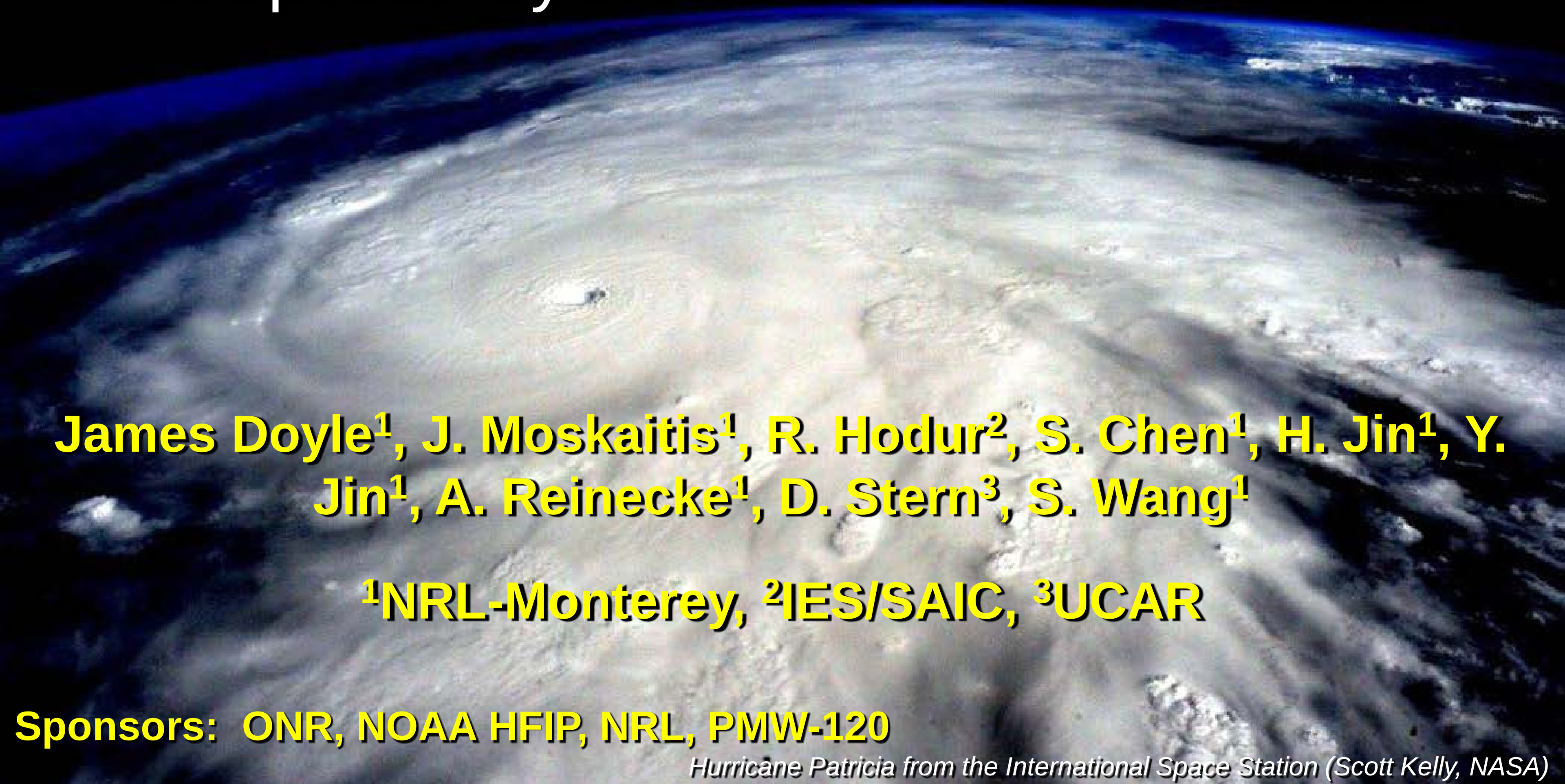
Most Promising Short and Long-term Directions to Improve Operational Tropical Cyclone Forecast Models



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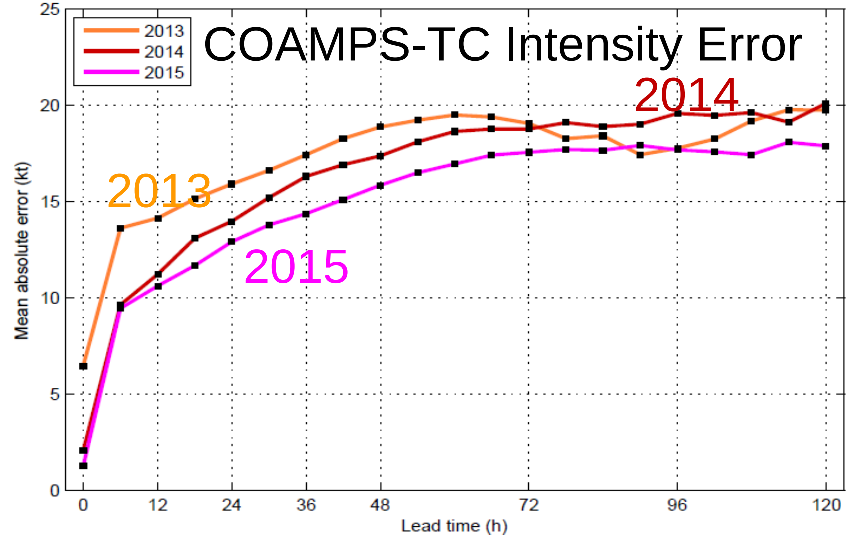
Sponsors: ONR, NOAA HFIP, NRL, PMW-120

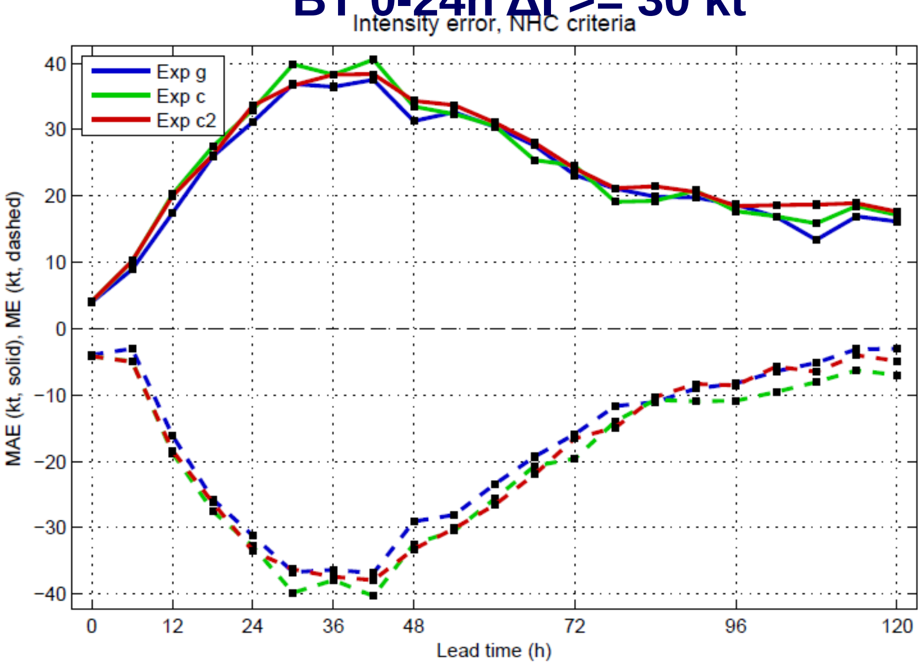
Hurricane Patricia from the International Space Station (Scott Kelly, NASA)

