A Hurricane Ian Case Study to Refine Hurricane Storm Surge Forecasting Using Physics-Based Deterministic and Probabilistic Meteorological Products

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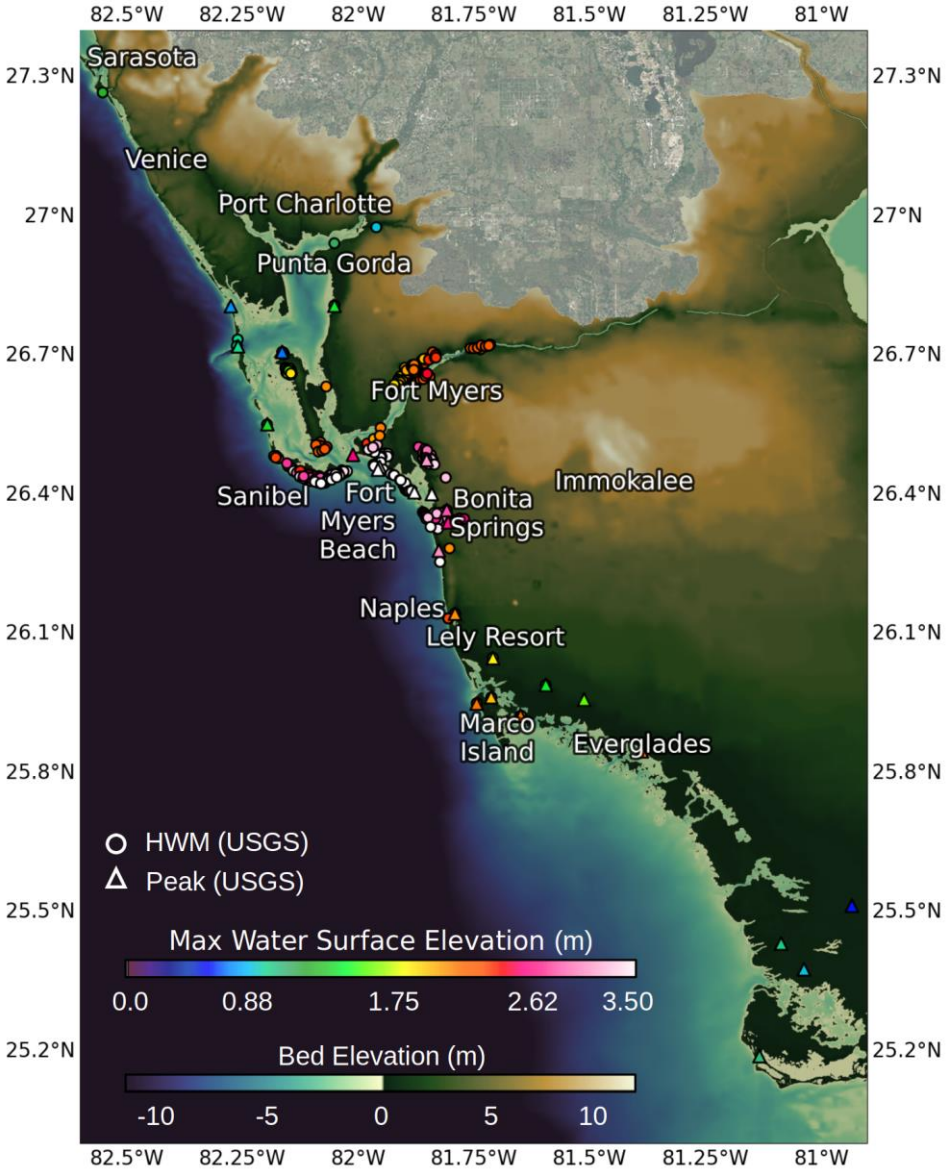
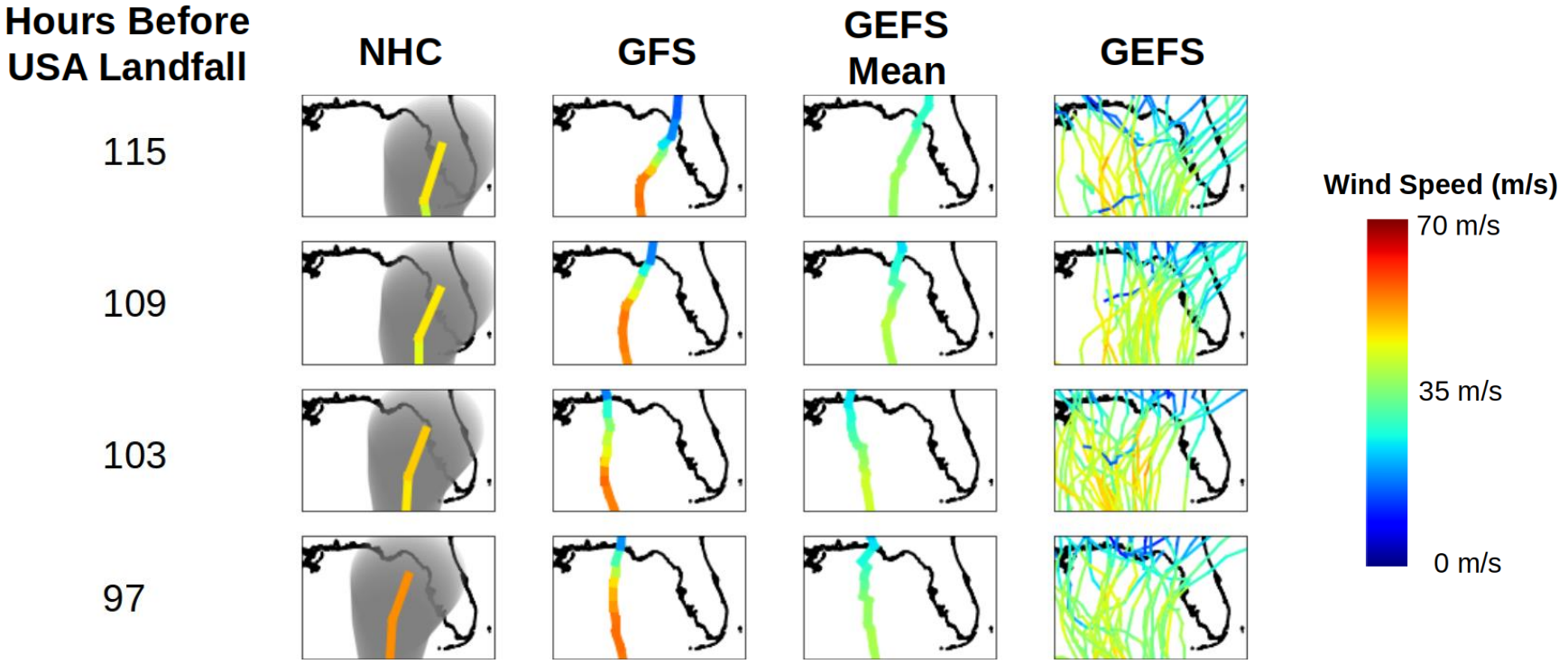
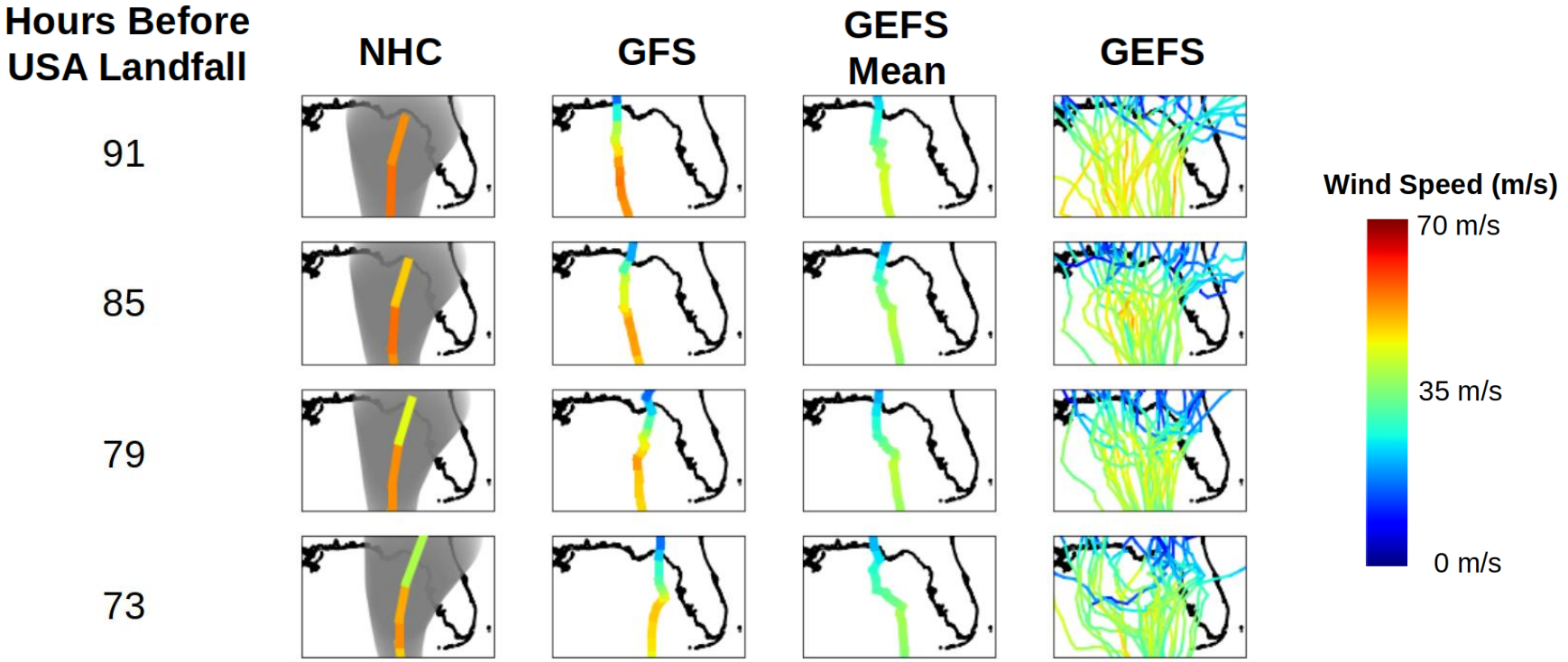


- **Hurricane Ian (2022) impacted Southwest Florida with significant surge near Fort Myers.**
  - **3.5m in coastal communities**
    - **-- Fort Myers Beach**
    - **-- Bonita Beach**
    - **-- Bonita Springs**
  - **2m on Caloosahatchee River**
  - **2m in Naples**



- High degree of meteorological uncertainty for Hurricane Ian
  - Most tracks biased too northwesterly
  - NHC Cone of uncertainty tighter than variability in ensemble tracks
  - GFS, GEFS and HRRR all have low wind speeds
  - Tracks towards Ft. Myers only about 1 day before landfall



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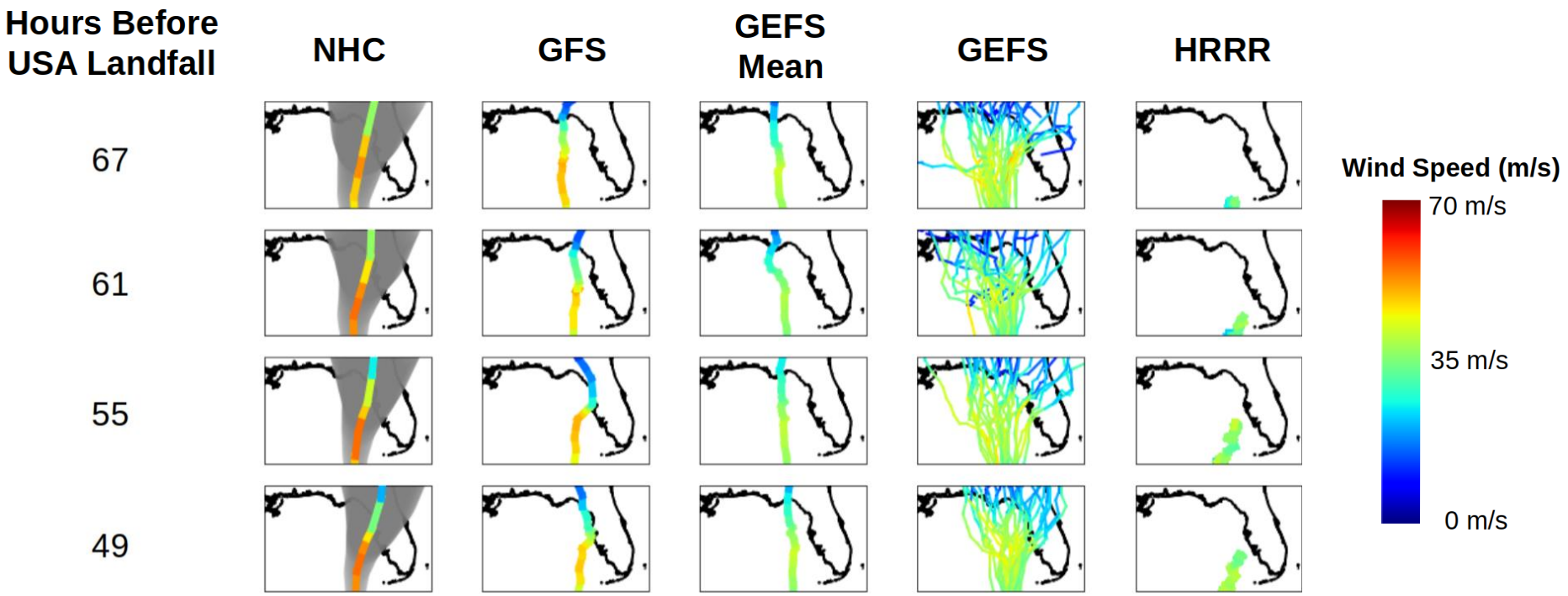

