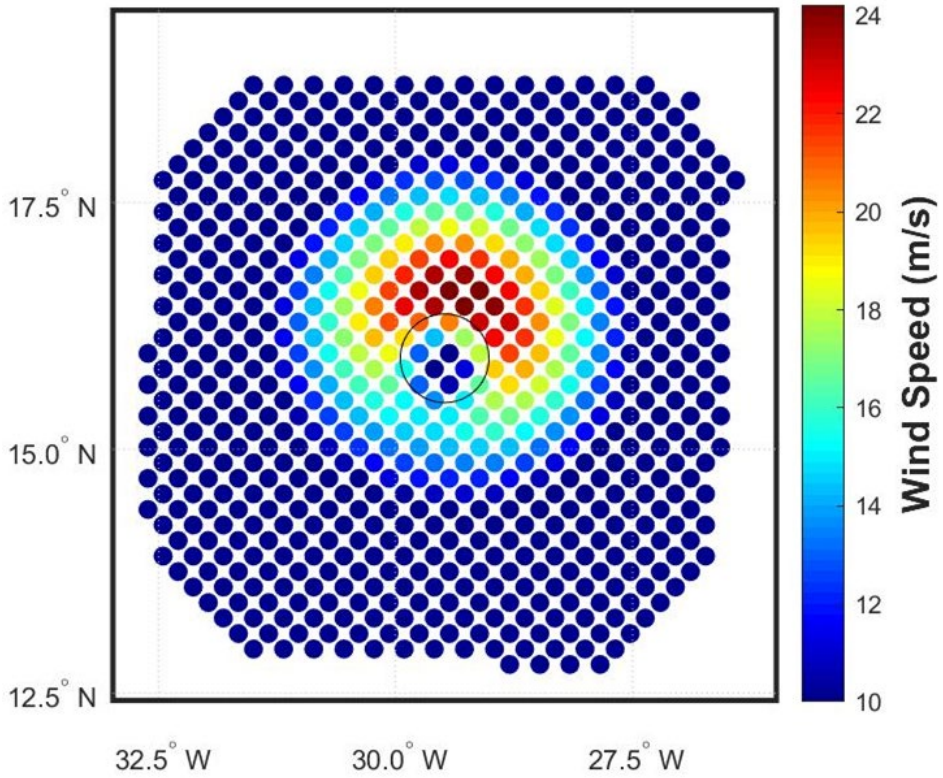
Parametric wind model is almost perfectly able to recreate the high wind speed region of the wind field in this case (strong, organized storm with canonical structure)

Wind Model (Difficult Case)

Real Wind Field



Best-Fit Wind Field

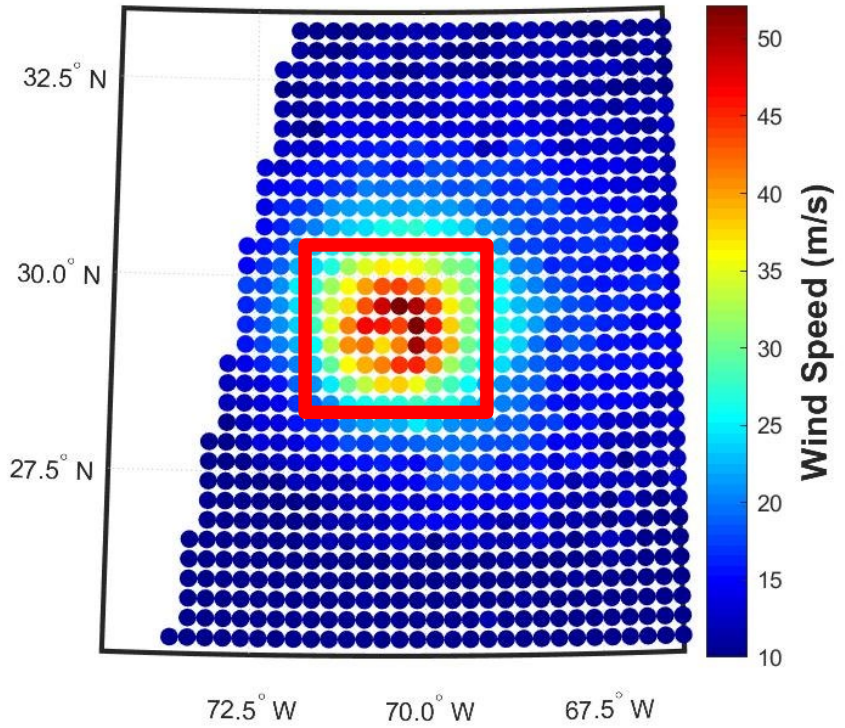


Parametric wind model gets the northern part of the storm correct, but isn't able to replicate many parts of this disorganized storm (this would require a more complex azimuthal dependence in model)

Input Wind Field

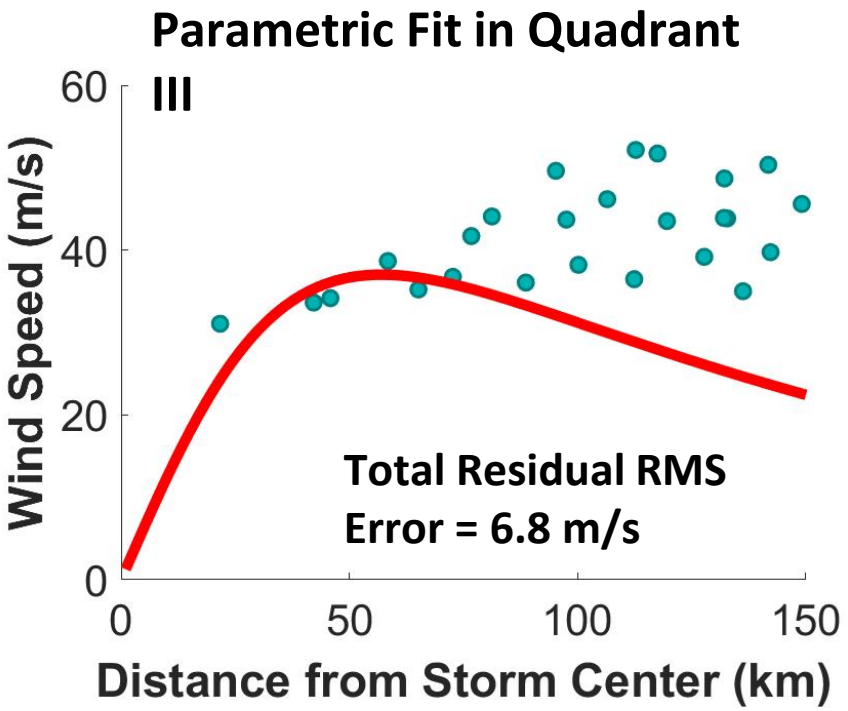
Search for the optimal storm center by assuming many storm center locations within the red box

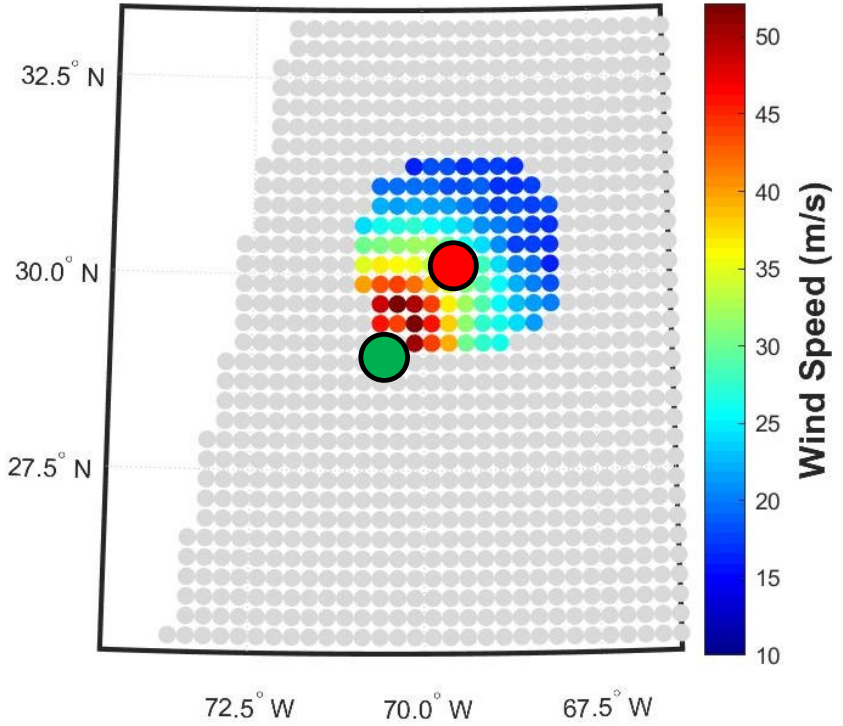
For each assumed storm center location, fit the parametric wind model from previous slide to wind speed measurements



Wind speeds measured in Hurricane Florence

Assume a Storm Center Location

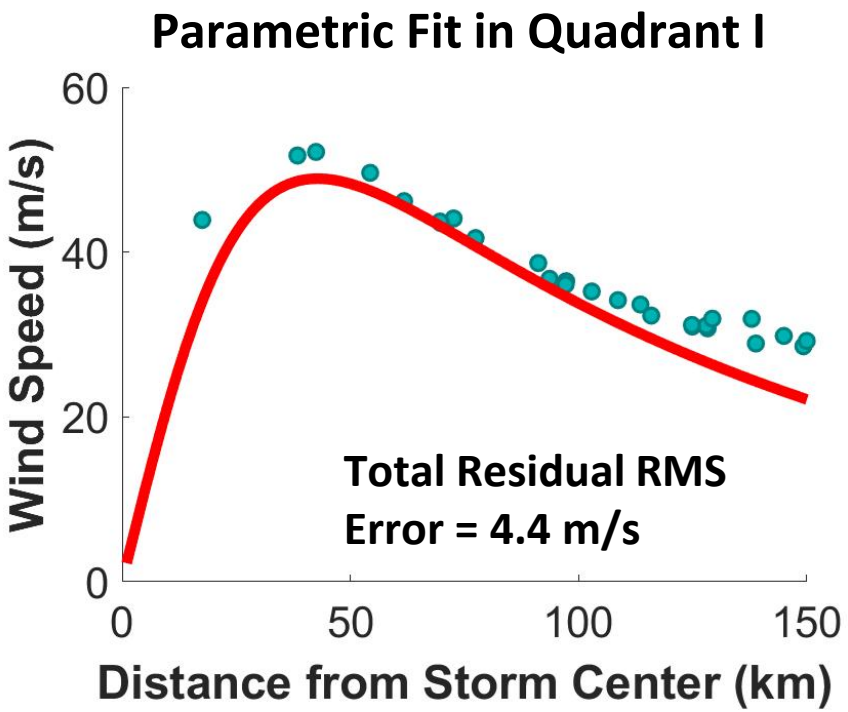


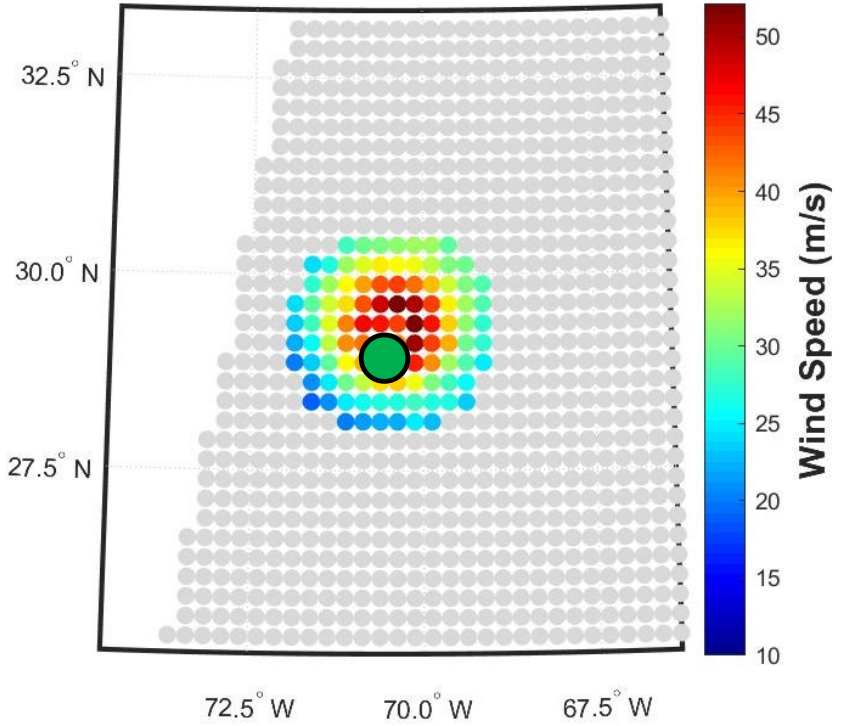


= Assumed center

= Correct center

Assume a New Center Location

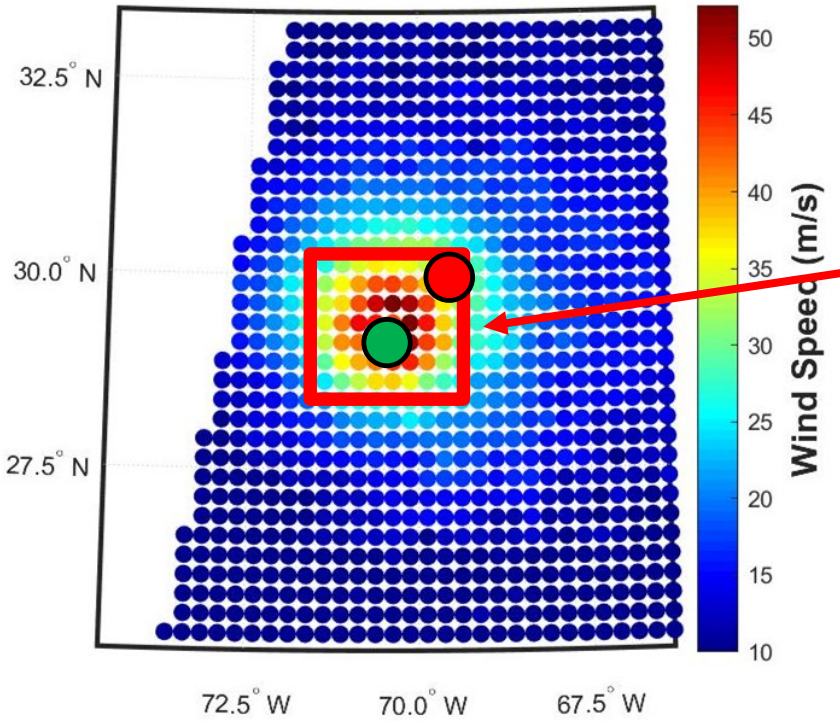


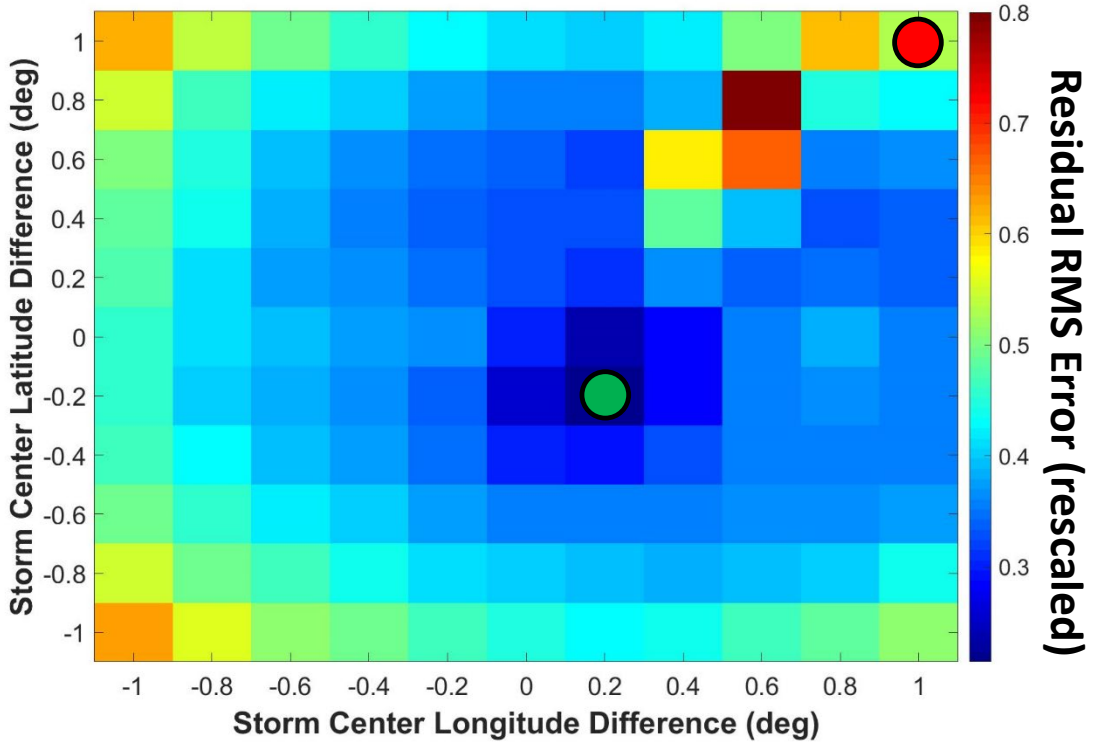


● = Correct Center & Assumed Center

Residual Error Surface

Repeat the process on the previous two slides for many other assumed storm center locations to generate a residual error surface (right image)