Motivation

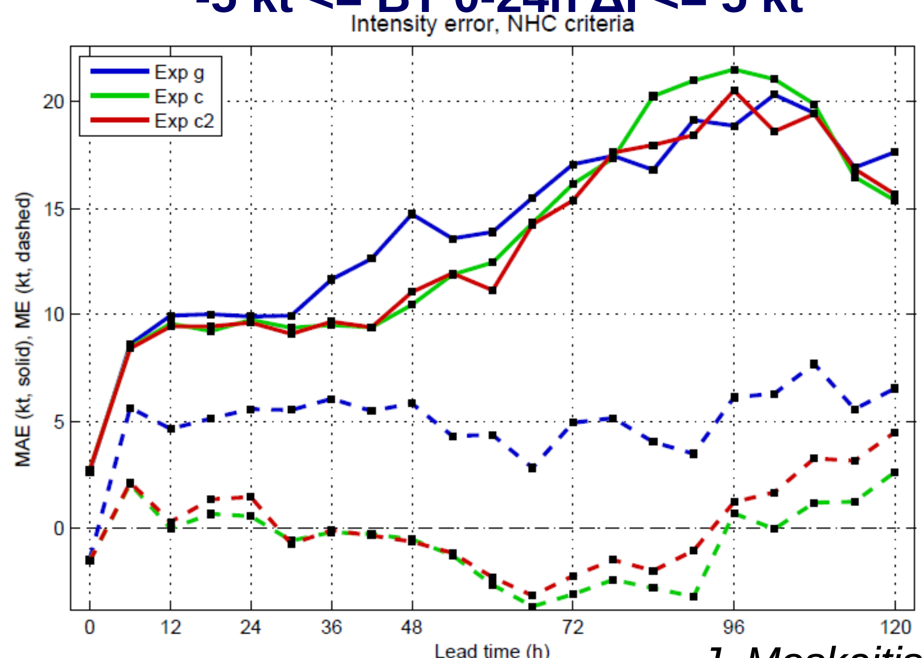
- **TC Track and Intensity Prediction**
  - Remarkable improvements in TC track predictions in past 2 decades.
  - Intensity prediction skill remains a great challenge (although some recent success)
  - Models are still poor at capturing TC intensity change (particularly RI & RD)
- **For this Presentation, Focus on Intensity (& Structure Prediction) Gaps**



BT 0-24h ΔI >= 30 kt



-5 kt <= BT 0-24h ΔI <= 5 kt



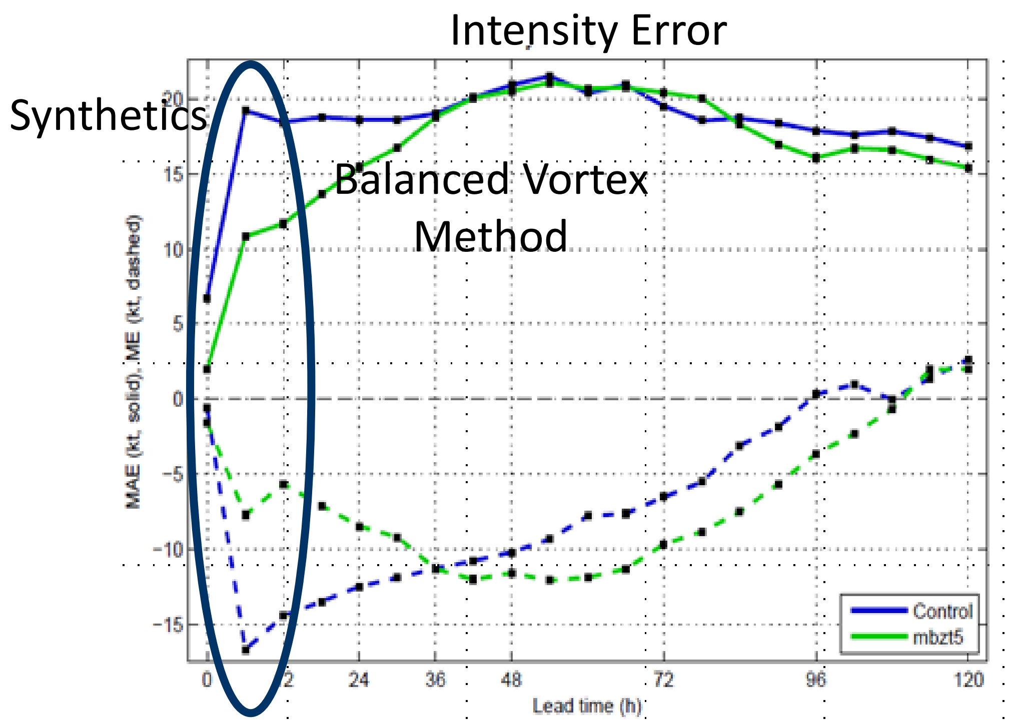
J. Moskaitis

1. Get Off To a Good Start

Initialization for Short-Term Intensity Forecasts

i) Initialize a more realistic vortex (short term)

- Represent structure, asymmetries at initial time
- Proper balance reflecting the *time tendency of intensity*
- “Advanced” initialization methods needed to move beyond bogus…
  - Current COAMPS-TC: Balanced vortex
  - Future: 4D-Var or hybrid methods for the vortex



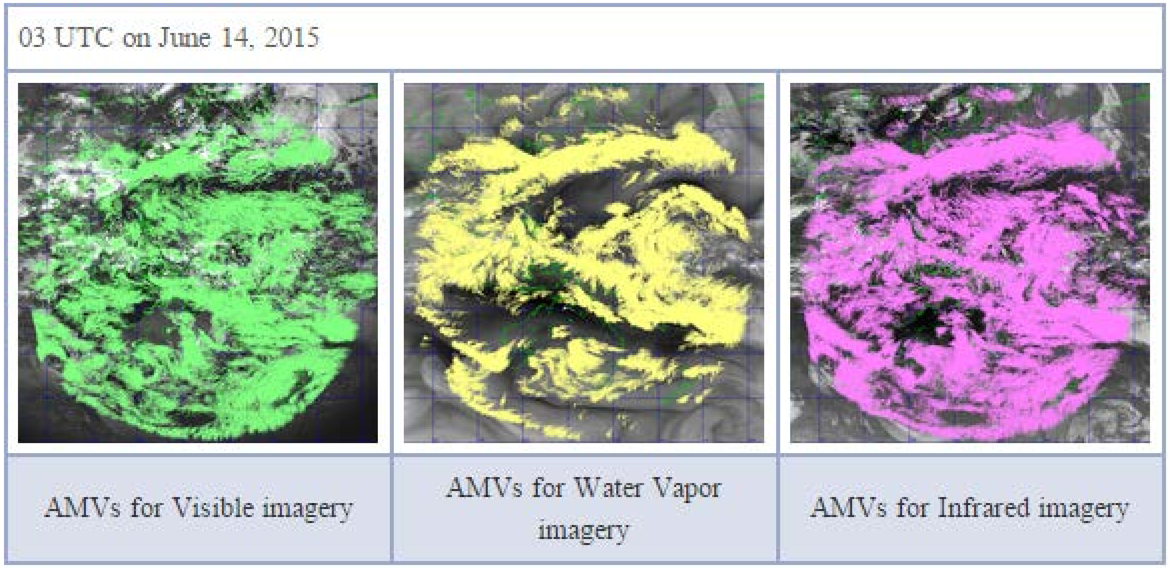
Results show new bogus decreases model spin-down during first 6-12 h

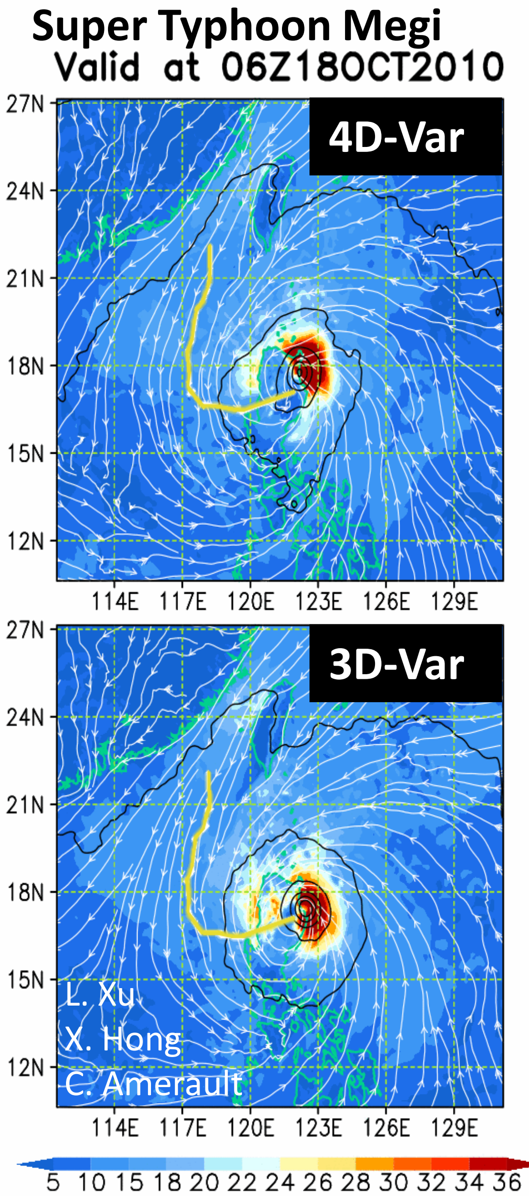
1. Get Off To a Good Start

Data Assimilation

ii) Assimilation in the Environment

- Advanced DA (e.g., 4D-Var & hybrid) to represent environment interactions.
- Assimilation through DA time window to represent intensity tendency.
- New era of *high-temporal freq.* AMVs (GOES-R, Himawari)
- DA in outflow layer may be critical (ONR-TCI)