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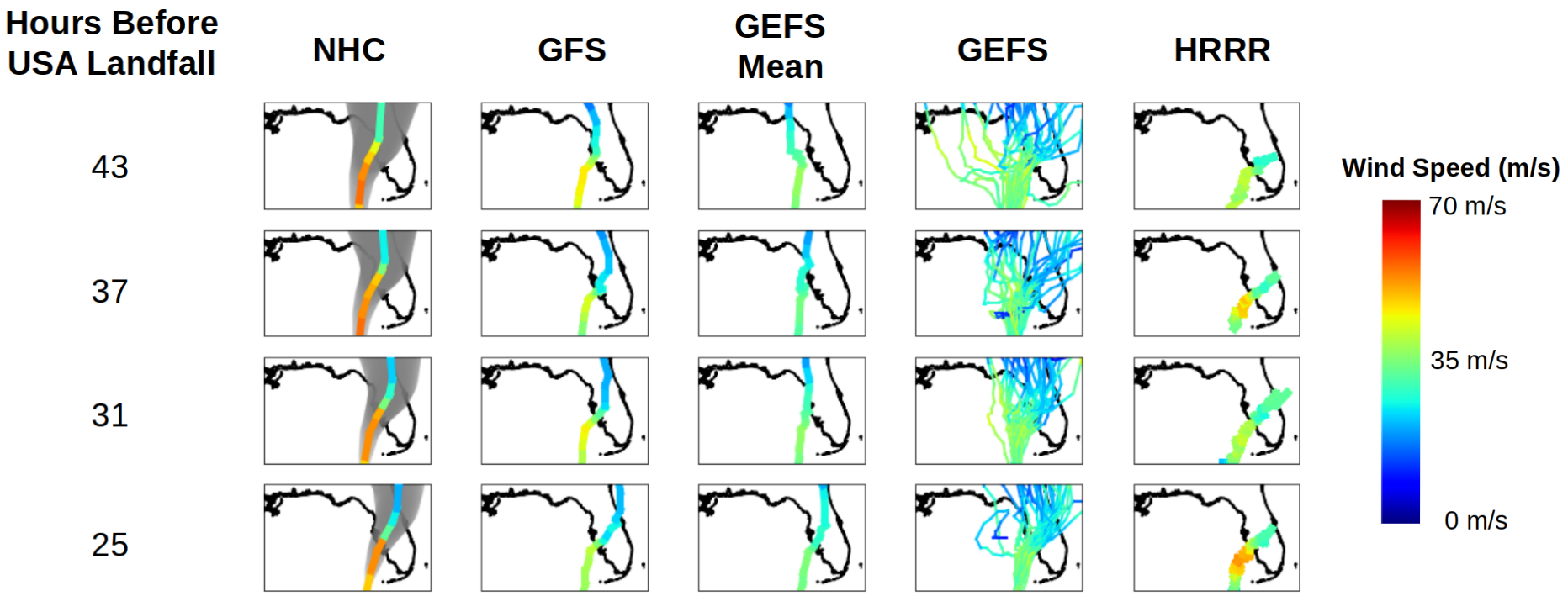

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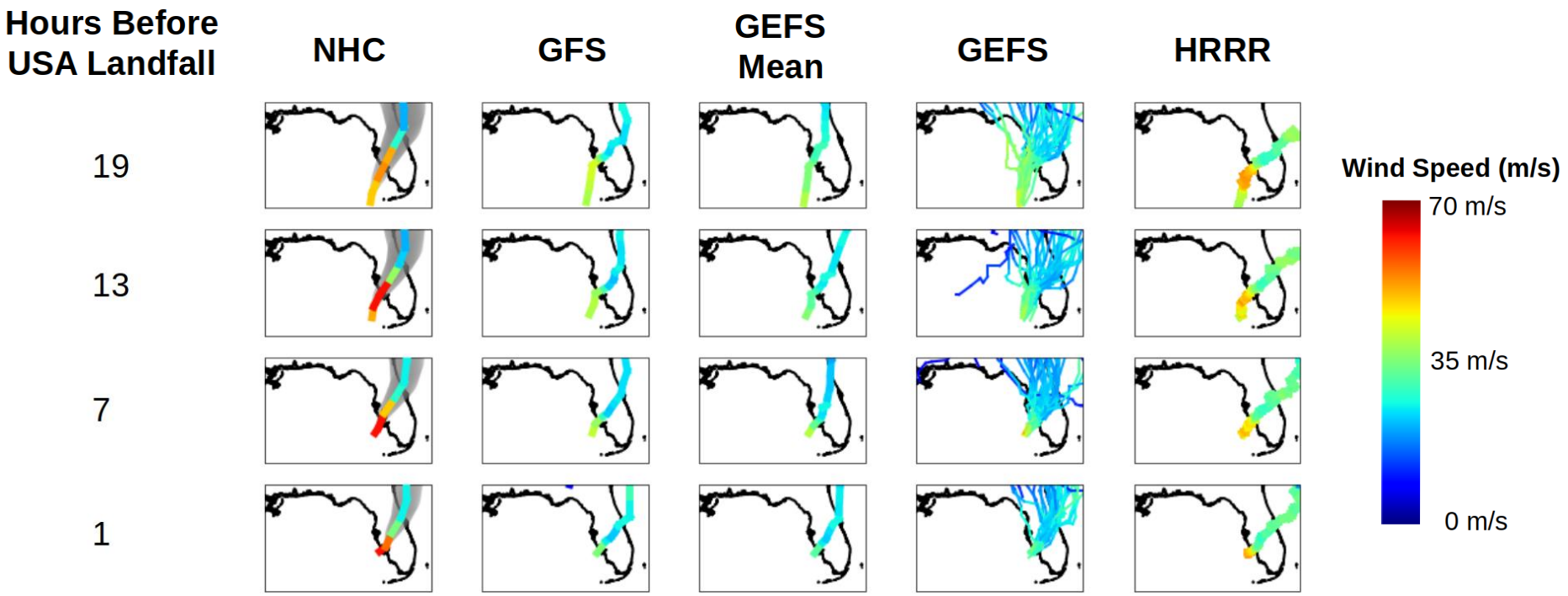

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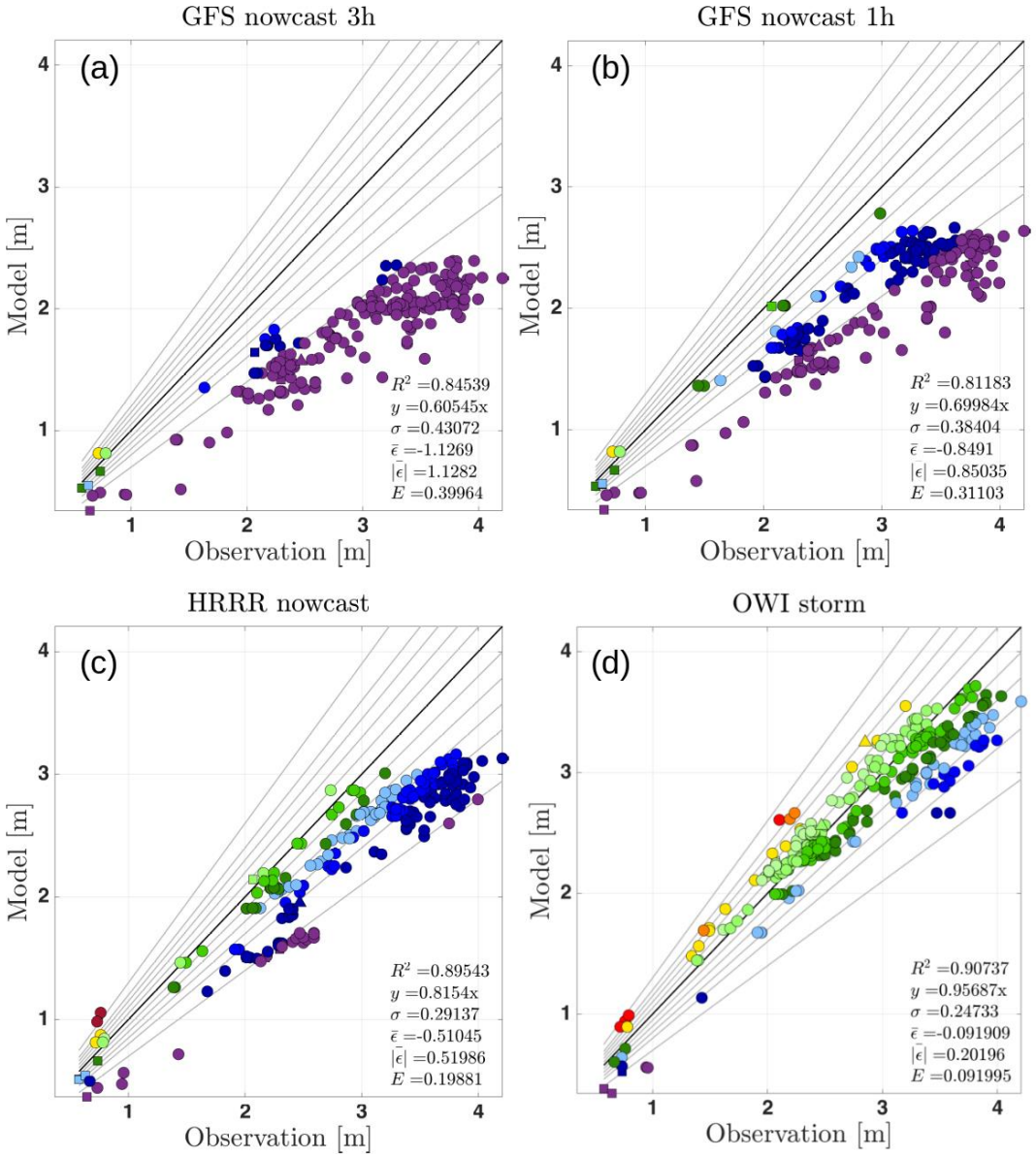
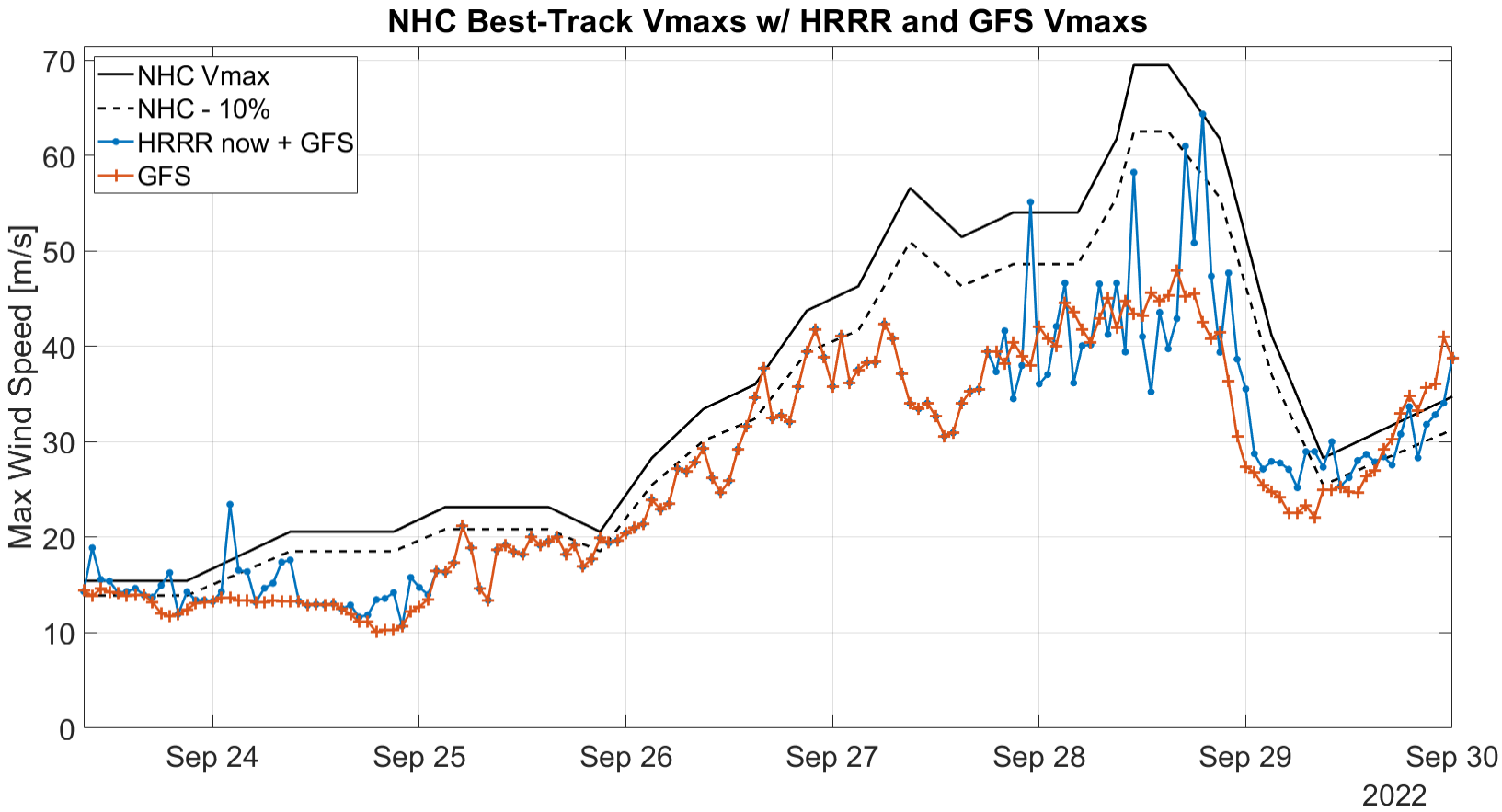
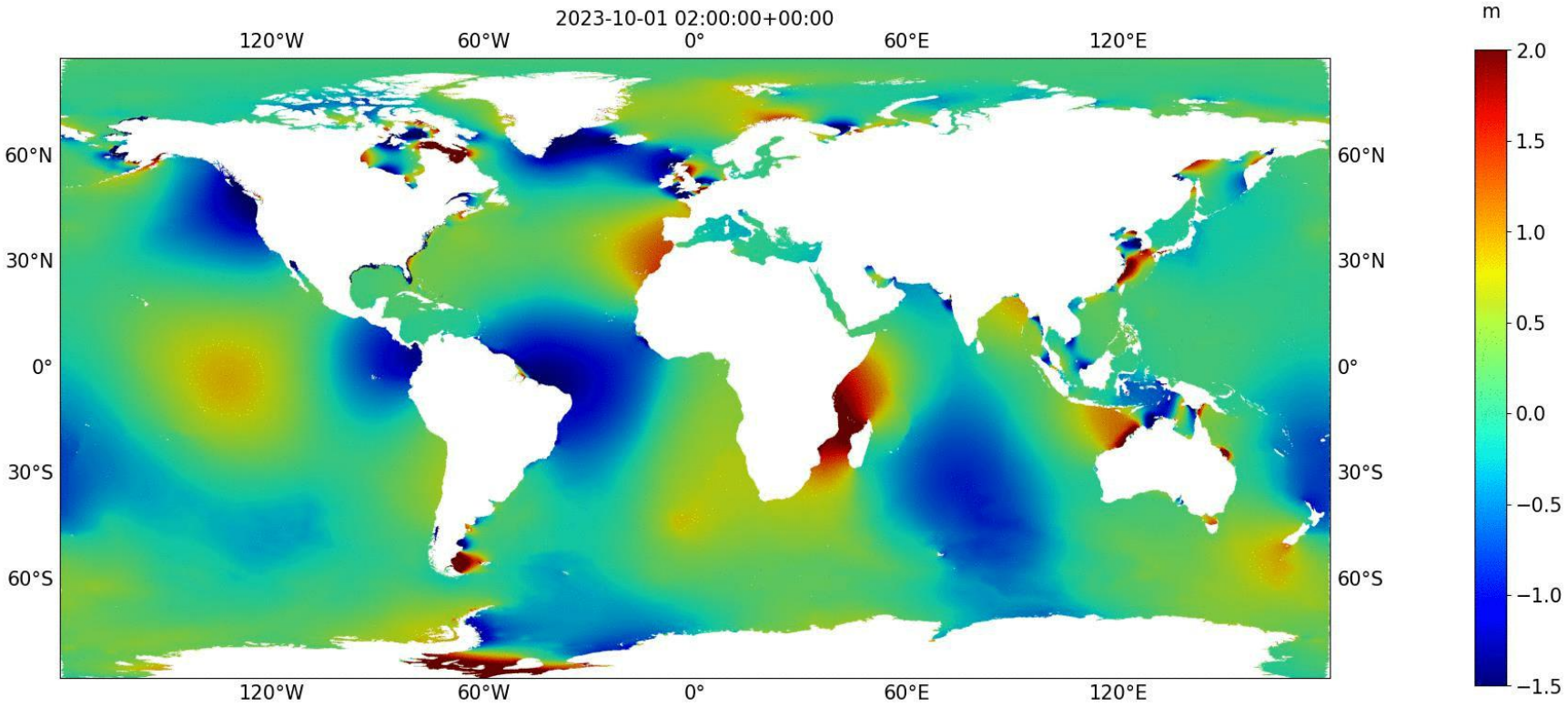


