Tropical Cyclone Modeling and Data Assimilation

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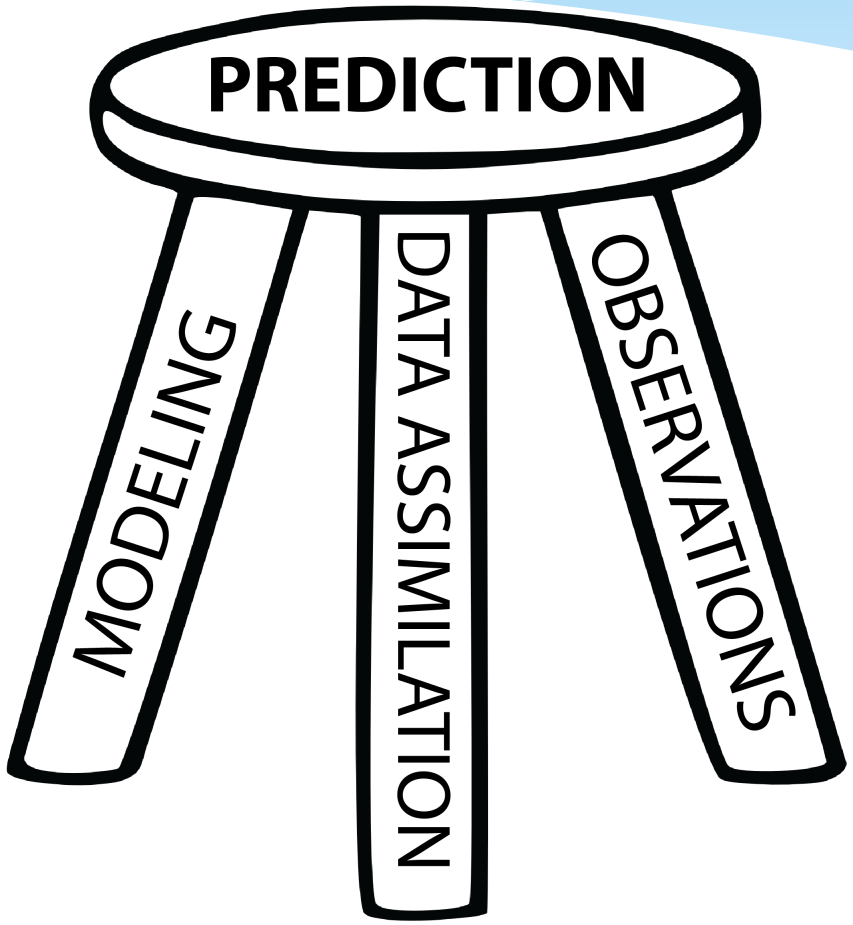
2023 WMO Workshop at NHC

Outline

- Background: Observations, modeling and data assimilation
- History: Improving forecasts by improving NWP
- Now: Recent and ongoing work
- Future: A new path forward

Background: Improving Forecasts



- Good forecasts require good modeling, data assimilation, and observations
- All of this requires substantial investment – no free lunch!

Background: Needed Investments

MODELING

- Computing
- Research
- People

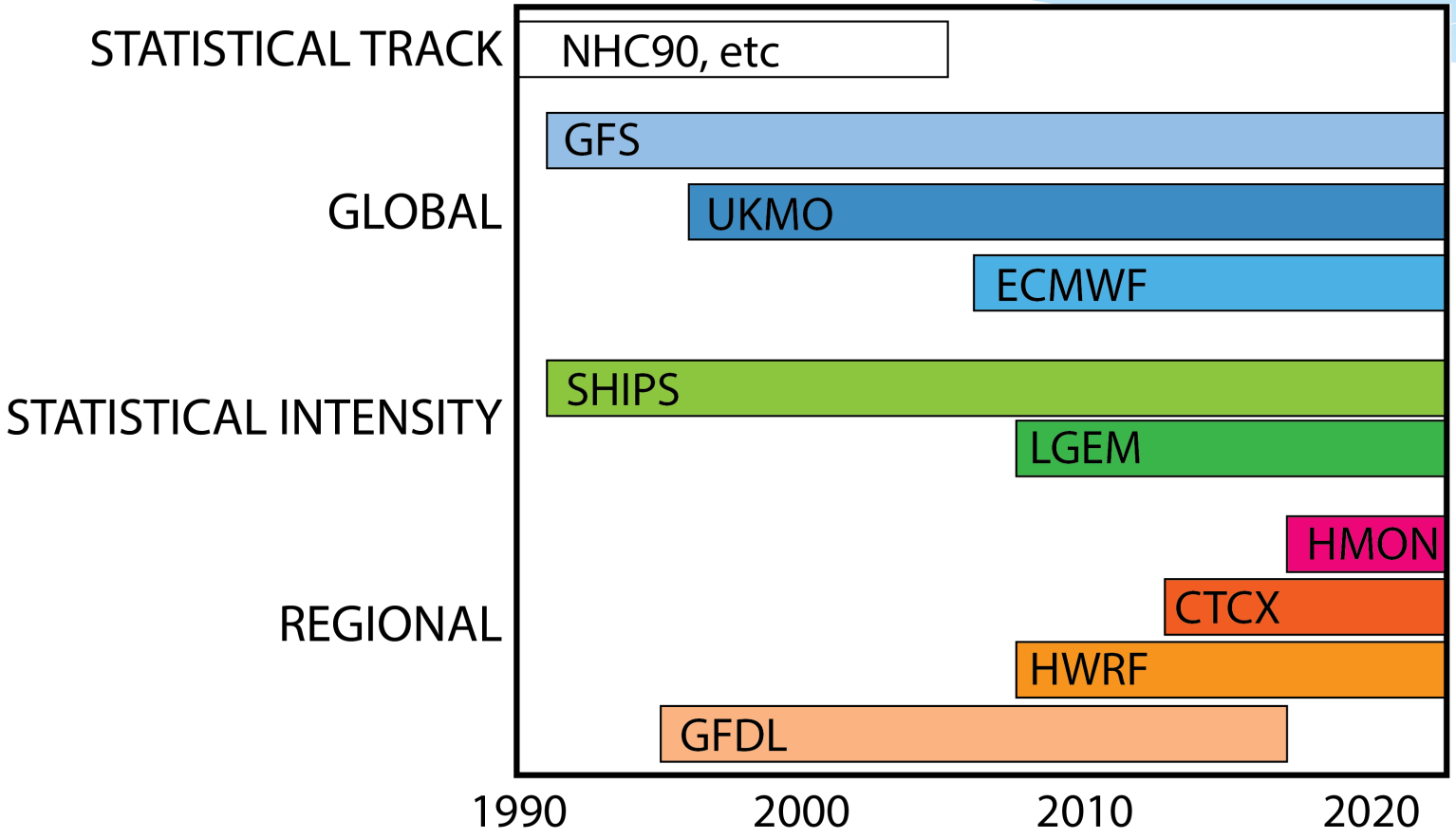
OBSERVATIONS

- Instruments & platforms
- Research
- People

DATA ASSIMILATION (DA)

- Computing
- Research
- People

Background: Modeling

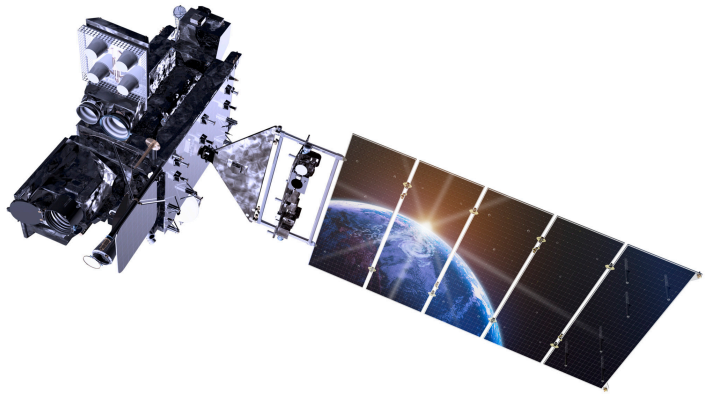


Models used by NHC since 1990

Background: Observations

TERRESTRIAL

SATELLITES



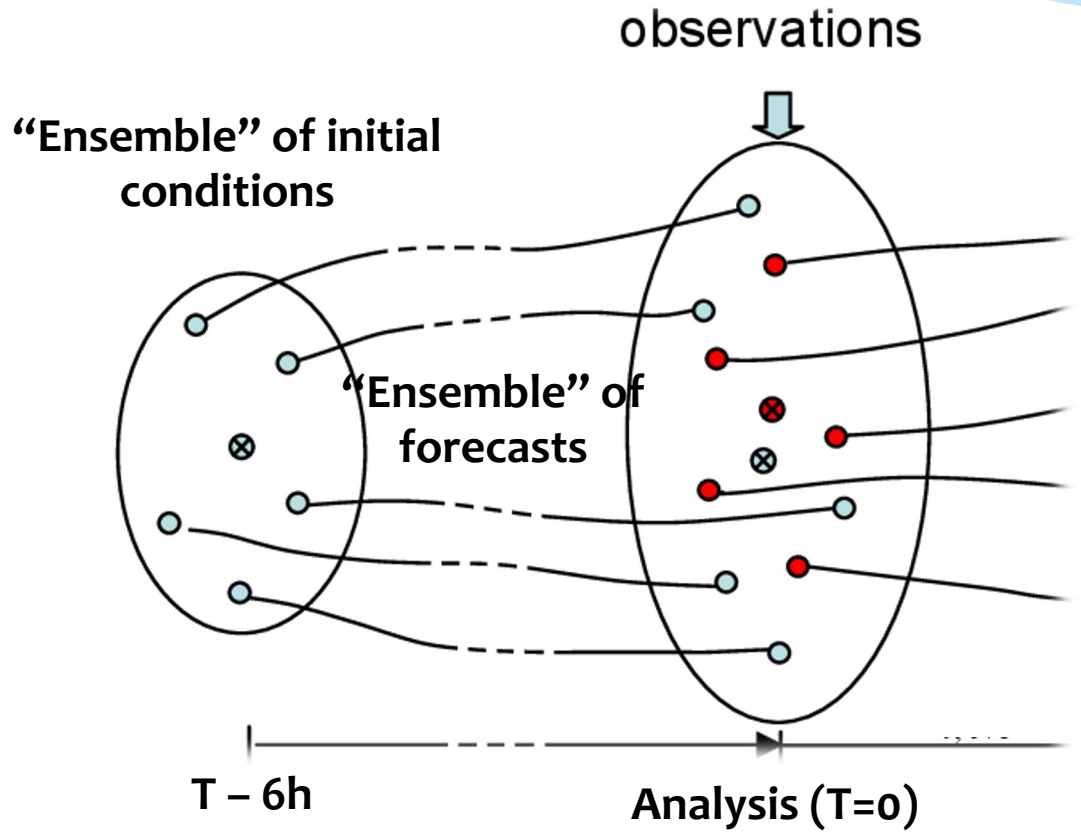
AIRBORNE

Background: Observations

- Current generation: Airborne “in situ” measurements are increasingly important

- Next-generation: Figure out how to use more satellite data

Background: DA Concepts

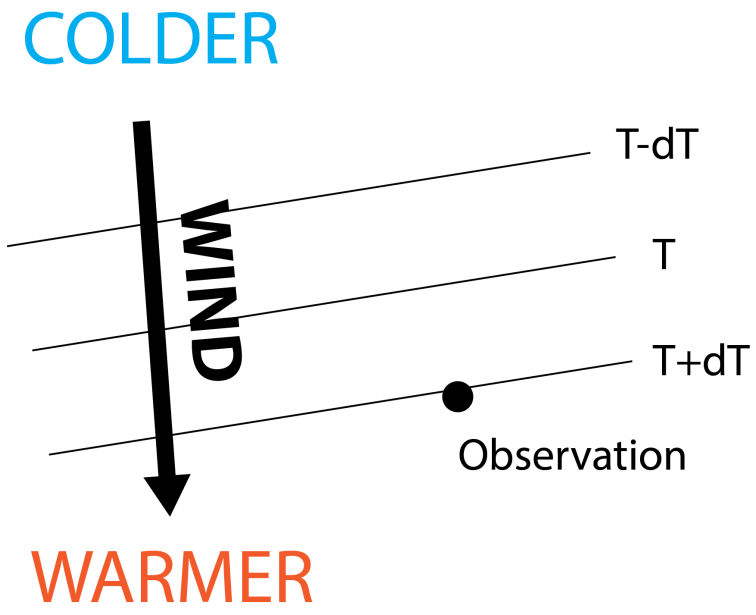


DA details:

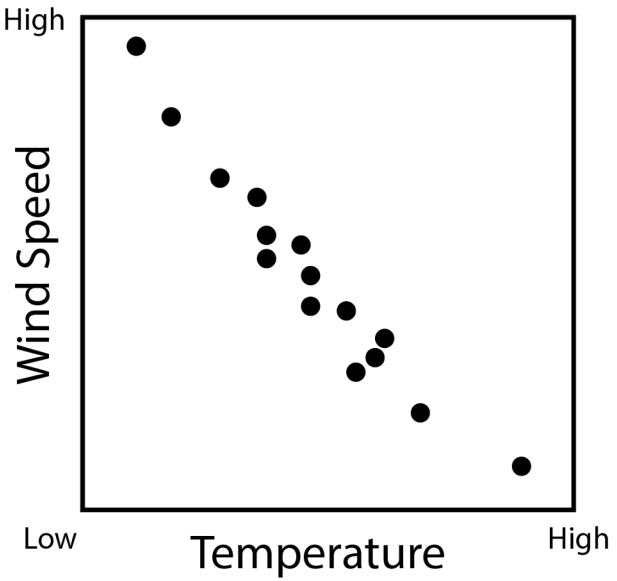
- DA provides initial conditions for a forecast (**analysis**)
- Update relies on **covariance** derived from a prior short-term ensemble forecast

Background: DA Concepts

Example 1: Cold air advection



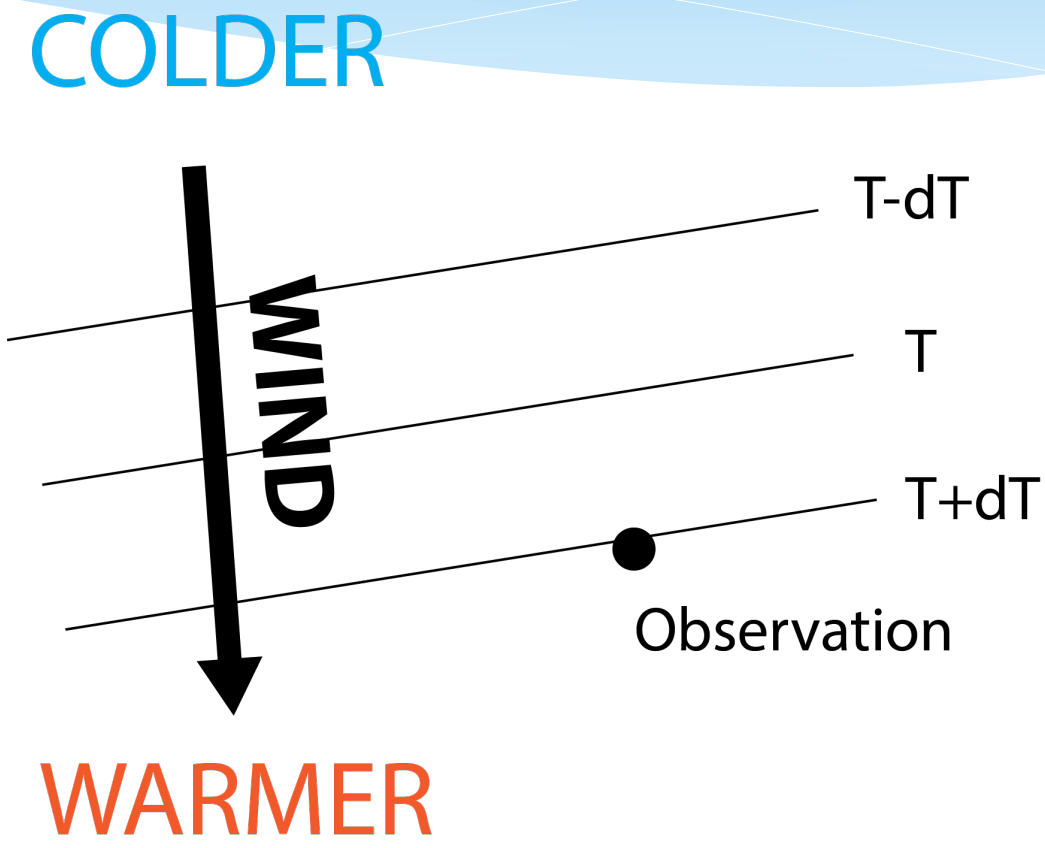
"Ensemble" of short-term forecasts provides covariance for DA



Background: DA Concepts

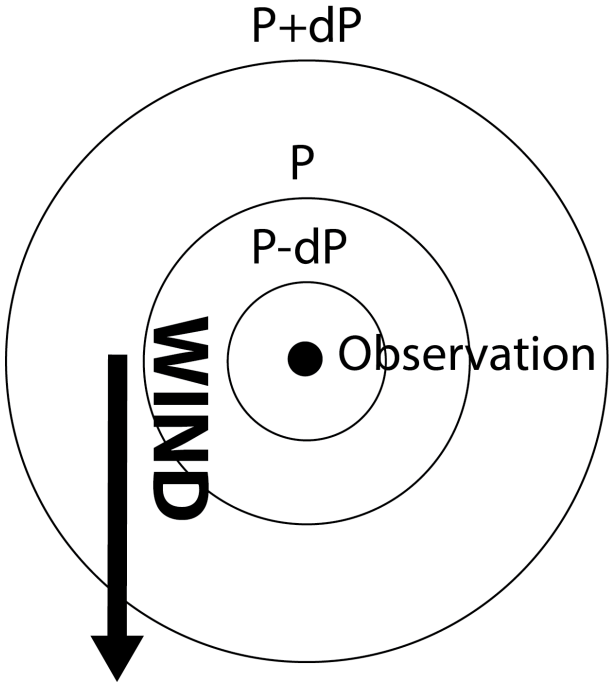
Example 1:

- Only wind is observed
- Observed wind speed is stronger than the short-term forecast
- How should DA update the regional temperature, even though it's unobserved?