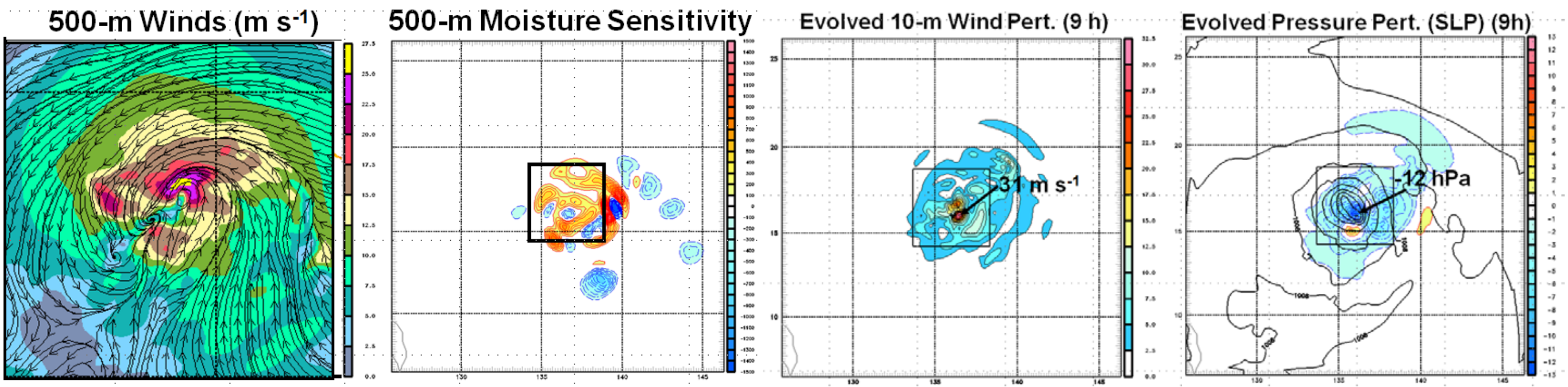


1. Get Off To a Good Start

Data Assimilation

iii) Data assimilation to initialize TC

- Accurately initialize vortex with no or minimal bogus (4D-Var, hybrid…)
- Represent the initial intensity & tendency
- Assimilate all inner core obs (satellite, dropsondes, SFMR, radar, etc.)
- Improved initial conditions of **moisture is critical**
- Tools for intensity targeting (observe where its needed)



Doyle et al. (2012)

Improved moisture data assimilation especially needed

- **TC intensification is very sensitive to initial low & mid-level moisture.**
- **Perturbations of 1g/kg can lead to large intensity changes (20 ms^{-1}/9h)**

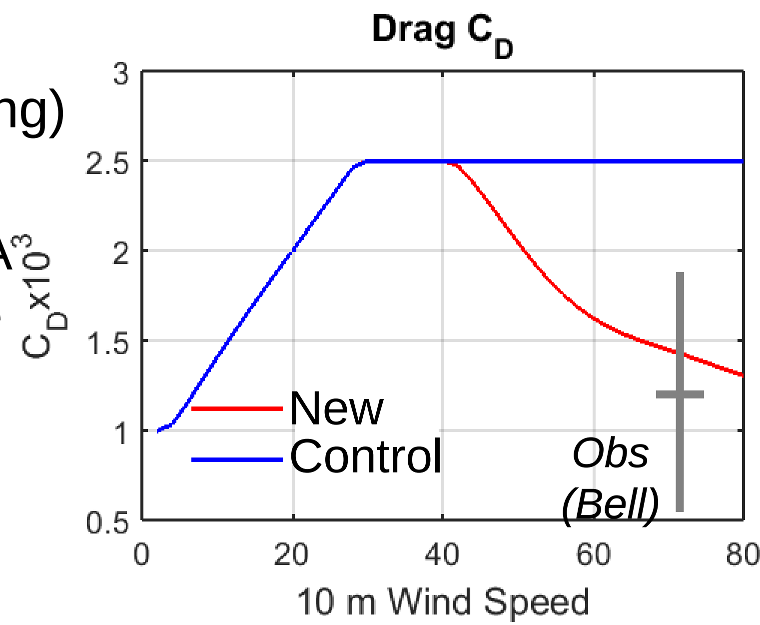
2. Improve Air-Sea Interaction Processes

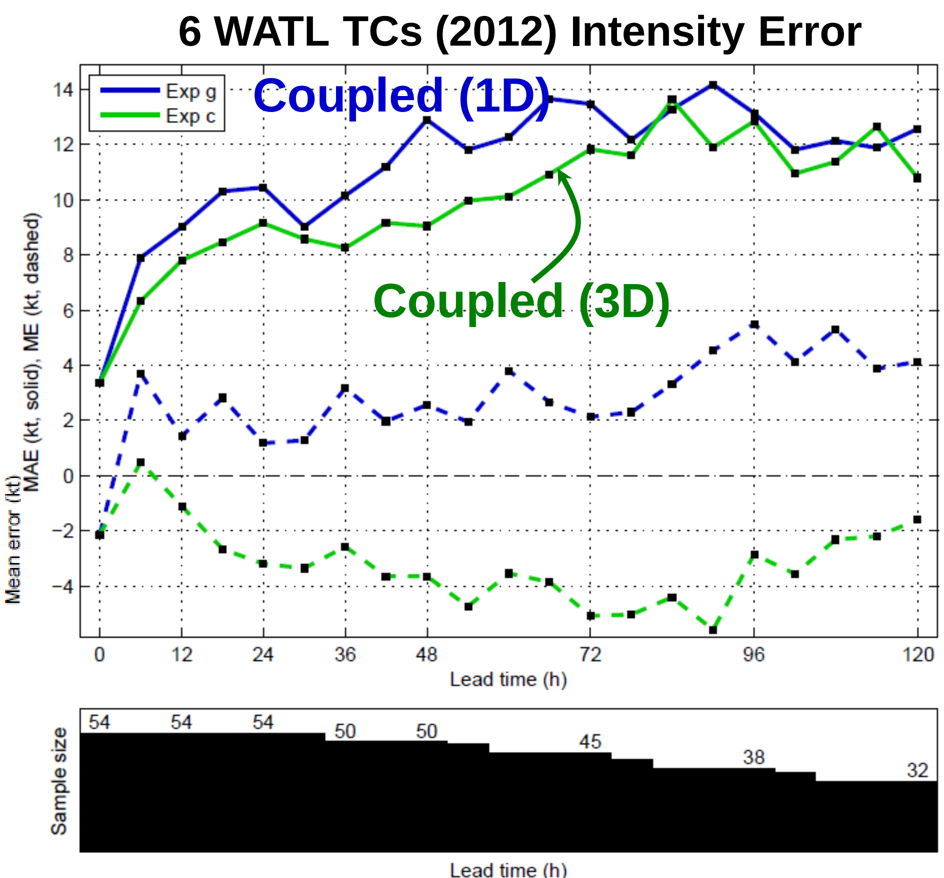
i) Improve the representation of Cd, Ck

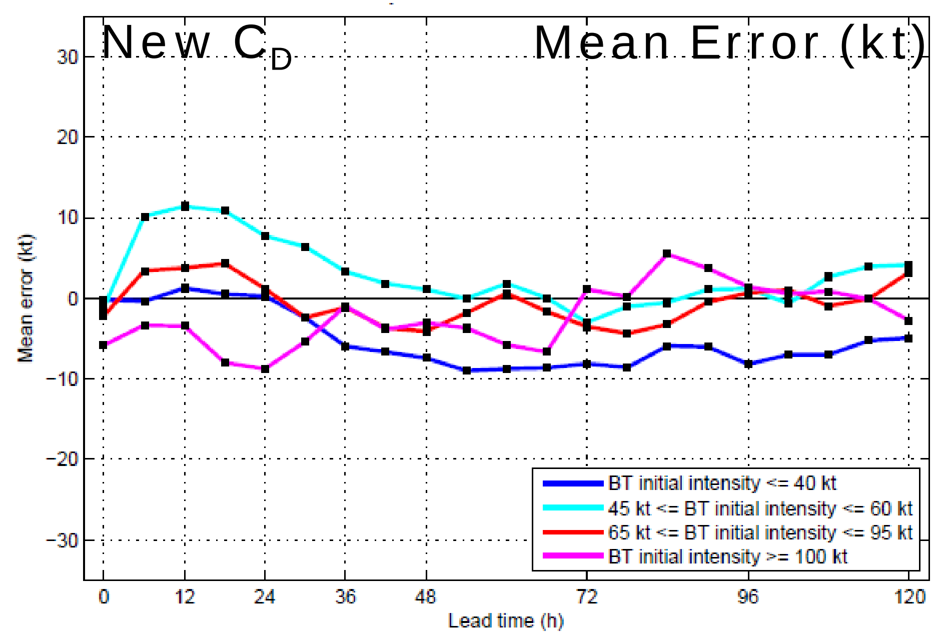
- Most sensitive parameters in the physics
- Wave state dependence (air-wave coupling)

ii) Advanced air-sea interaction coupling

- Air-ocean-wave coupling with coupled DA
- Consistent fluxes across air-sea interface