- **GFS and HRRR hindcast (reanalysis) products still underestimate surge levels.**
  - **Winds are too low.**

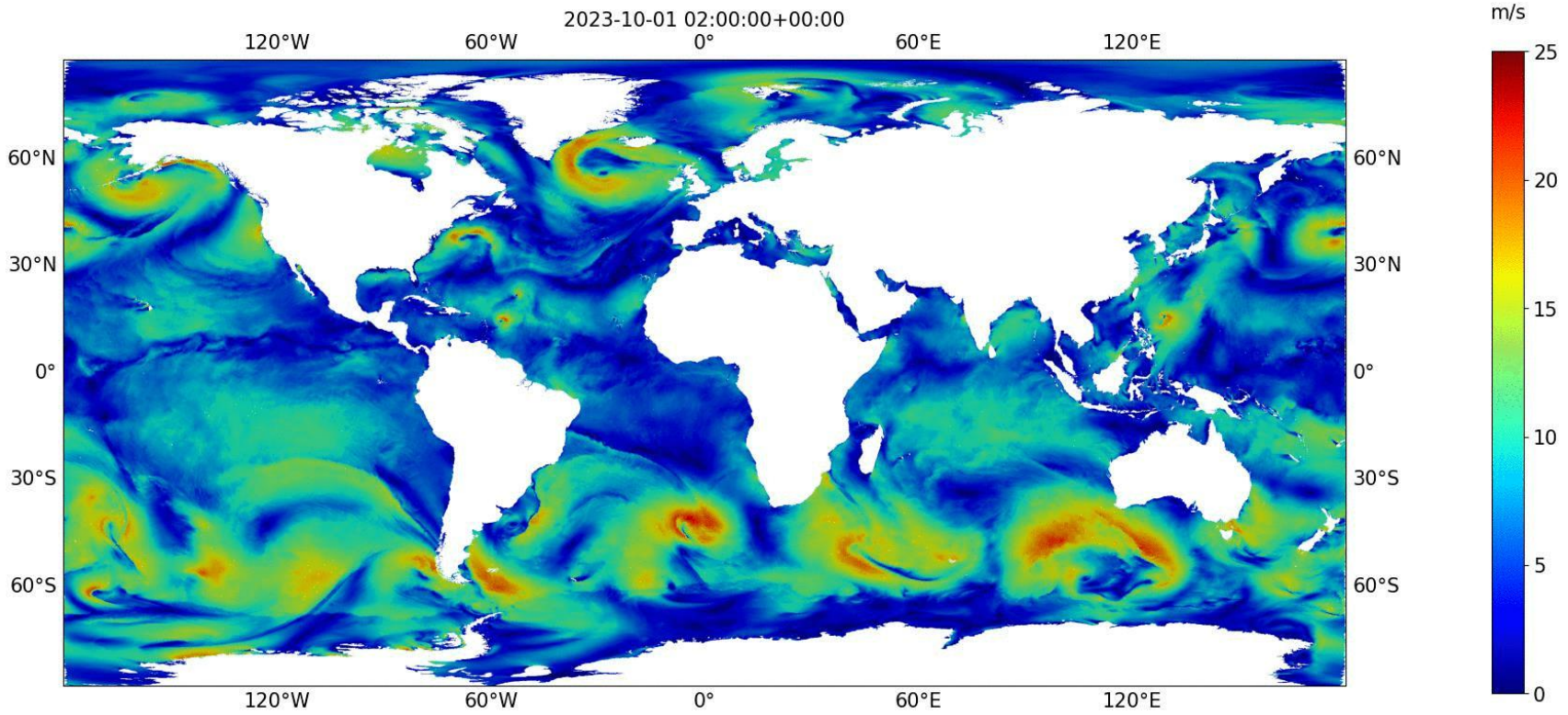
- **NHC Best Track and Forecast advisories approximate intensity well.**
  - **Use this to enrich underestimated met. forcing.**



- **Both GFS and HRRR reanalysis products have low Vmax's.**
  - **Forecast products have even lower Vmax's (shown previously).**



- **Global Surge and Tide Operational Forecast System (G-STOFS)**
  - **Uses ADCIRC model with GFS meteorological forcing.**
    - **Forecasts out to 7 days**
  - **Includes various other forcings**
    - **Tidal potential constituents, Garratt wind drag, self-attraction and loading tidal constituents, sea ice drag, bottom friction, internal tide wave drag**



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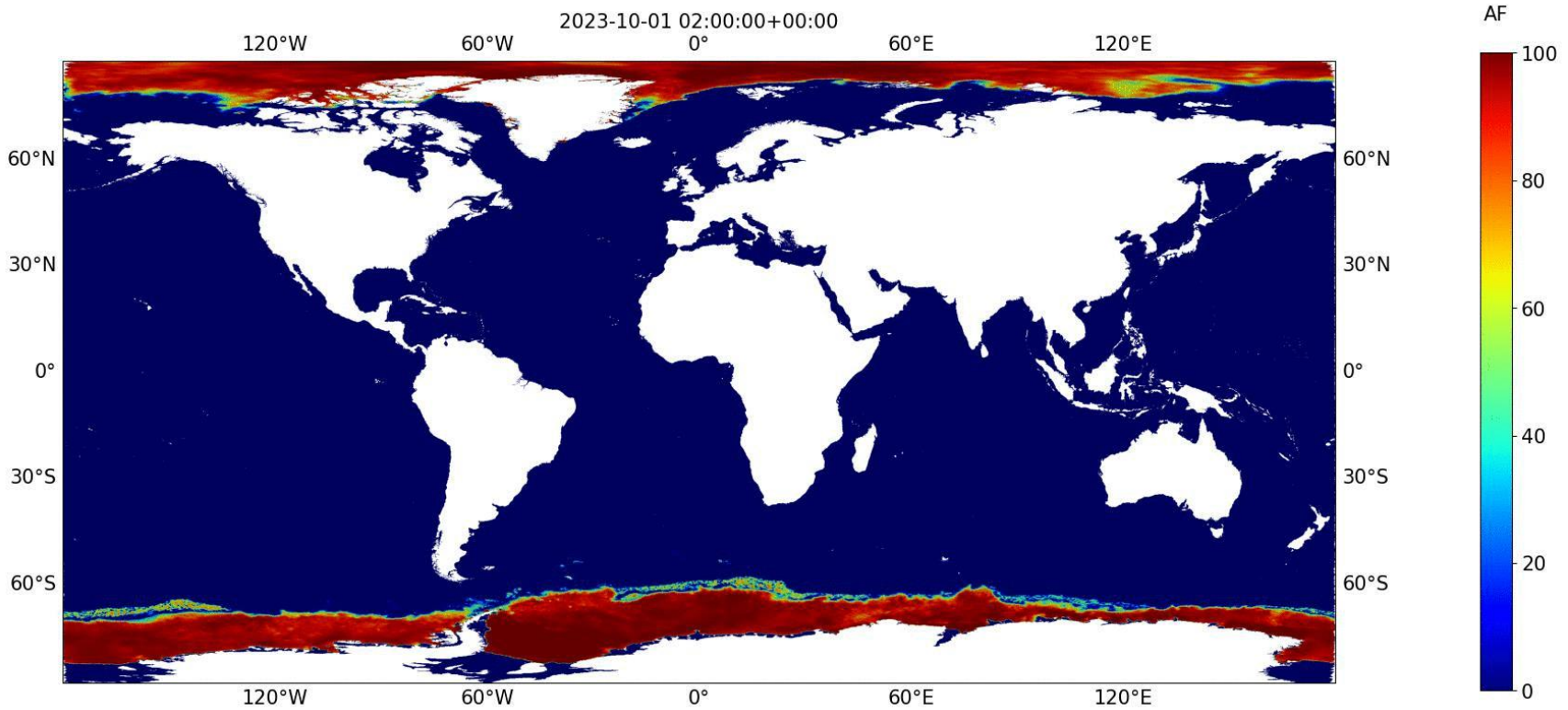