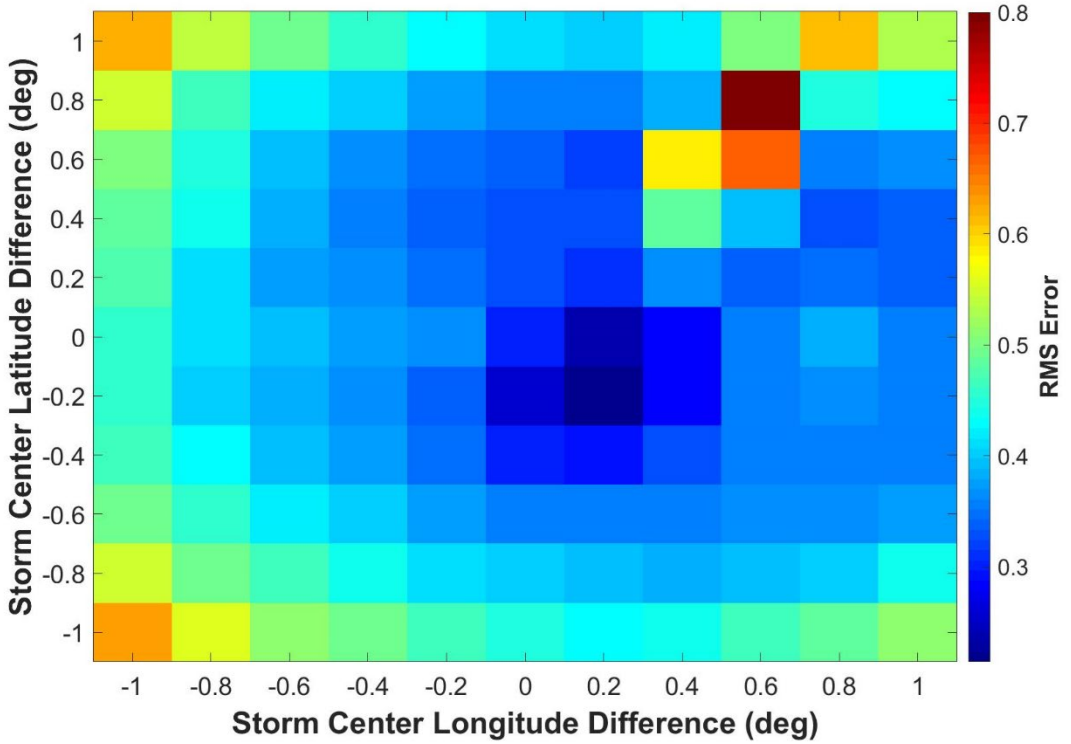
= Assumed Center #1 and Wrong Center

= Assumed Center #2 and Correct Center

Gaussian Fit to Error Surface

- Rather than choosing the lowest residual error as the storm center location, fit a 2D Gaussian
- Minimum of 2D Gaussian is the MTrack storm center location

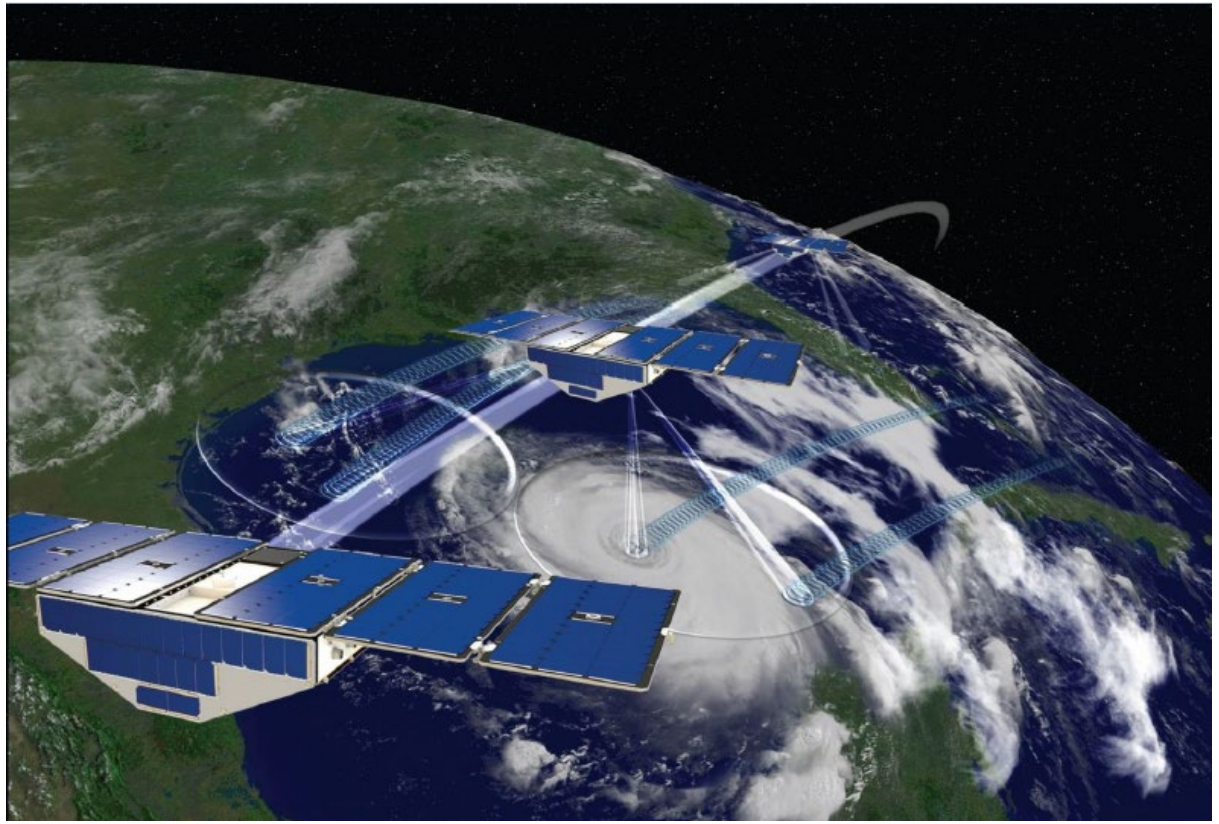
- Gaussian fit residual is low for a high confidence center fix
- Gaussian width is narrow for a high confidence center fix
- These two parameters map to a storm center uncertainty value in km



Part II
MTrack with CYGNSS

Cyclone Global Navigation Satellite System (CYGNSS)

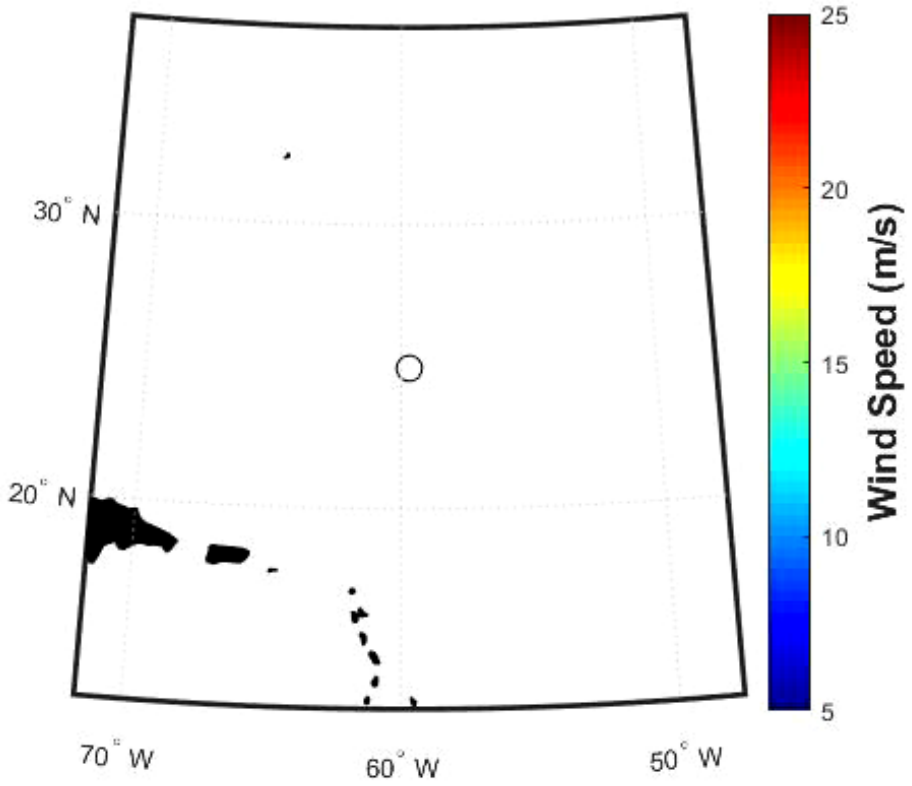
- Baseline Science Objective:
  - Measure ocean surface wind speed in tropical cyclones (in all precipitation conditions) with sufficient frequency to resolve genesis and rapid intensification
- Sponsor: NASA
- Launch Date: 15 December 2016
- # of Small Sats: 8
- Instrument Type: Bistatic Radar
- Coverage: +/- 35^{O} latitude
- Average Revisit Time: ~7 hours
- Spatial Resolution: ~25 km
- Latency: ~1 day



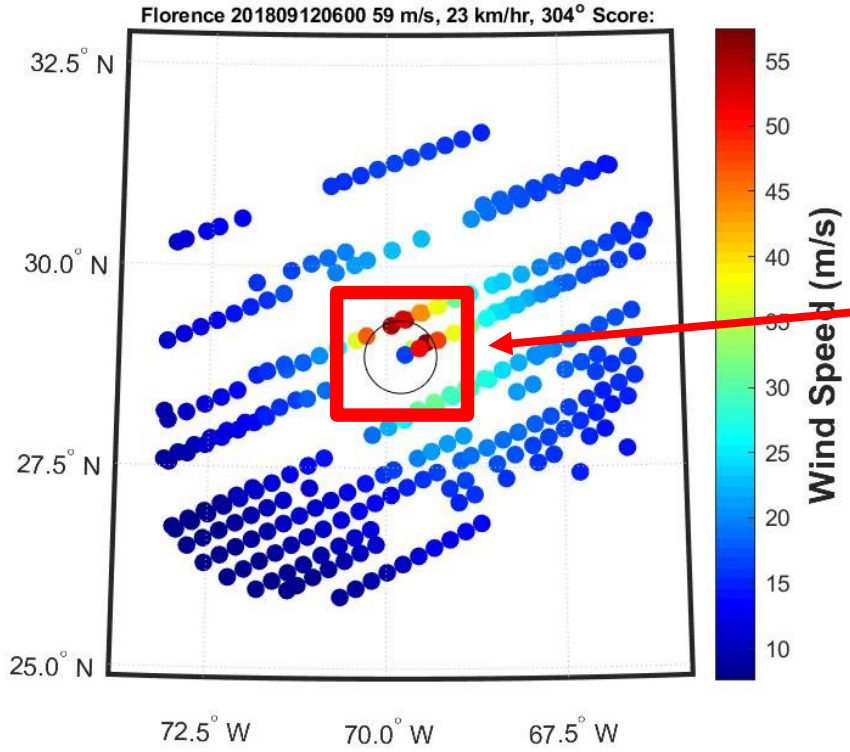
Algorithm Input: CYGNSS Winds

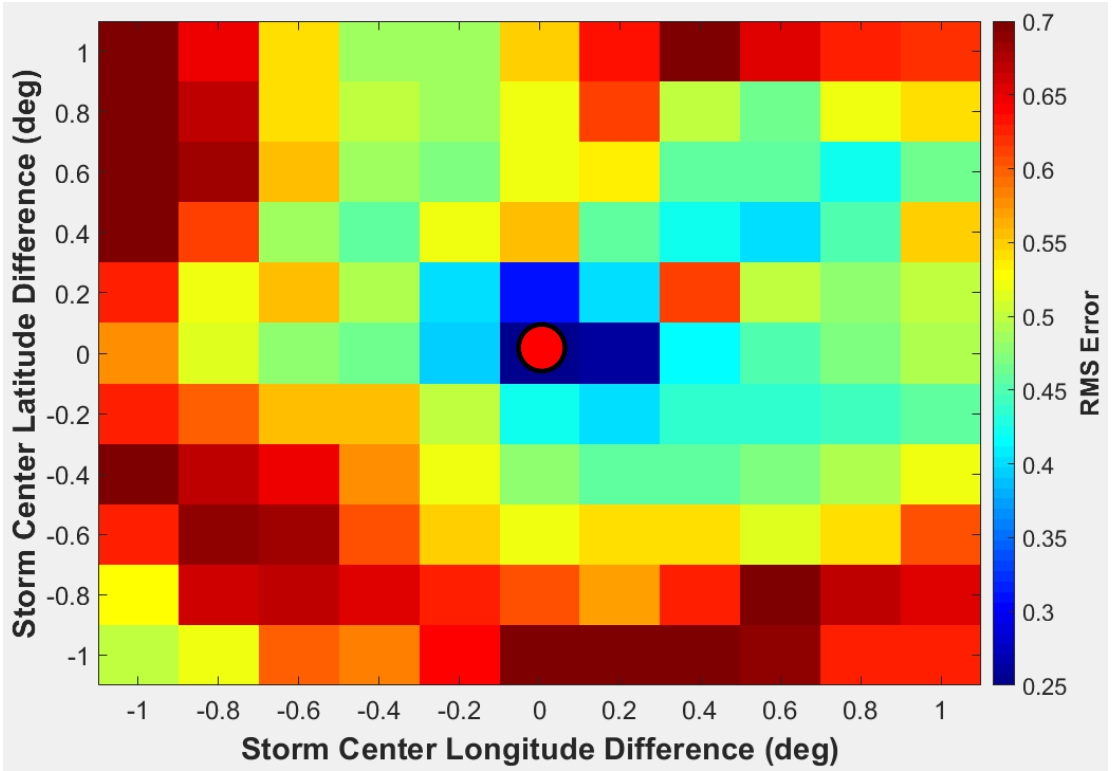
- CYGNSS sampling is pseudorandom because it's dependent on both the GPS and CYGNSS orbits
- Each overpass of a storm will have different distribution of measurements
- How to determine the storm center with randomly located "sampling gaps"?