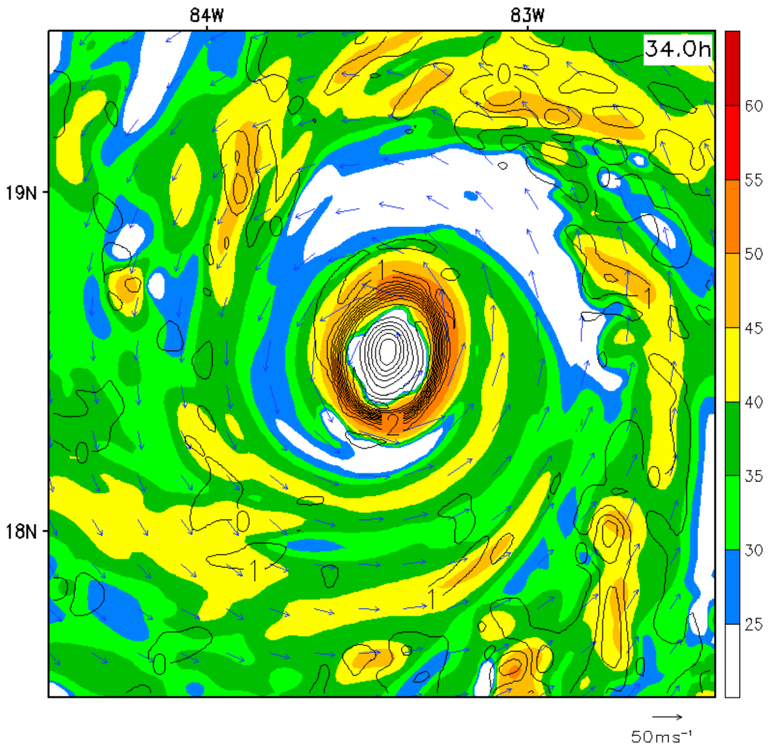




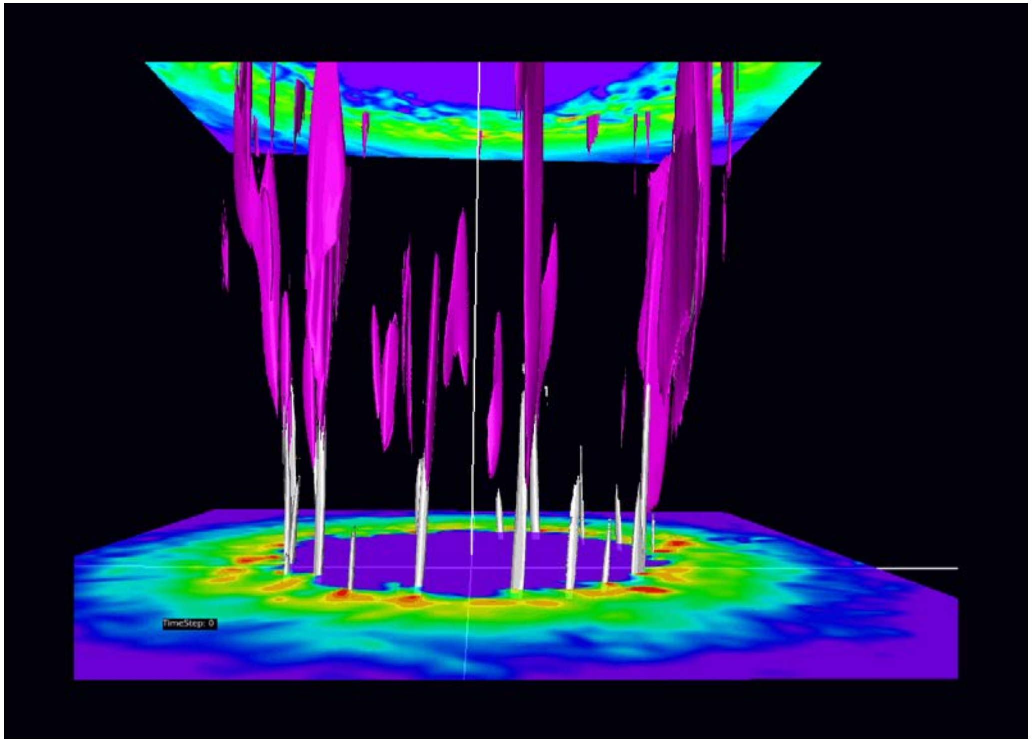
3. Advanced TC Model Physics

TC Community Physics

- Problem is too challenging for any one organization or entity
- Development of a community-based *TC Physics Suite* needed
  - TC fluxes, PBL, microphysics, shallow/deep convection, radiation
- Physics development informed by systematic observations and LES



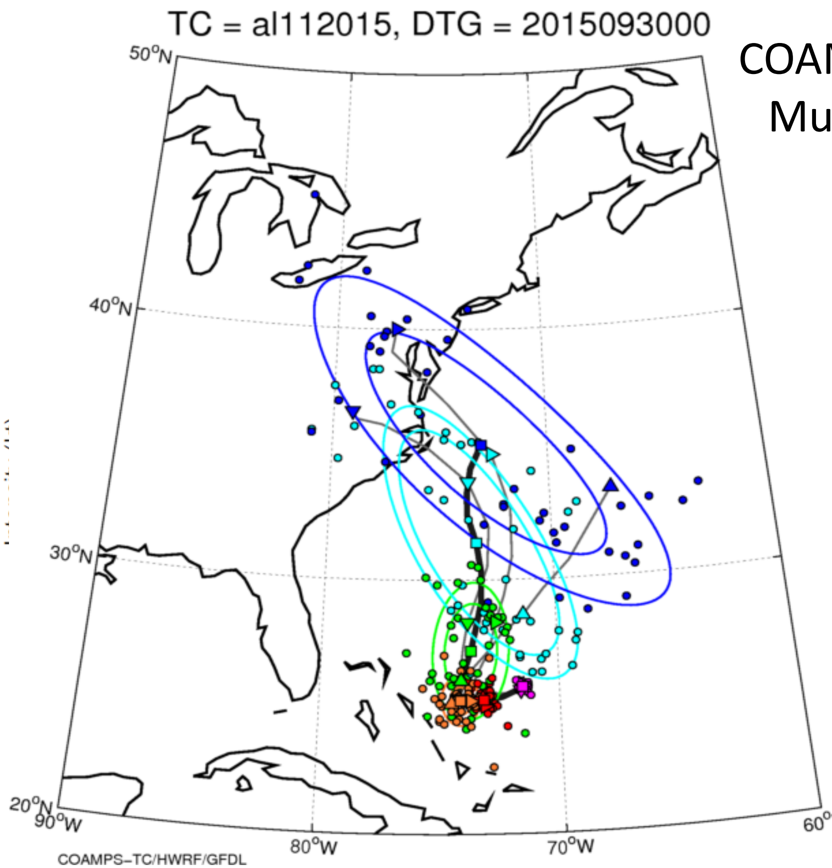
Eyewall replacement cycle in Hurricane Wilma using COAMPS-TC with 1.7 km resolution and more advanced physics (Thompson, new PBL) (Hao Jin)



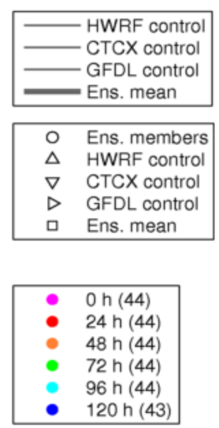
Large Eddy Simulation (dx=60m) of idealized hurricane using CM1 (Dan Stern and George Bryan)

4. High-Resolution Multi-Model Ensemble

- **Intensity changes (RI) may not be predictable in a deterministic sense.**
- **Multi-model ensembles are more capable of accounting for forecast uncertainty due to model & IC errors, than a single-model ensemble.**
- **Real-time HFIP ensemble: COAMPS-TC (3km), HWRF (3km), GFDL (6km)**
- **COAMPS-TC & HWRF control consensus and ensemble mean outperform their single-model counterparts in deterministic validation**