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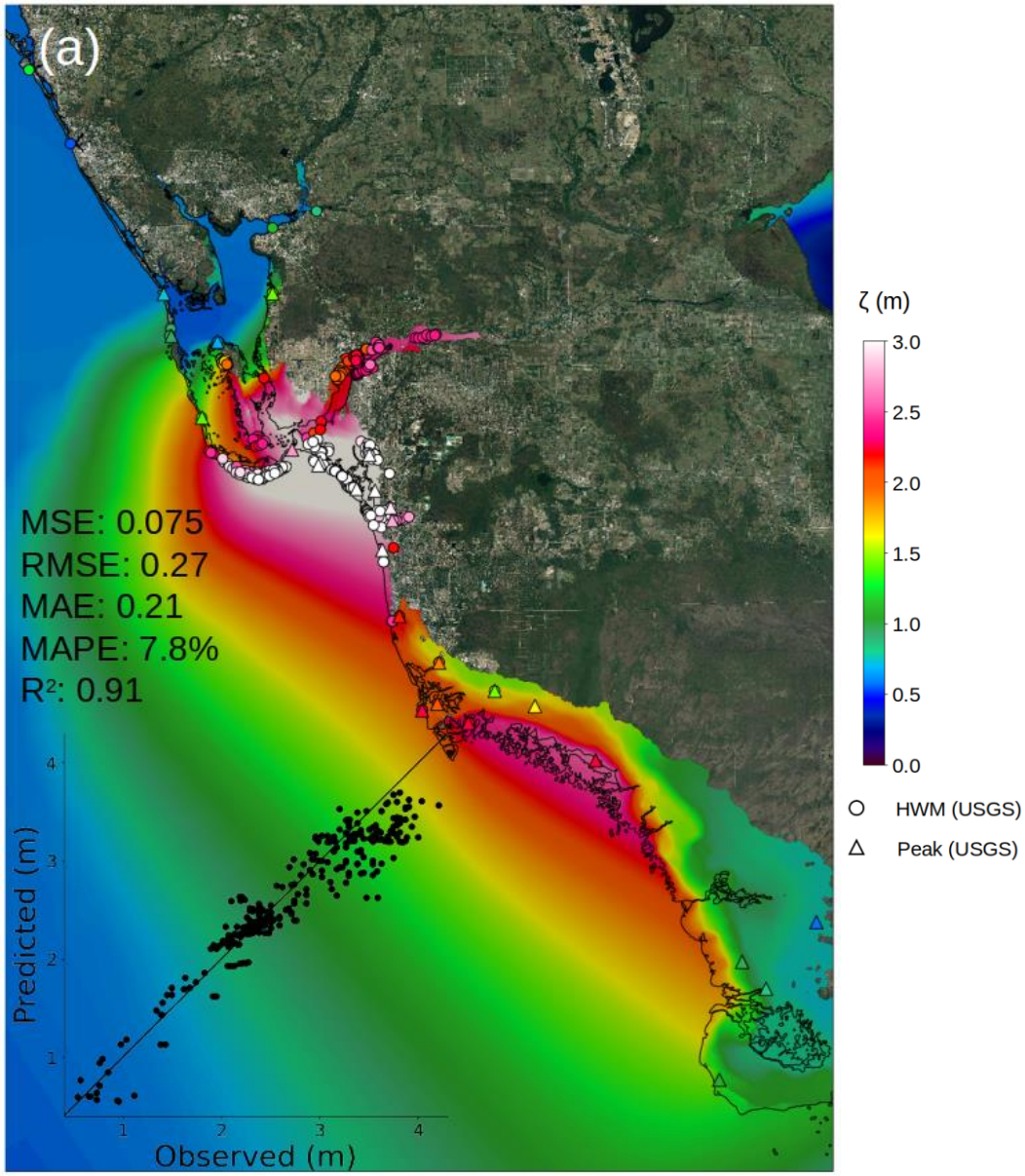
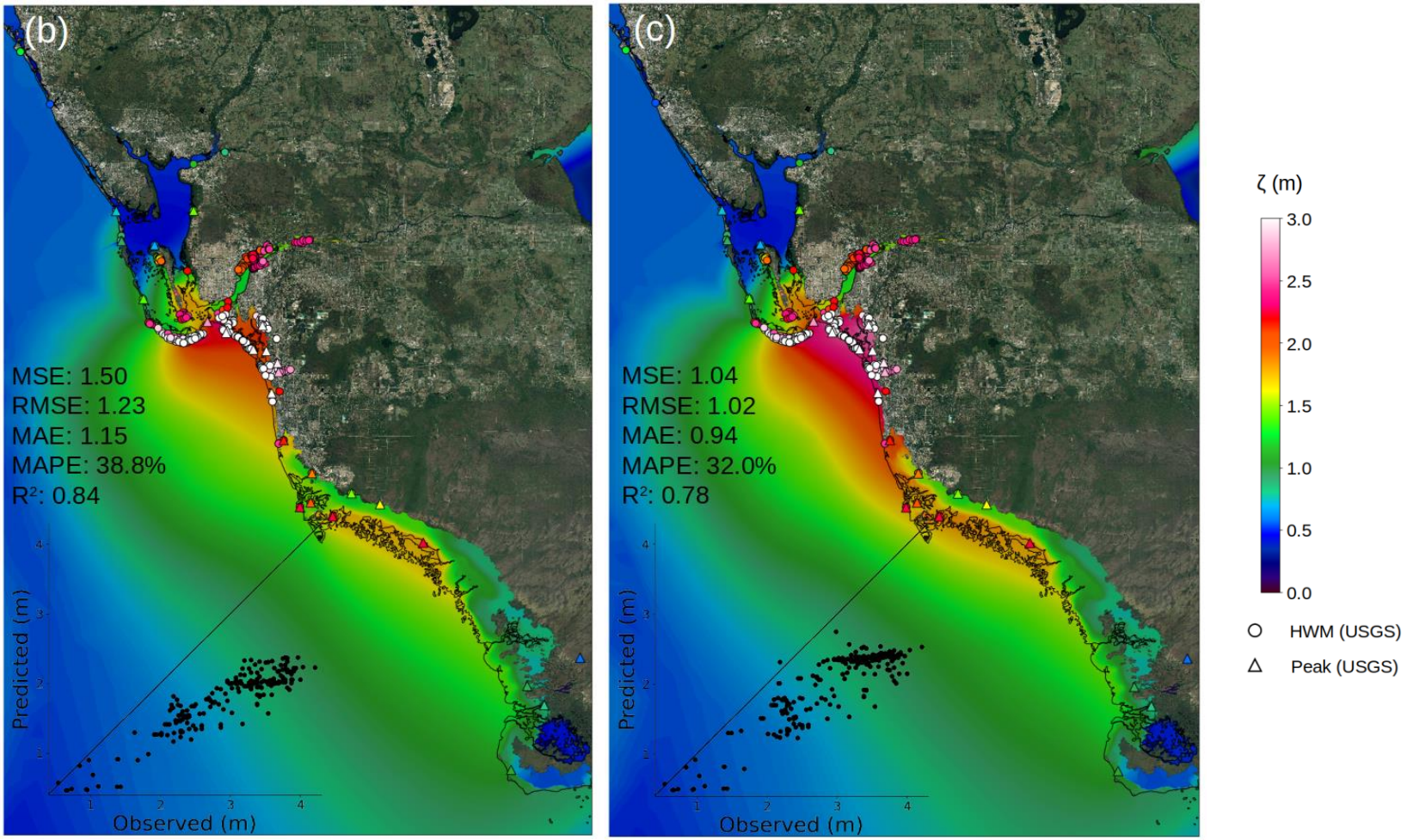


- **Surge levels from OWI accurate**
  - **These are "best" winds available.**
  - **→ Rules out deficiency due to met. forcing.**
  - **NO apparent bias and NO muted surge levels.**
  - **→ NO significant model discrepancy for Ian.**
  - **→ Meteorology only significant source of epistemic uncertainty, *i.e.*, poor met. → poor G-STOFS skill**

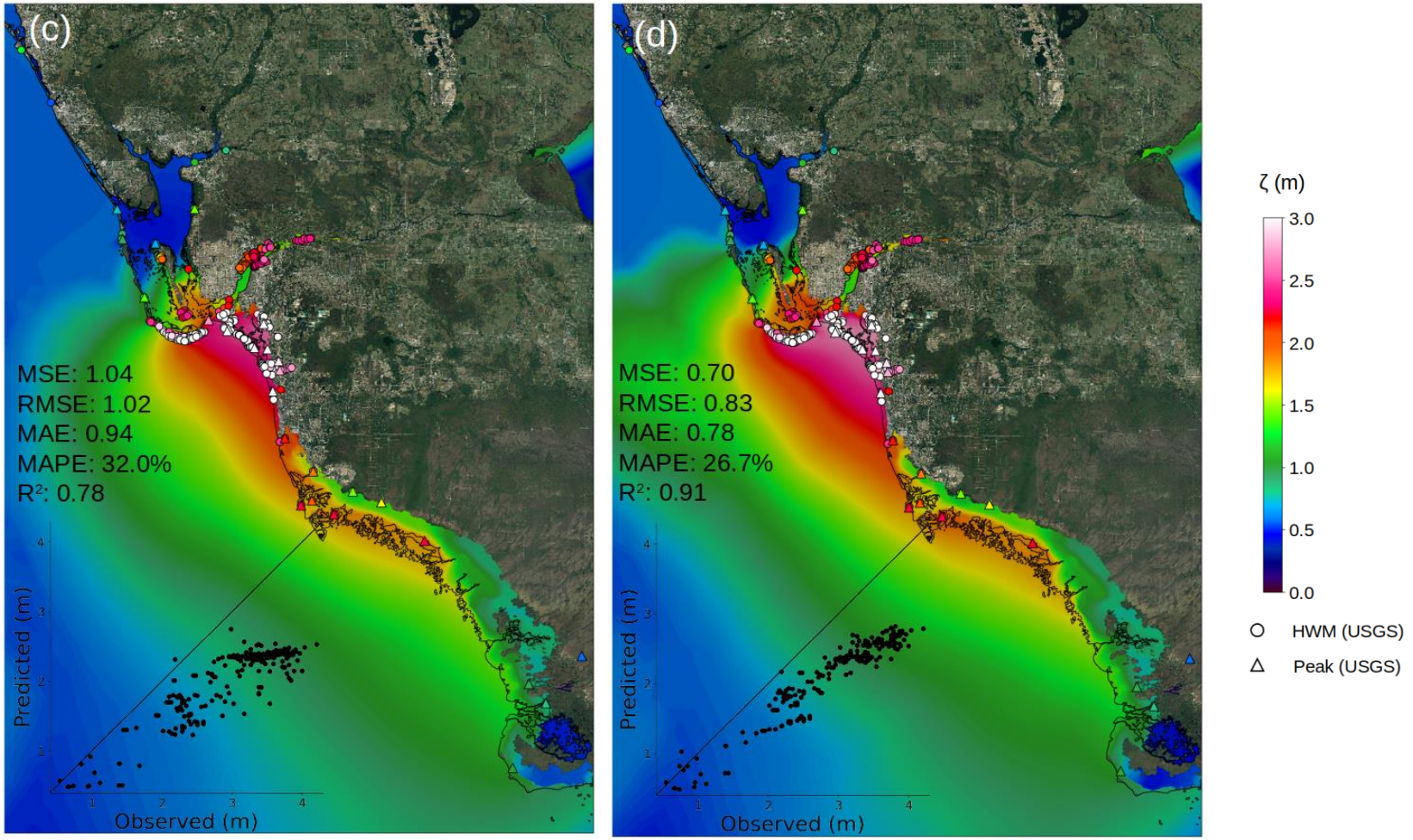
- **Interrogate a variety of wind products:**

Product	Deterministic?	Δx	Δt	Fcast Extent
GFS	Y	13km	1 hr	16 days
GEFS	N	25km	3 hr	16 days
HRRR	Y	3km	1 hr	2 days
OWI	Y	$.2^{o}$ -- $.02^{o}$	15 min	N/A