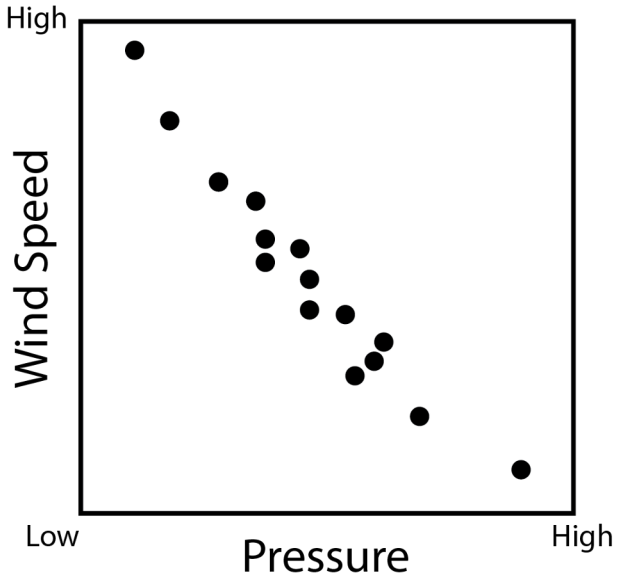


Background: DA Concepts

Example 2: Low pressure system



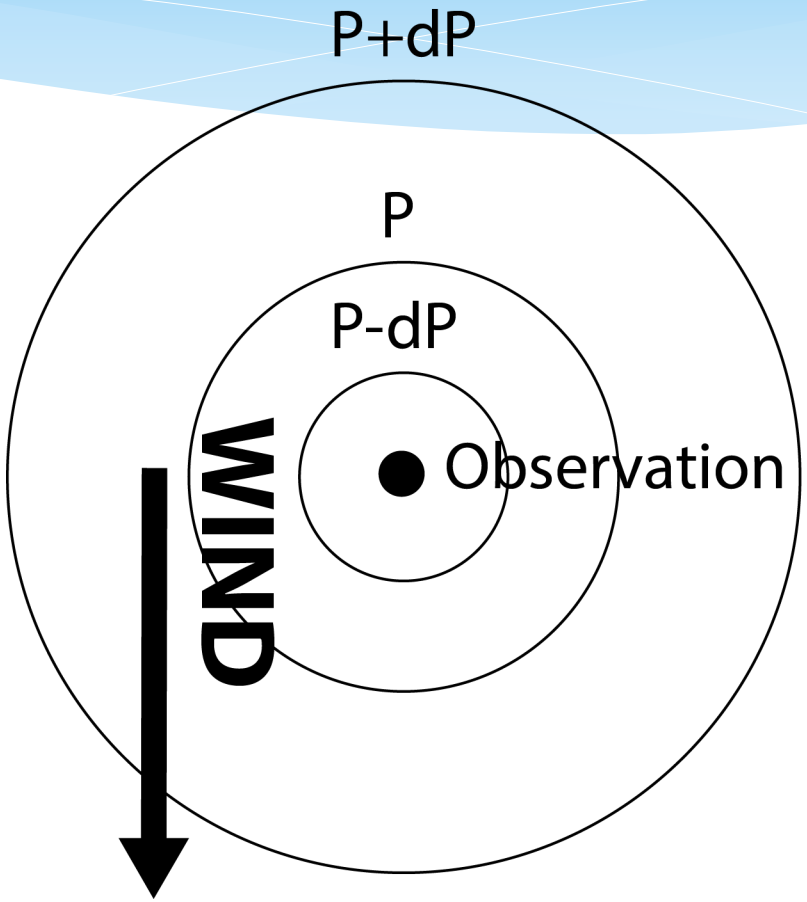
"Ensemble" of short-term forecasts provides covariance for DA



Background: DA Concepts

Example 2:

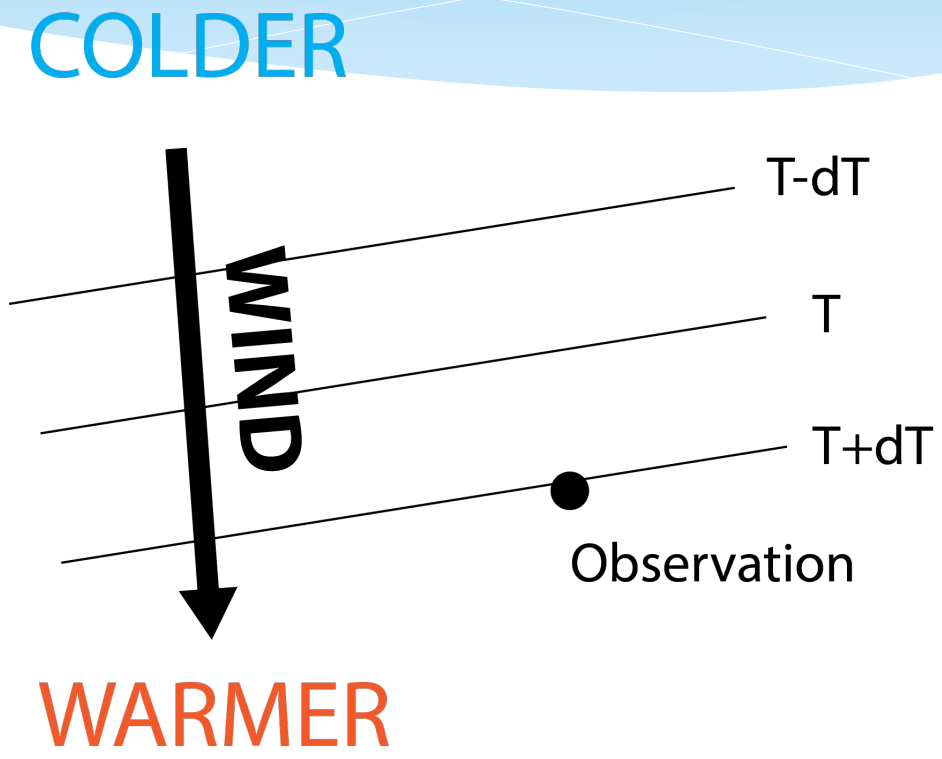
- Only pressure is observed
- Observed pressure is lower than the short-term forecast
- How should DA update the vortex-scale wind speed, even though it's unobserved?



Background: DA Concepts

Review - what DA does:

- Estimates atmospheric state (**analysis**)
- Combines prior forecast and current observations
- Relies on statistical relationships between variables (**covariance**)



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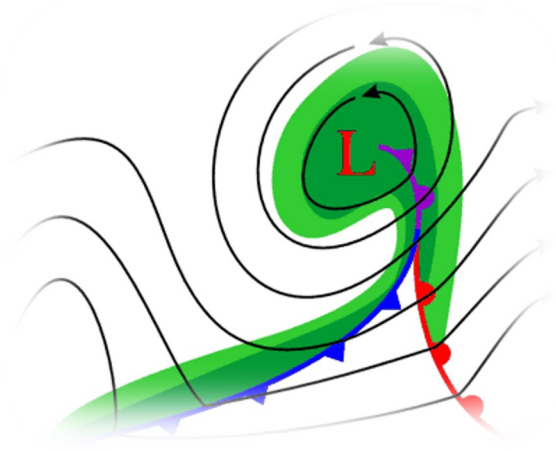
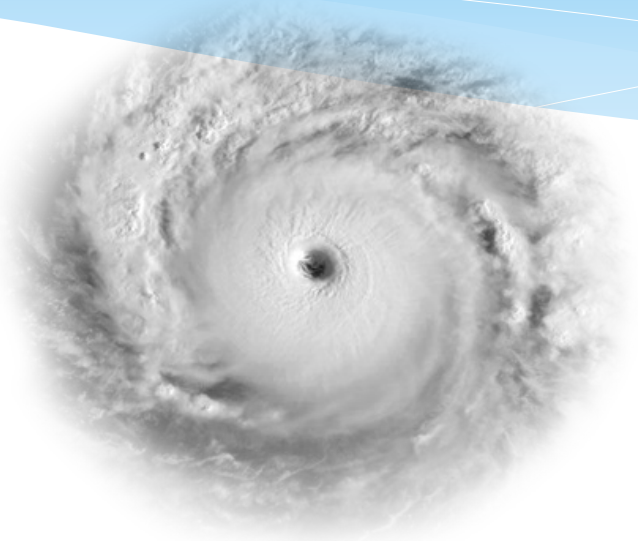




- Accurate analyses require reasonable covariance as well as good observations
- Covariance from a global ensemble is not great for hurricanes and is terrible for tornadoes

QUIZ!

Which of the below is required for accurate forecasts?

- A – A good model
- B – Good data assimilation
- C – Good observations
- D – All of the above

QUIZ!

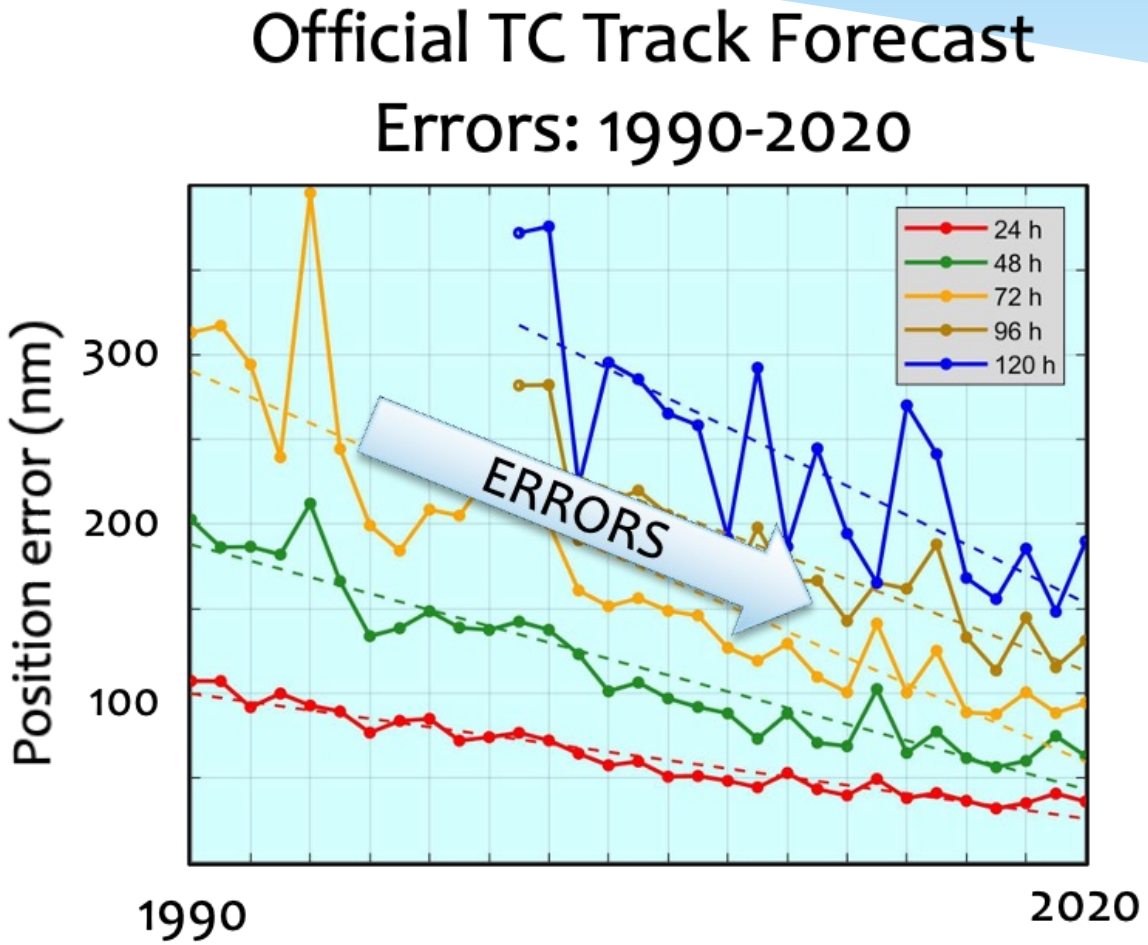
If observations show the hurricane vortex is stronger than predicted, how should the DA system update the temperature in the eye?

- A – no change
- B – higher
- C – lower

Outline

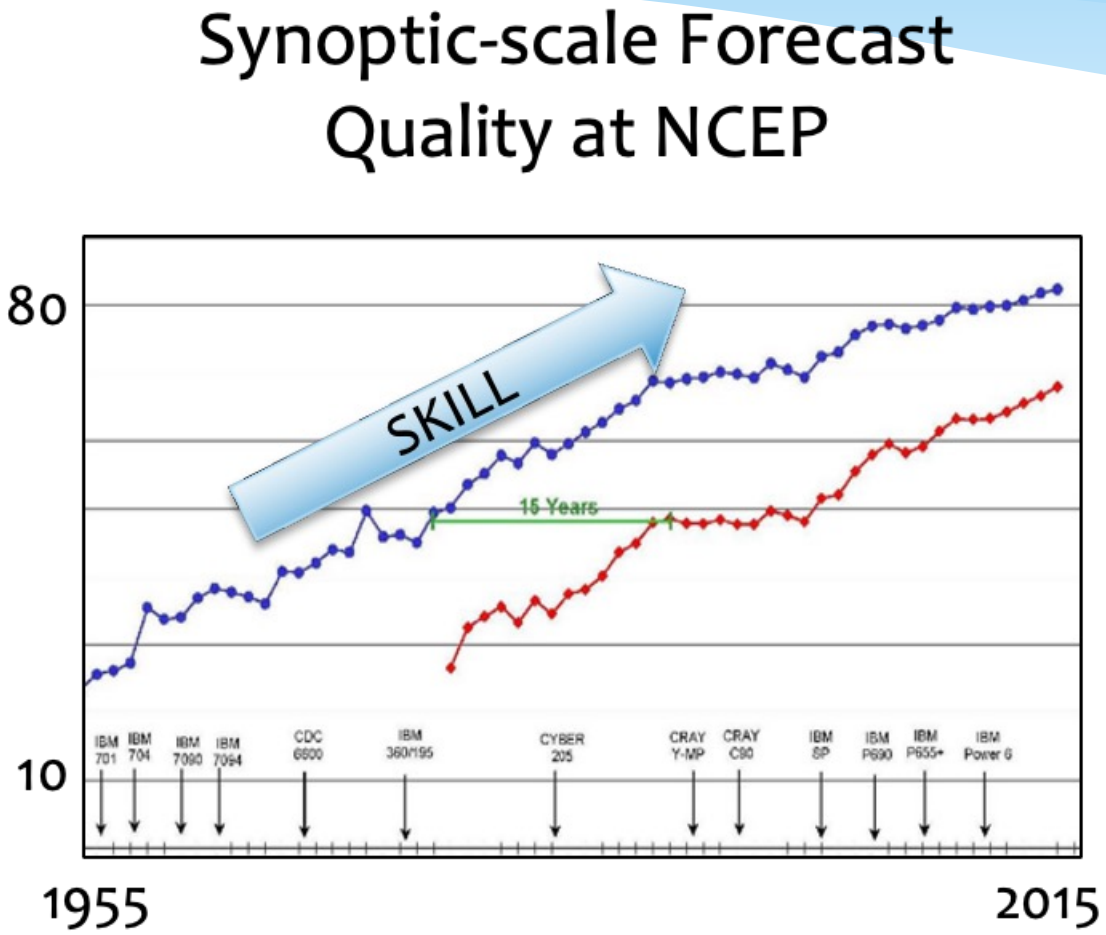
- Background: Observations, modeling and data assimilation
- History: Improving forecasts by improving NWP
- Now: Recent and ongoing work
- Future: A new path forward

History: Improving Errors



- Big track forecast improvement!
- Day-1 error in 1990 = Day-3 error now
- This is tied to better large-scale forecasts