Hurricane Florence 9/10/18 12-18 UTC



Center Fix with CYGNSS Input





Residual RMS Error (rescaled)

= Best Track center location (which is consistent with the MTrack center)

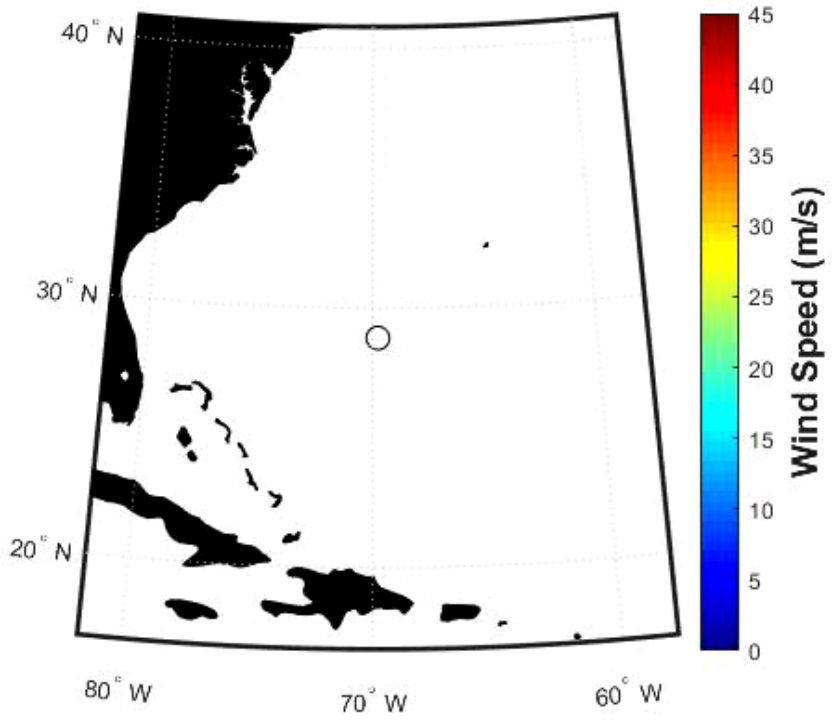
Part III
MTrack with SMAP

Soil Moisture Active Passive (SMAP)

- **Baseline Science Objective:**
  - **Observations of soil moisture and freeze/thaw state from space will allow significantly improved estimates of water, energy, and carbon transfers between the land and atmosphere**
- **Sponsor: NASA**
- **Launch Date: 31 January 2015**
- **Instrument Type: L-Band Radiometer**
- **Swath Width: 1000 km**
- **Coverage: Global**
- **Revisit Time: ~3 days**
- **Spatial Resolution: ~40 km**
- **Latency: ~1 day**

more complete coverage of TCs but with reduced frequency

Hurricane Florence



Animation is 10 mins of data

Example 1: Strong Storm, Resolved Eye

- **Storm centers must be obtained in near-real-time for SMAP to report wind radii information**
- **Storm center location on the right was produced automatically by interpolating the forecast from ATCF (Automated TC Forecasting)**
- **Wind radii are wrong in each quadrant because storm center is not consistent with wind field**
- **Storm center should be moved southeast**

Category 4 Hurricane

SMAP Winds Florence 2018-09-12 1050 UTC

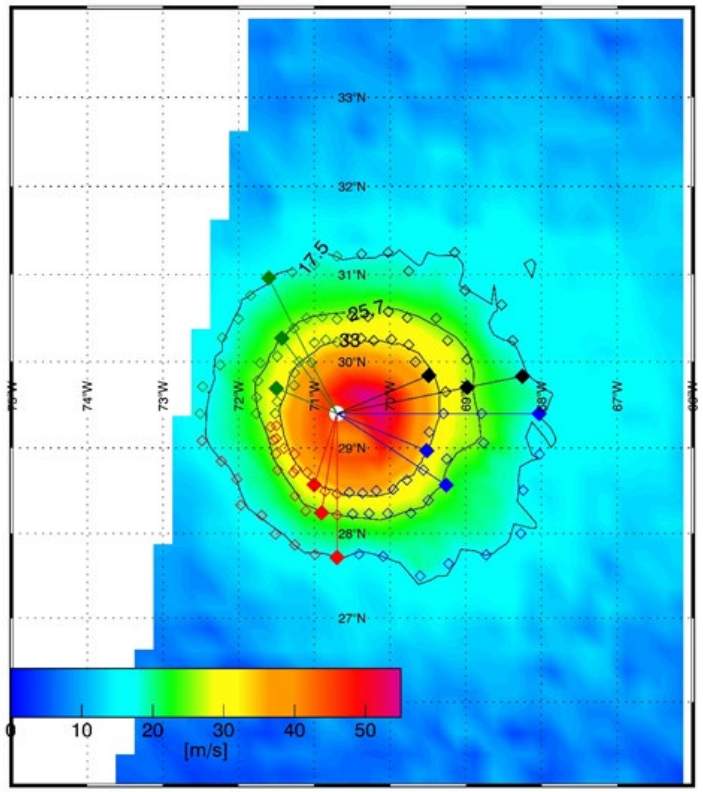
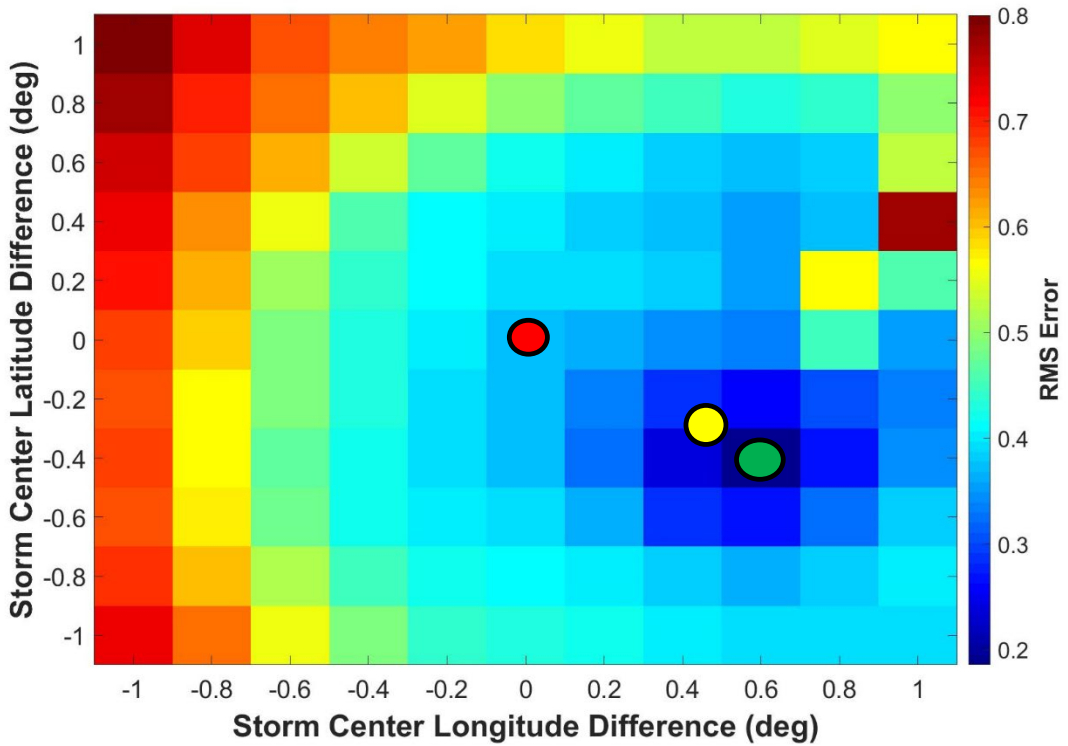
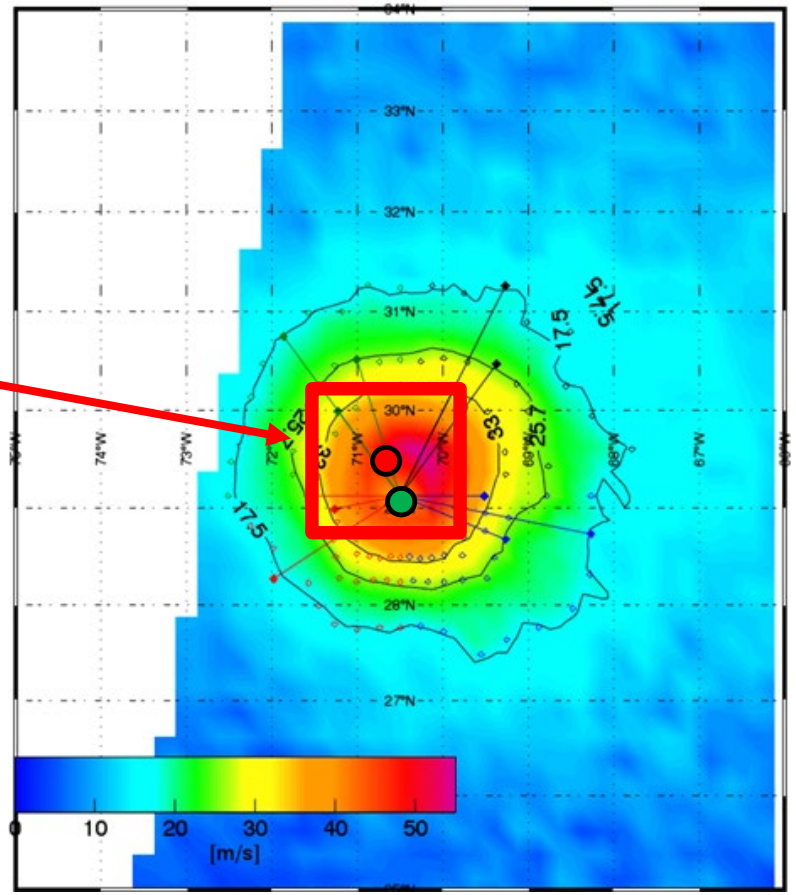


Image Credit: Lucrezia Ricciardulli, Remote Sensing Systems

Example 1: Strong Storm, Resolved Eye



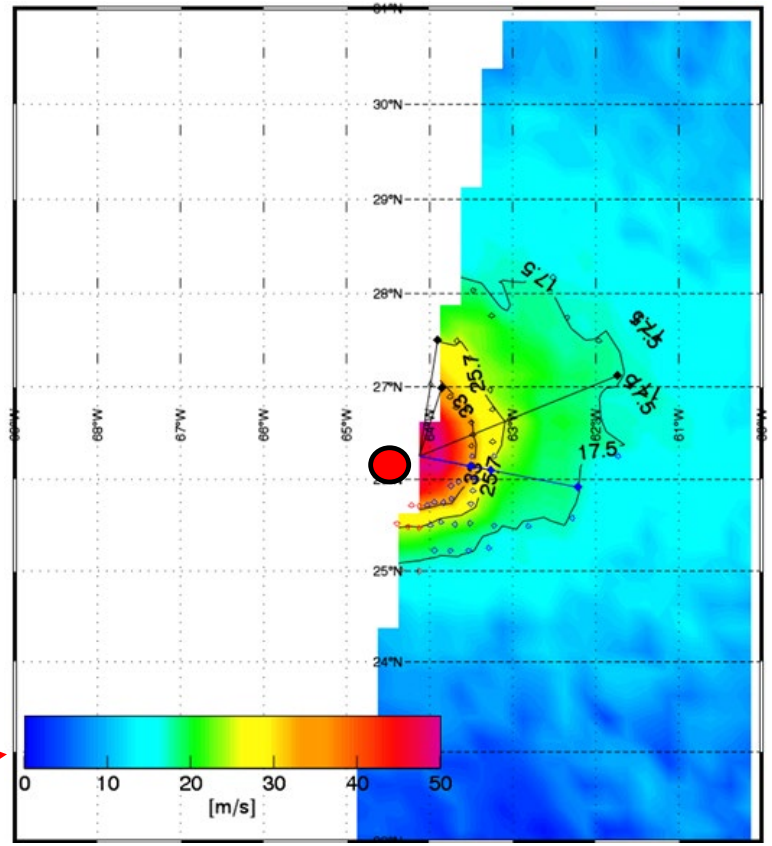


● = incorrect center from ATCF forecast
● = improved MTrack center
● = Best Track center

Example 2: Swath Edge

- **Best Track storm center location is off the swath edge**
- **Can MTrack make a reliable center fix when the center is off the swath?**