COAMPS-TC/GFDL/HWRF
Multi-Model Ensemble



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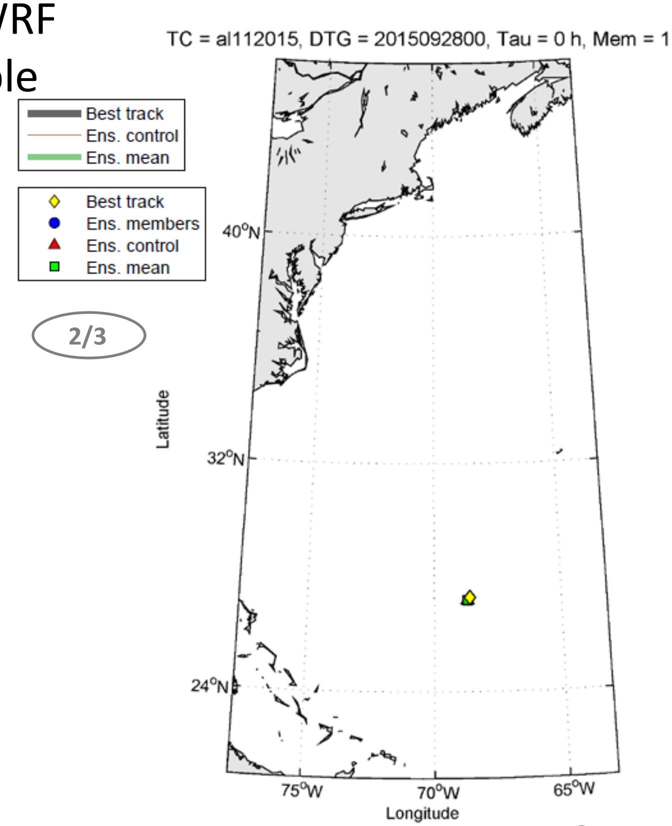
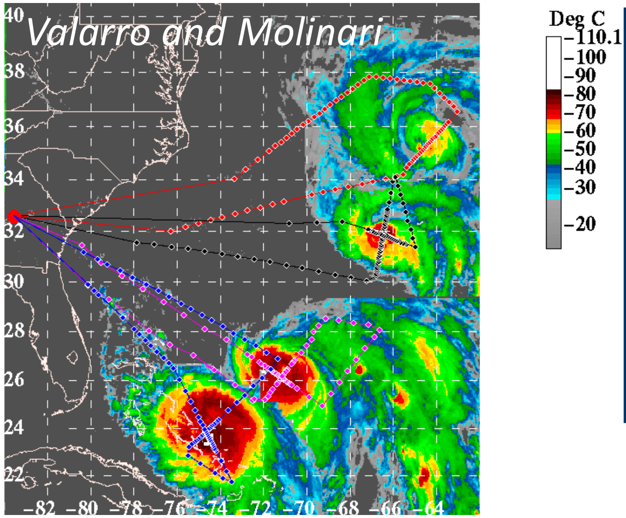
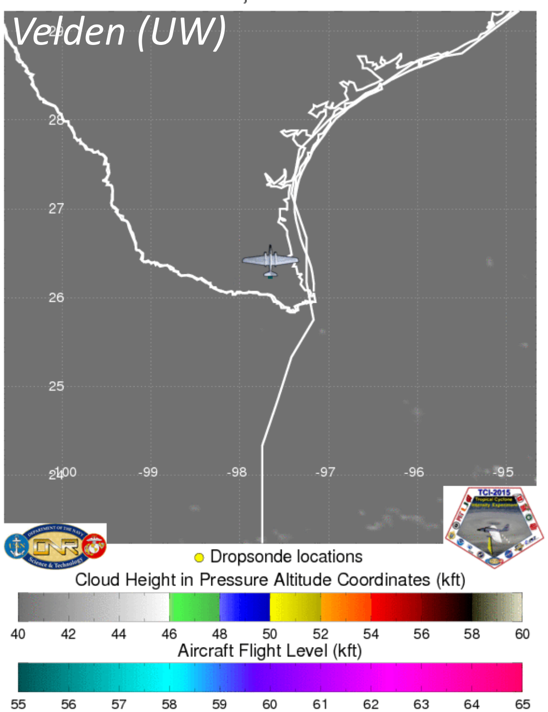


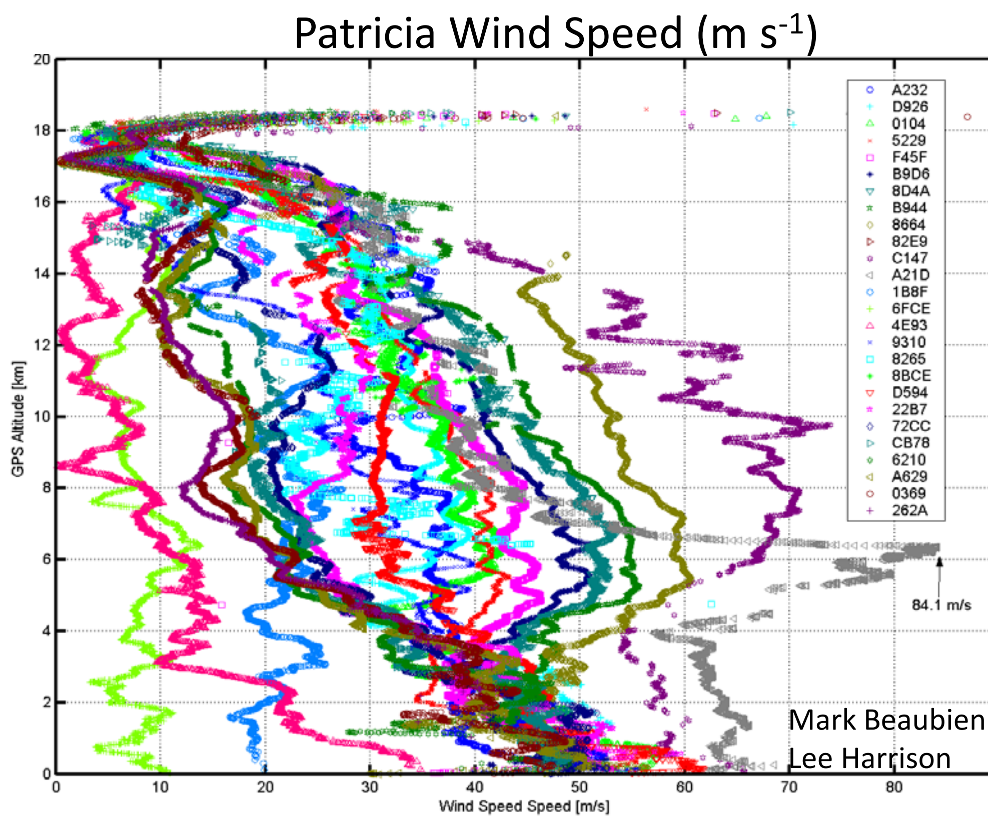
5. Model Evaluation and Verification



WB-57 flight track and HDSS dropsondes
on October 23, 2015 at 1805 UTC

- **Need to <u>routinely</u> evaluate models with more obs (radar, satellite, field data, …)**
- **Verifying only U_{max}, position is insufficient**
- **~800 dropsonde & HIRAD obs in Hurricanes Patricia, Joaquin, Marty in ONR TCI.**
- **More complete metrics needed.**