History: Improving Errors



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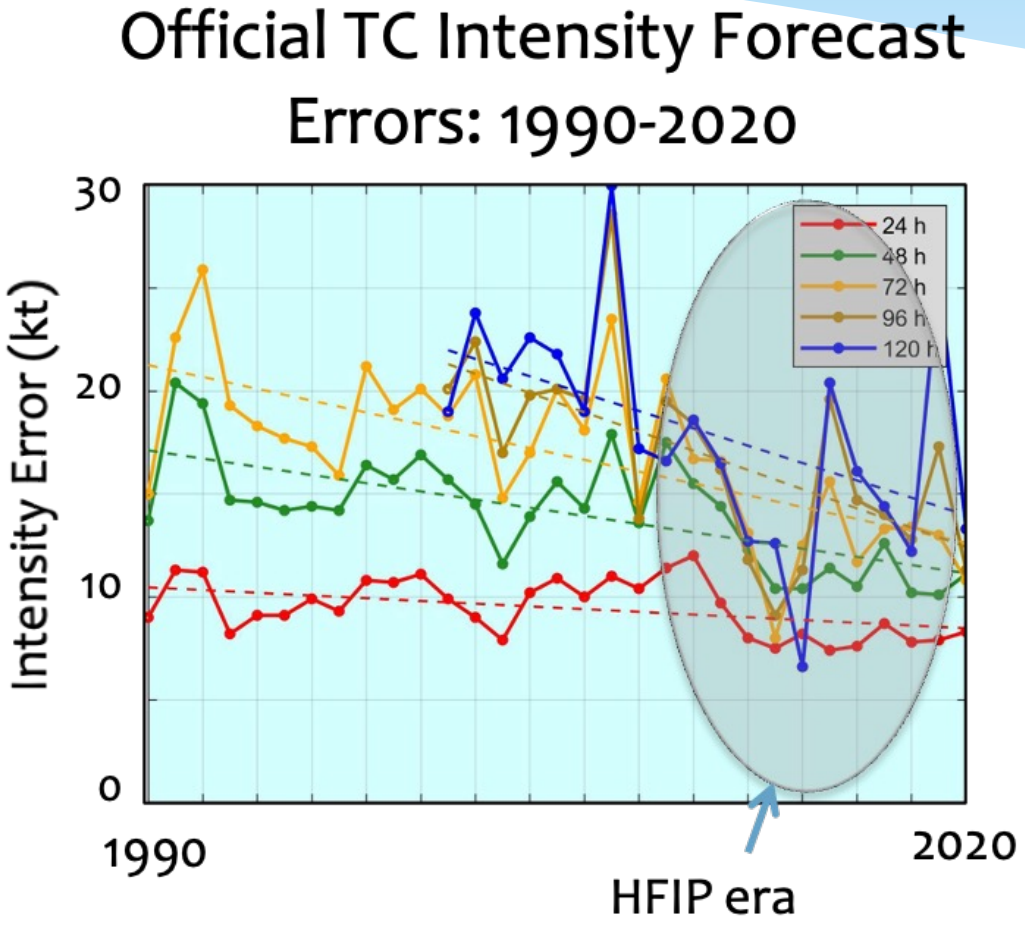
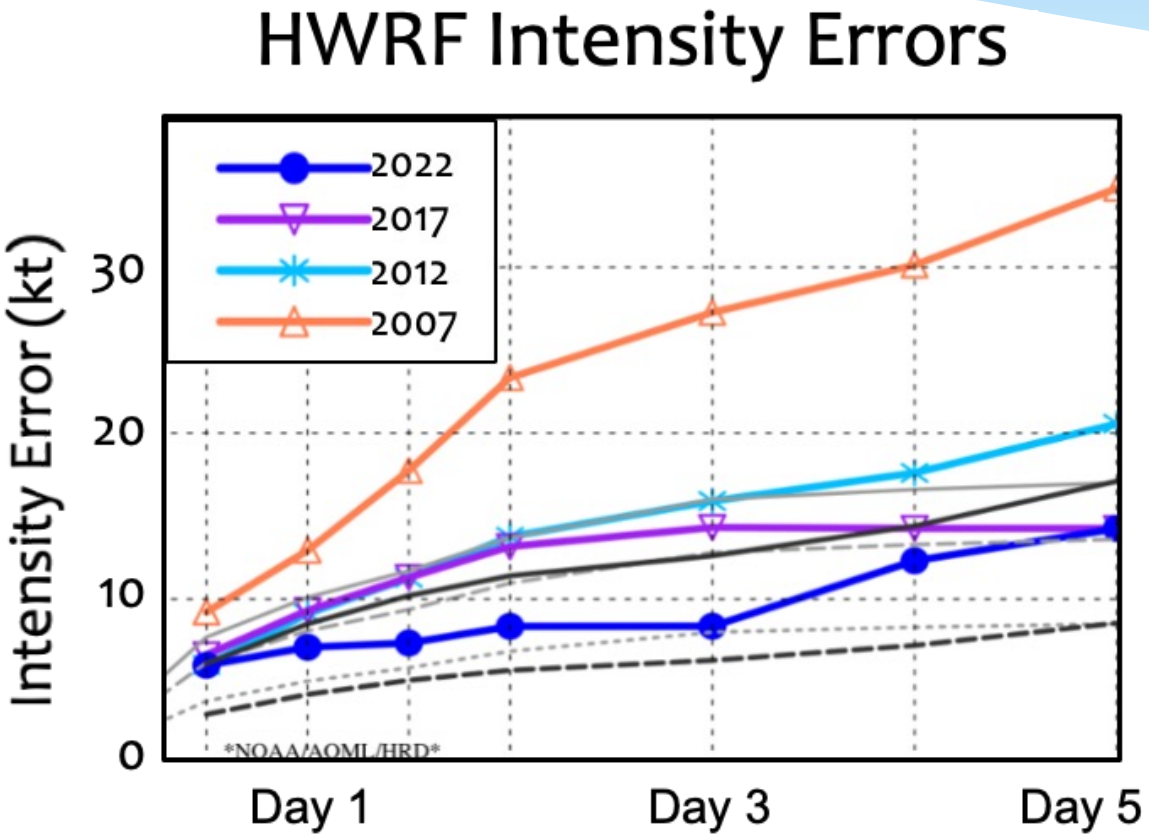
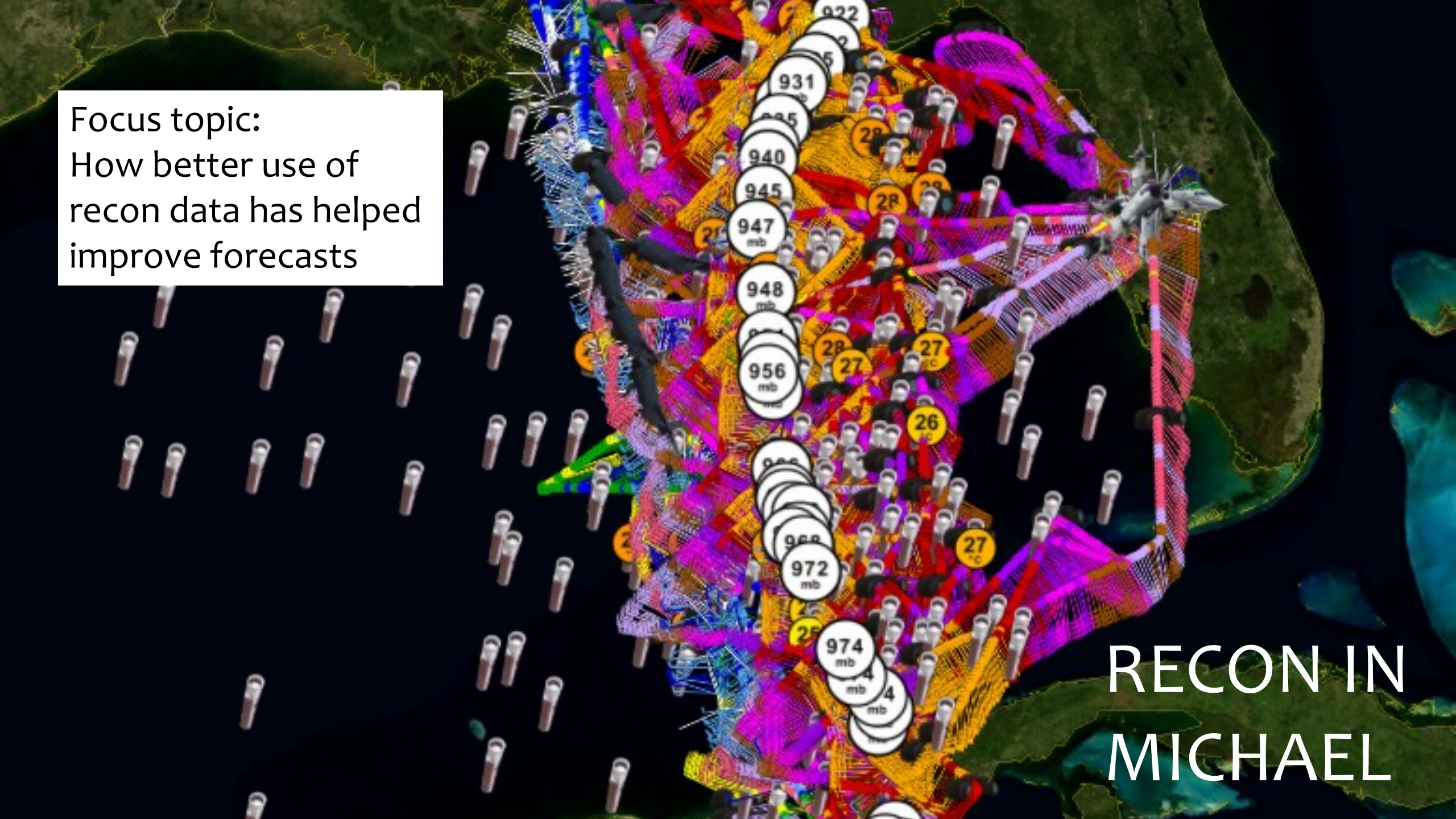


- Hurricane intensity forecasts have only recently improved
- Improvement a result of Hurricane Forecast Improvement Project
- BIG financial investment

History: Improving Errors



- Significant focus of HFIP has been developing HWRF
- As a result, HWRF has improved significantly over the past decade
- 60%+ intensity error reduction since 2007!


Focus topic:
How better use of recon data has helped improve forecasts
RECON IN MICHAEL

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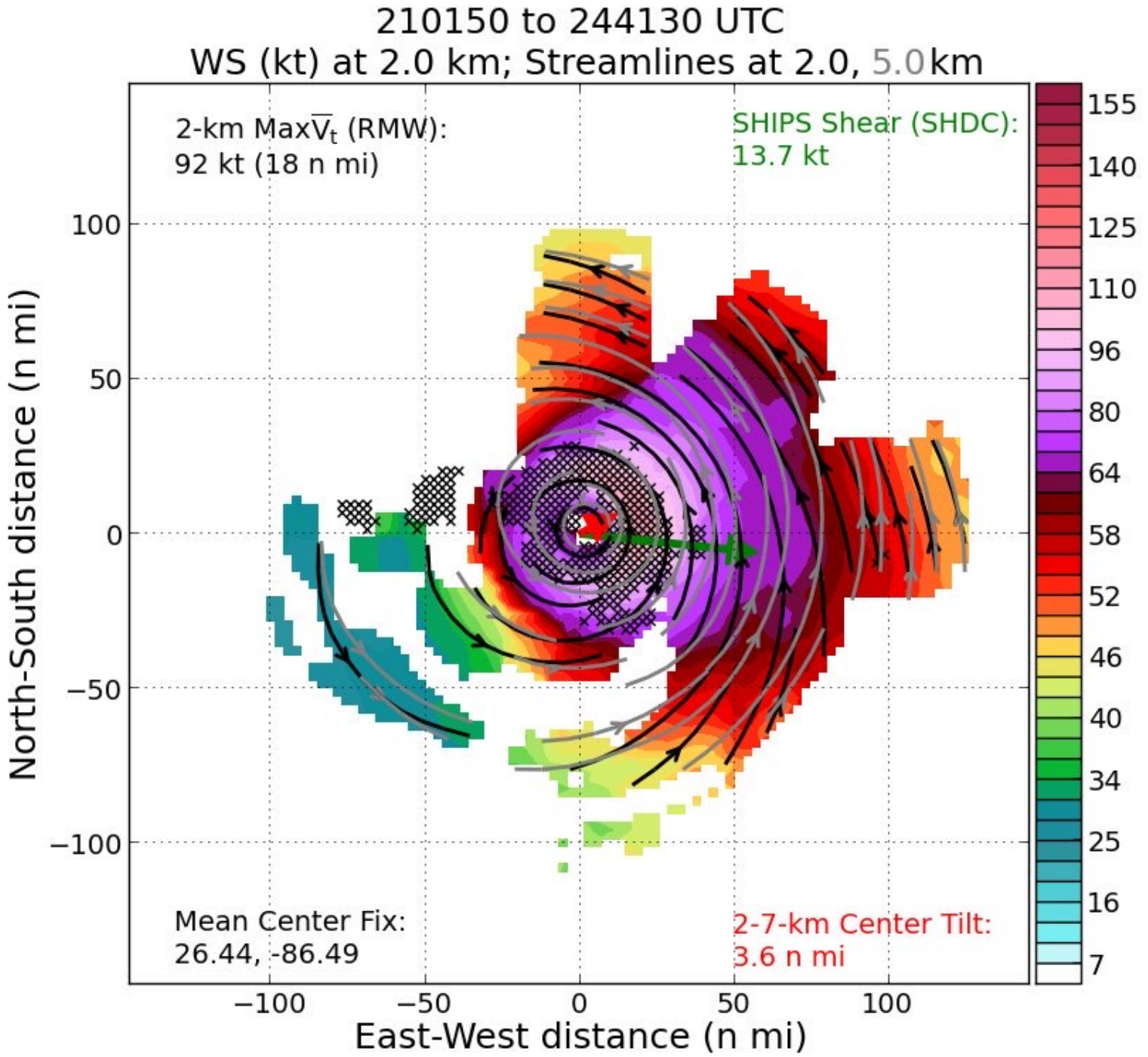
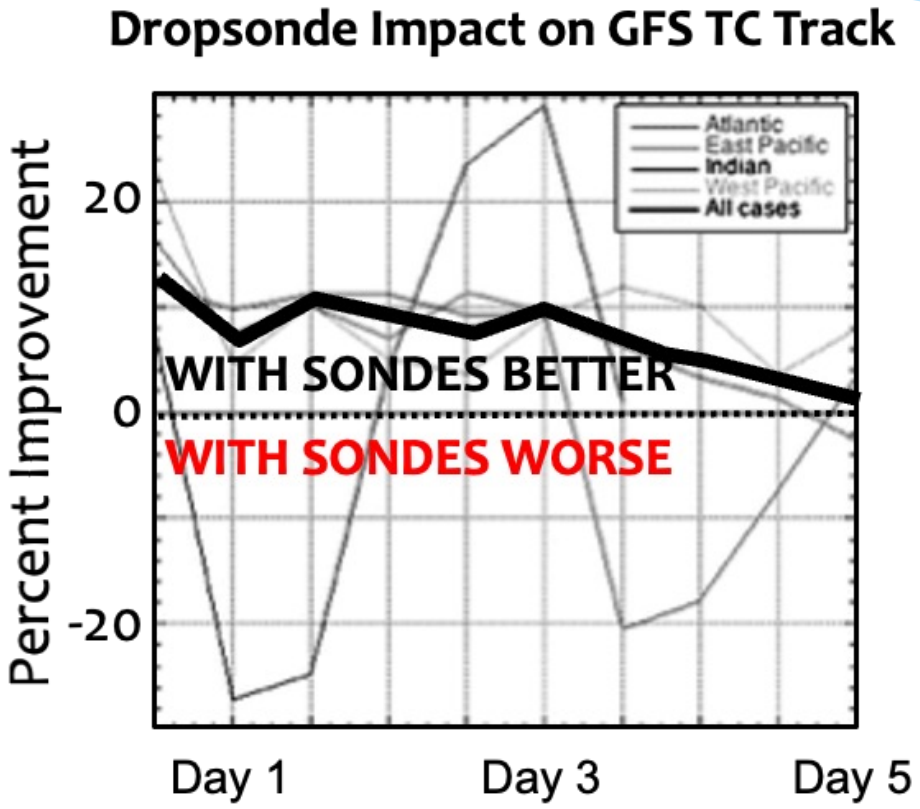
How better use of recon data has helped improve forecasts



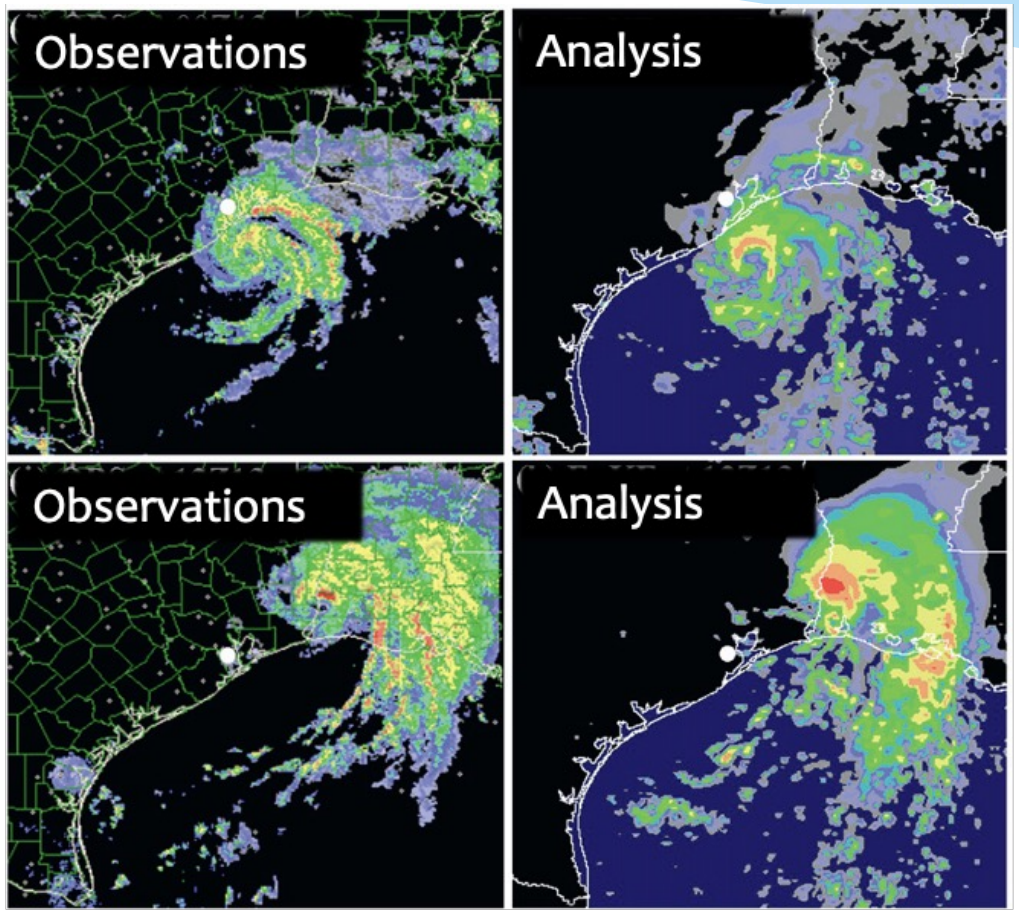
History: Improving NWP with TC Obs



Impact of dropsondes in September 2008

- US has used dropsondes in weather models for ~40 years
- Usage has dramatically increased
- Many studies have shown dropsondes improve track