SMAP Winds Florence 2018-09-11 1014 UTC



● = Best Track center

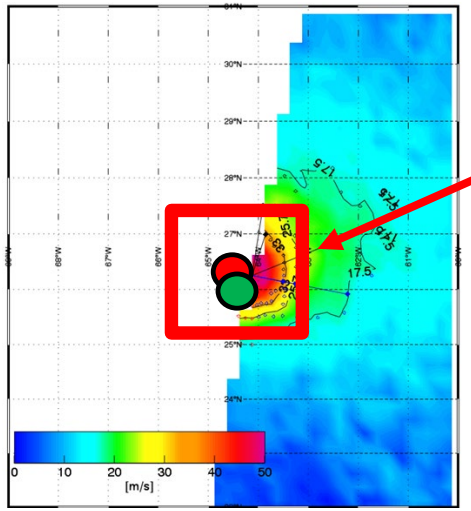
Category 4 Hurricane

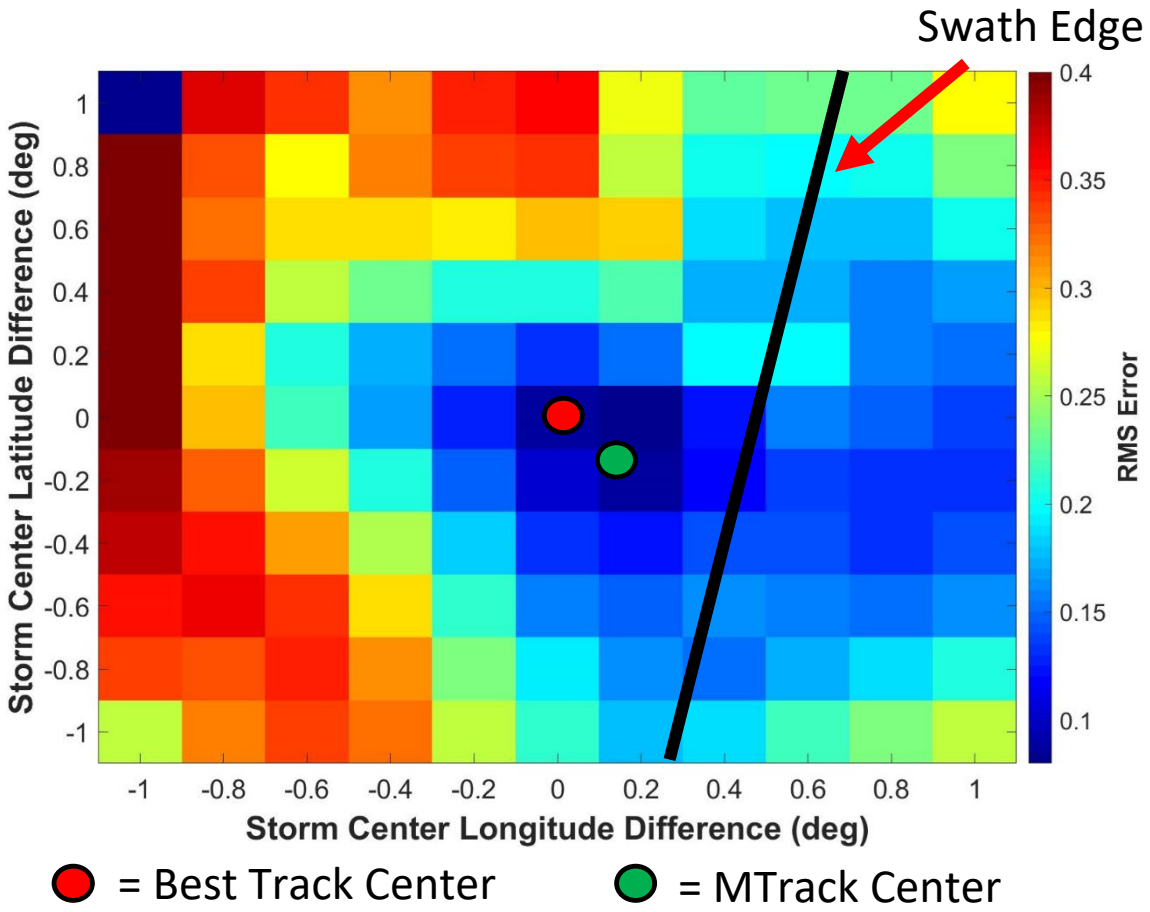
Image Credit: Lucrezia Ricciardulli, Remote Sensing Systems

Example 2: Swath Edge

- **MTrack shows high confidence in a storm center that is 16 km from the Best Track center, despite this center location being off the swath**

- **MTrack can work well on the swath edge because it is designed to operate with data gaps**

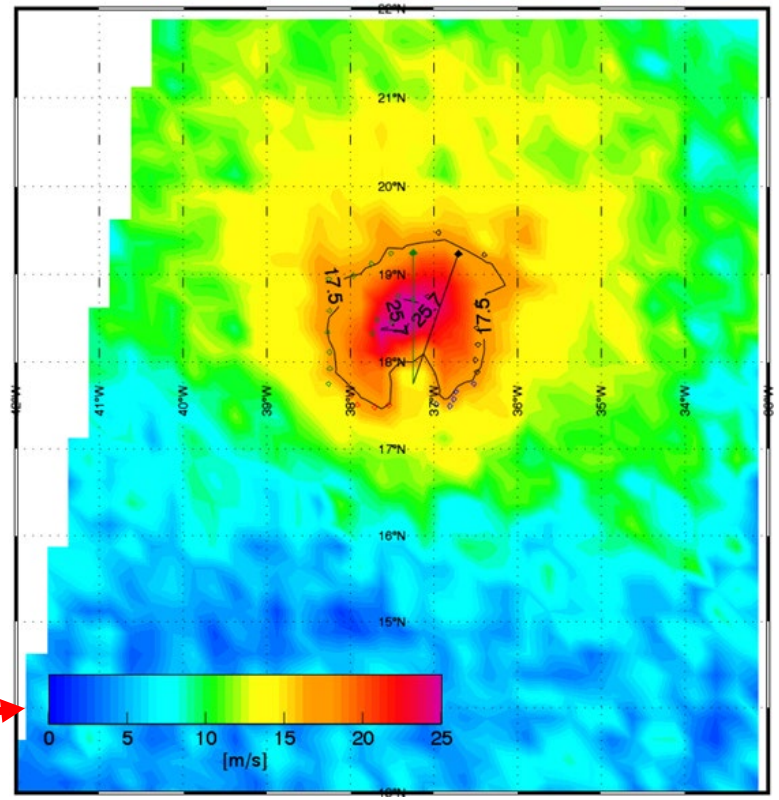




Example 3: Weak, Disorganized Storm

- **Tropical Storm Florence is less organized in this case**
- **Weak, disorganized storms—this is where other techniques have the most difficulty in finding the storm center location**

SMAP Winds Florence 2018-09-03 838 UTC



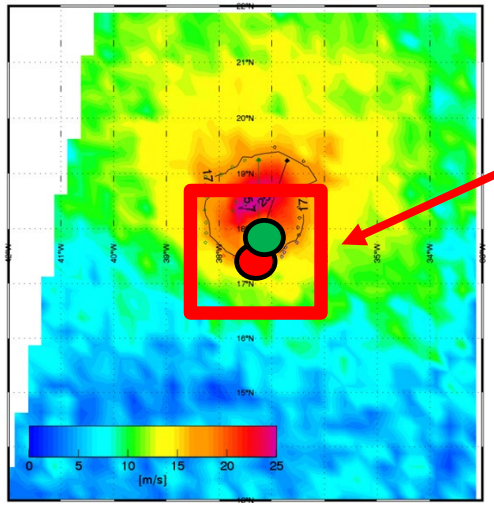
Below Hurricane Strength

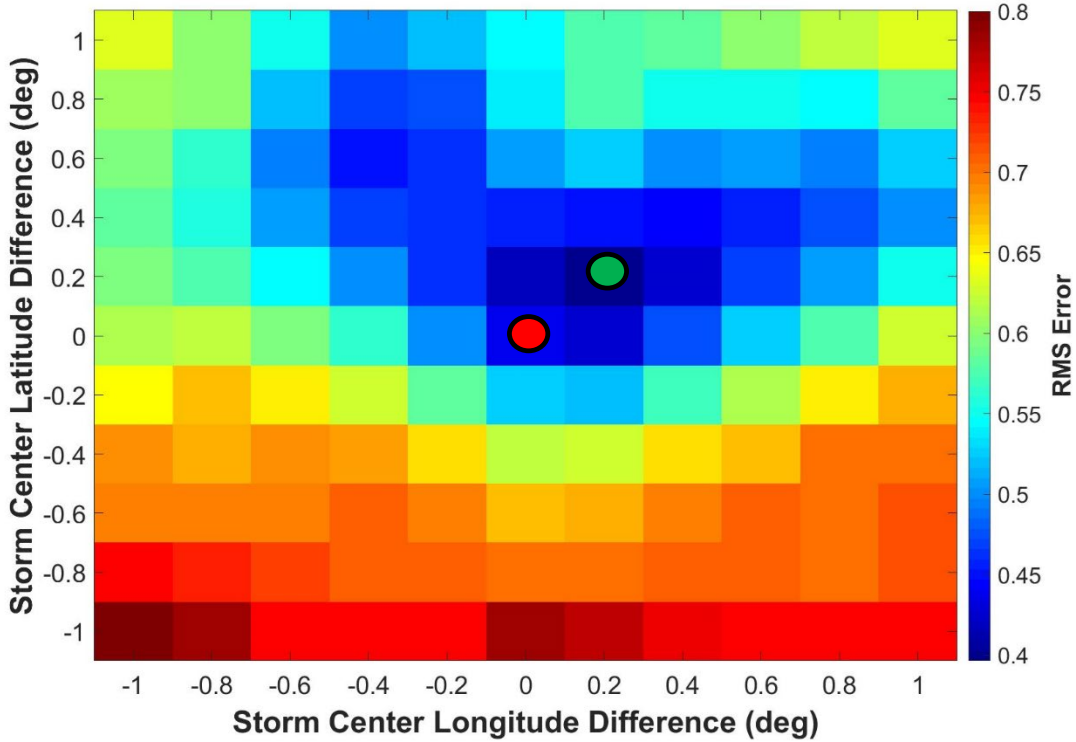
Image Credit: Lucrezia Ricciardulli, Remote Sensing Systems

Example 3: Weak, Disorganized Storm

- **Although parametric wind model can't perfectly fit to a disorganized wind field as I showed earlier, it's close enough for MTrack to generate reliable storm center fixes**

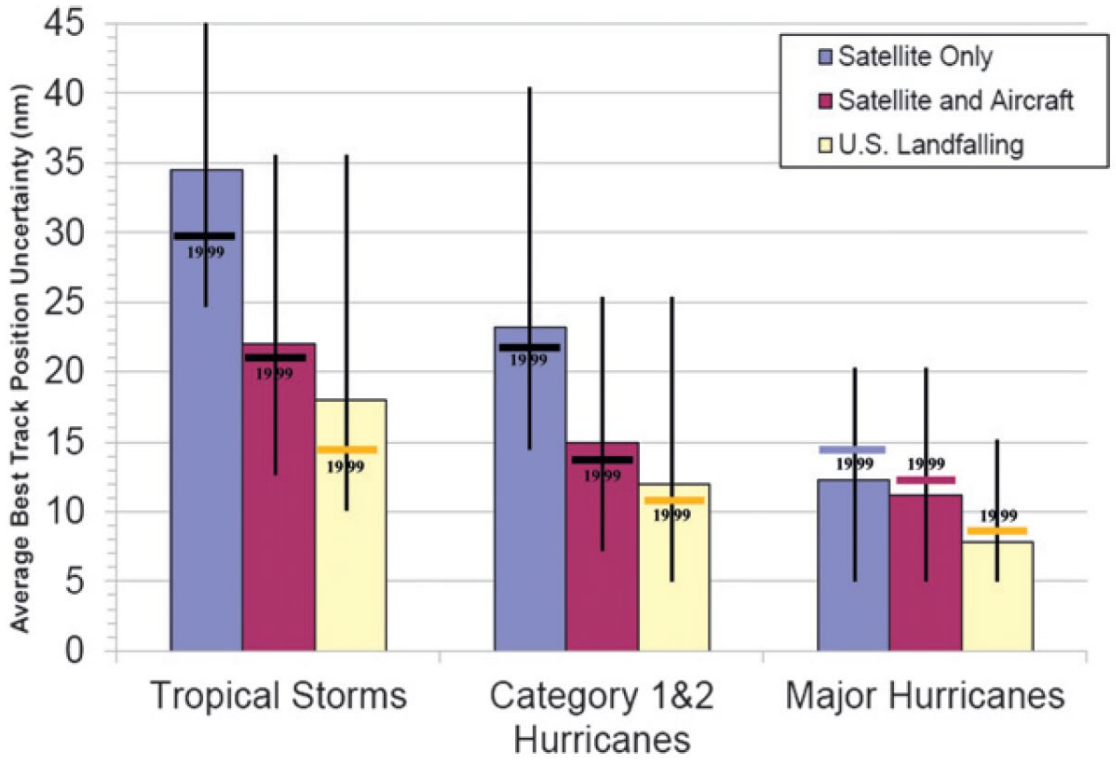
- **MTrack solution has high confidence in a center 25 km from Best Track (within error margin for weak storm)**

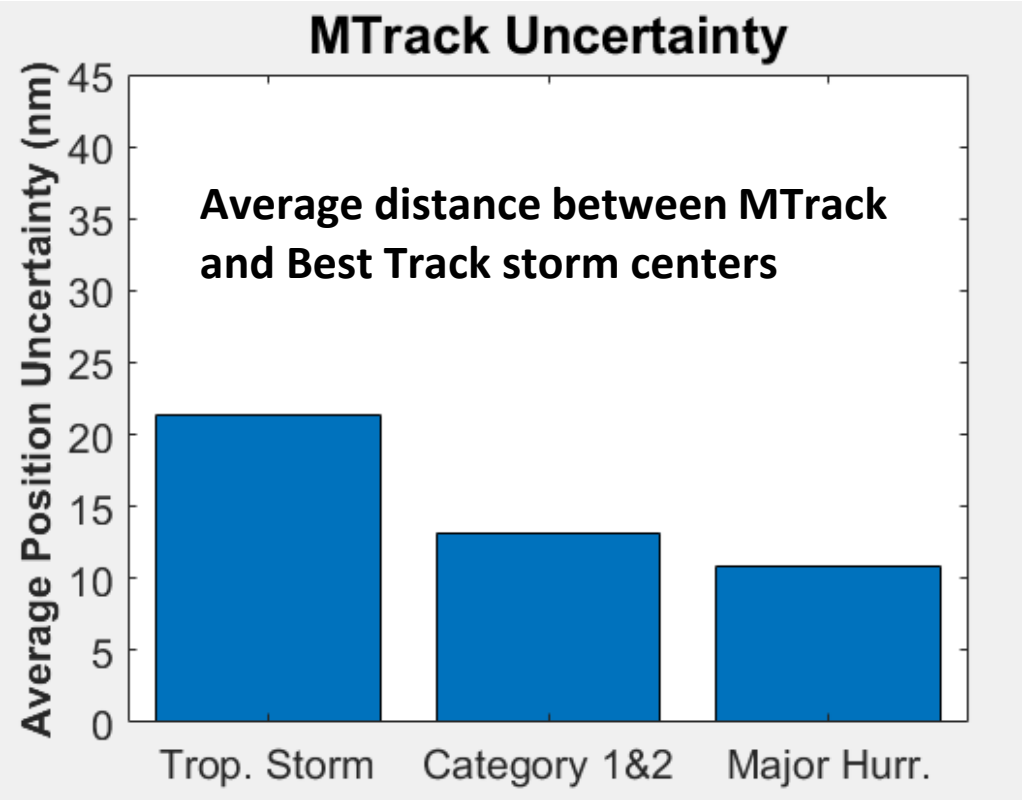




= Best Track Center = MTrack Center

Best Track vs MTrack





Landsea, C.W. and J.L. Franklin, 2013: Atlantic Hurricane Database Uncertainty and Presentation of a New Database Format. *Mon. Wea. Rev.*, **141**, 3576-3592, DOI: 10.1175/MWR-D-12-00254.1

Conclusion

- MTrack is an automated storm center fix algorithm that is compatible with wind speed measurements from many different satellites
- The MTrack approach allows for storm centers to be found from wind fields fraught with gaps
- Works with SMAP winds, even when the storm center is off the swath
- MTrack solution has little sensitivity to wind speed perturbations/error and no sensitivity to first guess location
- Error increases as storms get weaker and more disorganized (like Best Track)
- Average distance between MTrack and Best Track storm centers is 21, 13, and 10 nm for tropical storms, Cat 1-2 hurricanes, and major hurricanes, respectively. These numbers are similar to the Best Track uncertainty values.