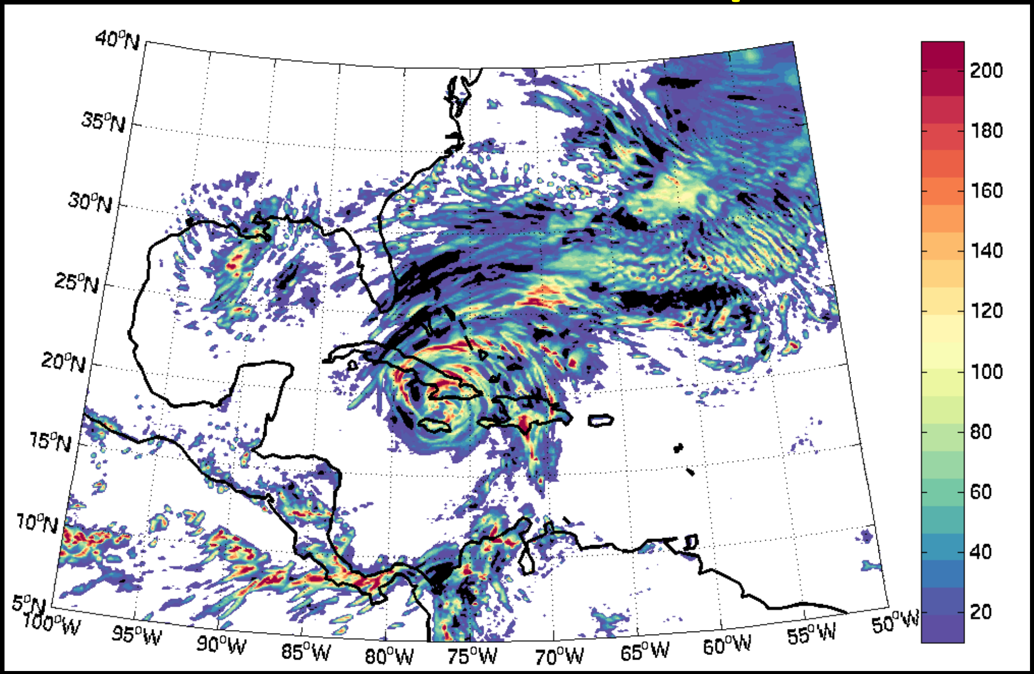
6. Next-Generation Models

Navy's NEPTUNE

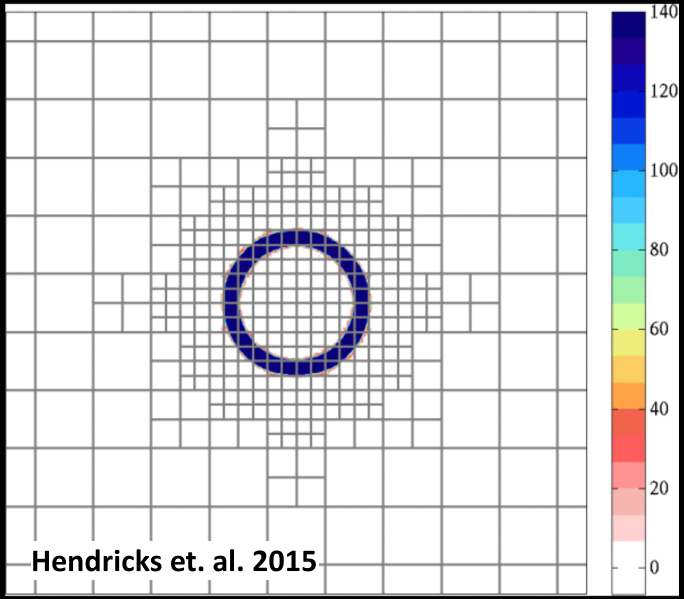
- Utilize advanced numerical methods in a global model (e.g., spectral element in Navy's NEPTUNE) to better resolve TCs and the environment.
- Goal is to achieve global cloud resolving scales (no cu-param. needed) with adaptive mesh refinement capability to better resolve TC and cloud processes.
- Highly scalable on next-generation computer architectures (100K to 1M cores)

Hurricane Sandy

12-h Accumulated Precipitation



Adaptive Mesh Refinement



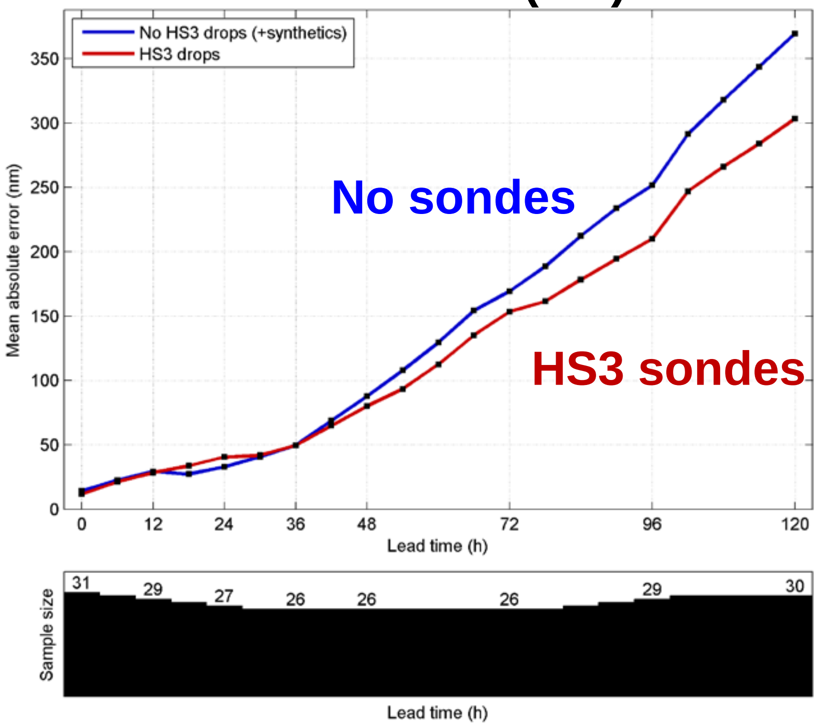
Summary

Key Short and Long-term Directions to Improve Operational TC Models

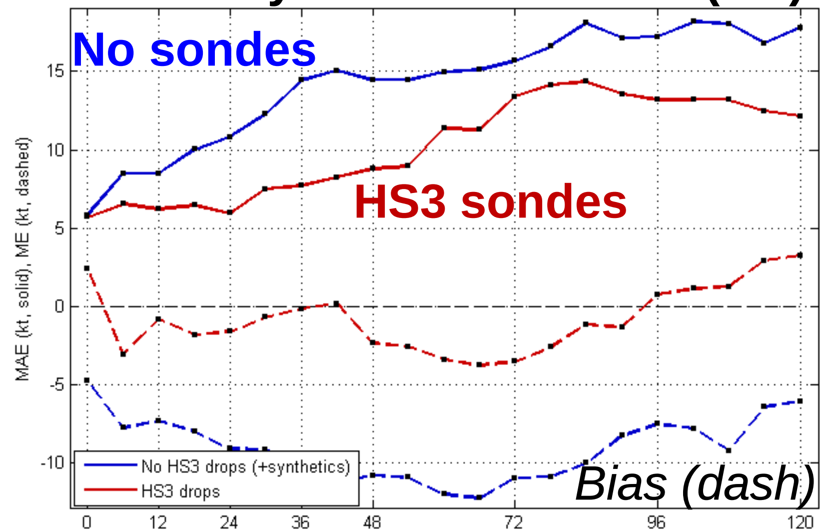
1. **Advanced DA needed, reduce short term intensity error, target moisture**
2. **Improve air-ocean-wave interactions in models**
3. **Advanced TC model physics through community development**
4. **High-res. multi-model ensembles for probabilistic intensity prediction**
5. **High-resolution observations to evaluate the models**
6. **Next generation global (and limited area) model capable of cloud-resolving resolutions for TC applications (e.g., Navy's NEPTUNE)**

Impact of HS3 Dropsondes for Nadine

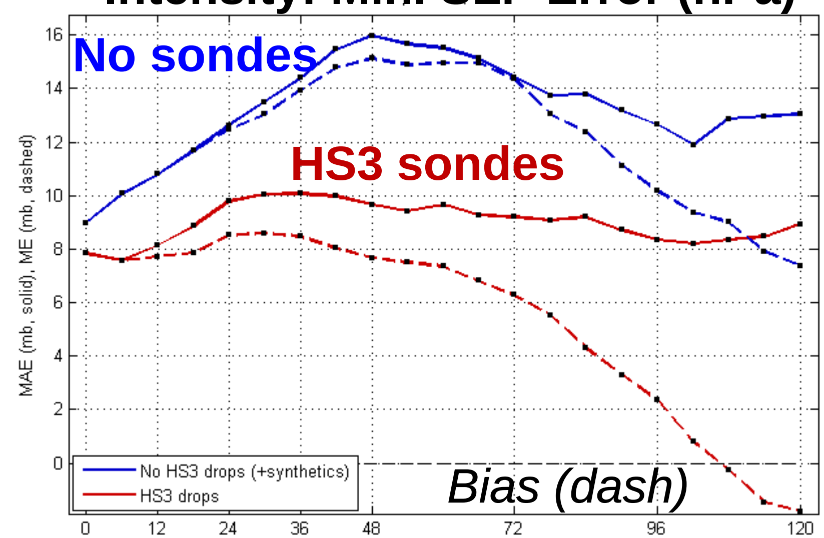
Track Error (nm)



Intensity: Max. Wind Error (kts)