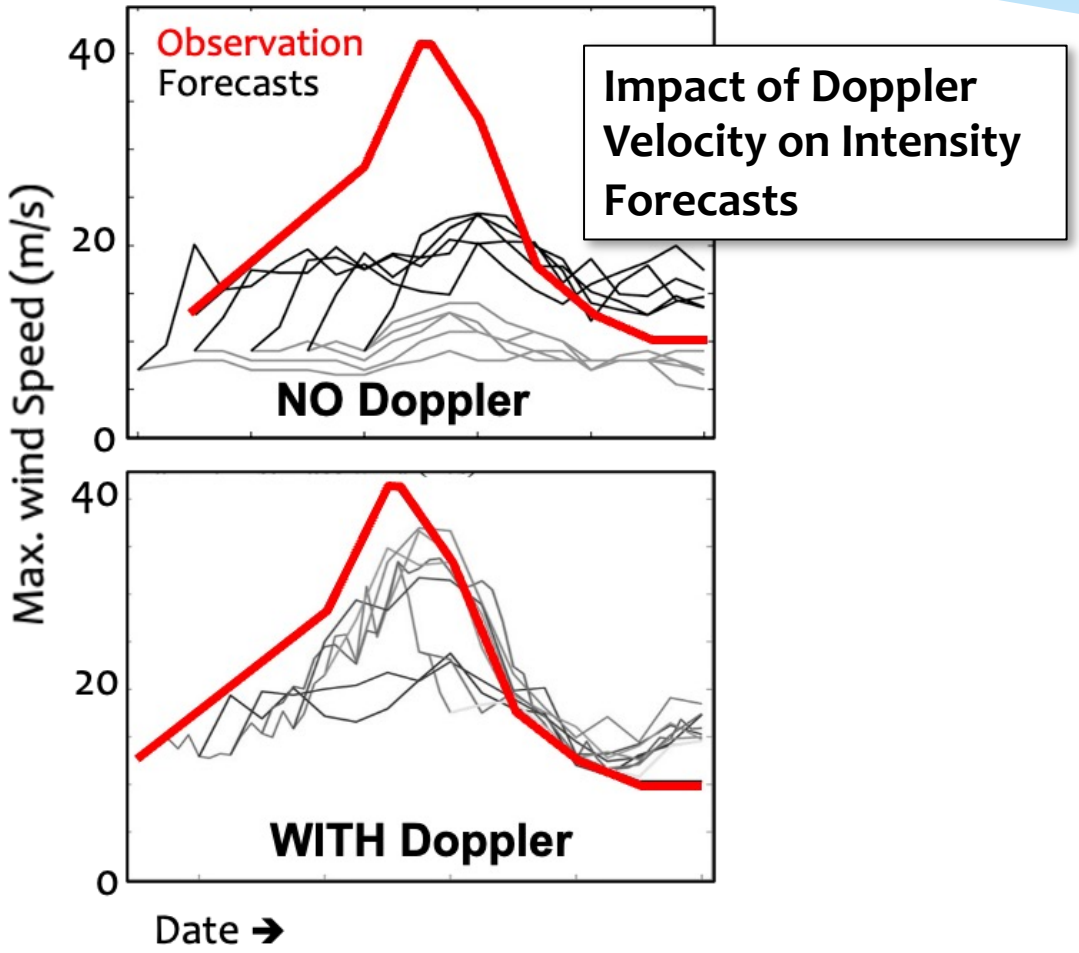
History: Improving NWP with TC Obs



Experimental PSU DA system: Analyses vs. Obs

- ~15 years ago, we found that 88D Doppler velocity could benefit coastal TC forecasts
- Assimilating radar data significantly improved **experimental** PSU analyses and forecasts

History: Improving NWP with TC Obs



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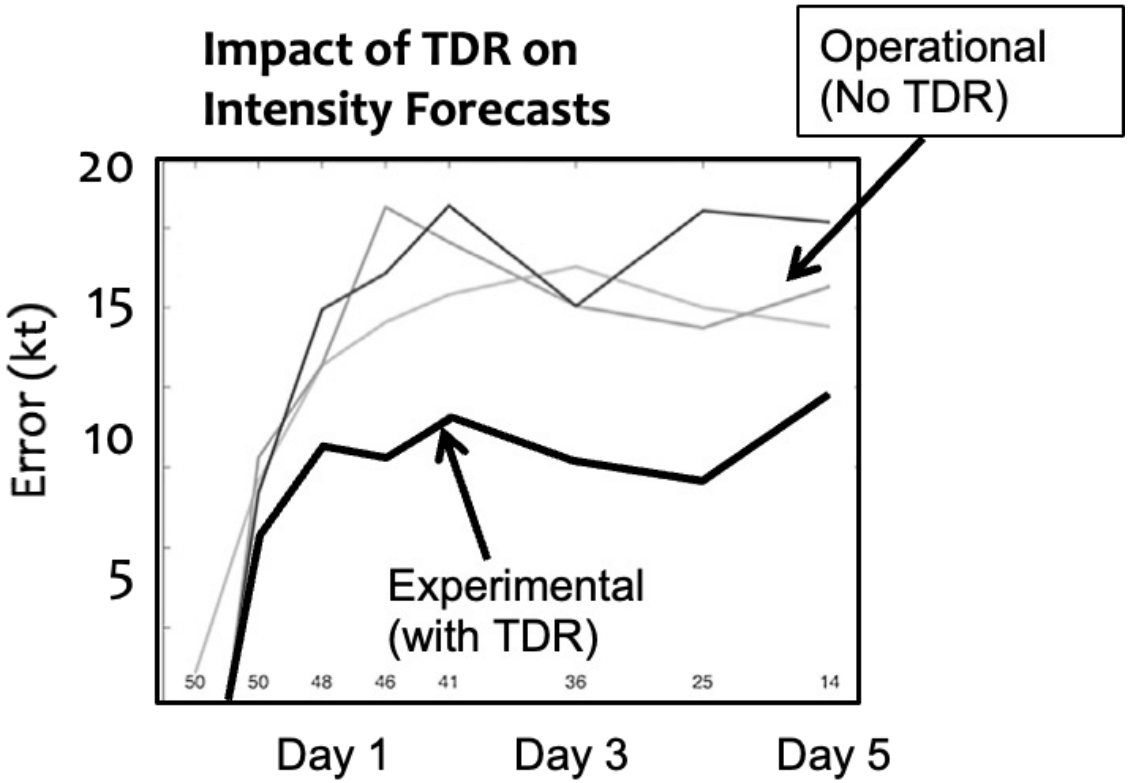
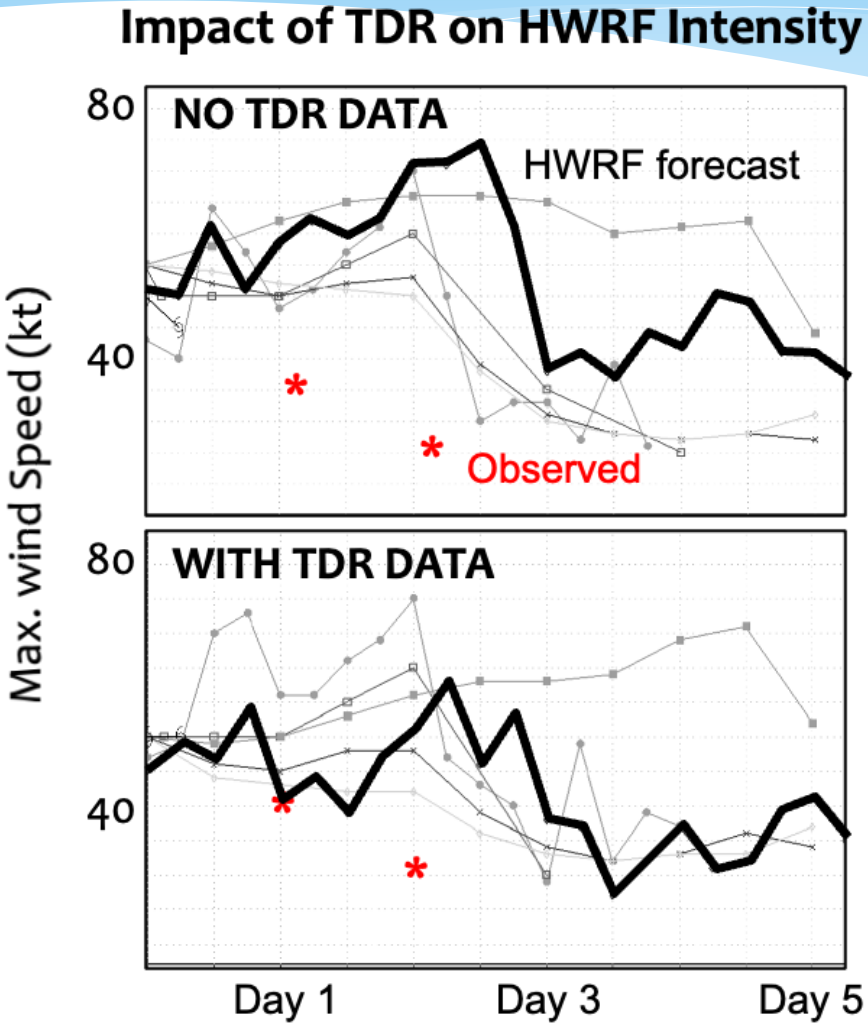
History: Improving NWP with TC Obs



- Assimilating tail Doppler radar (TDR) velocity from NOAA recon also improved **experimental** PSU forecasts

- These results led to operational assimilation of TDR **(research to operations)**

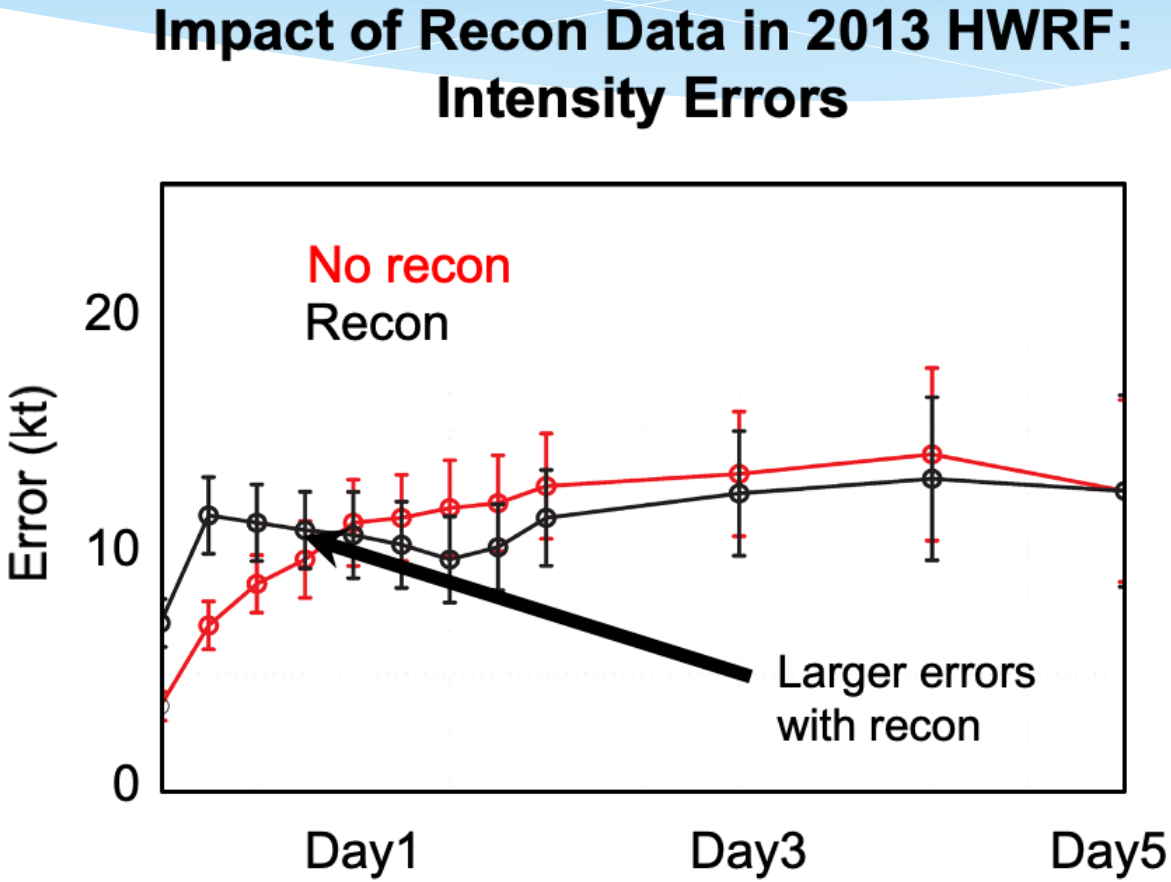
History: Improving NWP with TC Obs



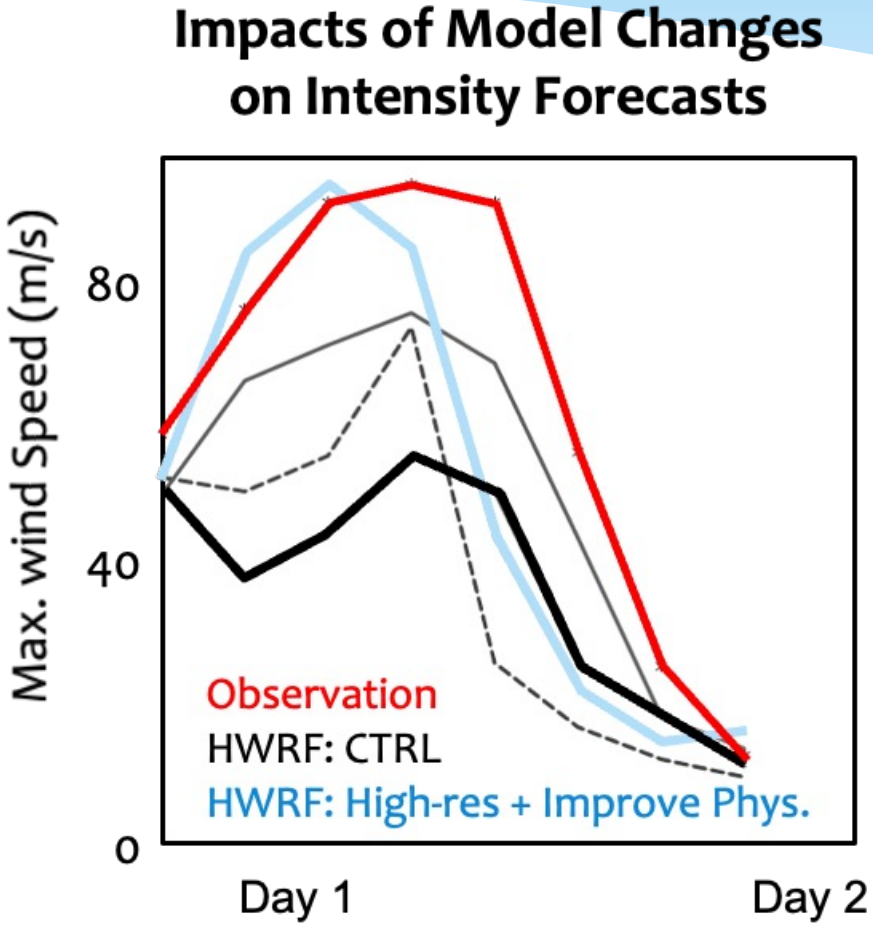
- **Operational** HWRF began assimilating TDR data in 2013
- For weak storms, HWRF substantially improved with TDR

History: Improving NWP with TC Obs

- Results worse over larger sample
- Short-term forecast degradation
- Physics and DA deficiencies for strong storms