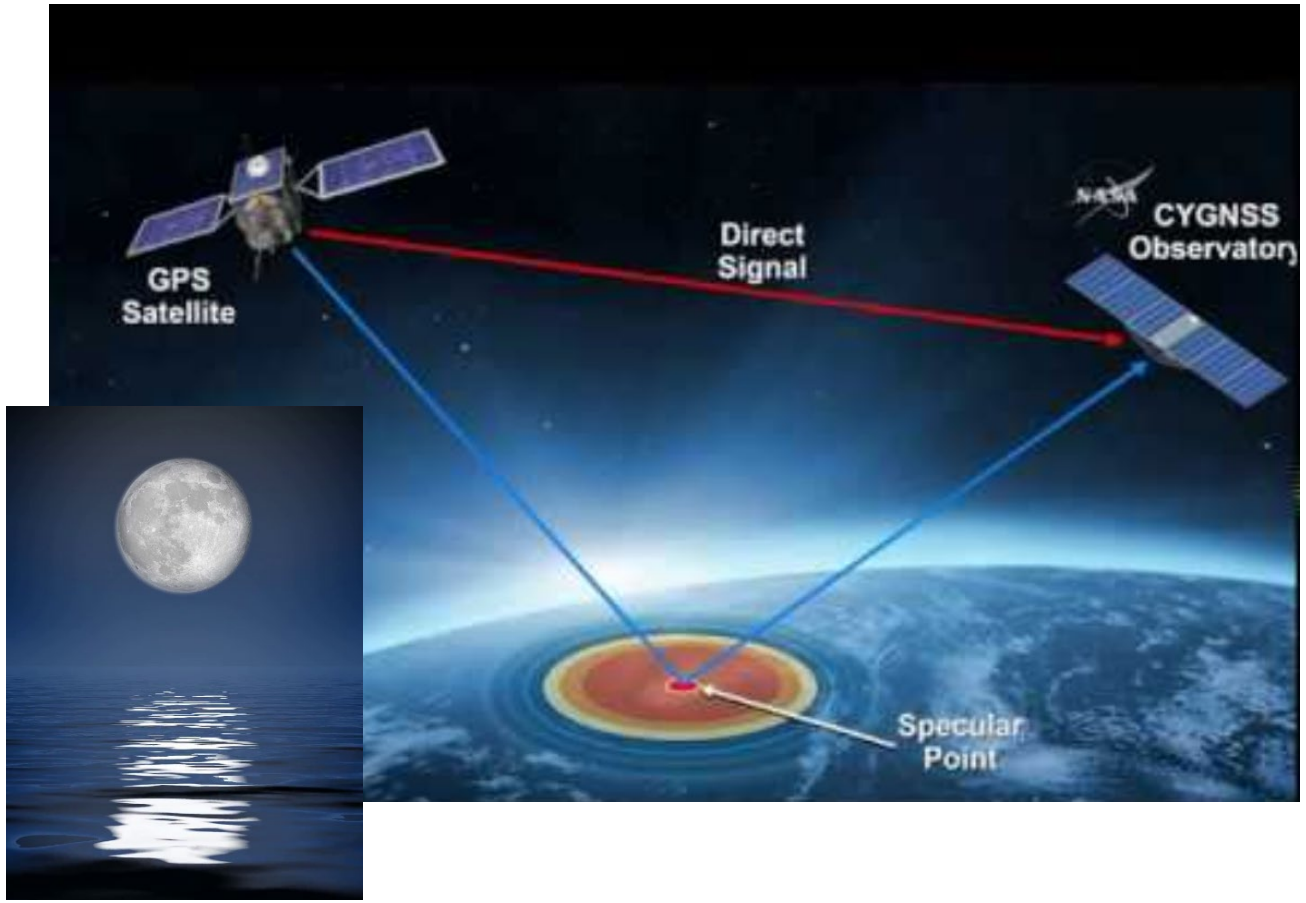
Thank you!!

Please tell me your suggestions and feedback (especially for new applications)

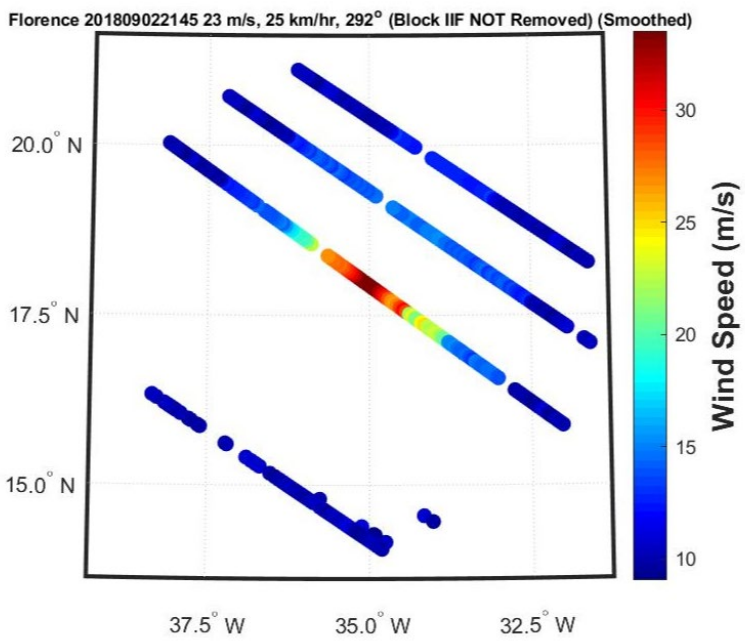
Additional Slides

CYGNSS Operation

- CYGNSS receives two signals from GPS:
  - Direct path signal
  - Signal scattered from Earth's surface
- Based on the GPS transmit power, we know how much power the satellite should receive in wind-free conditions
- Power received from specular point decreases as the ocean surface roughens

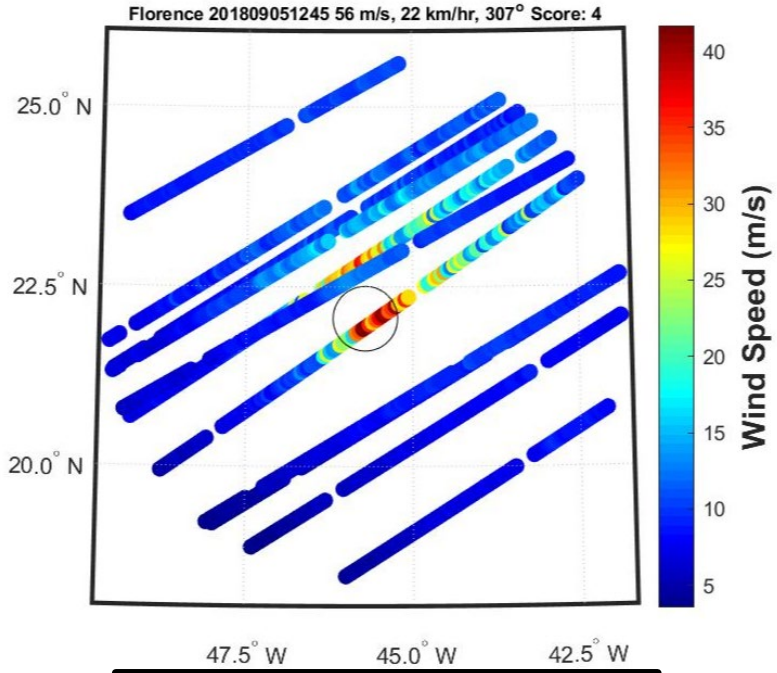


Duration is Latitude Dependent



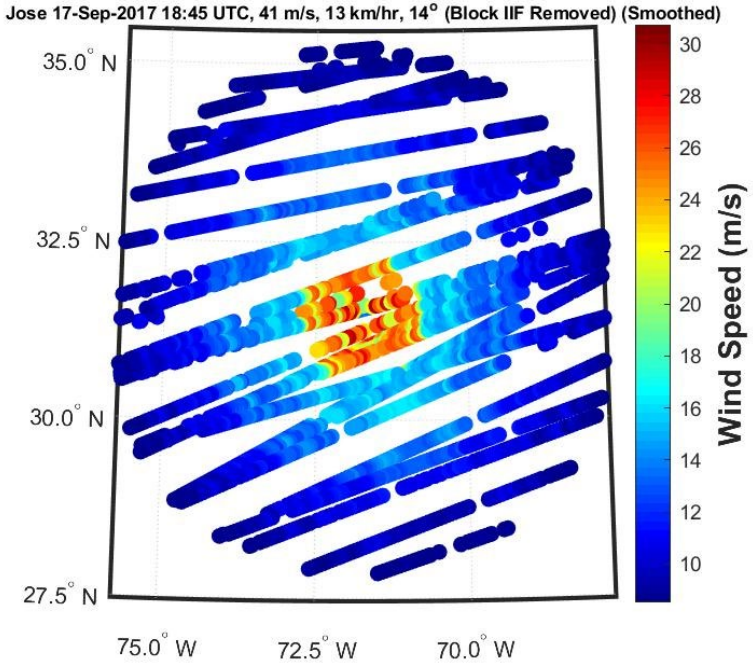
Low Latitude Case

3 Hour Duration Examples



Mid Latitude Case

YSLF L2 V2.1 CYGNSS Data



High Latitude Case

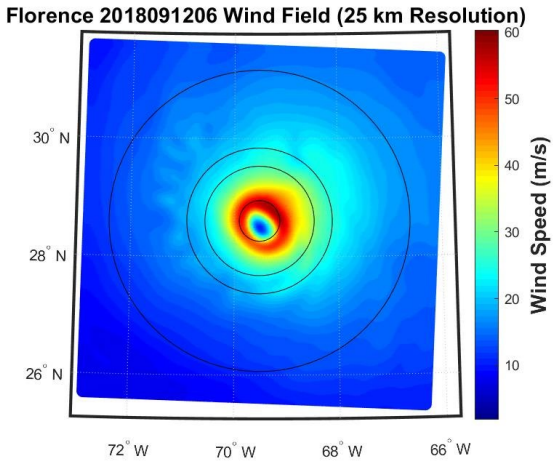
Radially smoothed over 10 km

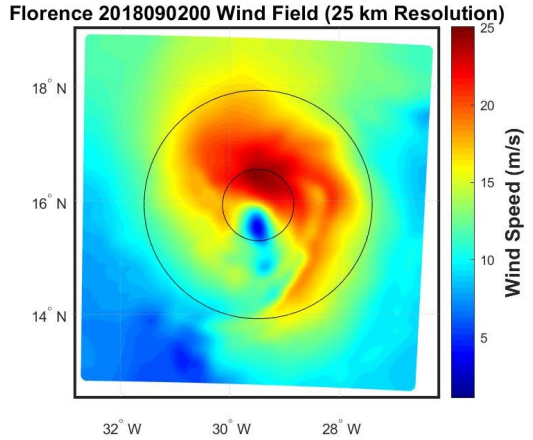
Strong vs Weak TCs

Strong cyclones typically have:
-more consistent structure
-clear, ring-shaped eyewall
-clearer, more pronounced eye
-more organized rain bands
-co-located MSLP matches rotational center

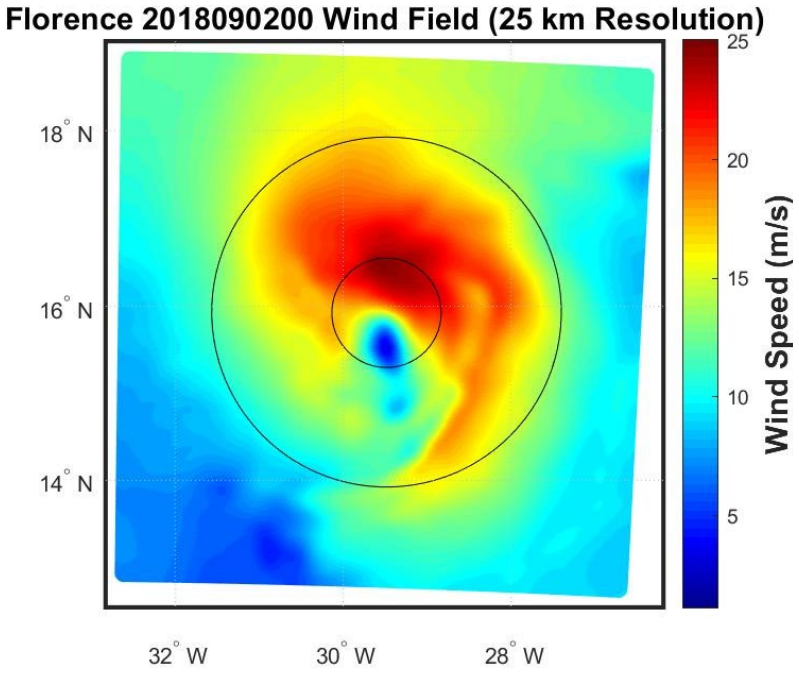
MTrack performance is better for strong storms because the wind structure matches the assumed model

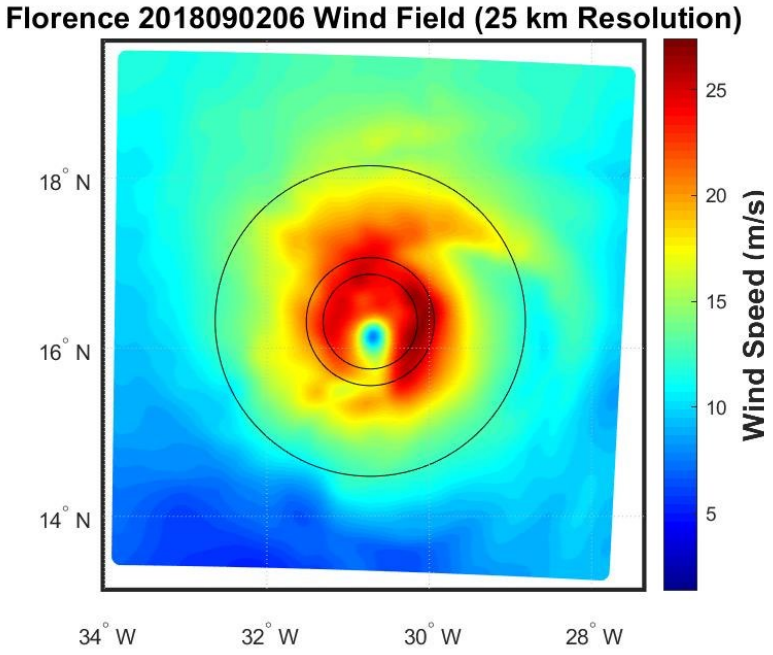
Other methods (e.g. ARCHER) fit ring shapes to eye and spiral shapes to rain bands to make center fix