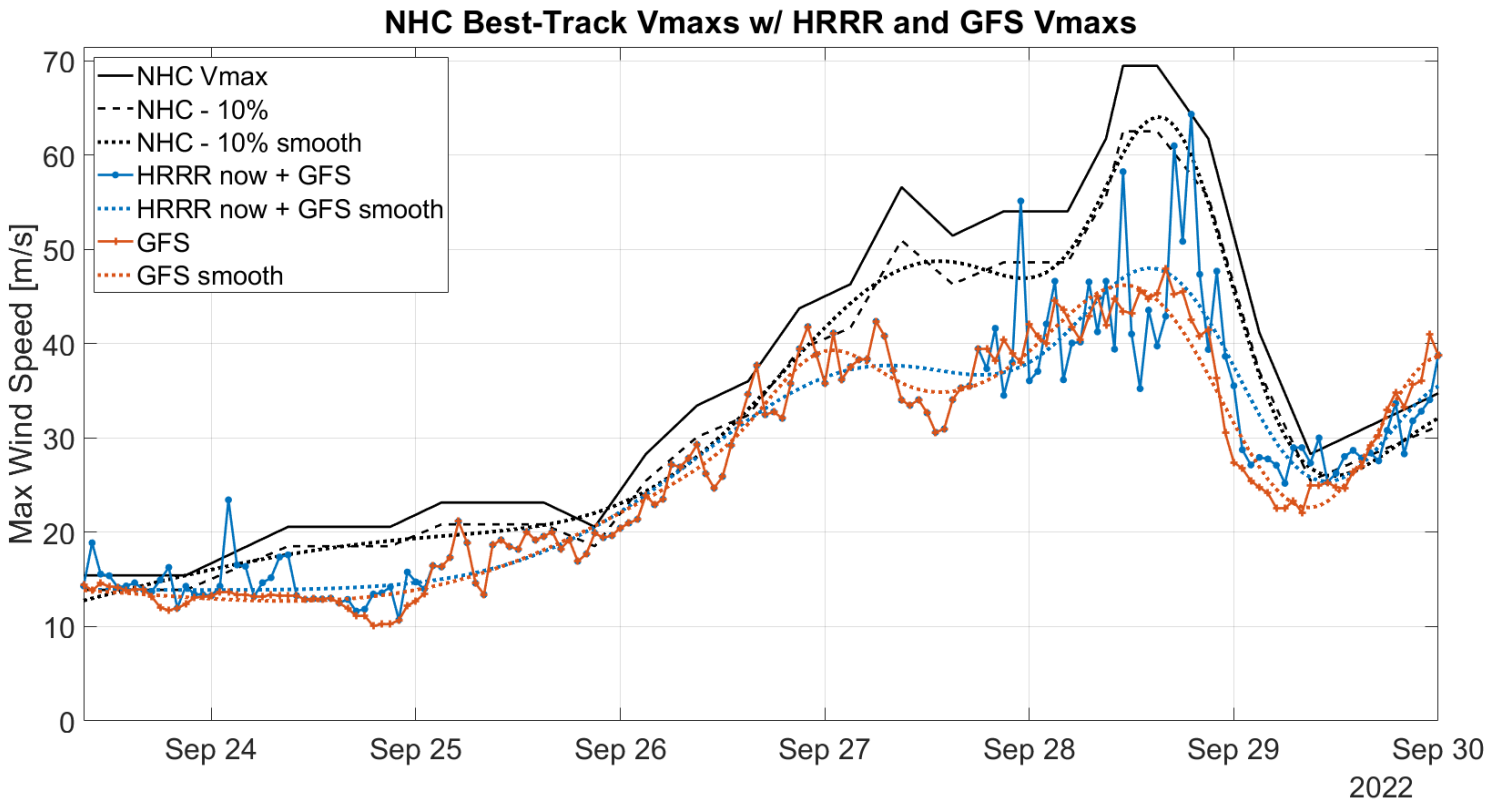
- **What impact, if any, do Δx and Δt have on G-STOFS results?**
  - **May need to compensate for lower resolution if using GEFS for Probabilistic Storm Surge Guidance (PSSG)**



- **Both 3-hr (left) and 1-hr (right) GFS forcings underestimate surge.**
  - **1-hr forcing closer to HWMs and peaks**
  - **1-hr gives about +30% surge and better error stats.**

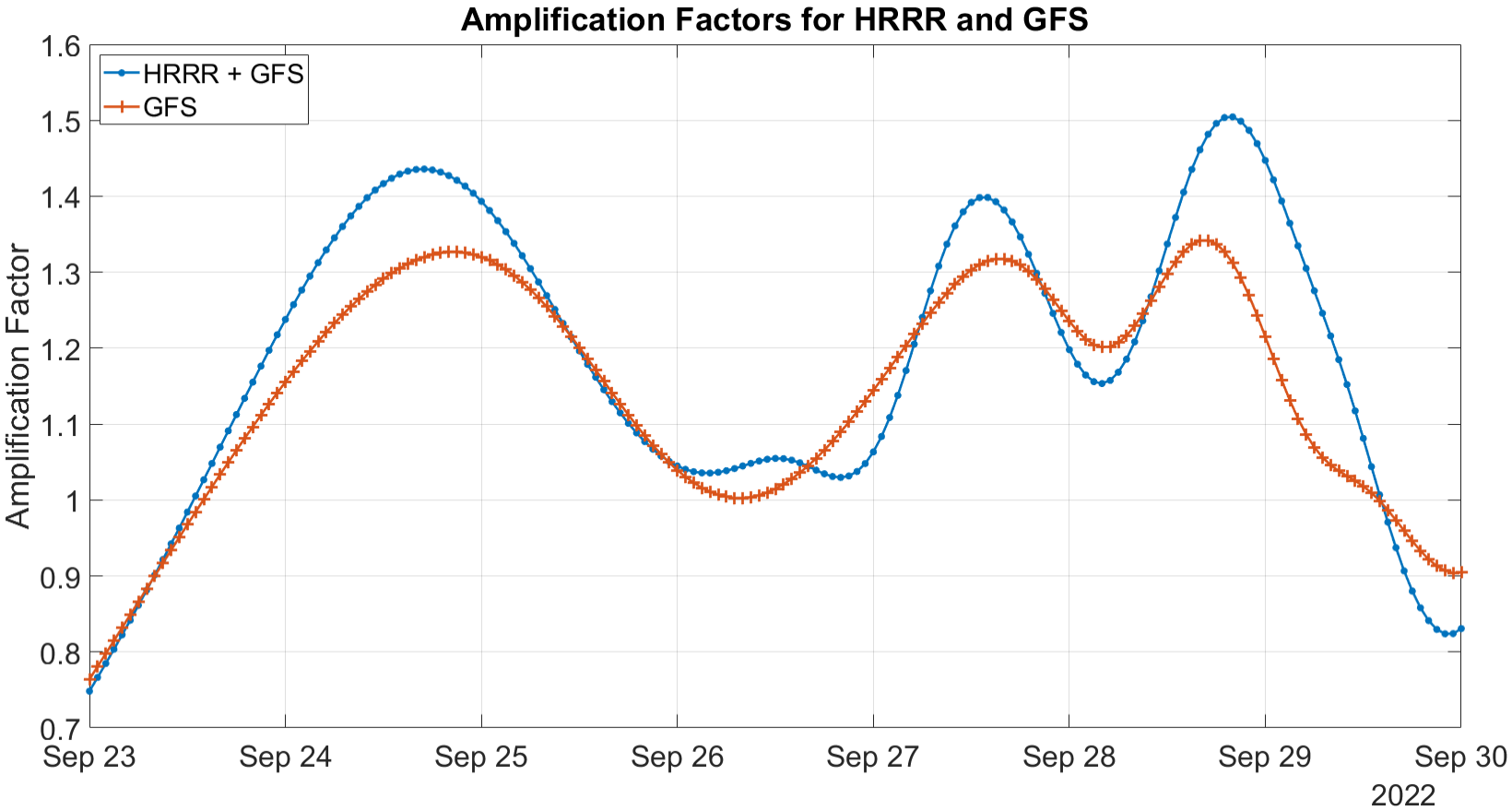


- **GFS (13 km, on left) provides lower surge levels than HRRR (3km, on right).**
  - **Higher grid resolution increases flood levels by up to 20%.**
  - **Surge levels are still too low, especially along Caloosahatchee River.**
    - **Motivates assimilation strategy informed by NHC best track/advisories.**