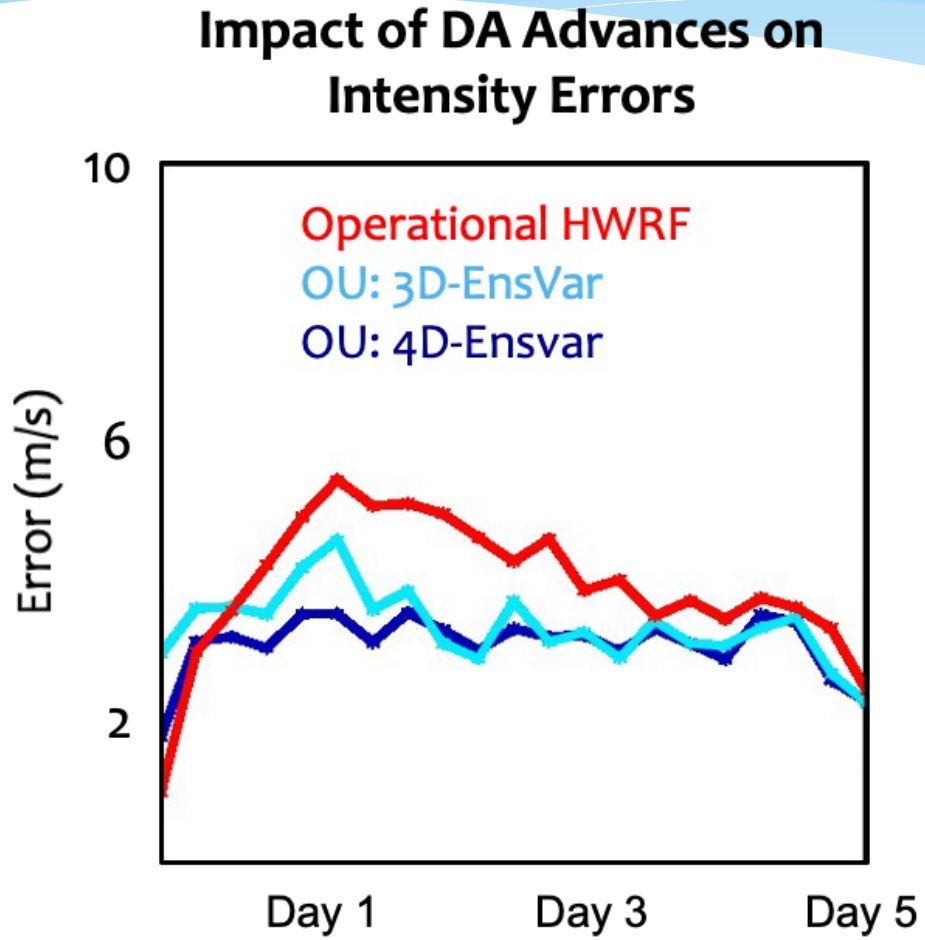


History: Other NWP Improvements



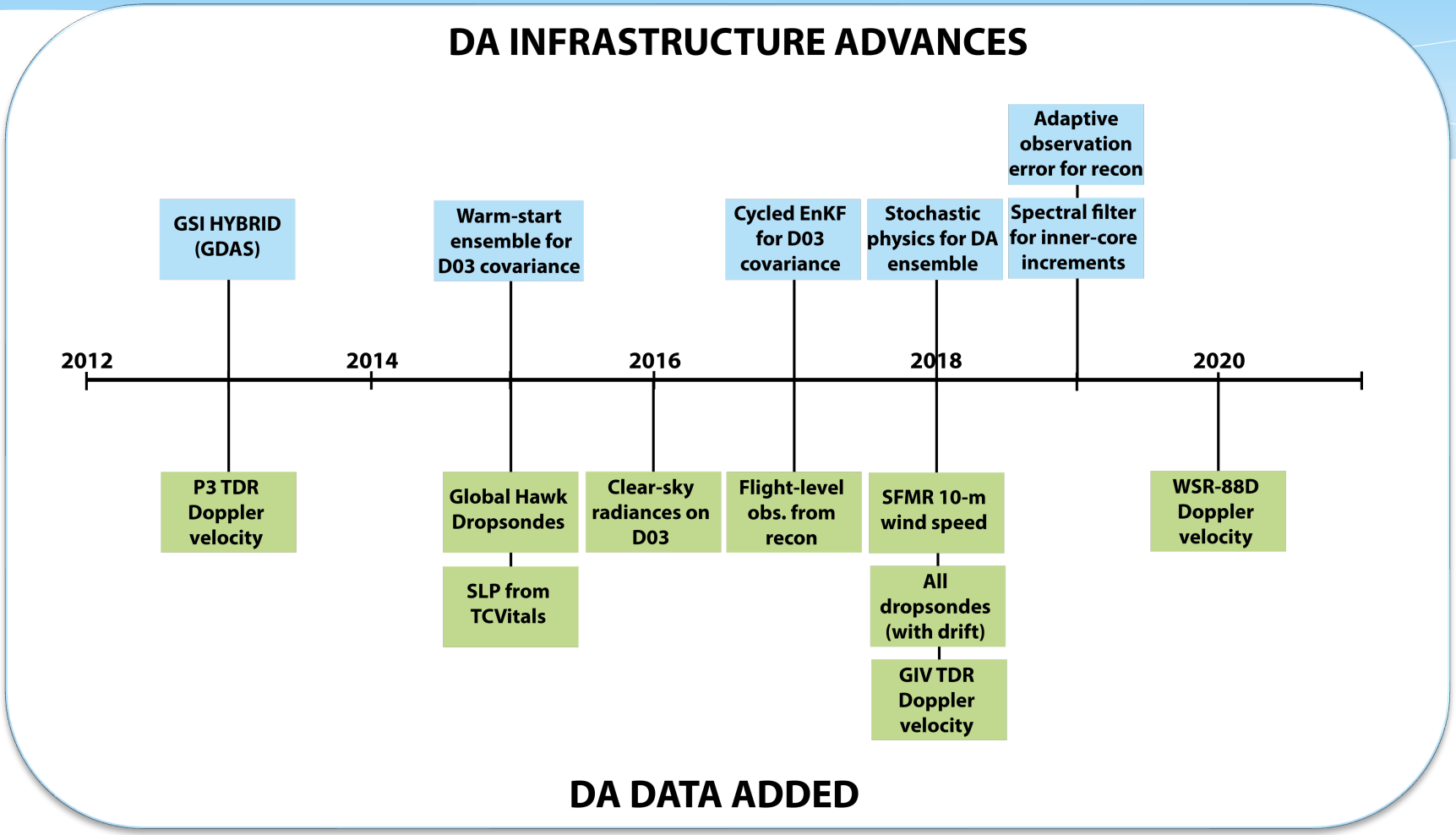
- Necessity: Increasing resolution AND improving physics
- Challenge: make physics changes that don't make every TD a Cat 5

History: Other NWP Improvements



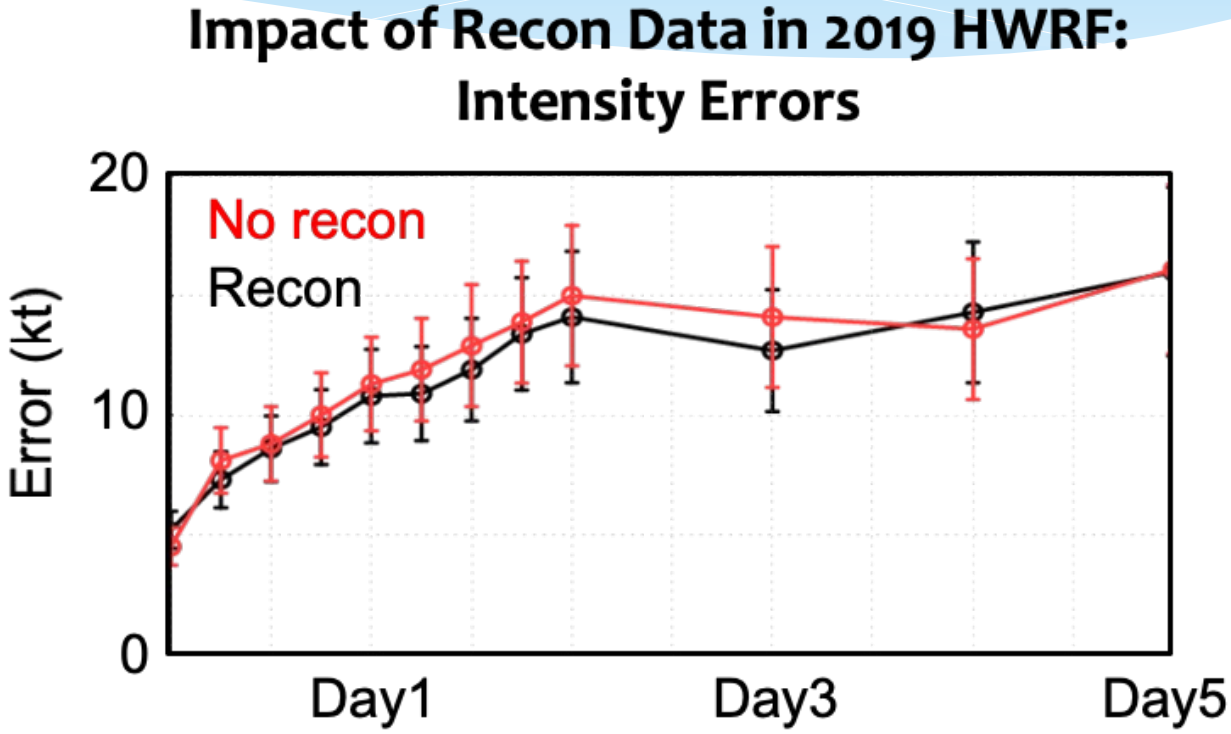
- DA improvements are also necessary
- **Experimental** OU HWRF system with better DA performs much better

History: HWRF Improvements



History: HWRF Improvements

- Recon benefit assessed in 2016-2018 high impact storms
- Many major hurricanes in this sample
- Recon improved intensity 10-15% through 72h

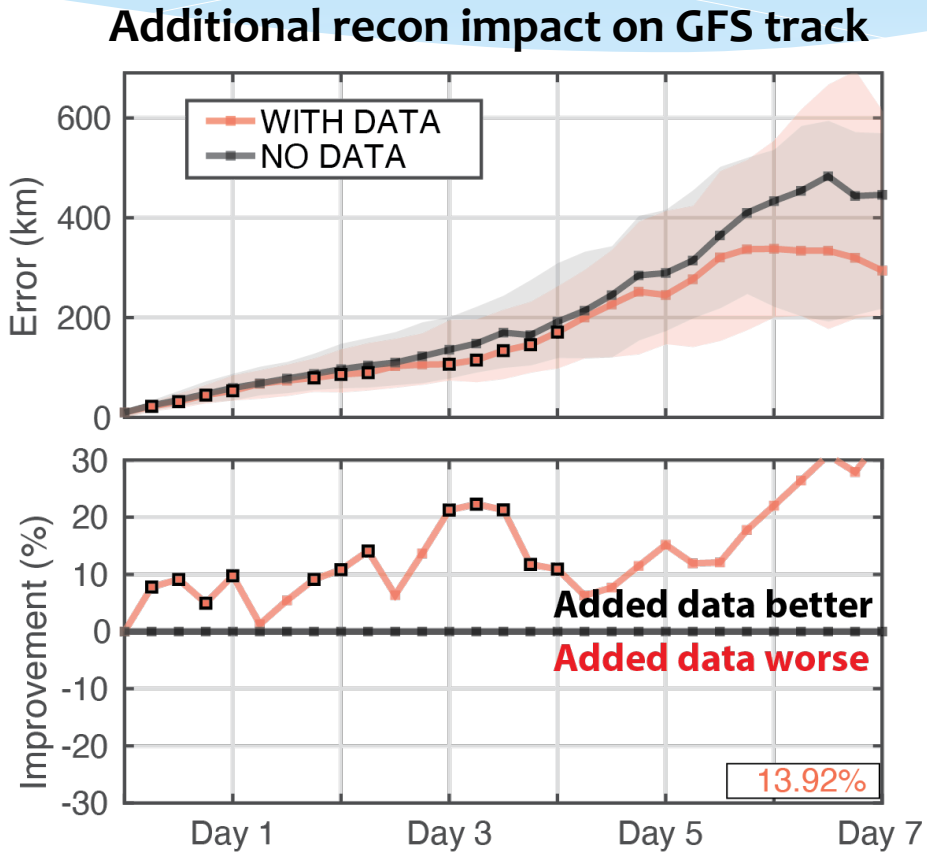


BUT WAIT…

THERE'S MORE!

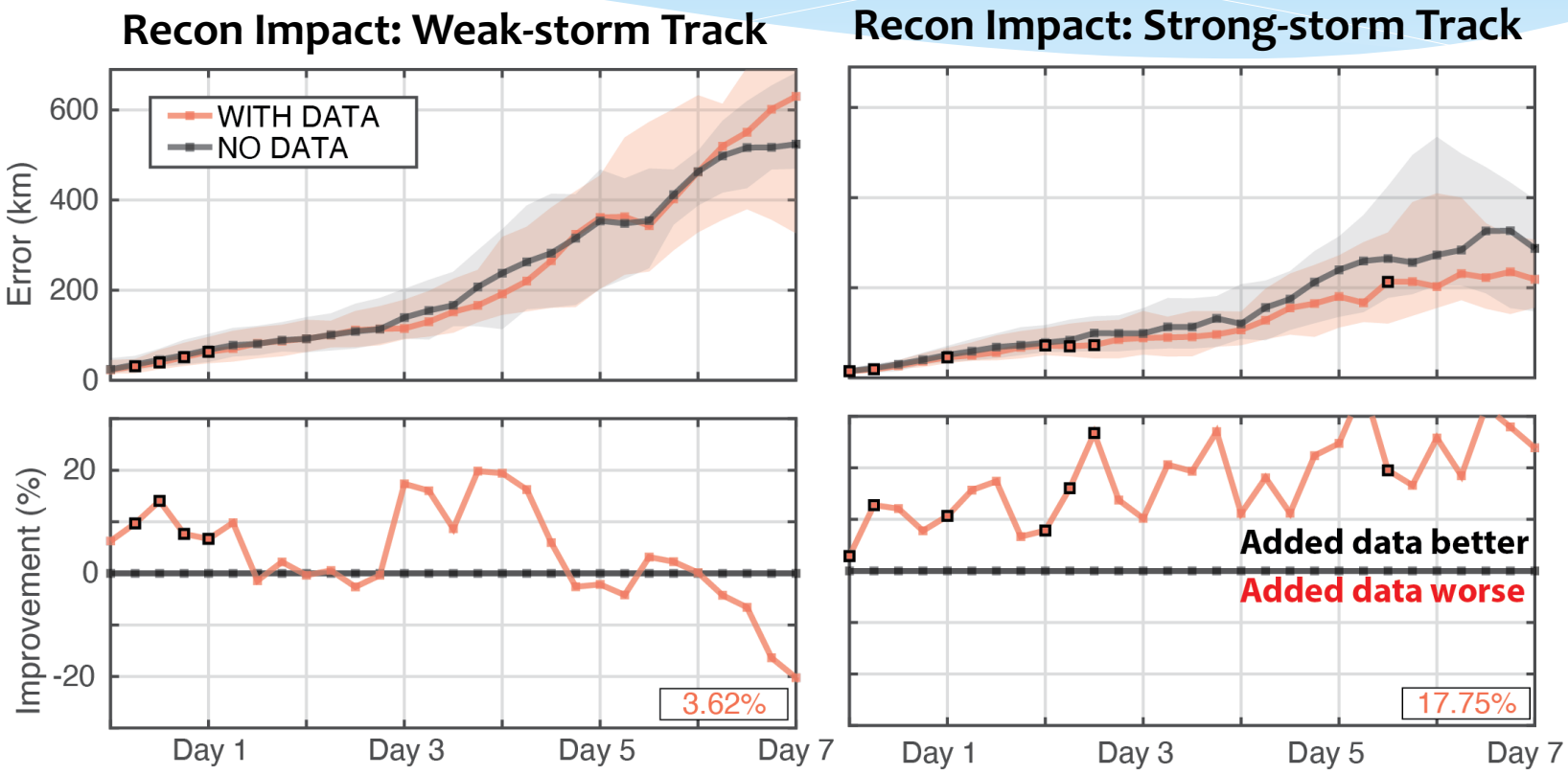
History: GFS Improvements

- GFSV16 upgrade in March 2021 included better use of dropsondes and flight-level data
- Added data improves track in sampled storms 10-20%



History: GFS Improvements

- Less positive impact of recon on tracks of weaker storms
- Could suggest DA system problem



QUIZ!

When did hurricane intensity forecasts REALLY begin to improve?

- A – 1990
- B – 2000
- C – 2010
- D – 2020

QUIZ!

Why did reconnaissance data initially degrade short-term intensity forecasts in HWRF?

- A – Model physics problems in HWRF
- B – Data assimilation problems in HWRF
- C – All of the above
- D – None of the above

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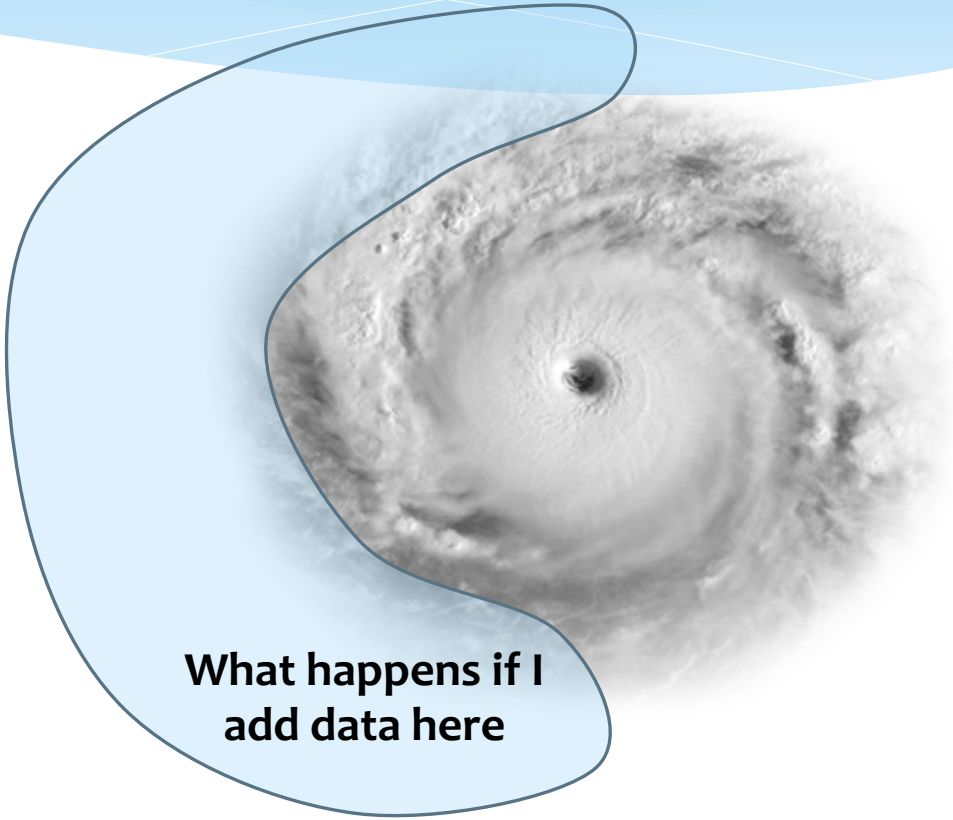
Now: Intro to OSEs

With a model that performs well, one can more effectively evaluate observing-system experiments **(OSEs)**

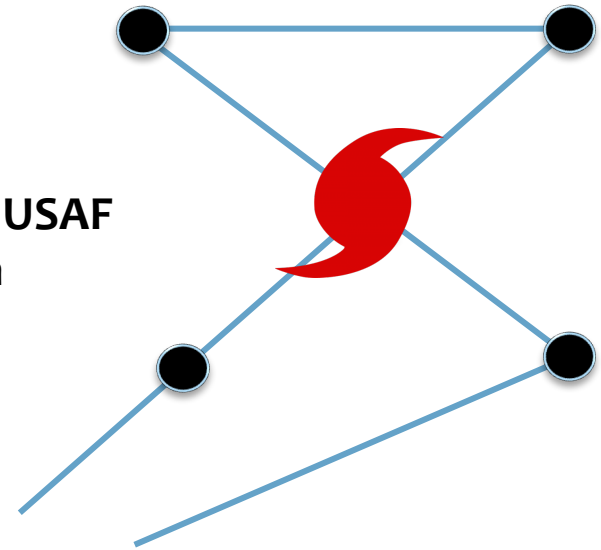
?