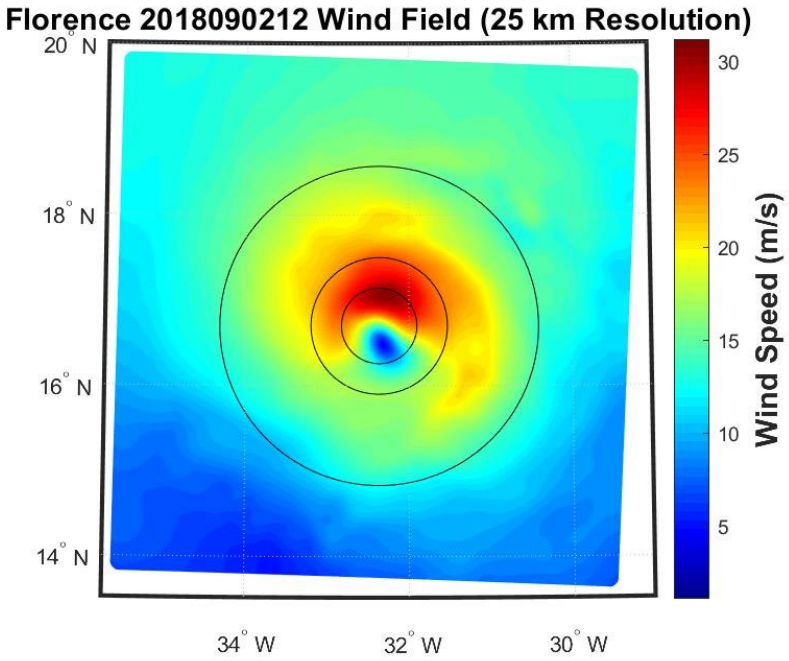




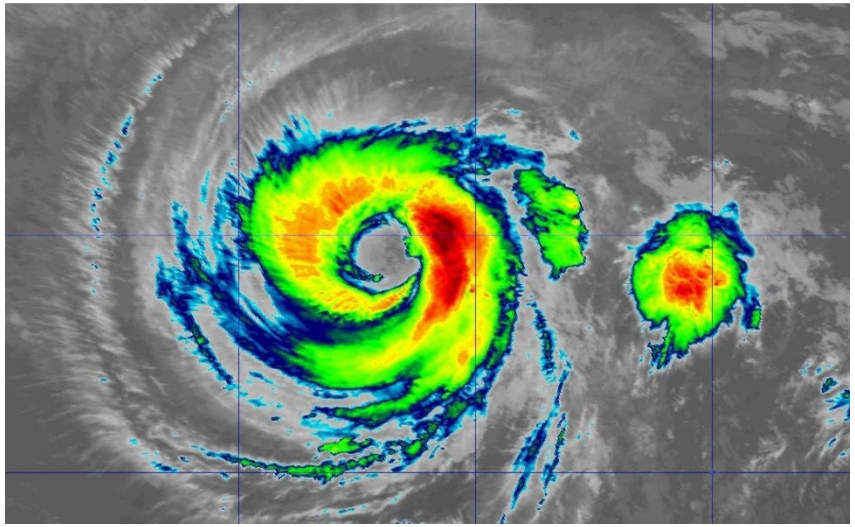
TS Evolution

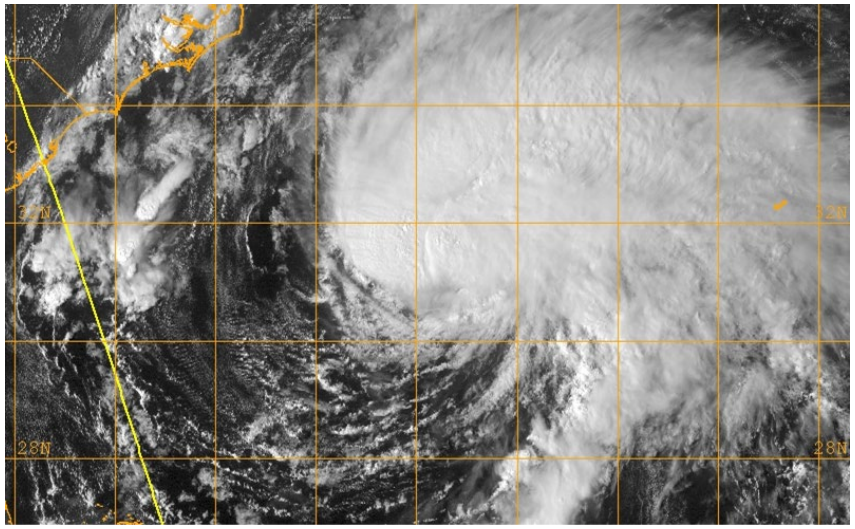






-Wind field isn't consistent with MTrack's assumed model.
-Highly variable structure makes it difficult to pick just one model to represent tropical storms



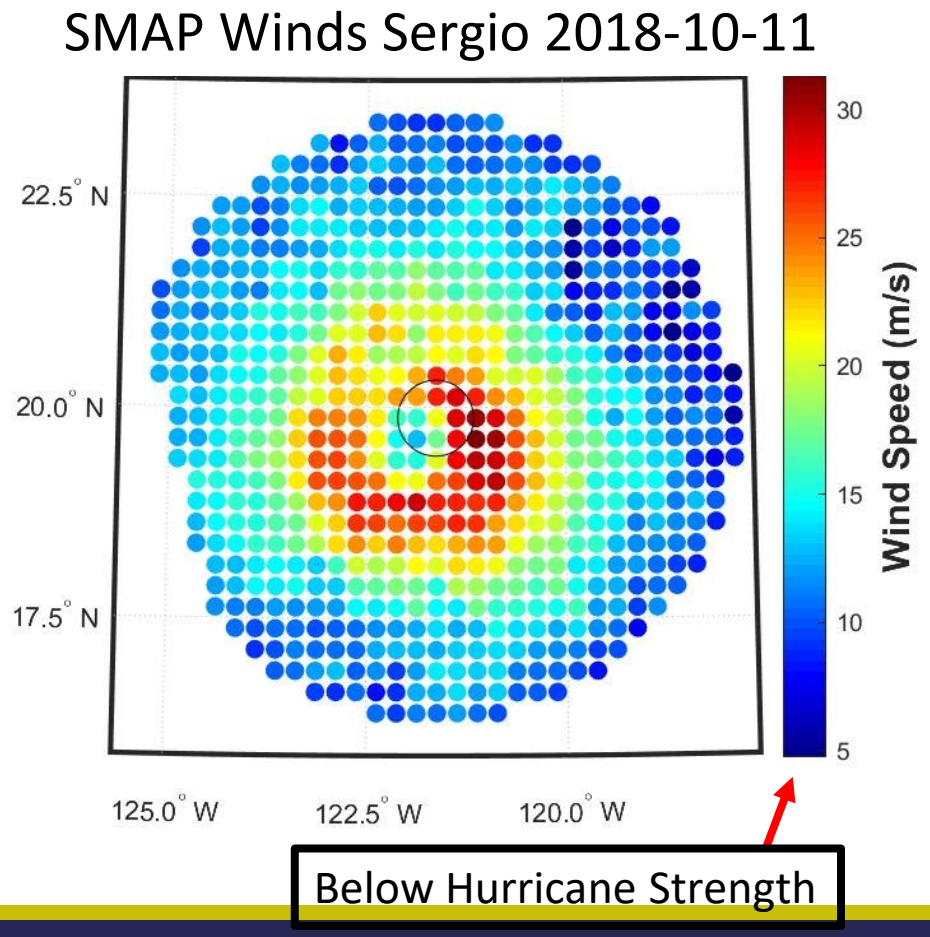


Existing Techniques

- Storm center location is often determined manually by experienced forecasters but there can be bias between forecasters and sometimes the eye is shrouded making the center location difficult to spot
- Automated techniques fit ring to eyewall or spirals to rain bands (ARCHER). Can struggle for weak disorganized storms with no visible eye.
- MTrack is fully automated and has the potential to perform with more consistency than manual forecasting and with more accuracy than existing automated techniques for weak TCs without a visible eye

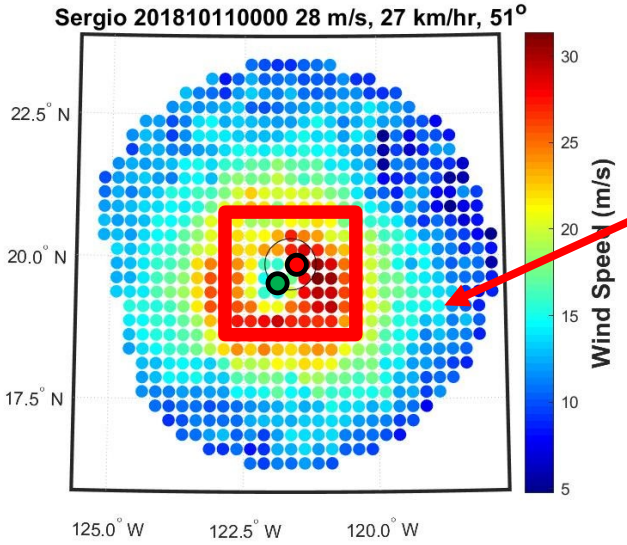
Example 4: Improved Center Fix

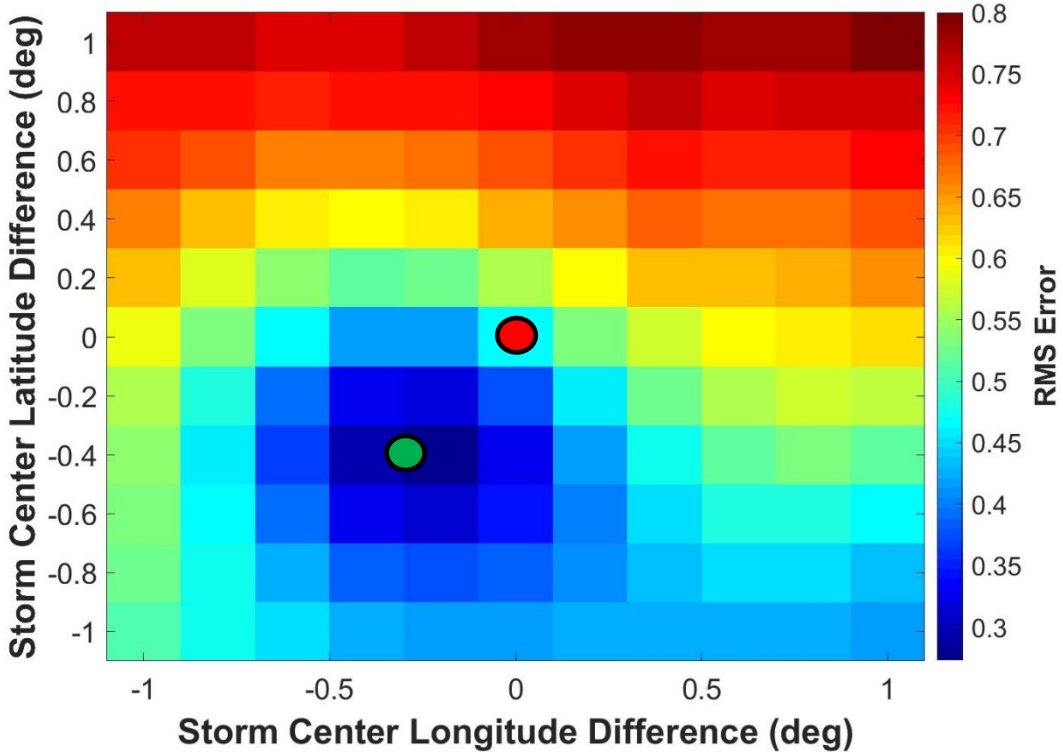
- Tropical Storm Sergio is less organized in this case
- Weak, disorganized storms—this is where other techniques have the most difficulty in finding the storm center location
- Best Track storm center (circle on wind field) appears to be too far northeast



Example 4: Improved Center Fix

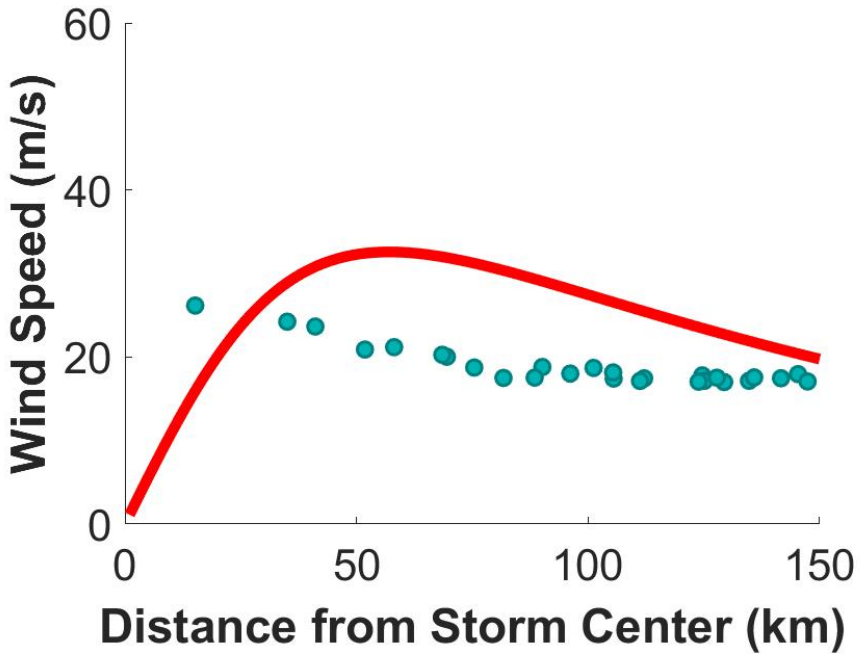
- MTrack is still able to work because of all the tunable parameters in fit
- MTrack solution is 50 km southwest of Best Track and appears to be an improved storm center location