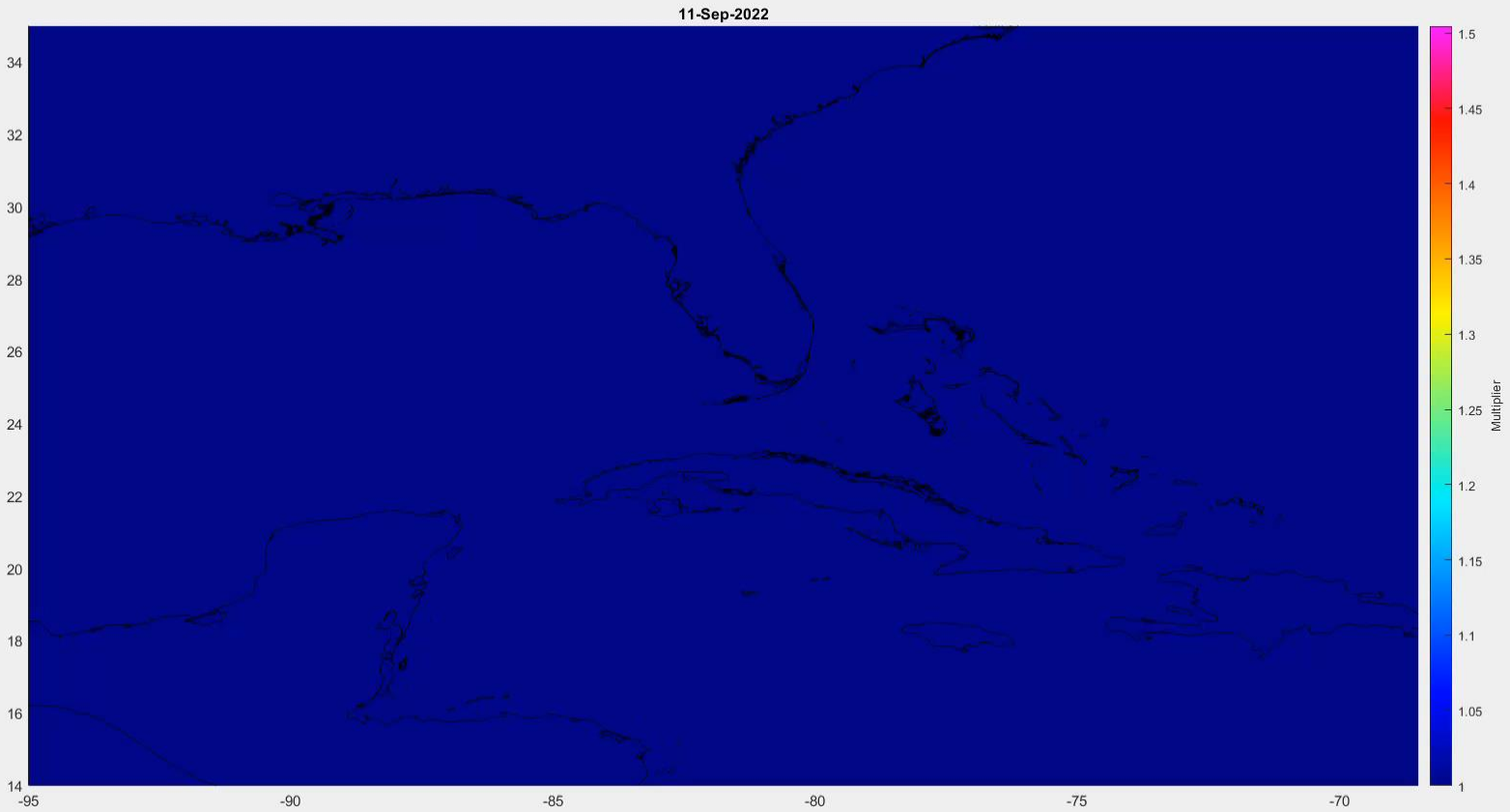


- **Use NHC Vmax's to inform wind amplification for other products.**

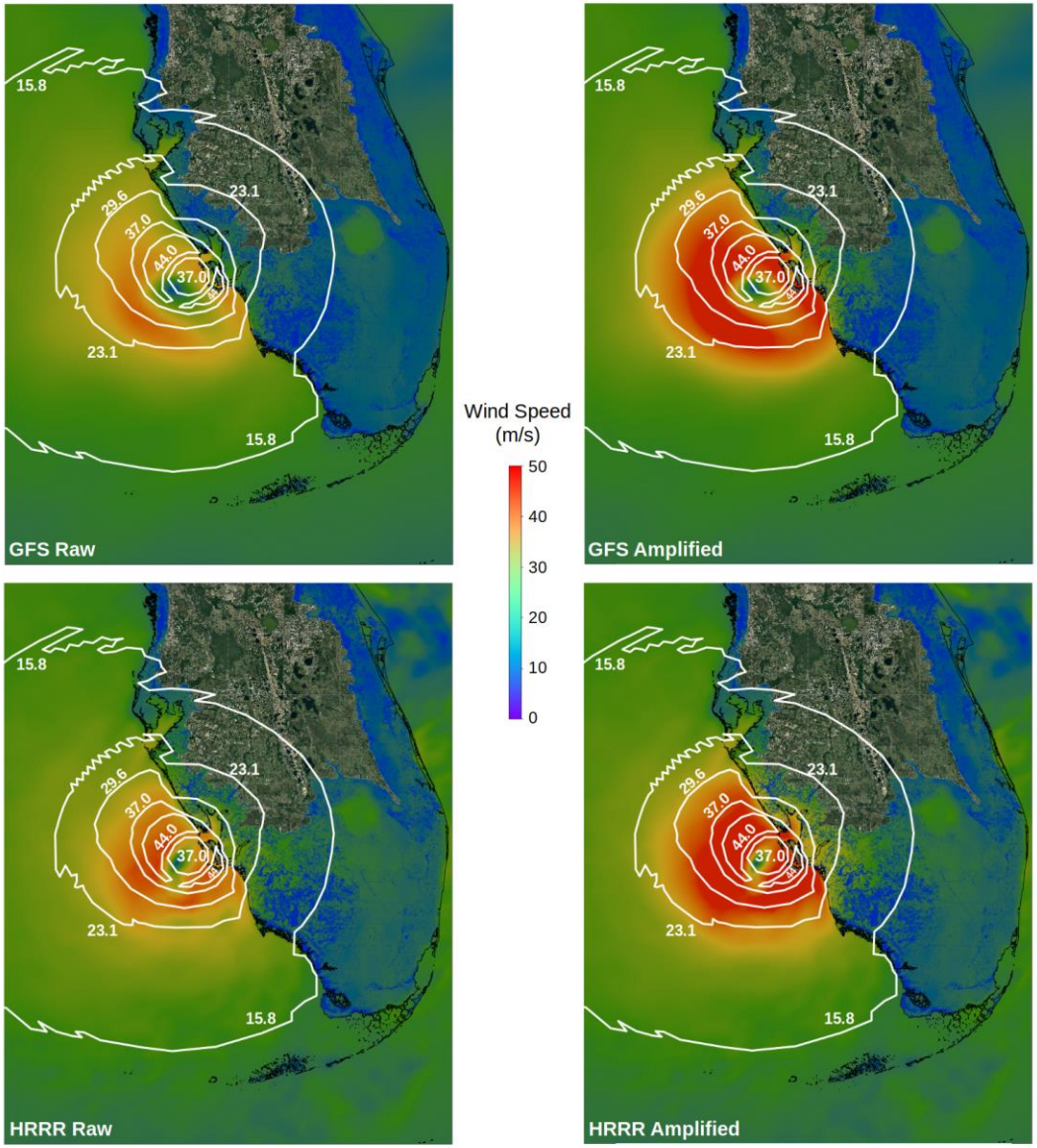
1. **Reduce NHC Vmax by 10% to approximately convert 2-min winds to 10-min.**
2. **Smooth NHC reduced Vmax curve by fitting a series of Gaussian curves.**
3. **Find time-series of Vmax's from dynamical wind product.**
4. **Smooth dynamic wind product's Vmax's in the same way as in step 2.**
5. **Divide smoothed NHC Vmax curve by smoothed wind product Vmax curve.**



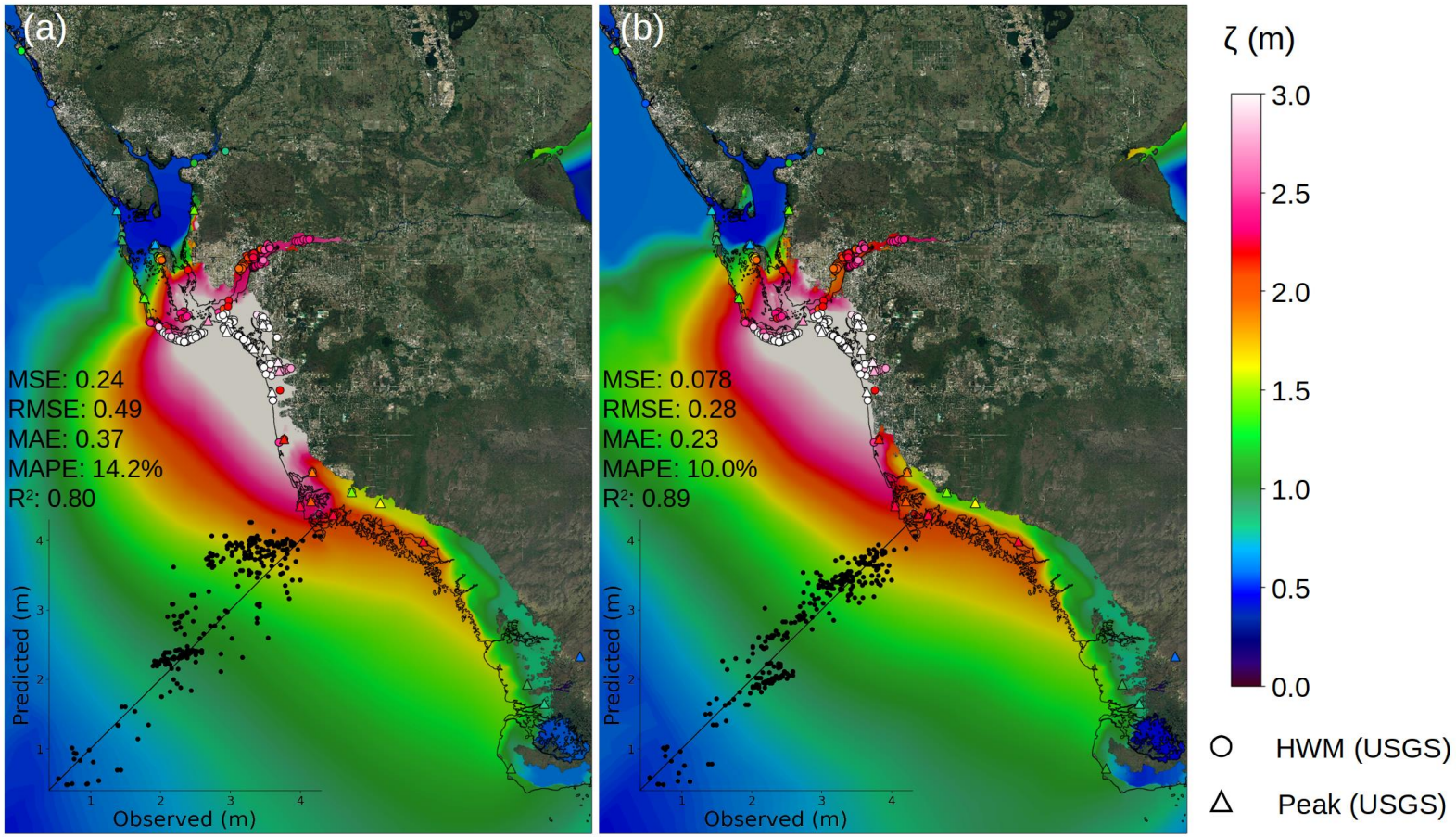
- **Provides amplification factor as a function of time.**
  - **Only apply factors > 1.**



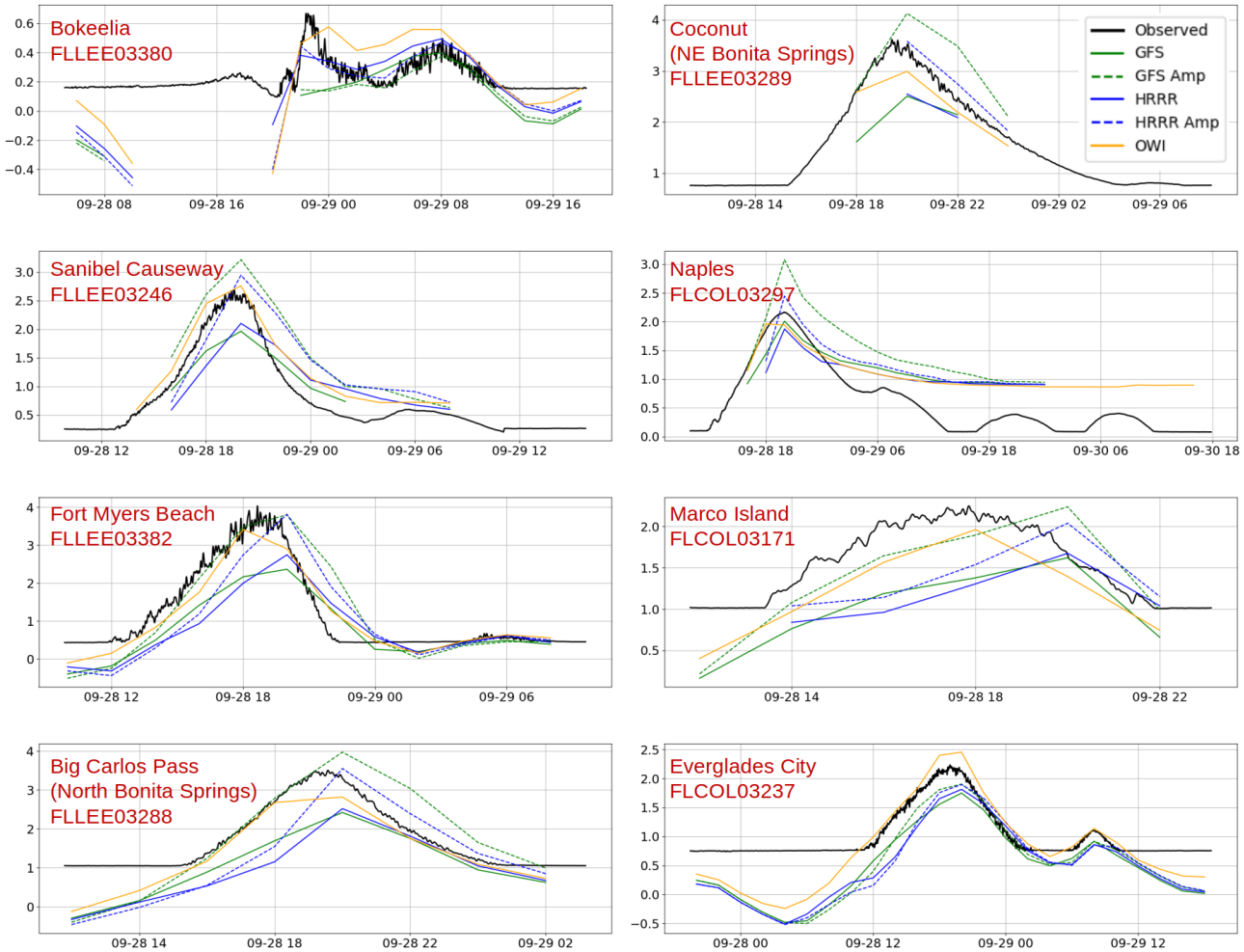
6. Amplify winds within 64-kt radius (averaged over all quadrants) by full factor.
7. Scale down amplification factor to 1 at boundary of 50-kt radius (averaged).



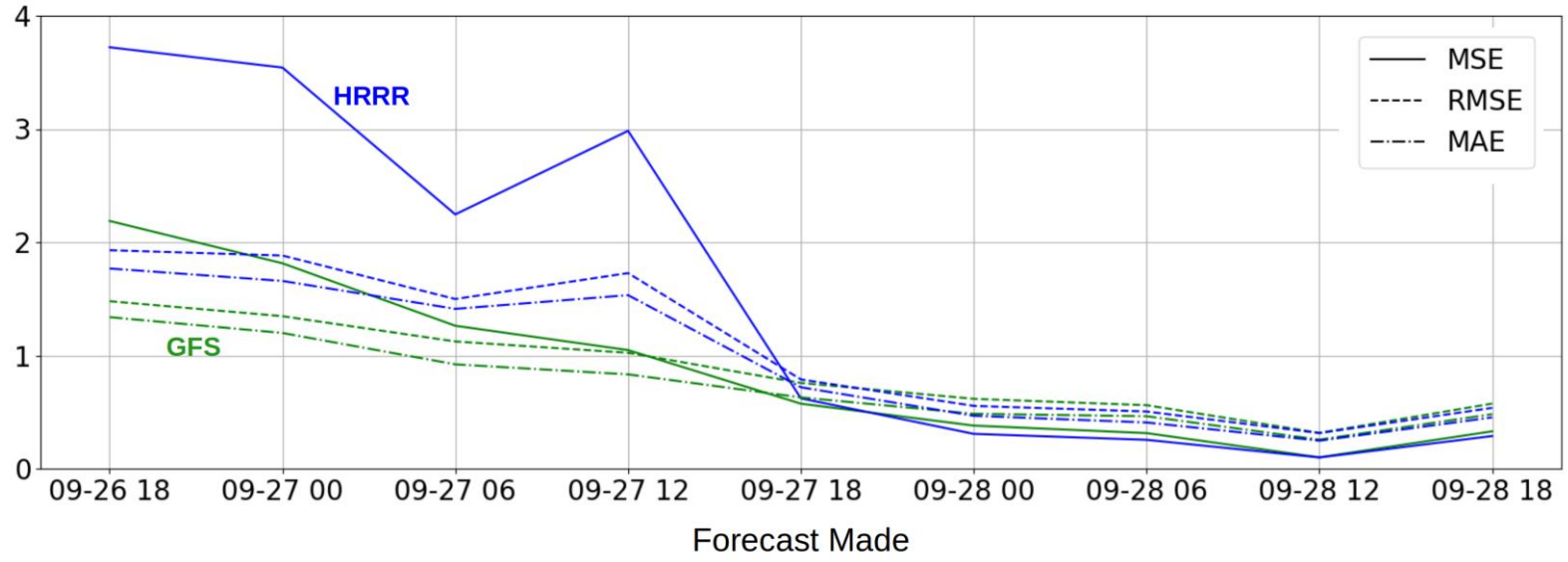
- Amplified winds provide better agreement w/ measured data.
  - Compare with Aircraft-Based Tropical Cyclone Surface Wind Analysis (ABTCSWA)
    - -- assimilates aircraft recon. w/ satellite data
  - Winds greater than 40 m/s especially better represented.