Now: Recent OSE Work

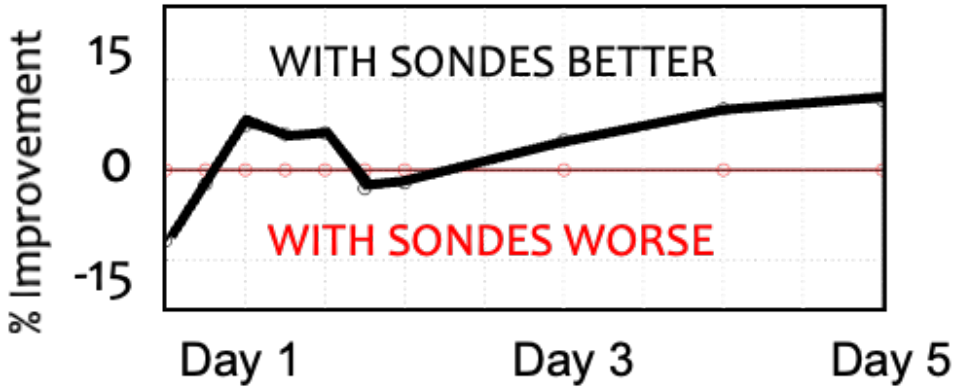
Example 1: "End-point" dropsondes added to C-130 missions in 2018

Typical USAF pattern



Add dropsondes at turn points

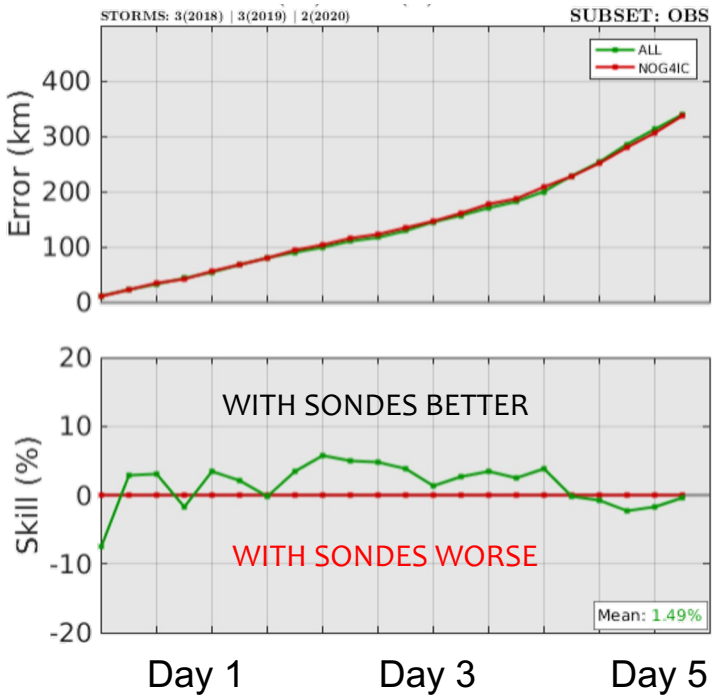
Dropsonde Impact on HWRF Intensity

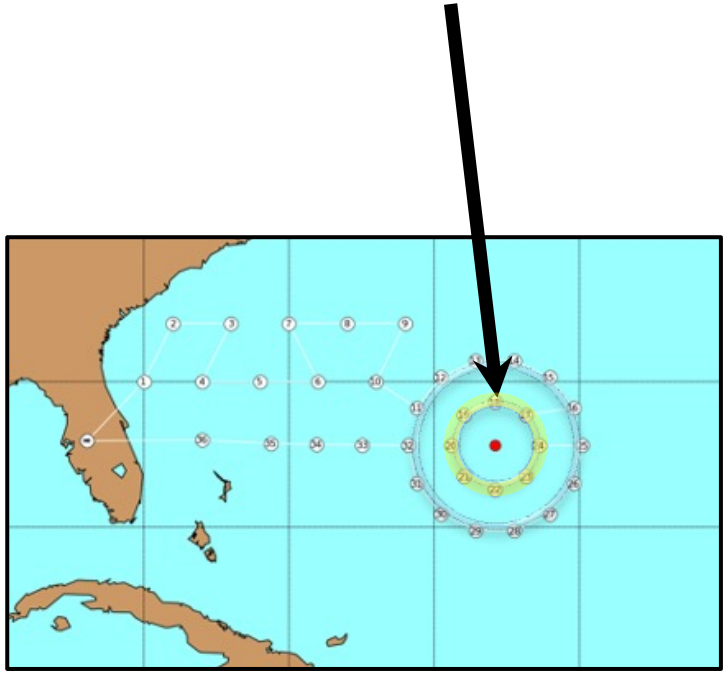


Now: Recent OSE Work

Example 2: G-IV "Inner circumnav" added in 2018

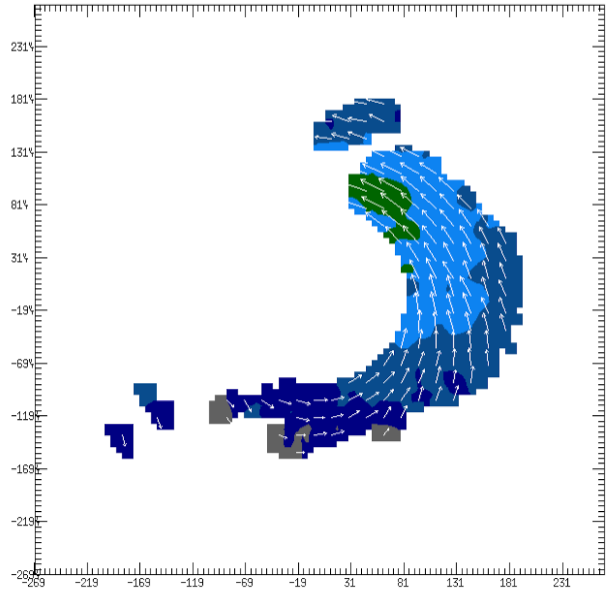
Inner Circumnav Sondes: Impact on HWRF Track





G-IV dropsondes for Hurricane Florence

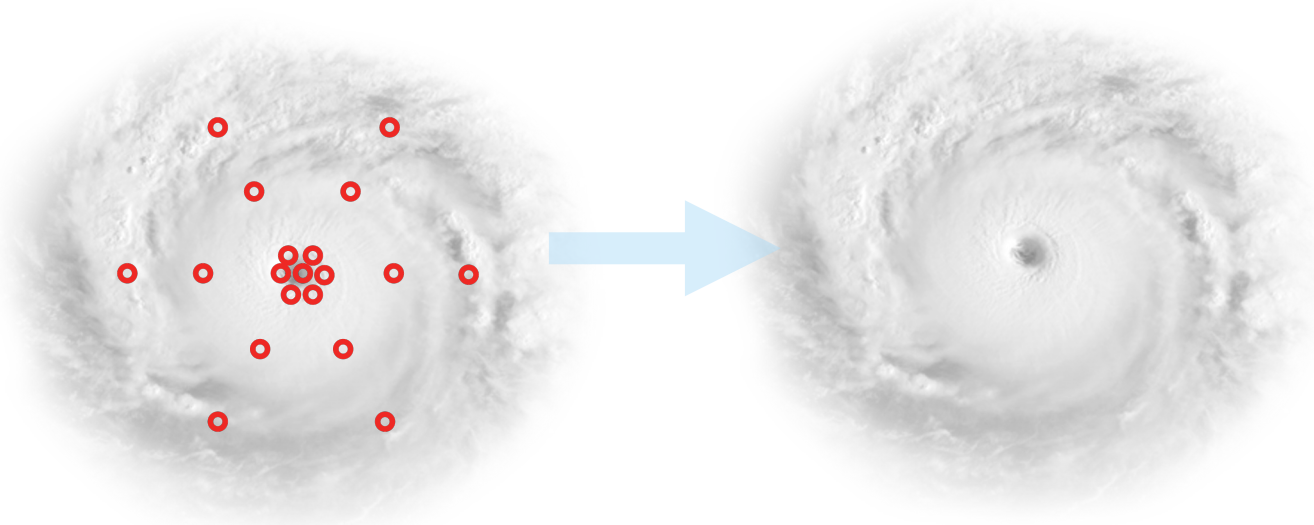
Inner Circumnav Bonus: Additional TDR Data



Now: Recent OSE Work

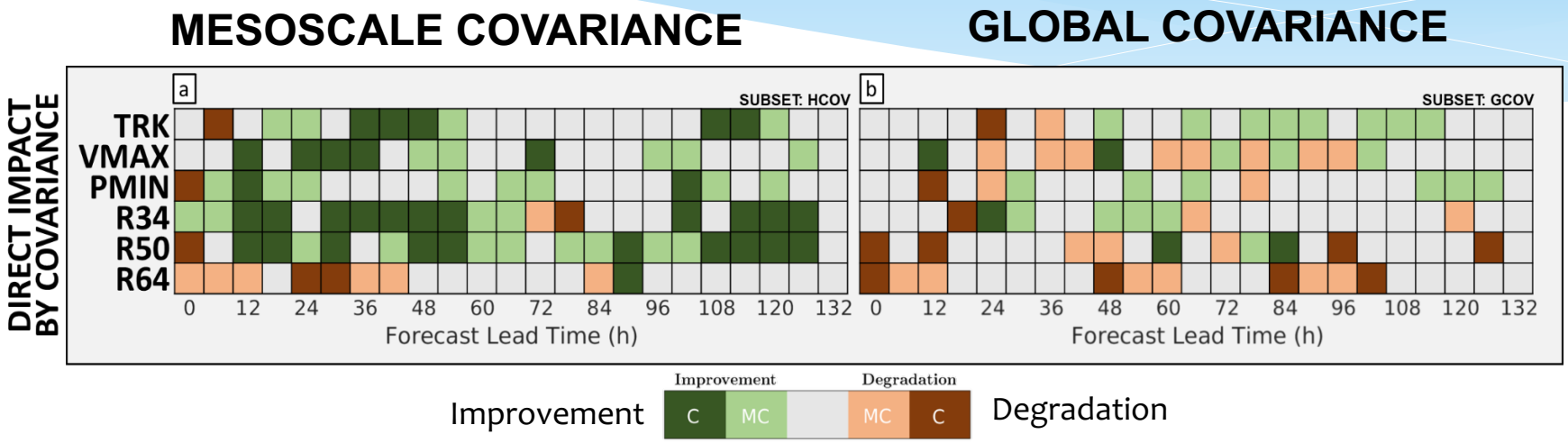
OK, but how do dropsondes affect the forecast… overall?

- We know they improve the track forecast
- We also know they cost $
- A lot of unknowns



What happens in HWRF if we take away ALL dropsondes?

Now: Ongoing OSE Work

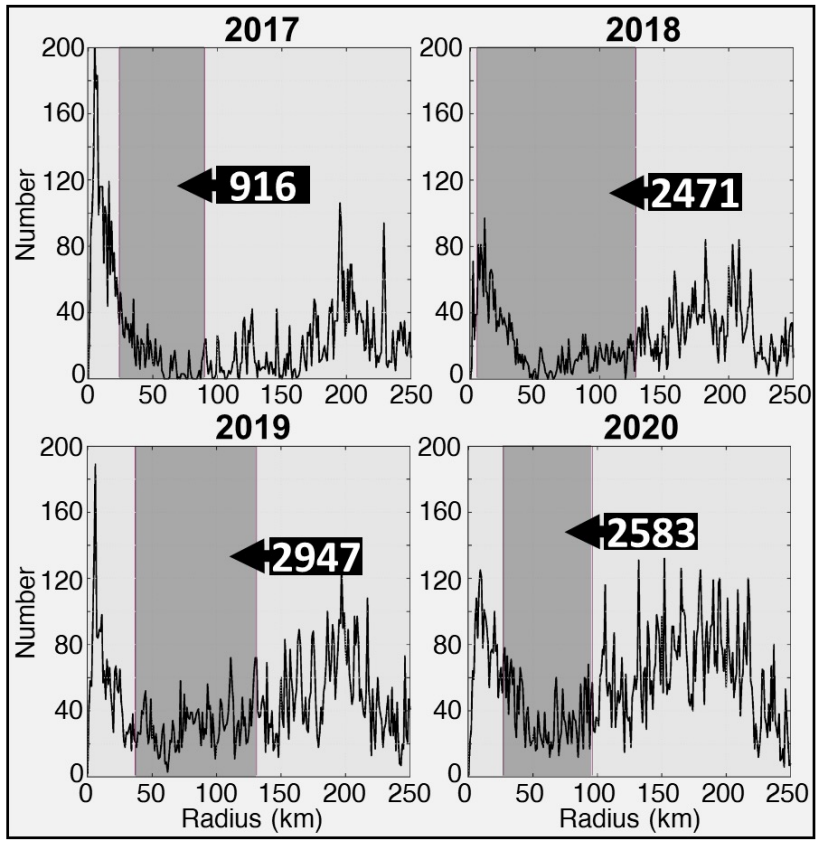


Overall impact of dropsondes in HWRF:

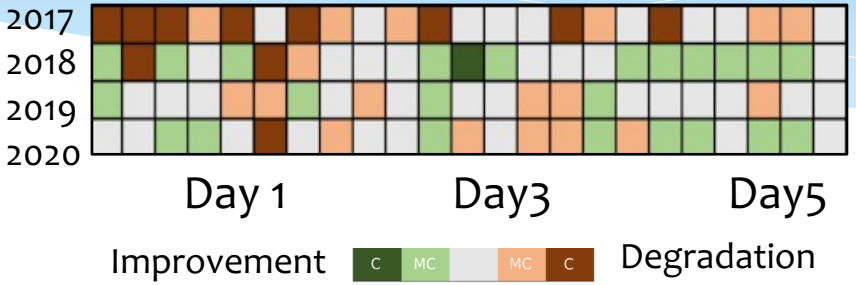
- Benefits mainly when using mesoscale covariance
- Big benefits for significant wind radii(!)
- What's up with R64?