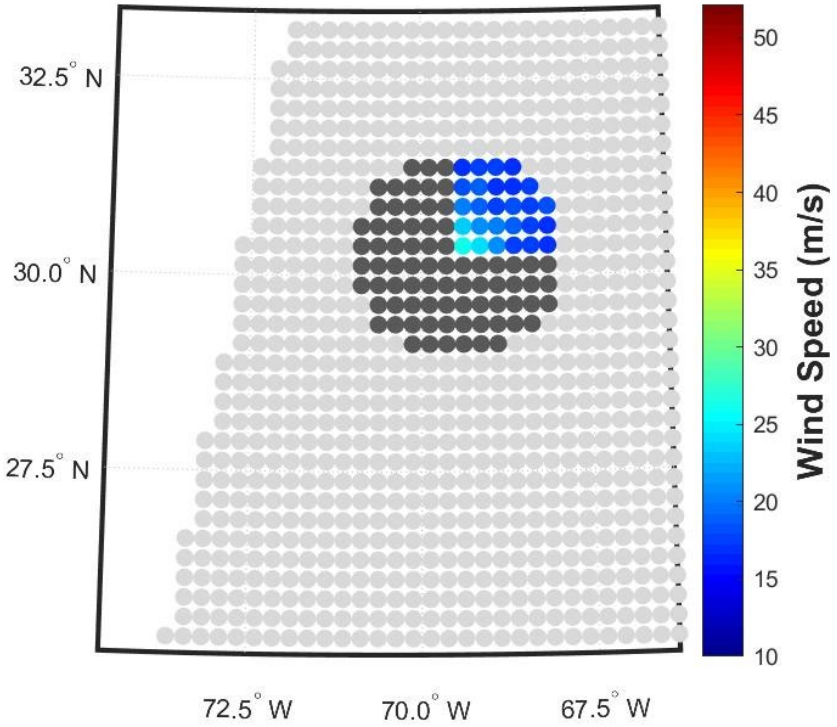




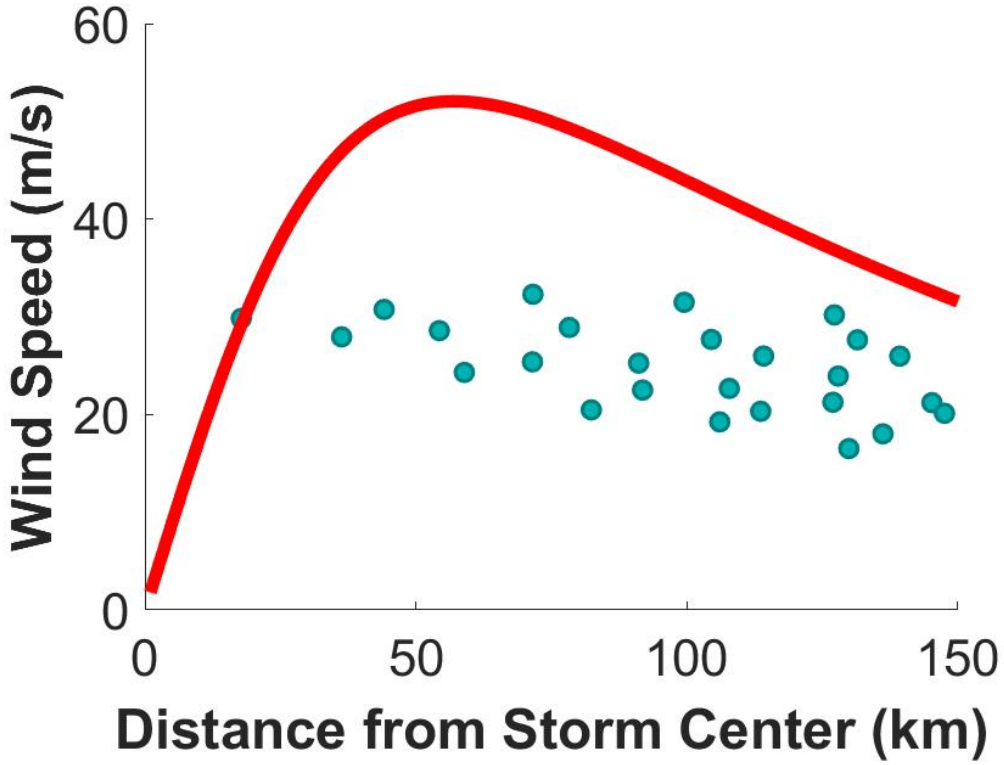
= Best Track Center = MTrack Center

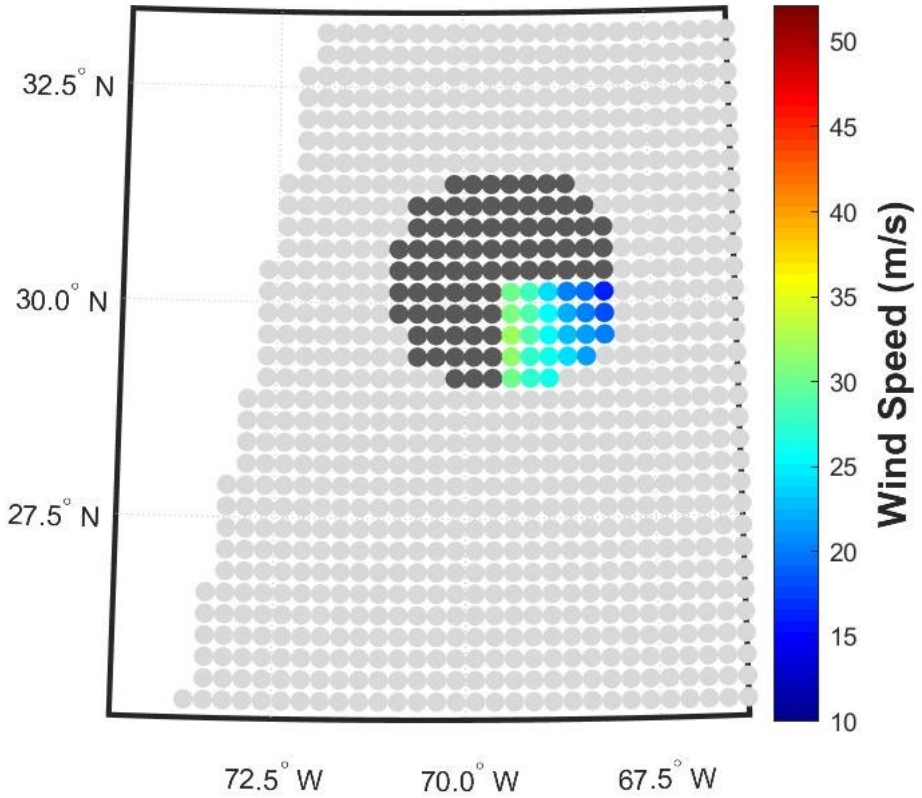
Quadrant I


Wind Speed (m/s)
60
40
20
0
0
50
100
150
Distance from Storm Center (km)

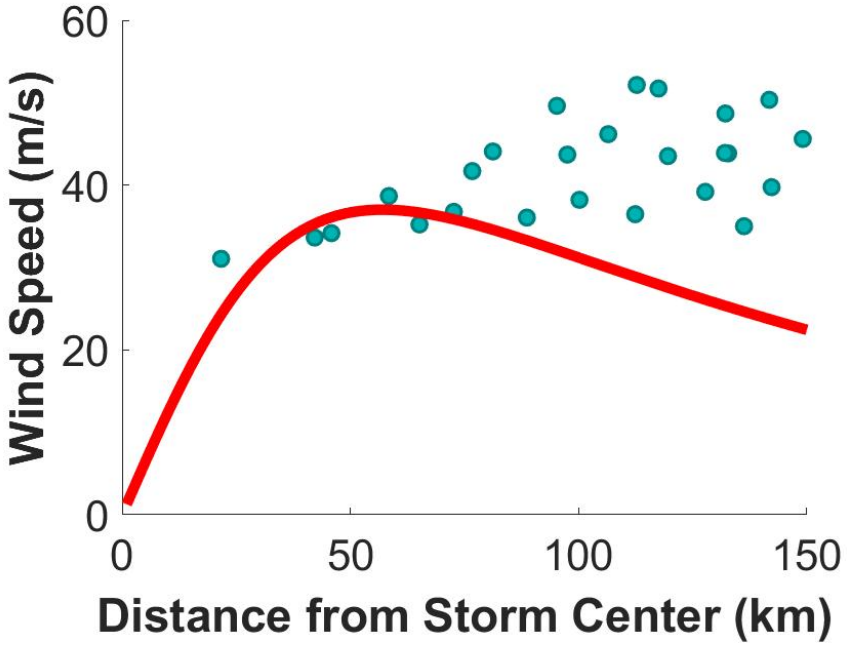

32.5° N
30.0° N
27.5° N
72.5° W
70.0° W
67.5° W
Wind Speed (m/s)
50
45
40
35
30
25
20
15
10

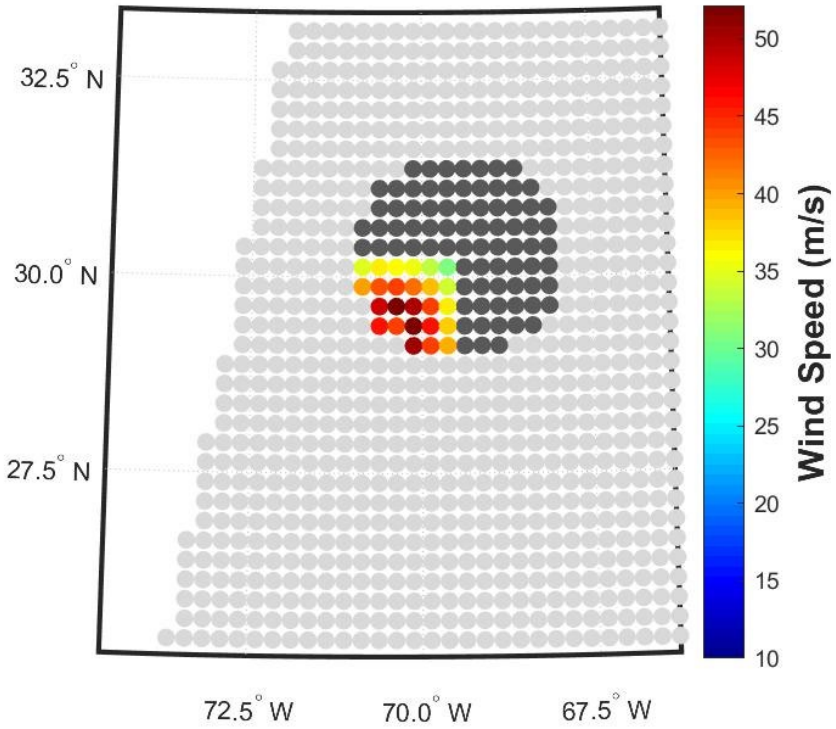
Quadrant II


Wind Speed (m/s)
60
40
20
0
0
50
100
150
Distance from Storm Center (km)

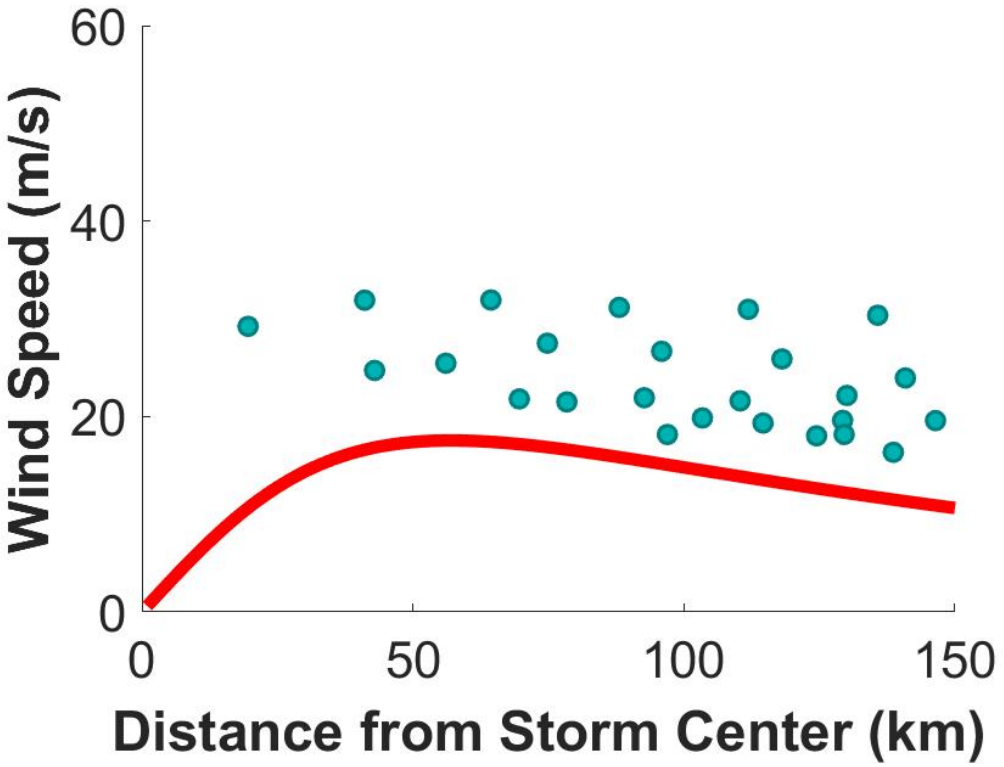

32.5° N
30.0° N
27.5° N
72.5° W
70.0° W
67.5° W
50
45
40
35
30
25
20
15
10
Wind Speed (m/s)