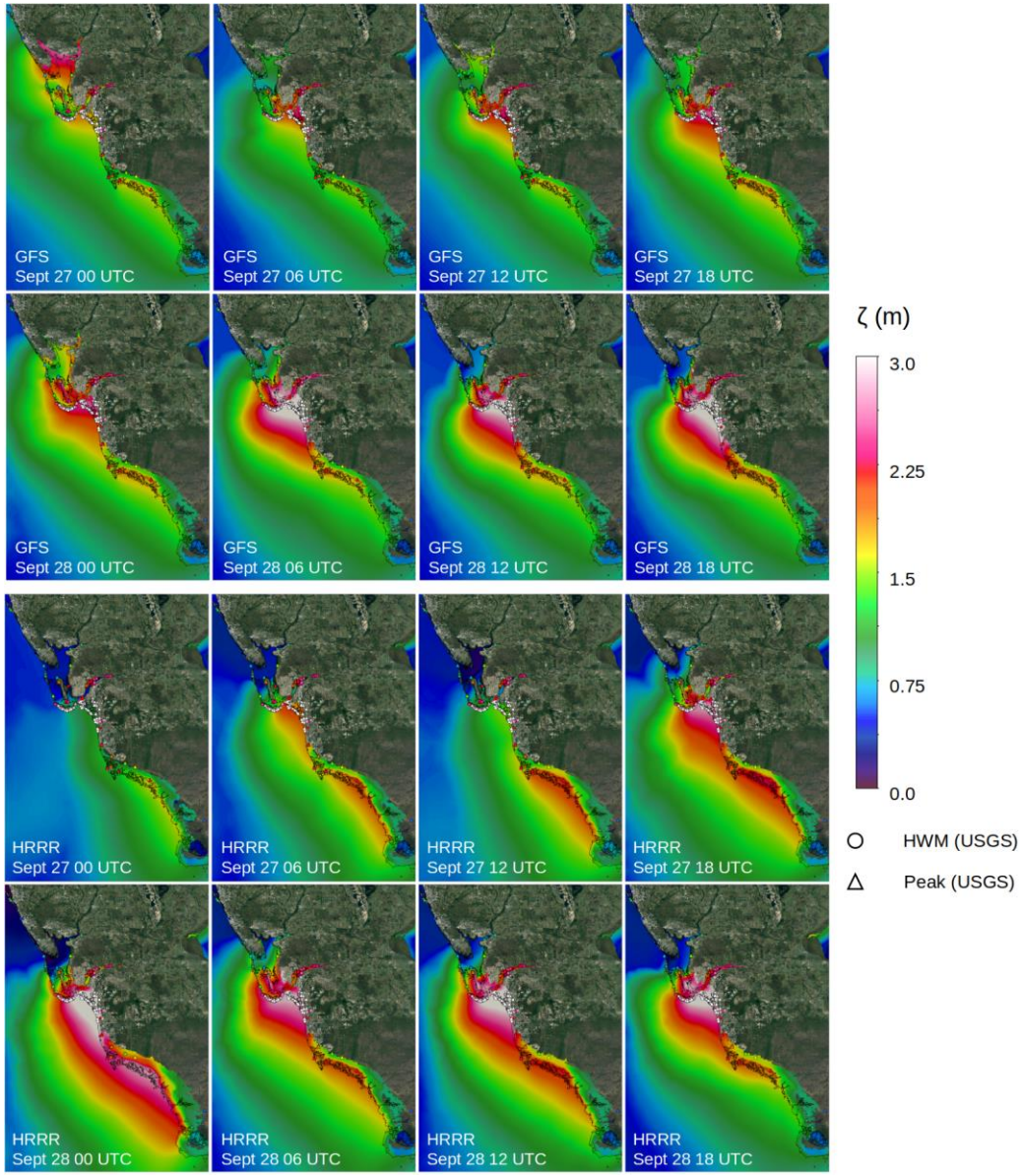
- **Amplified HRRR (right) has better error statistics than amplified GFS (left).**
  - **Both products still capture the relevant max. surge levels.**



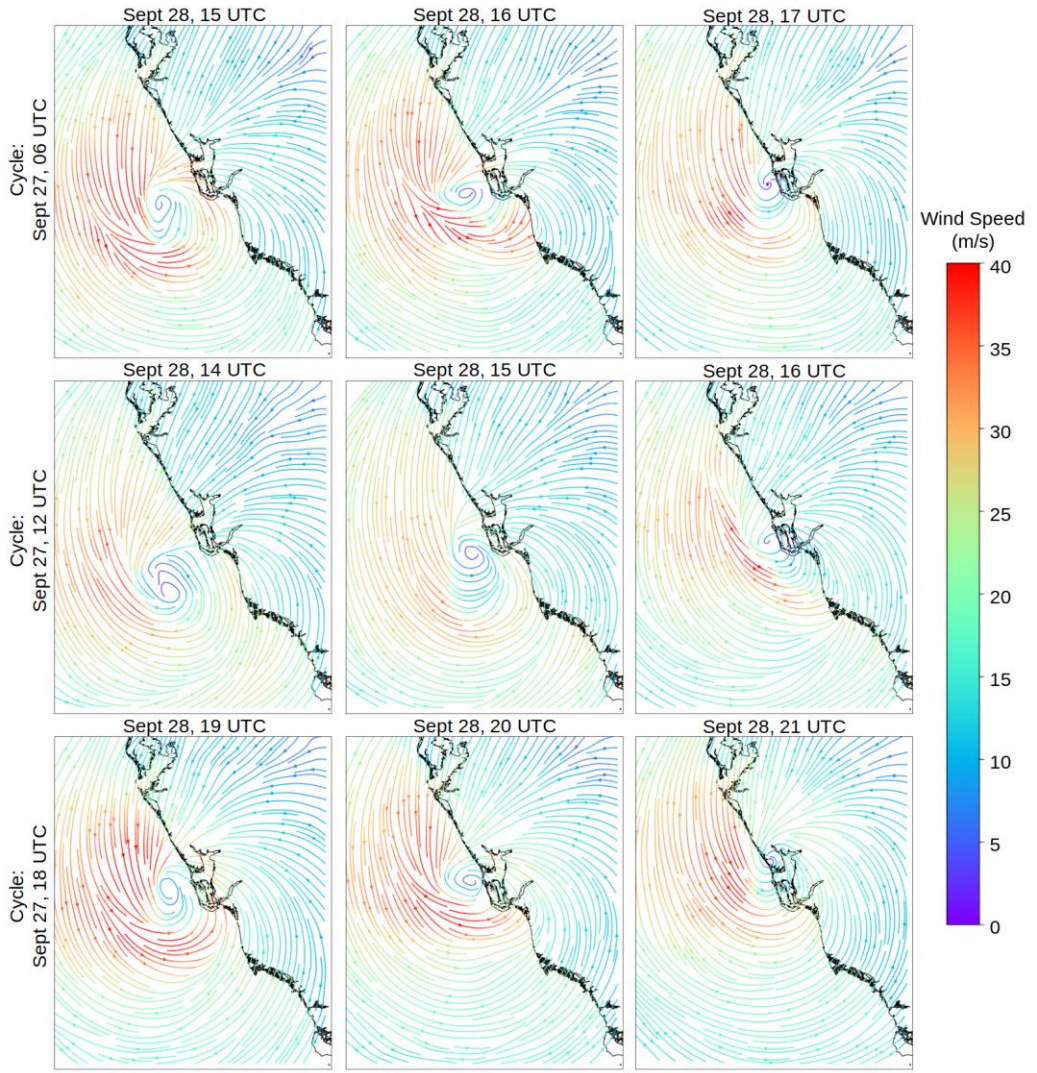
- **Hydrographs show amplified winds match (or exceed) the peak but are "lagged".**
  - **Also, much slower drawdown compared to OWI in some places.**
  - **Likely due to errors in track.**



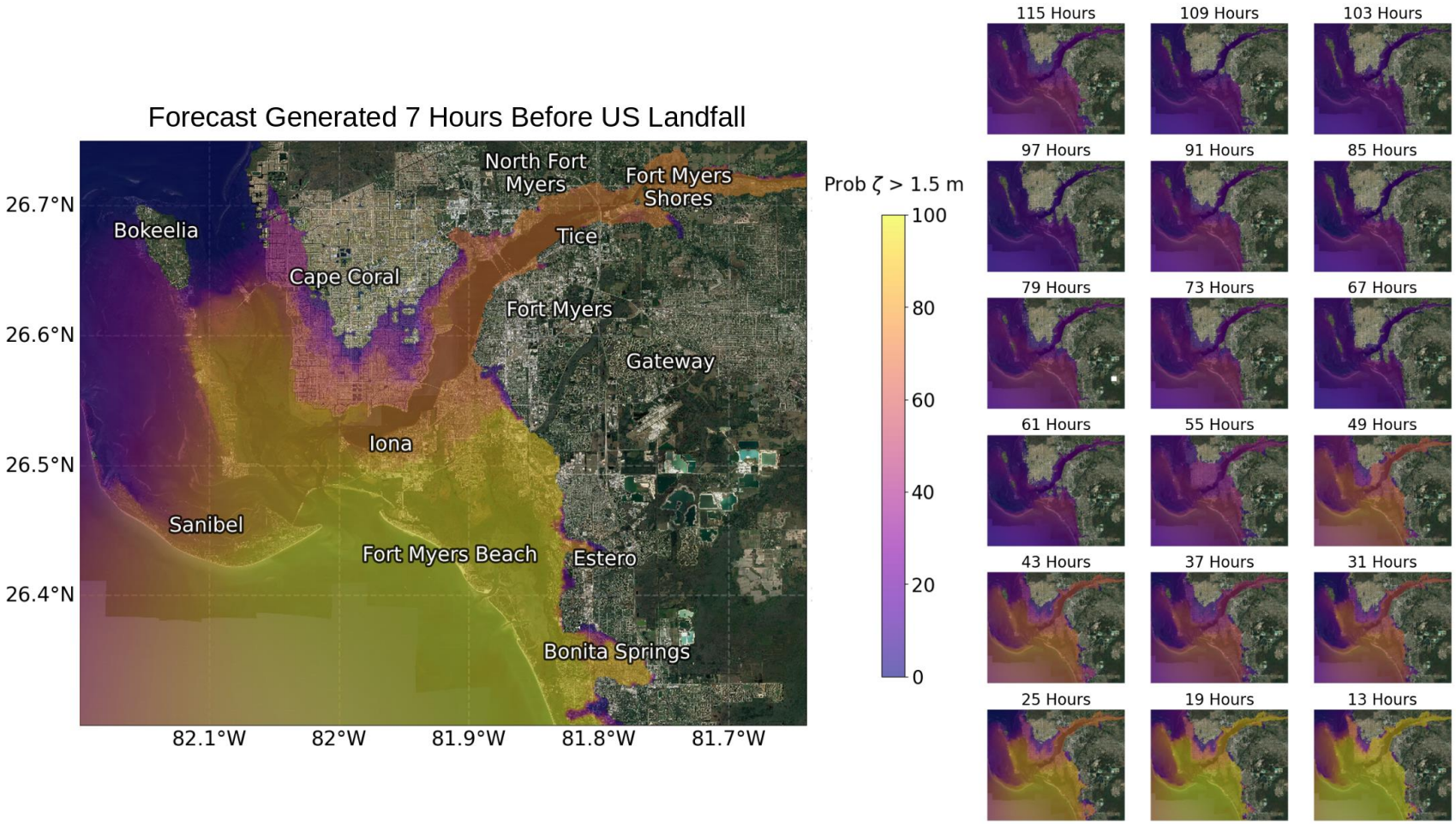
- Analogous strategy can be adopted for forecasts.
- Use Vmax's and wind radii from most recent NHC advisory.
  - Both GFS and HRRR skillful ~24 hours prior to landfall (9/28 19:00)
  - Both give elevated water levels before then, but too low.