Now: Ongoing OSE Work

Dropsondes in R64 region



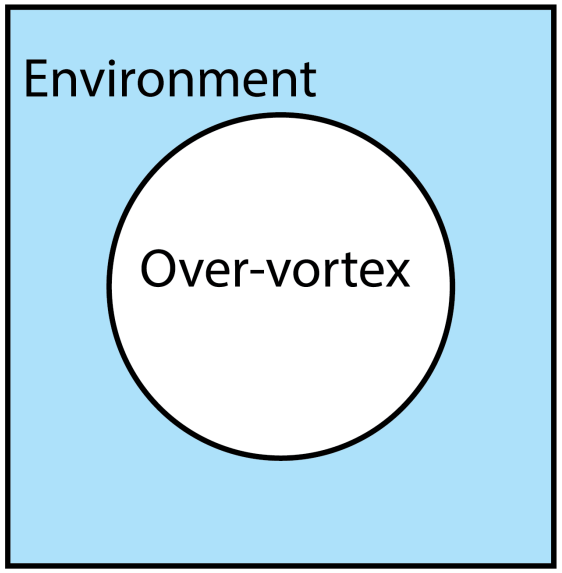
Dropsonde Impact on R64



- R64 degraded in 2017 only
- Degradation corresponds with poor near-core coverage
- Improved coverage and impacts starting in 2018

Now: Ongoing OSE Work

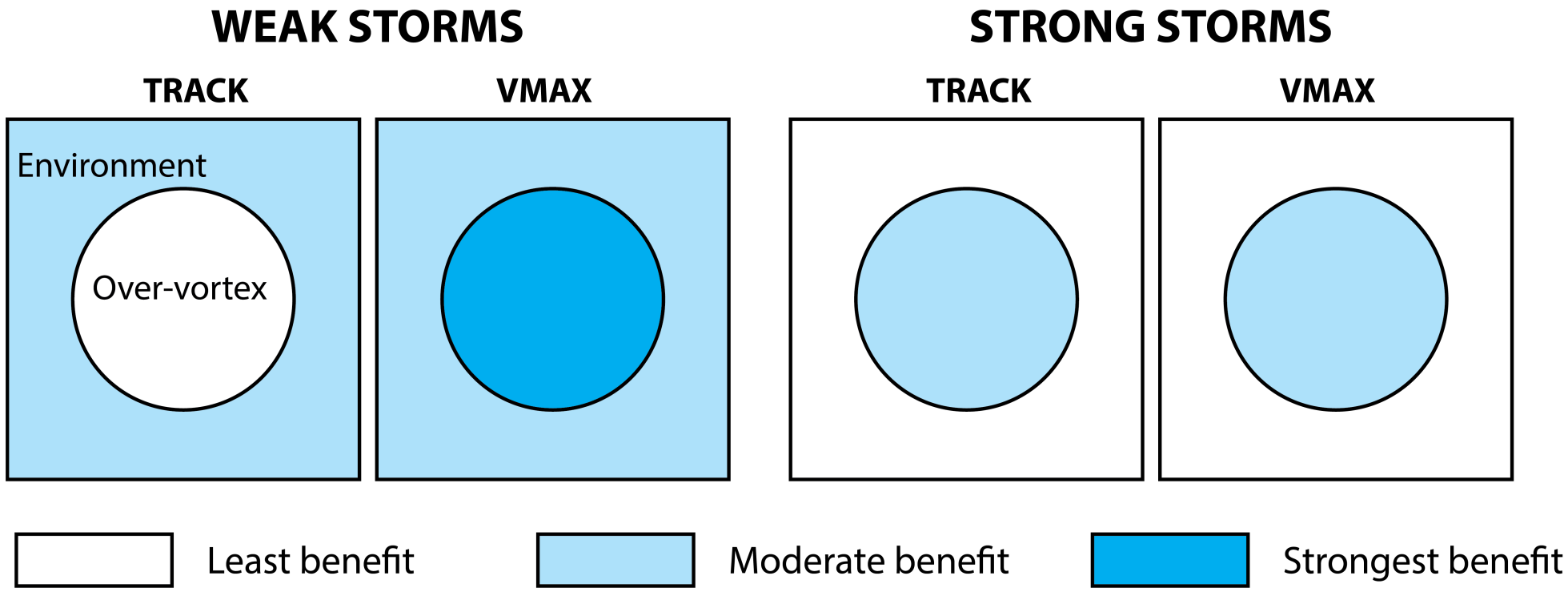
Can we say anything about how different dropsondes affect the forecast differently? ***YES!***



Example: *What are the relative impacts of environmental and over-vortex dropsondes?*

Now: Ongoing OSE Work

Comparing environmental vs. over-vortex dropsonde impacts



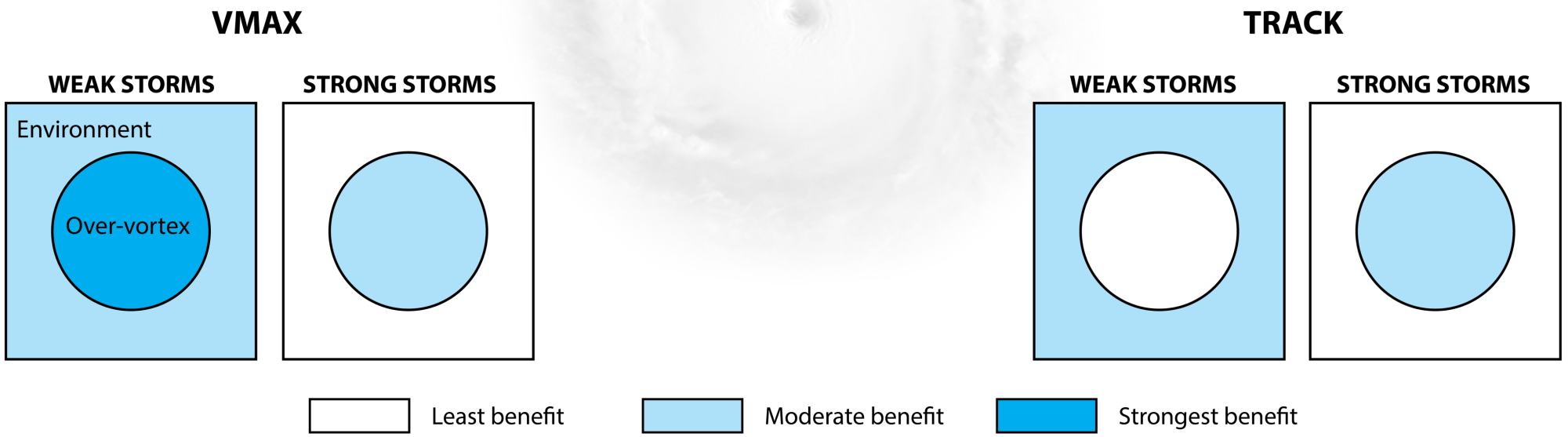
Now: Ongoing OSE Work

FOR INTENSITY (VMAX):

- Over-vortex in all storms (HUGE benefit for weak storms)
- Environment in weak storms

FOR TRACK:

- Environment in weak storms
- Over-vortex in strong storms



Now: Ongoing OSE Work

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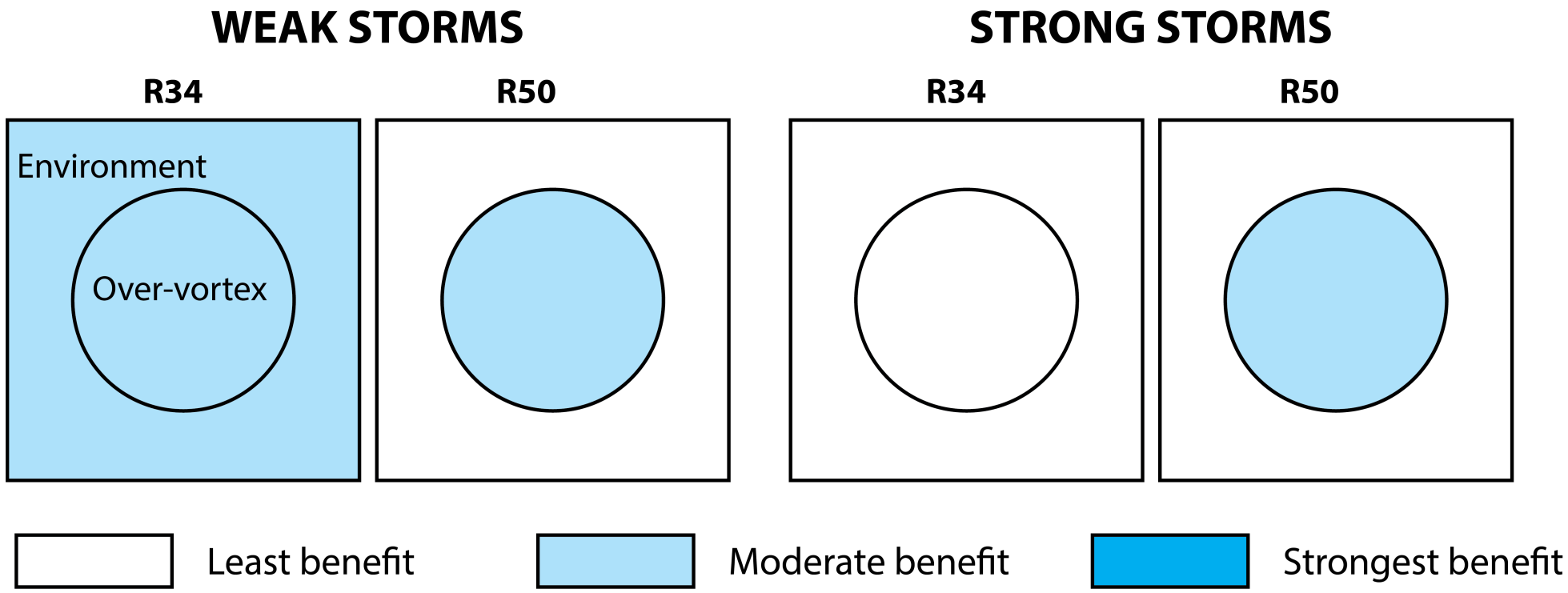
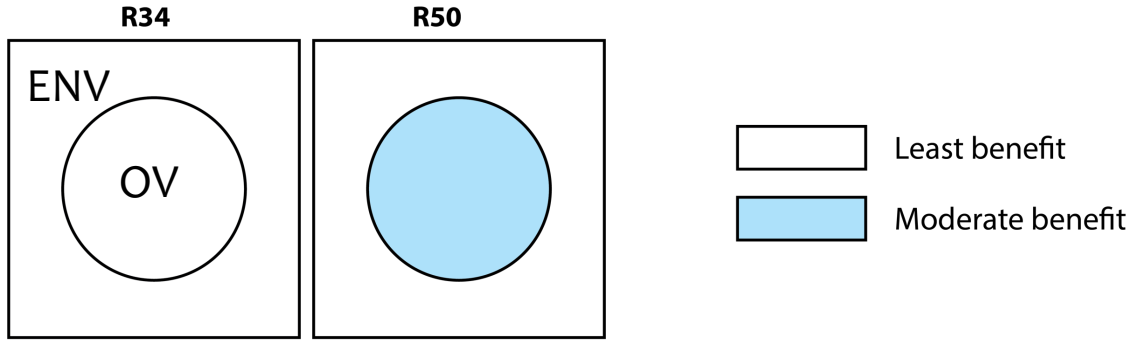


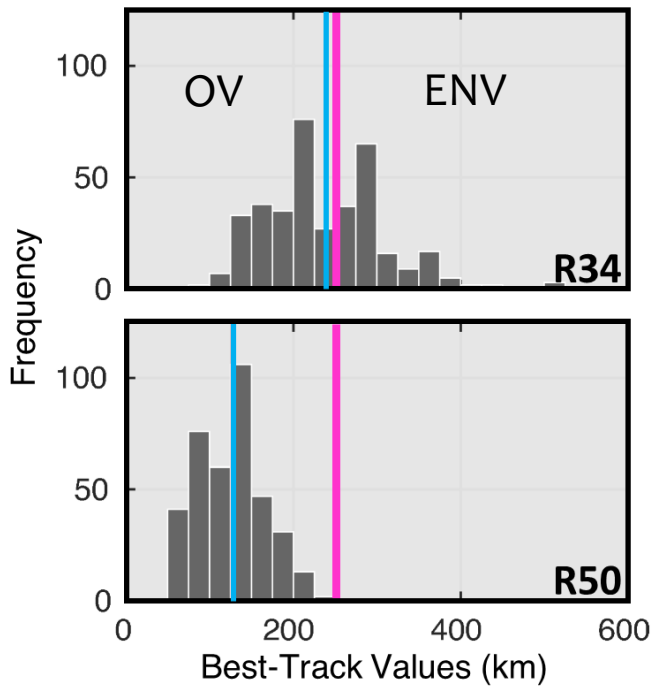
Now: Ongoing OSE Work

A closer look at strong storms:

- Observed R50 lies in the "over vortex" region
- Observed R34 near the vortex/environment border
- Sondes *either* in environment or over-vortex can improve R34, but neither region dominates

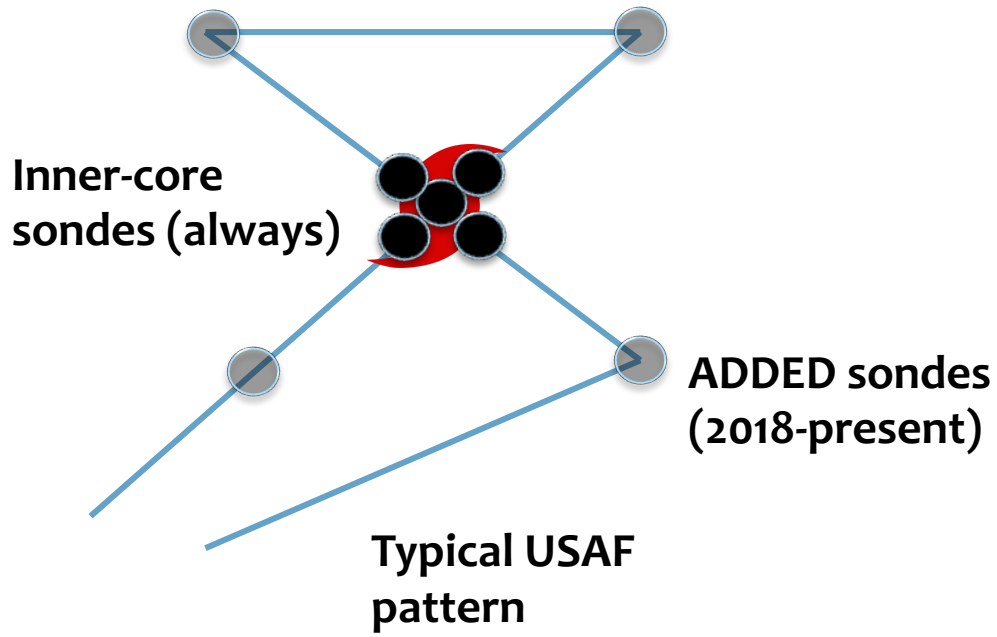


Observed R34 and R50



Now: Ongoing OSE Work

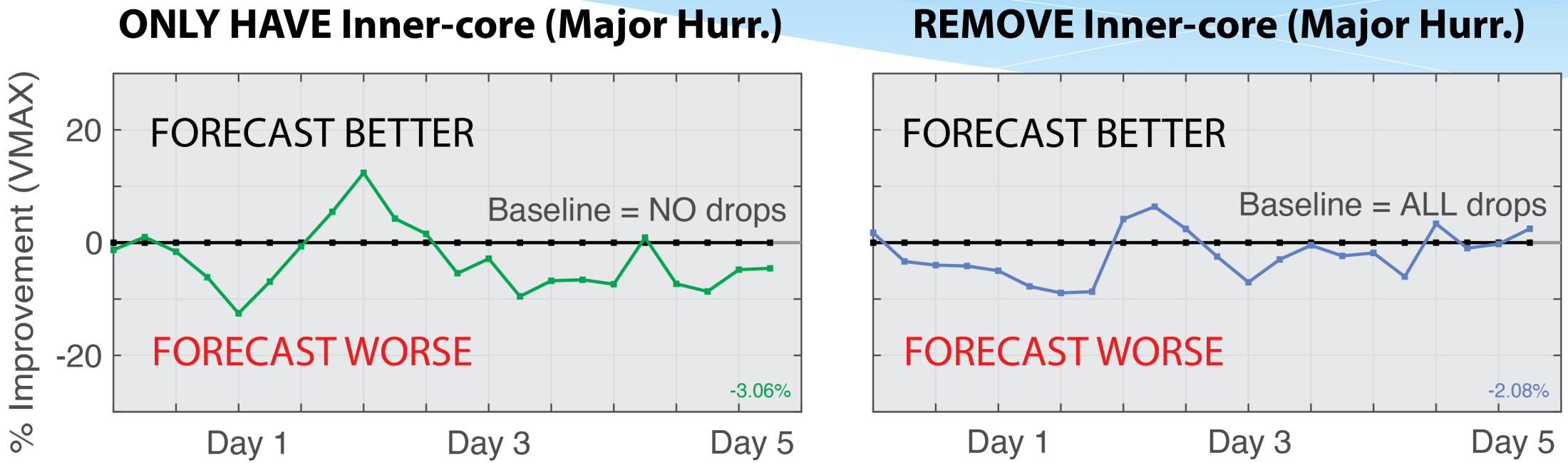
Turning back to that USAF pattern….



TWO QUESTIONS:

1. What happens if we ONLY HAVE inner-core dropsondes
2. What happens if we TAKE AWAY inner-core dropsondes

Now: Ongoing OSE Work

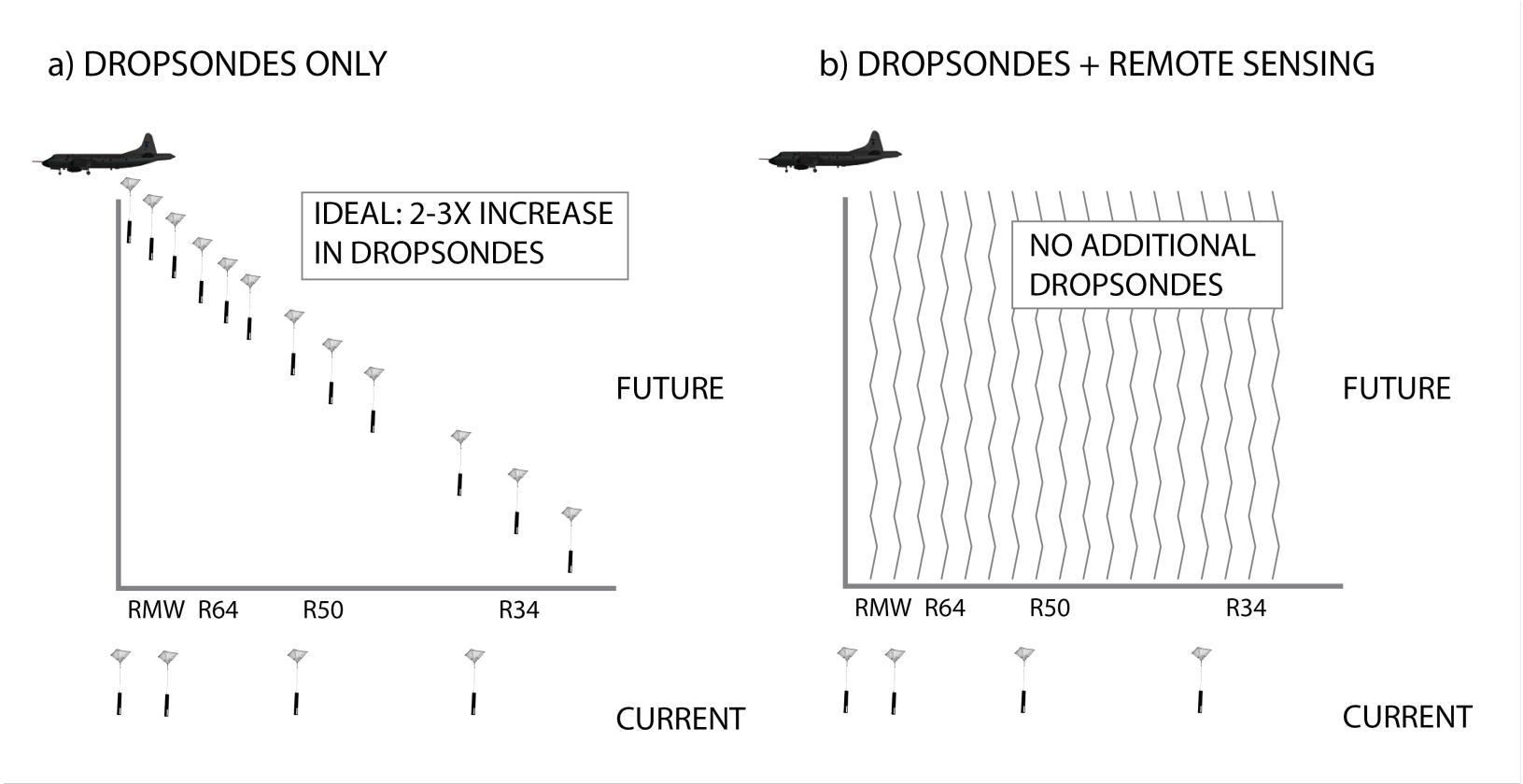


1. ONLY inner-core sondes: Inner-core sondes degrade forecast (left)
2. Good sonde sampling: Inner-core sondes improve forecast (right)

Now: Ongoing OSE Work

For optimal sampling, we need either:

- Significantly more dropsondes; or
- Remote sensing



QUIZ!