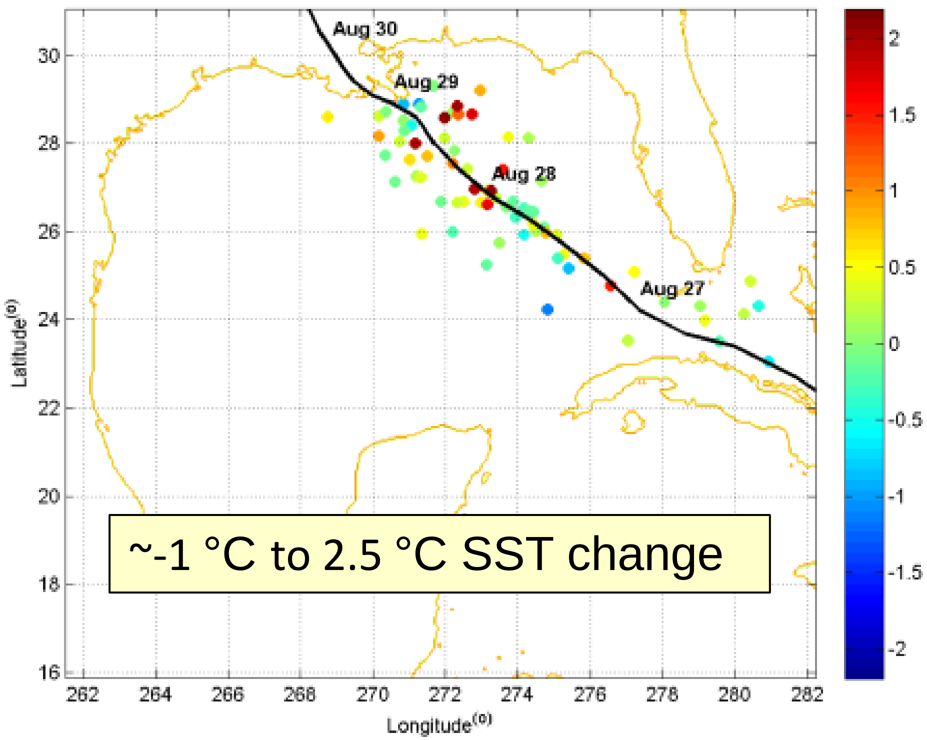
Intensity: Min. SLP Error (hPa)



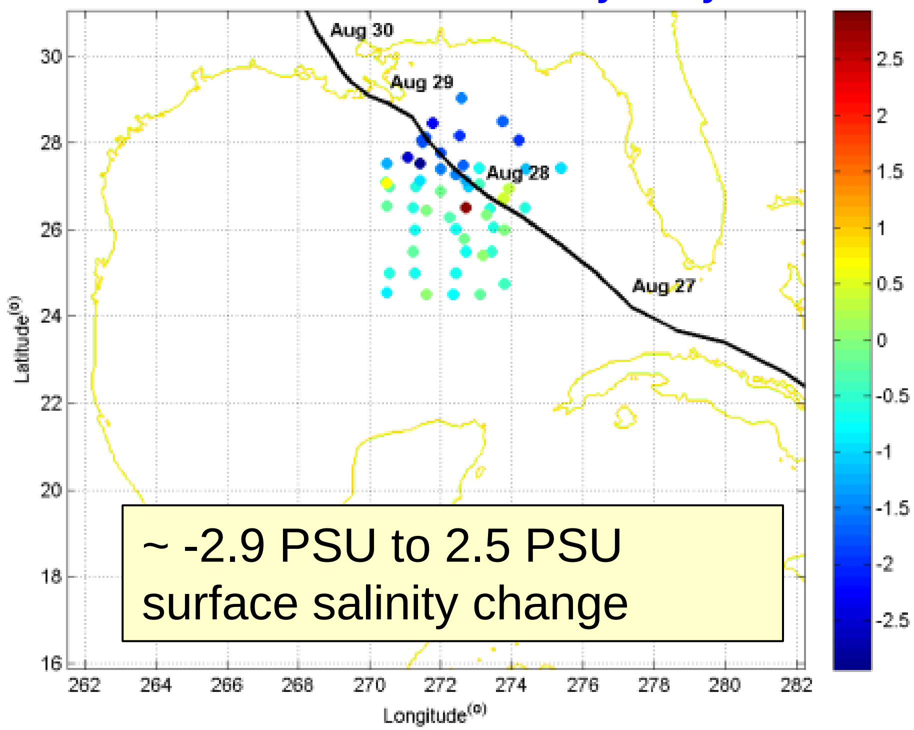
- **Sensitive regions are often well observed by HS3 dropsondes**
- **Dropsonde impact experiments performed for 19-28 Sep. (3 flights)**
- **COAMPS-TC intensity and track skill are markedly improved using HS3 drops.**
  Future: New QCed sondes, impact vs. altitude, EnKF & 4D-Var studies

Assimilating the High-resolution in-Situ Ocean Observations

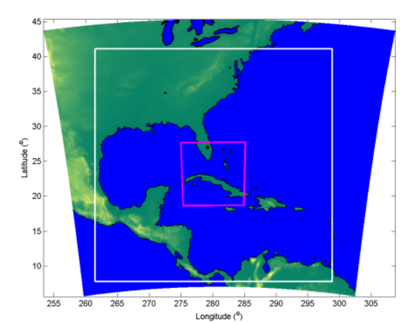
SST (°C)
Observation - COAMPS SST analysis



Surface Salinity (PSU)
Observation - COAMPS salinity analysis



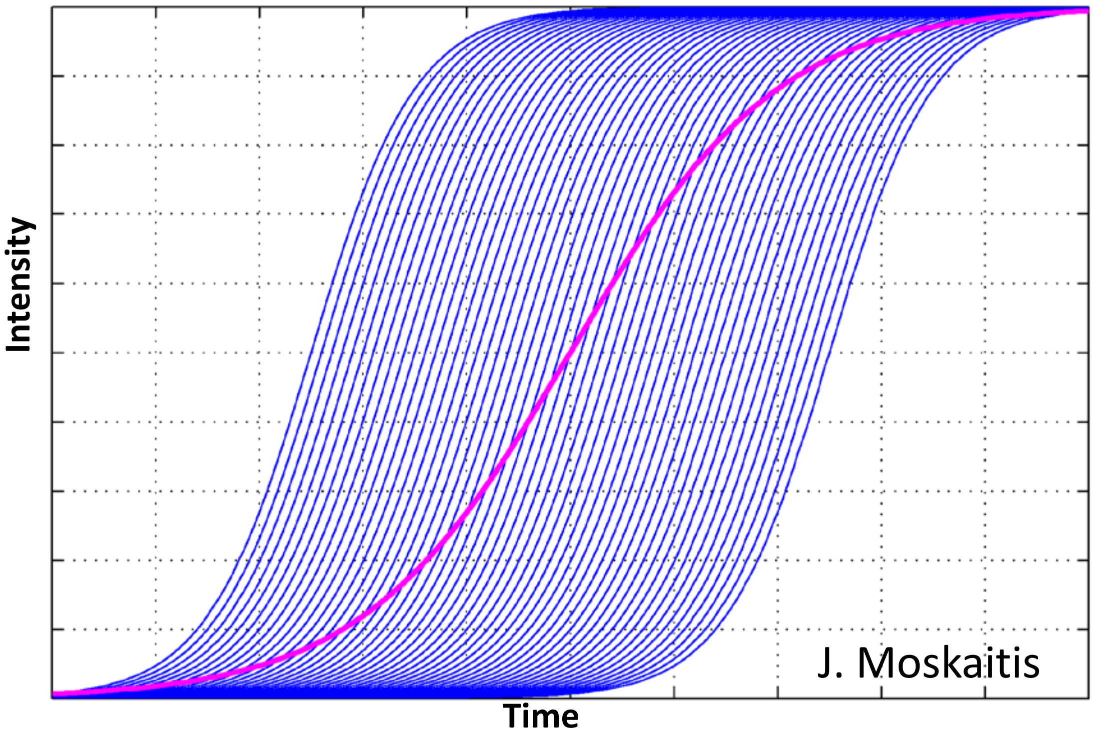
- Hurricane Isaac in-situ ocean observations:
  - **A**irborne E**x**pendable **B**athy**T**hermograph (AXBT)
  - Airborne E**x**pendable **C**onductivity, **T**emperature, **D**epth Profiler (CTD)
  - **A**irborne E**x**pendable **C**urrent **P**rofiler (AXCP) ocean observations
- Up to -2.5 °C SST and -2.9 PSU salinity changes from COAMPS analysis at 0000 UTC 25 Aug, 2012



5. Model Evaluation and Verification

Model verification metrics for Intensity need to be improved.

- Currently, TC intensity prediction models are developed to minimize the MAE of deterministic forecast intensity time series.
- Goal of MAE minimization in development of models inhibits the ability to predict rapid intensity changes due to penalty of mis-timed RI events.
- Need to make an ensemble intensity prediction (blue curves); unfortunately we trained our models to produce forecasts like the magenta curve.
- Develop models in “ensemble mode”; minimize CRPS or probabilistic metrics



The deterministic forecast that minimizes expected MAE at all lead times (red) (the median of the true pdf). It has same form as the verifying intensity time series.

The optimal deterministic forecast, with the same form as the verifying intensity time series, can be “a real bust”. If you get the timing wrong, large errors are likely. For example, the expected error of a forecast (black) is 68% higher than optimal forecast.