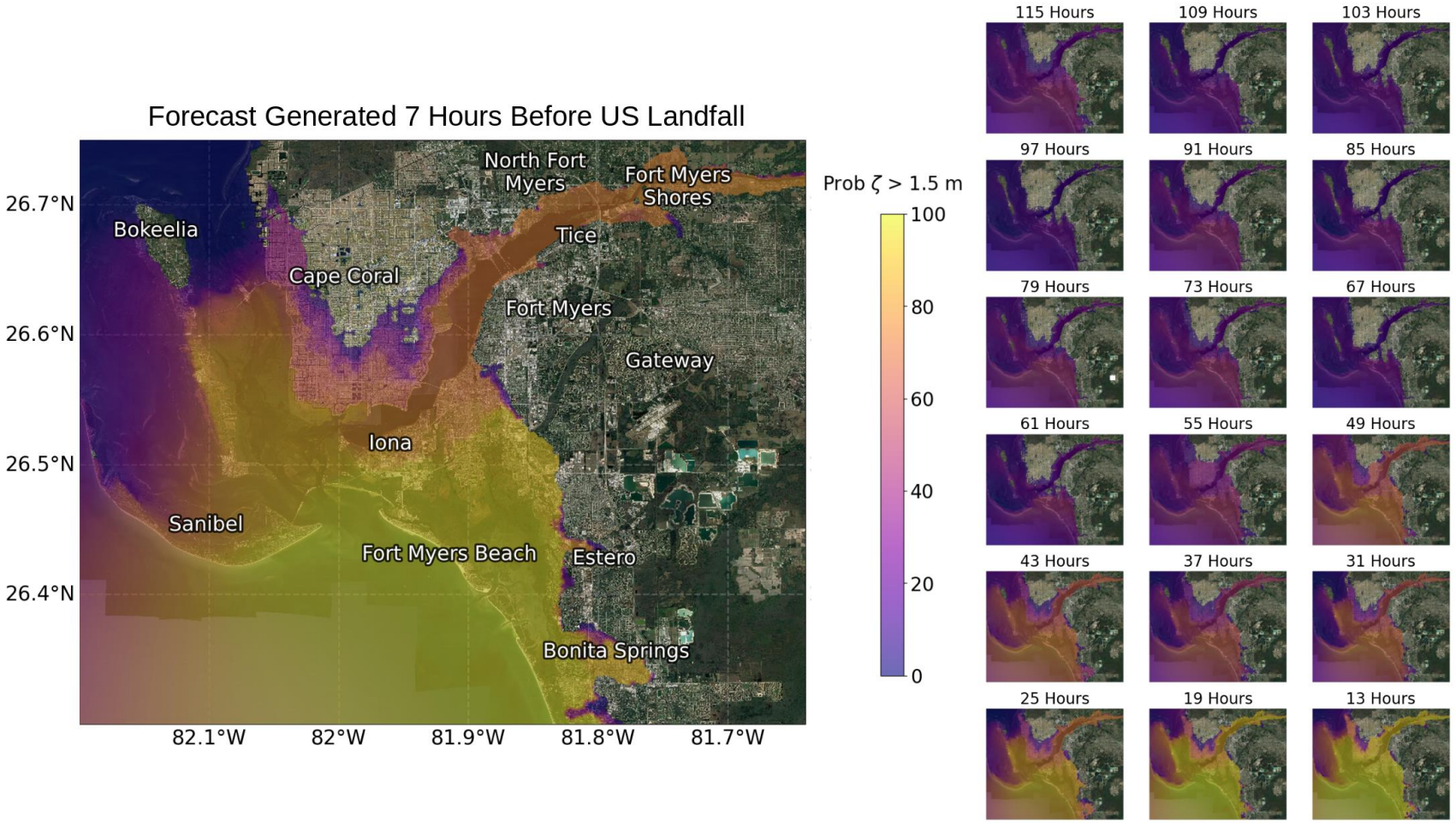
- **Lower surge levels for >24-hours before landfall attributed to poor tracking.**
- **HRRR Sep 27, 12:00 fcast. shows lower surge in Ft. Myers than fcasts. on Sep 27 06:00 or Sep 27 18:00.**
  - **Model is very sensitive to met. forcing here.**
  - **HRRR winds more volatile.**



- High volatility w/ model sensitivity motivates using ensemble fcasting.
  - Sep 27 06:00 and Sep 27 18:00 fcasts. show high winds at Ft. Myers beach near land fall time.
  - Sep 27 12:00 fcast. has much lower winds here.
- Using GEFS accounts for volatility, and amplification accounts for low winds.

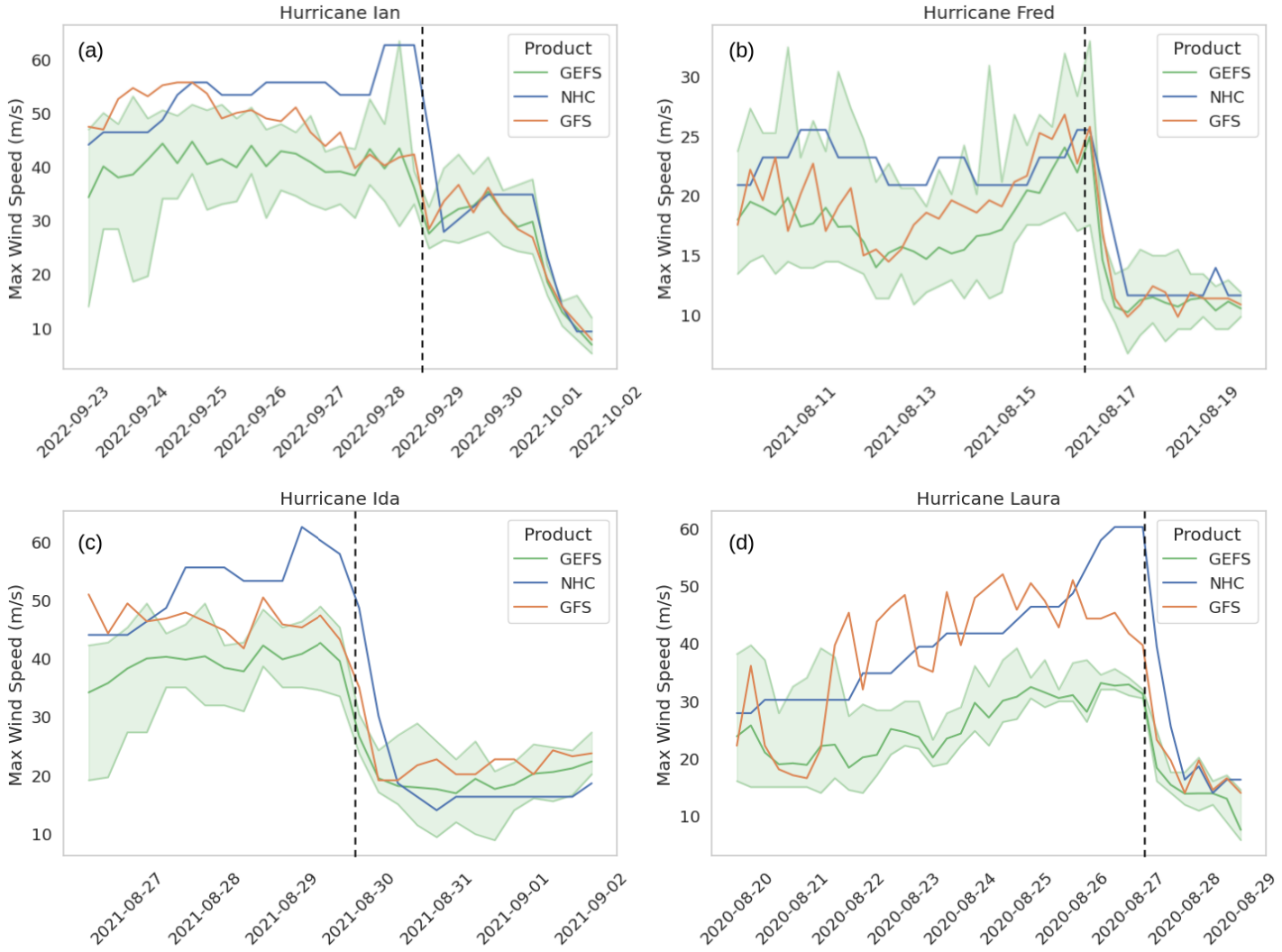


- **Exceedance probabilities from amplified GEFS show surge risk > 2 days out.**
  - **KDE of PDF for max. water level – 31 ensemble members weighted equally.**
  - **At least a handful of members track near Ft. Myers.**
  - **Exceedance prob. ~70% for coastal communities, 48 – 24 hours out.**
    - **-- Becomes 100% at 19 hours out and >75% along Caloosahatchee River.**



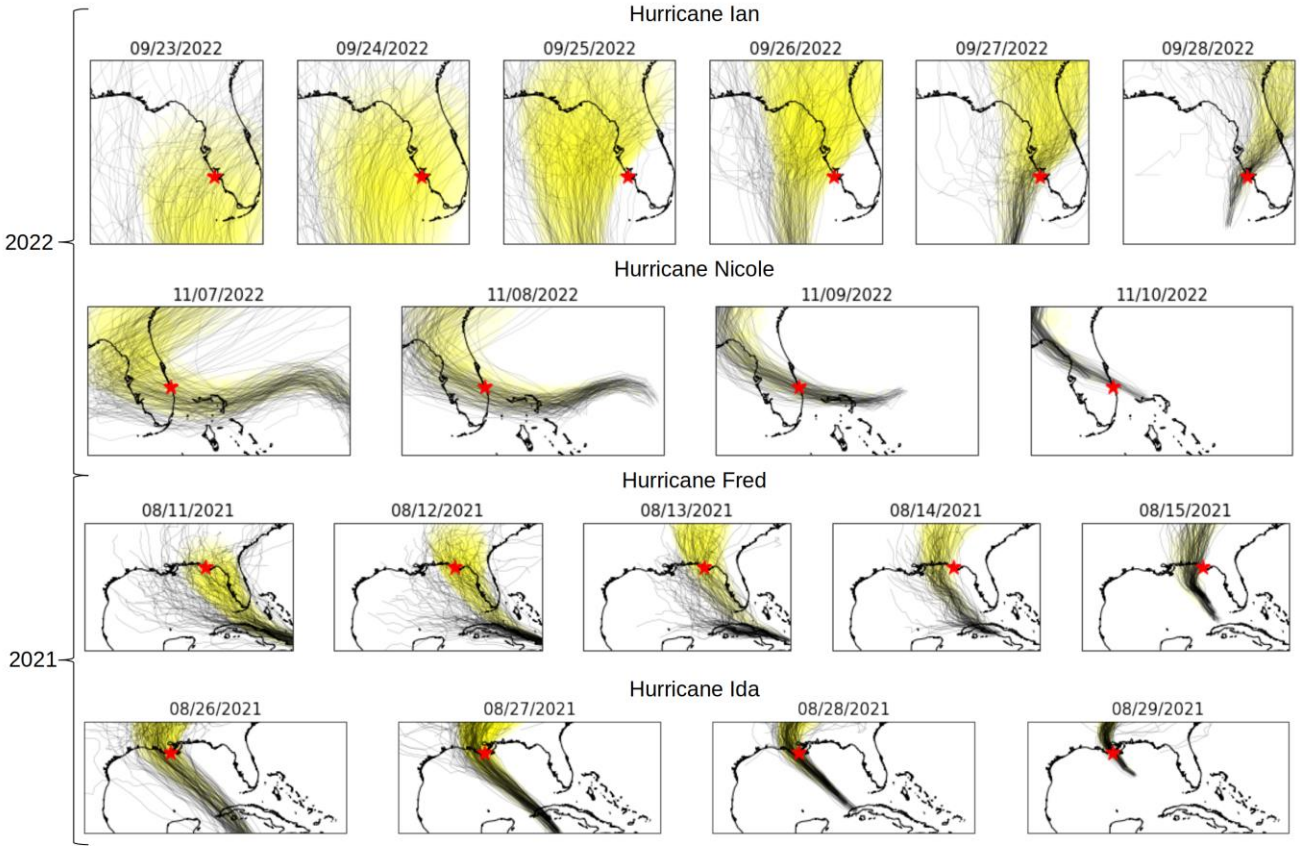
- **Conclusion: by assimilating wind speed data from NHC we can enhance both deterministic and probabilistic storm surge guidance (PSSG).**
  - **Deterministic products prone to track errors.**
  - **PSSG more effective, since it also accounts for track errors.**

Bonus Slide 1



- **Other storms also show similarly underpredicted wind speeds.**
  - **This method should be generally applicable for any storm forecast.**

Bonus Slide 2



- **We prefer amplification of ensemble vs. using synthetic vortices for 2 reasons:**

1. **Tracks are generally confined to NHC cone of uncertainty.**
   - **Cone based on past 5 years of track fcasts. over basin.**
   - **Fixed temporal variability for a given year, not accounting for impact of met. on track variability.**
   - **Ensemble storm tracks can vary much more widely than this.**
     - **-- e.g. Ian vs. Nicole, 2022 and Fred vs. Ida, 2021**
2. **Synthetic vortices reduce complexity of the system.**
   - **Synthetic approach uses a reduced parameter set.**
   - **May miss dynamics particular to the storm event.**