Where should reconnaissance sample to *most* benefit a TC intensity forecast?

- A – In the TC vortex
- B – In the TC environment
- C – Ahead of the TC
- D – None of the above

QUIZ!

True or false: Sampling in a TC vortex can improve the track forecast.

- A – True
- B – False

Brief summary

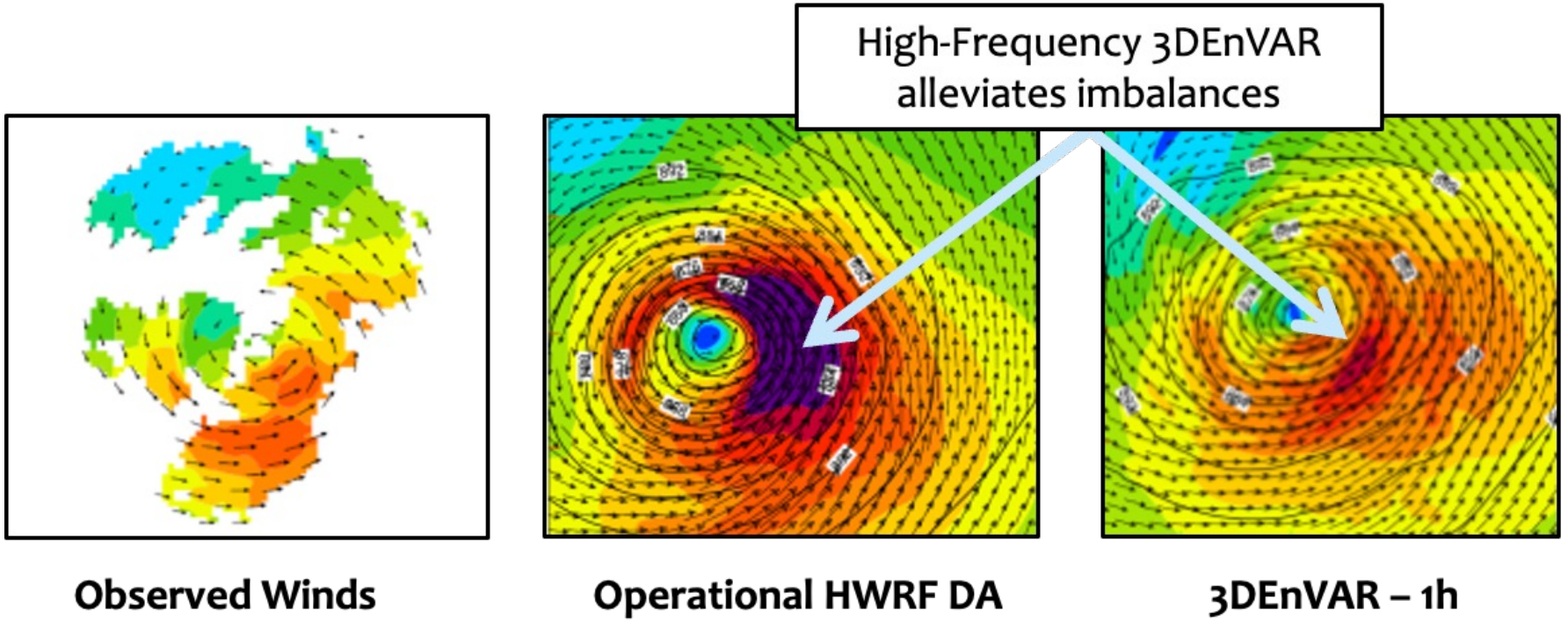
- Track and intensity errors are both improving
- DA & physics improvements jointly improve model performance
- Significant improvements in HWRF, GFS, and approach to reconnaissance

Outline

- Background: Observations, modeling and data assimilation
- History: Improving forecasts by improving NWP
- Now: Recent and ongoing work
- Future: A new path forward

Future Direction: Improving DA

Improving the DA system improves analyses of TCs

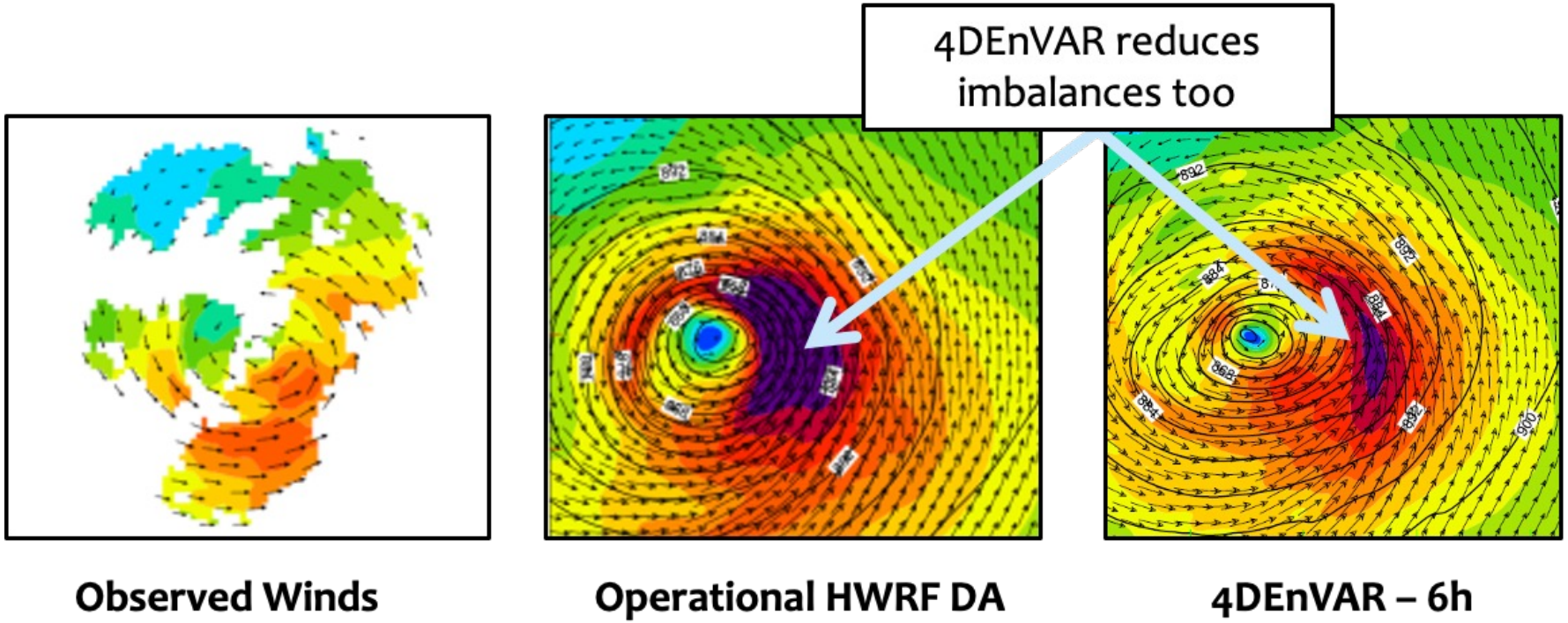


Observed Winds | **Operational HWRF DA** | **3DEnVAR – 1h**

Observations vs DA: Analyses Using Experimental OU HWRF System

Future Direction: Improving DA

Improving the DA system improves analyses of TCs



Observed Winds

Operational HWRF DA

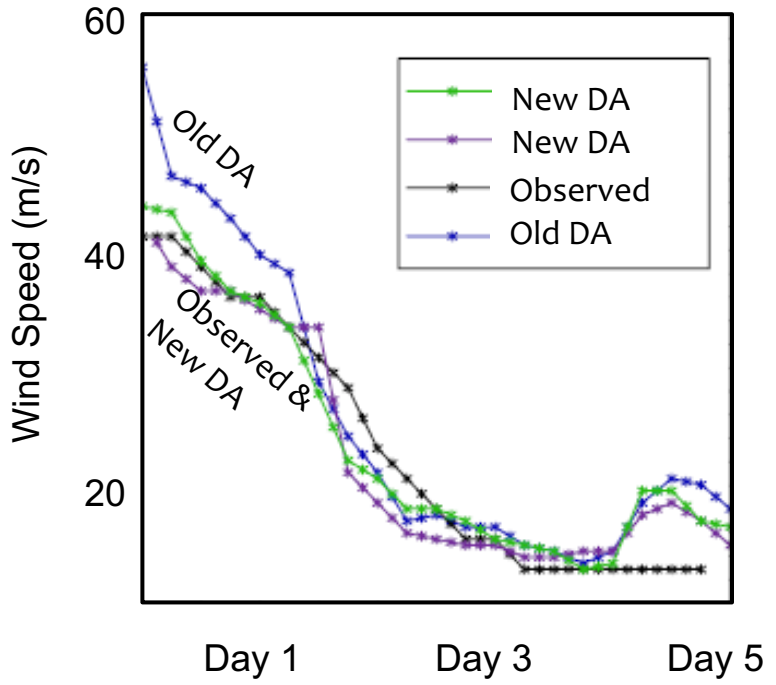
4DEnVAR – 6h

Observations vs DA: Analyses Using Experimental OU HWRF System

Future Direction: Improving DA

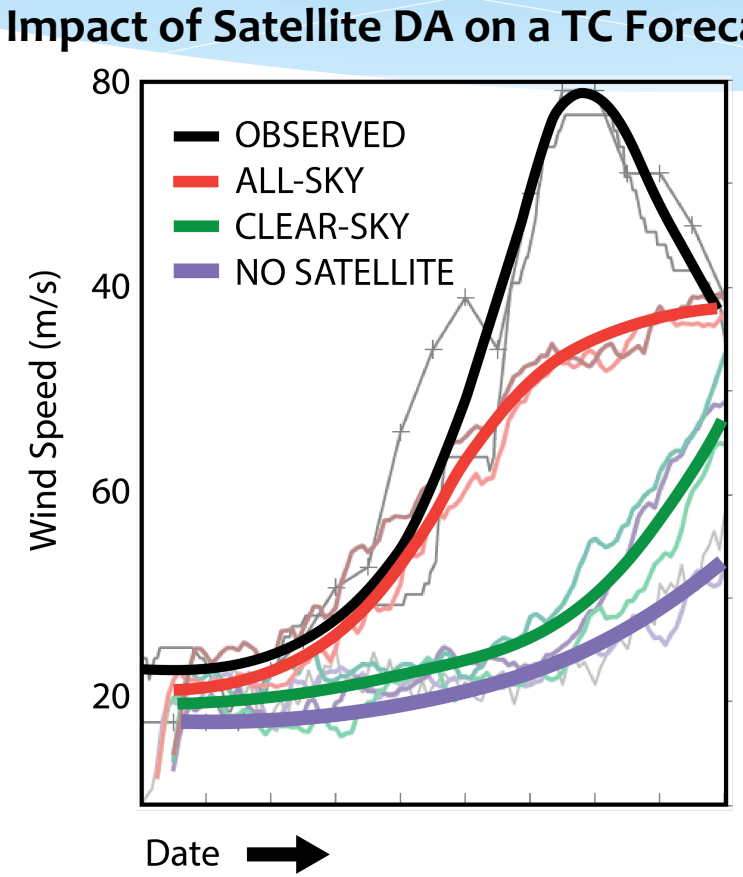
- Better analyses means better forecasts!
- Better DA is being being developed for next-generation hurricane model
- This appeals to researchers

Intensity forecasts initialized from various analyses



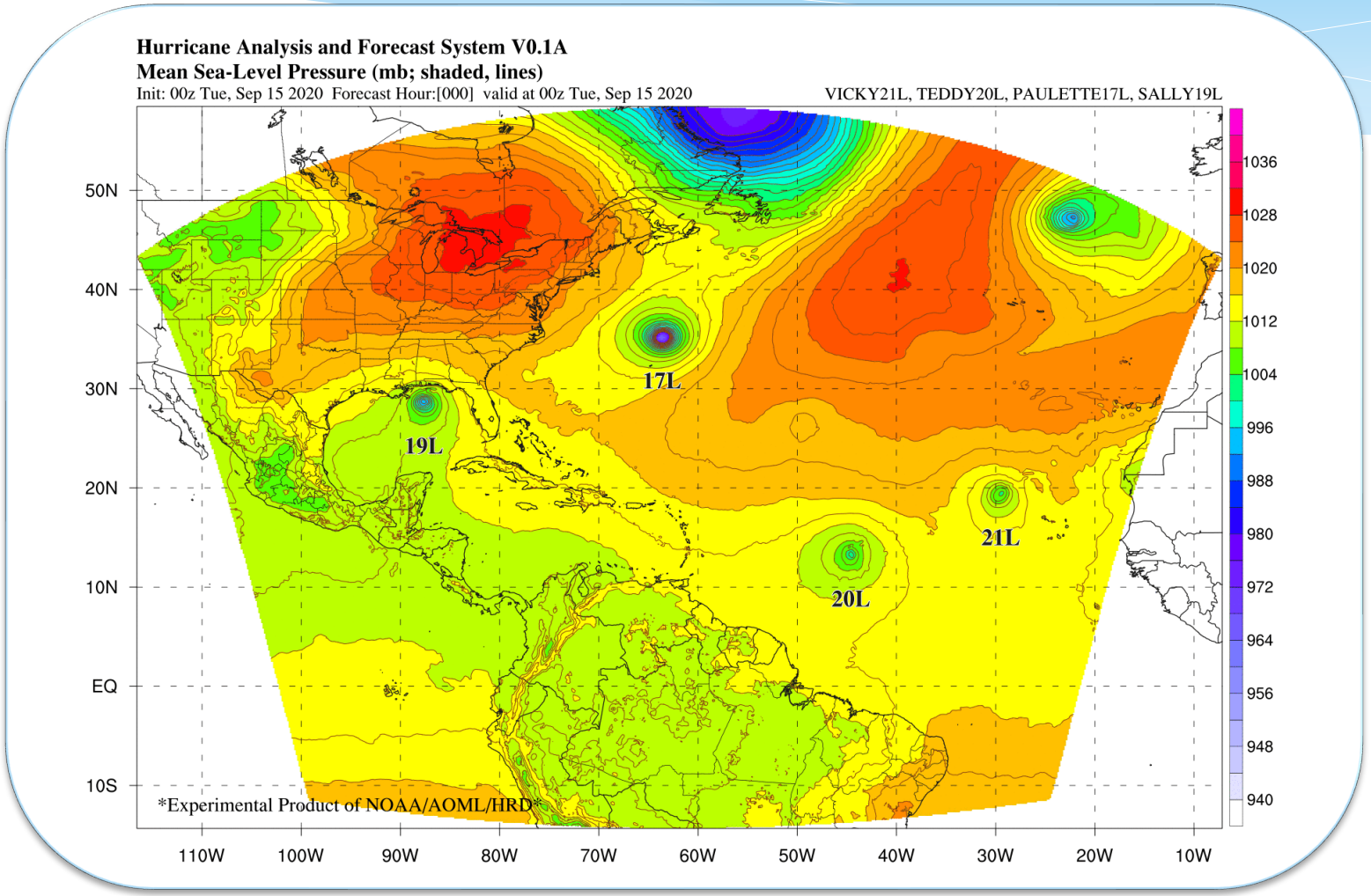
Future Direction: Improving DA

- Most storms do NOT have recon
- Satellite DA needs to help!
- Satellite DA for TCs is where recon DA was 10 years ago
- Initial results are showing amazing possibilities



Future Direction: HAFS

(Hurricane Analysis and Forecast System)



Future Direction: HAFS

(Hurricane Analysis and Forecast System)

MAJOR POTENTIAL BENEFITS OF HAFS:

- More flexible / capable data assimilation system than HWRF
- Much better use of satellite data than HWRF
- Realistic storm interaction, not possible in HWRF

RESULT:

- Better initialization of vortex and environment
- Improved track and intensity forecasts

Conclusions

- NOAA TC prediction is undergoing dramatic advancements
- We are using more of the available data in DA
- Long term plans address ongoing issues and allow for greater data usage
- The above factors should contribute to forecast improvement… BUT

Conclusions

- This will all be contingent upon how much our society wants to invest into it…