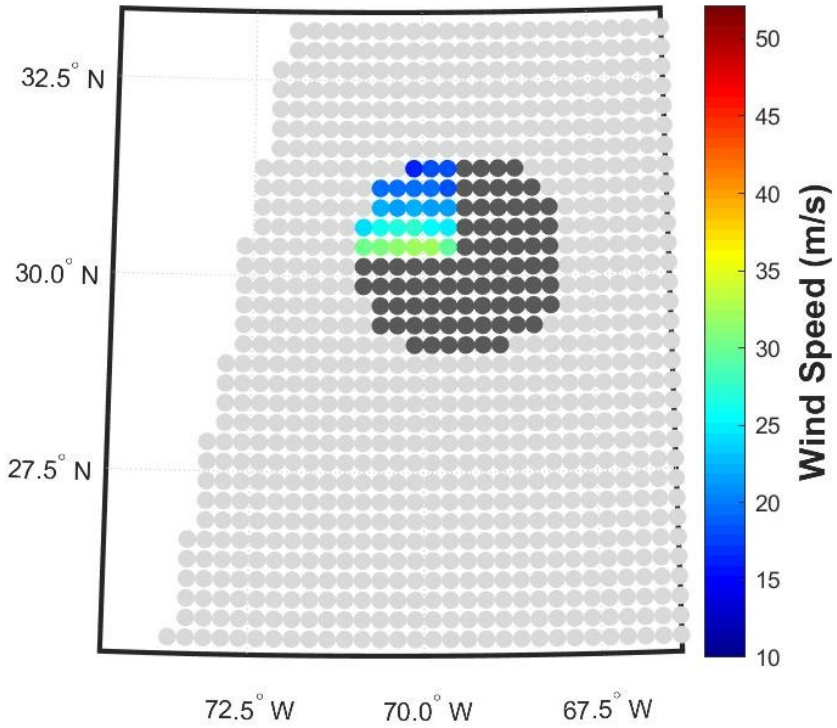
Quadrant III





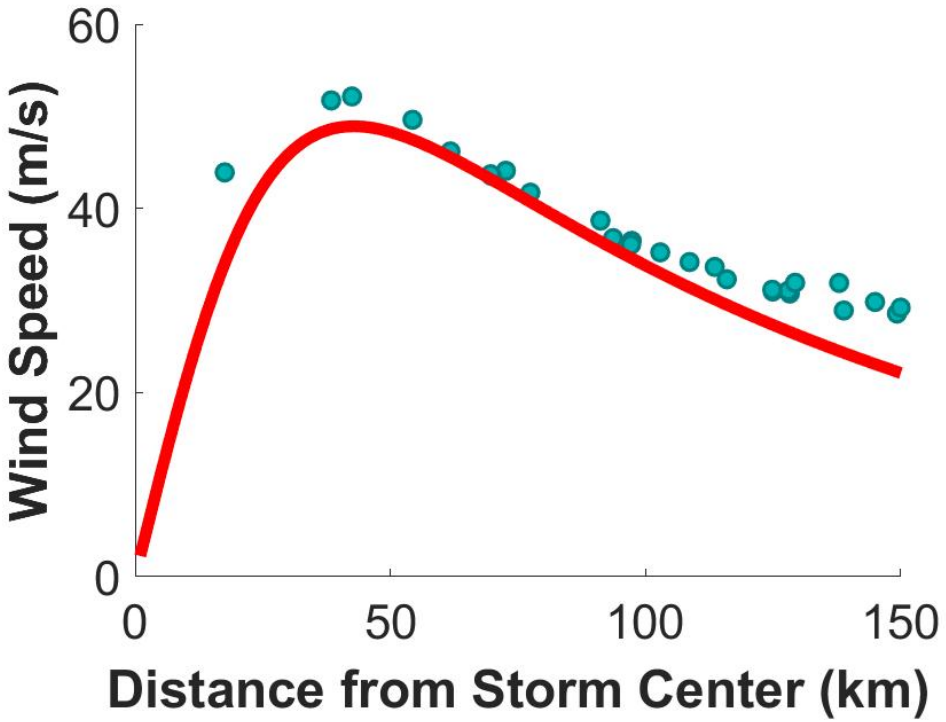
Quadrant IV

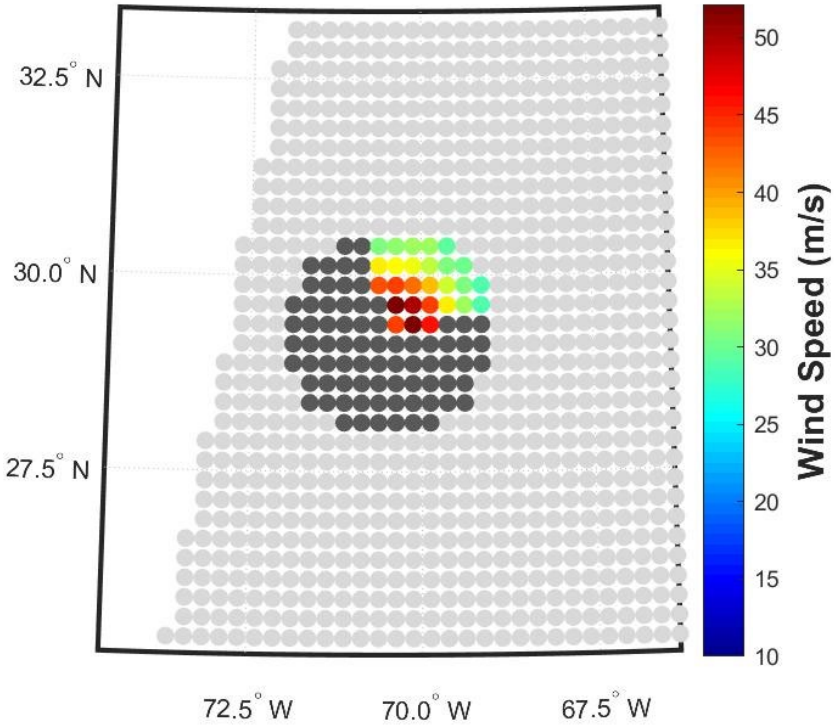




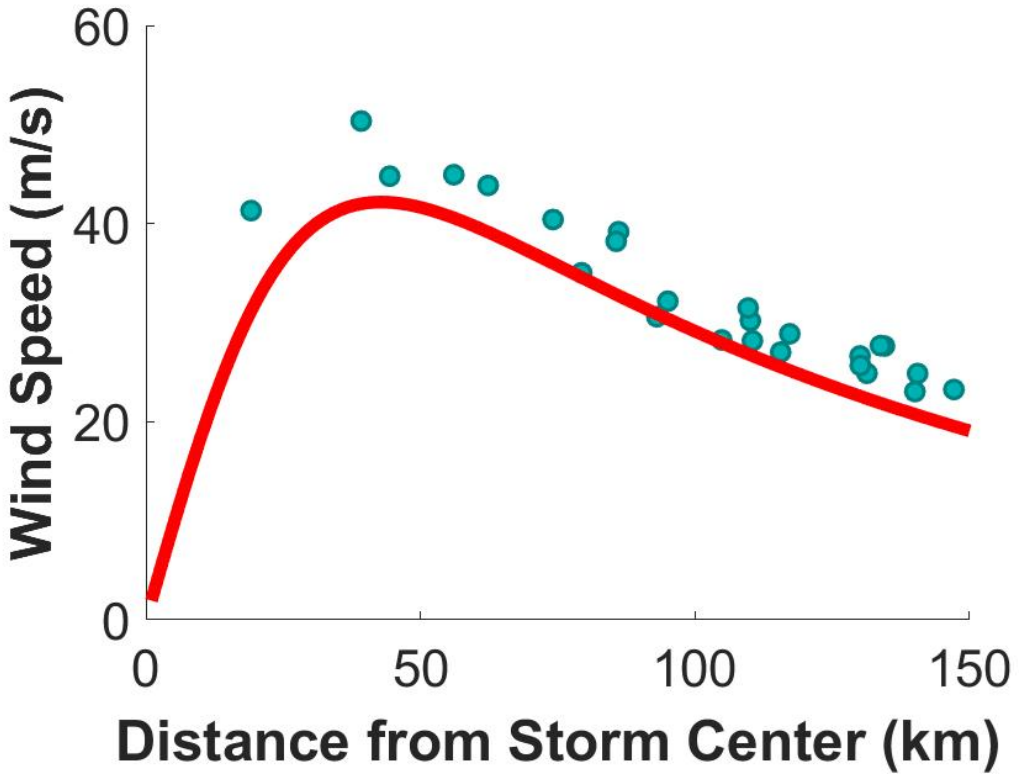
Rms = 6.8 m/s

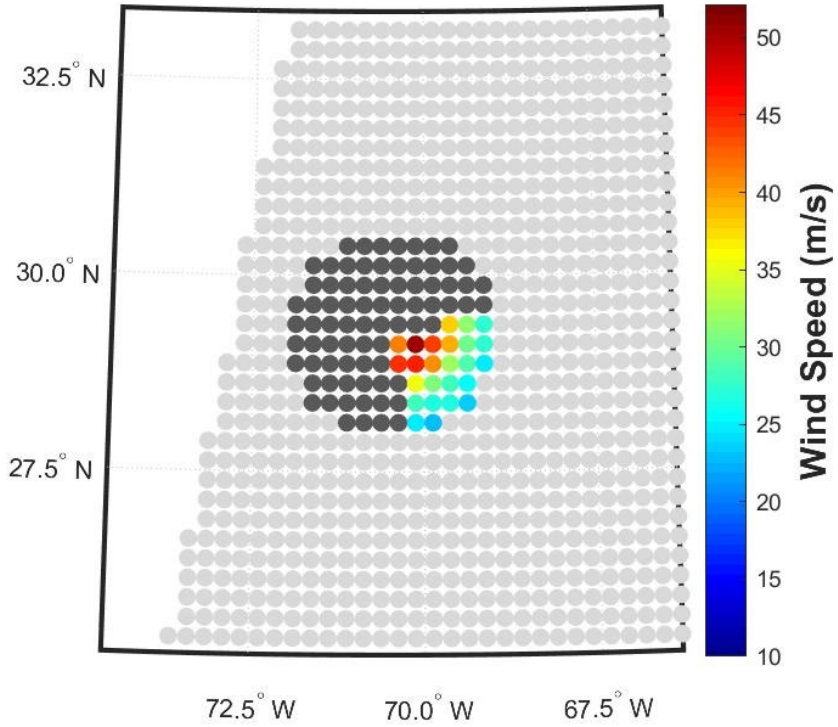
Quadrant I


Wind Speed (m/s)
60
40
20
0
0
50
100
150
Distance from Storm Center (km)

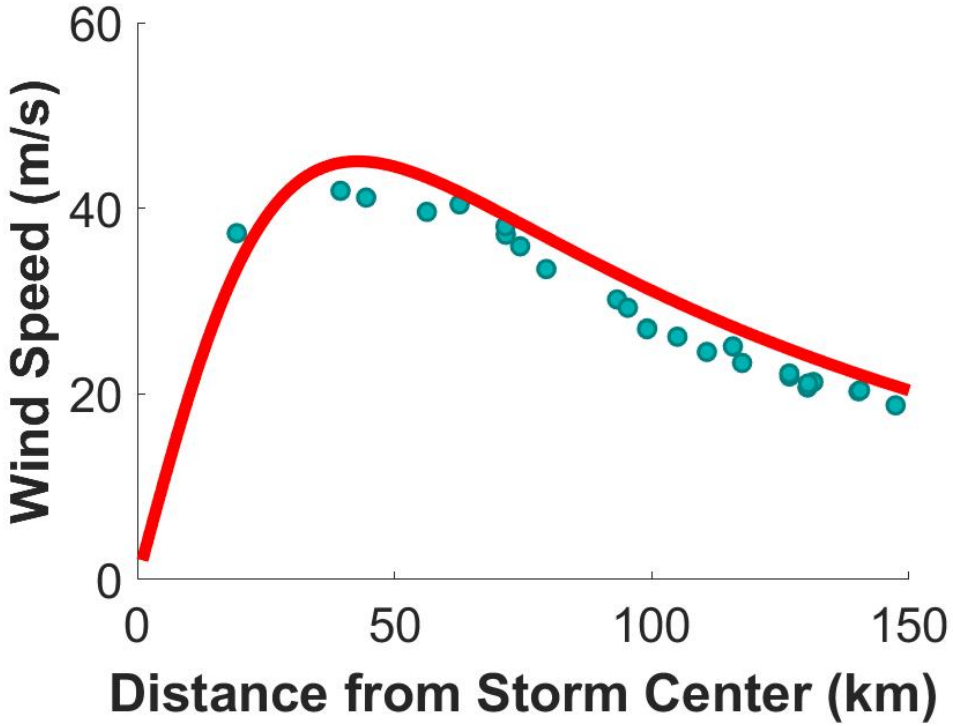

32.5° N
30.0° N
27.5° N
72.5° W
70.0° W
67.5° W
Wind Speed (m/s)
50
45
40
35
30
25
20
15
10

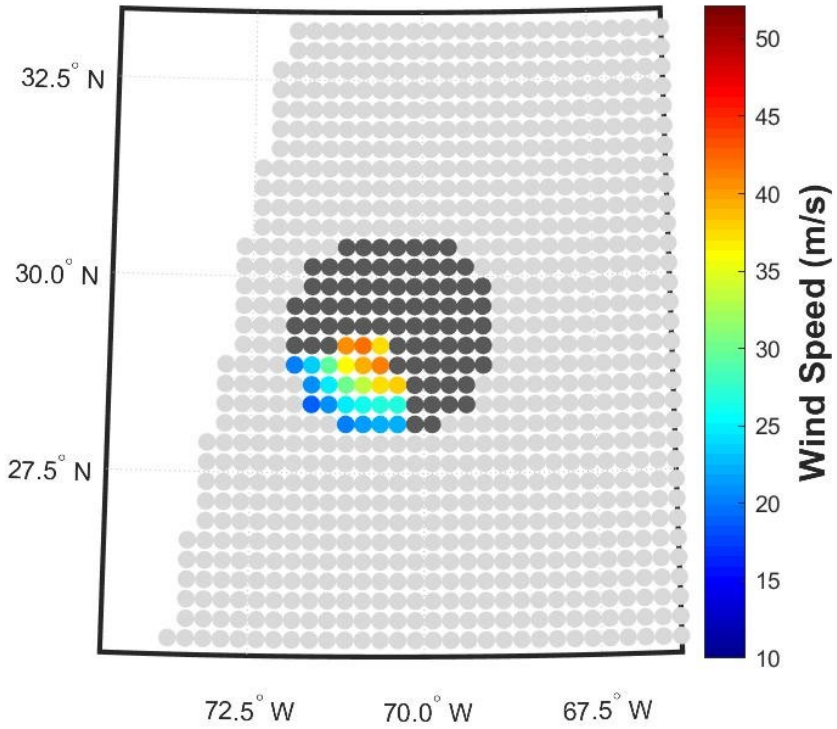
Quadrant II


Wind Speed (m/s)
60
40
20
0
0
50
100
150
Distance from Storm Center (km)

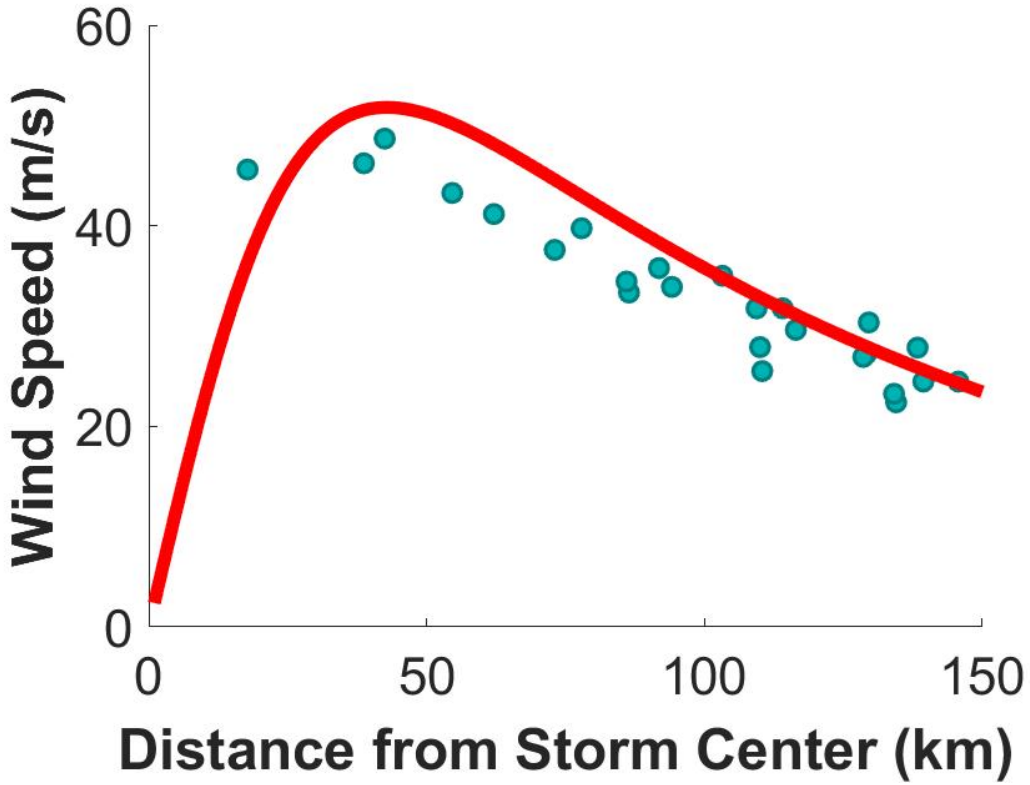

32.5° N
30.0° N
27.5° N
72.5° W
70.0° W
67.5° W
Wind Speed (m/s)
50
45
40
35
30
25
20
15
10

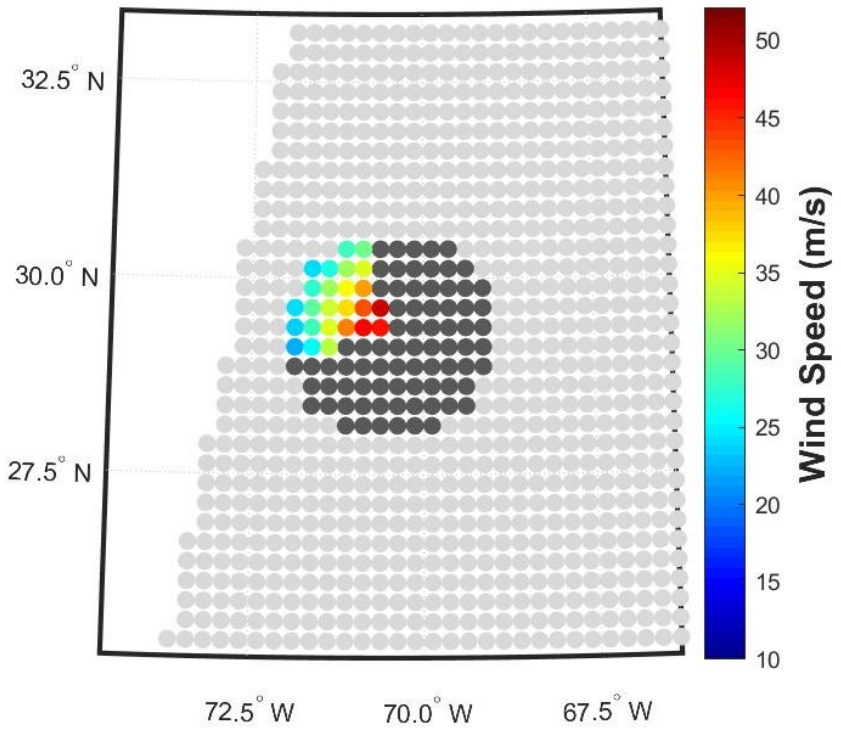
Quadrant III





Quadrant IV


Wind Speed (m/s)
60
40
20
0
0
50
100
150
Distance from Storm Center (km)


32.5° N
30.0° N
27.5° N
72.5° W
70.0° W
67.5° W
50
45
40
35
30
25
20
15
10
Wind Speed (m/s)