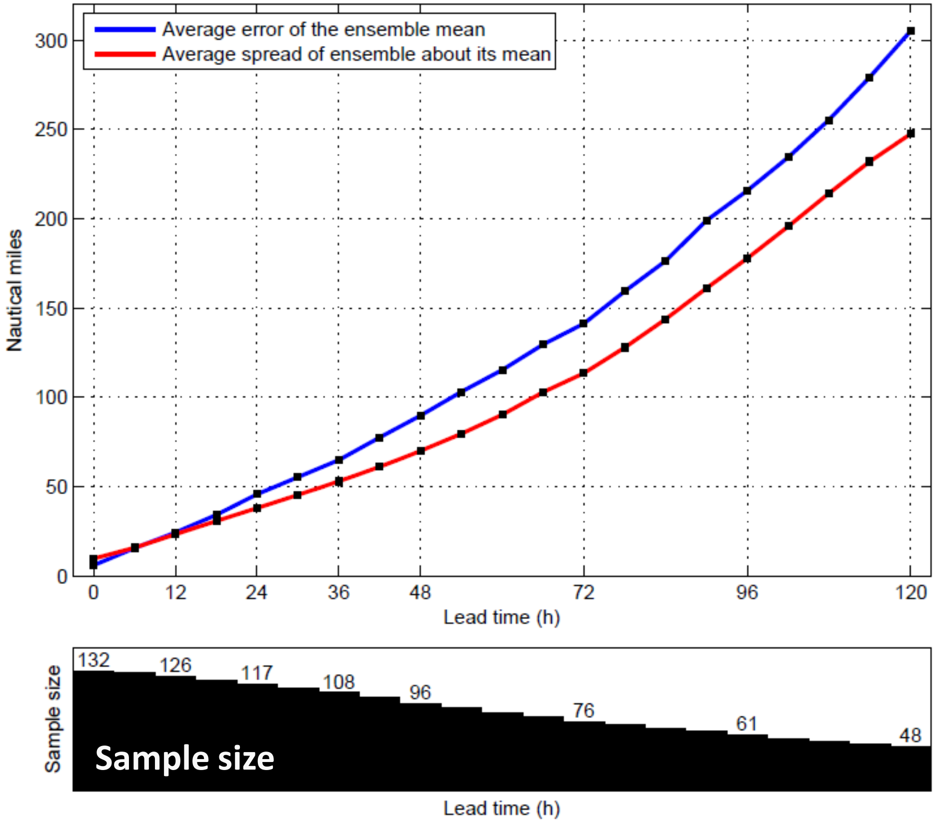
A “low-error” option is to hedge against timing errors by forecasting an intensity time series with the wrong form: a slower growth rate for a longer period of time. The expected error of the magenta forecast is only 12% higher than that of the optimal forecast.

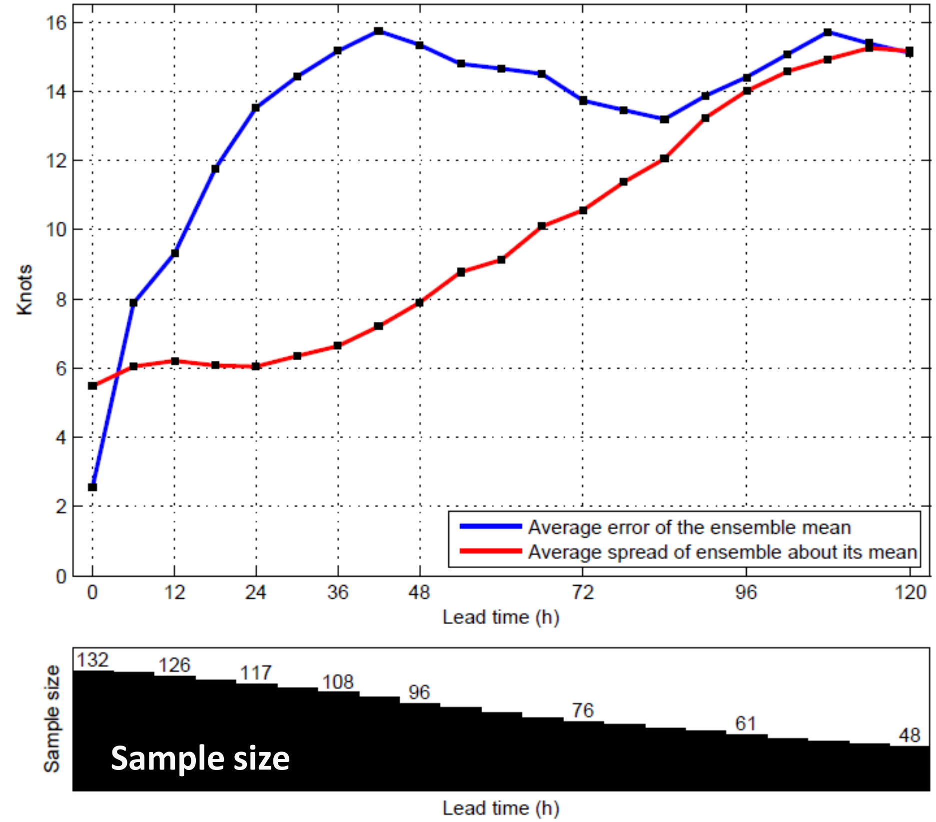
4. High-Resolution Multi-Model Ensemble

Real Time Demonstration in 2015

Probabilistic verification: Ensemble spread vs. Ensemble mean error

Track ***COAMPS-TC & HWRF*** ***Intensity***





For track, ensemble is underdispersive for all but the earliest lead times

For intensity, ensemble needs more spread from 12 to 84 h; spread growth is too slow

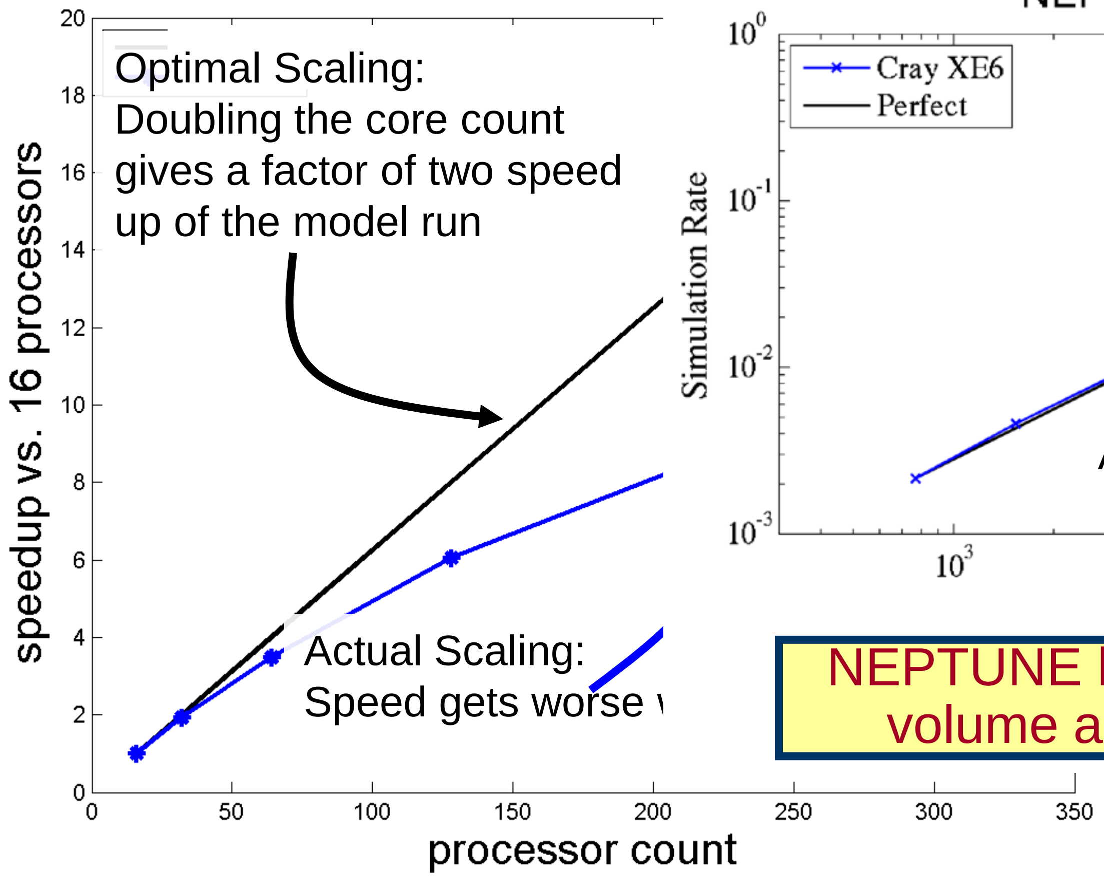
Improved representation of model error (e.g., stochastic physics) is needed for improved spread-skill relationship for intensity ensemble.

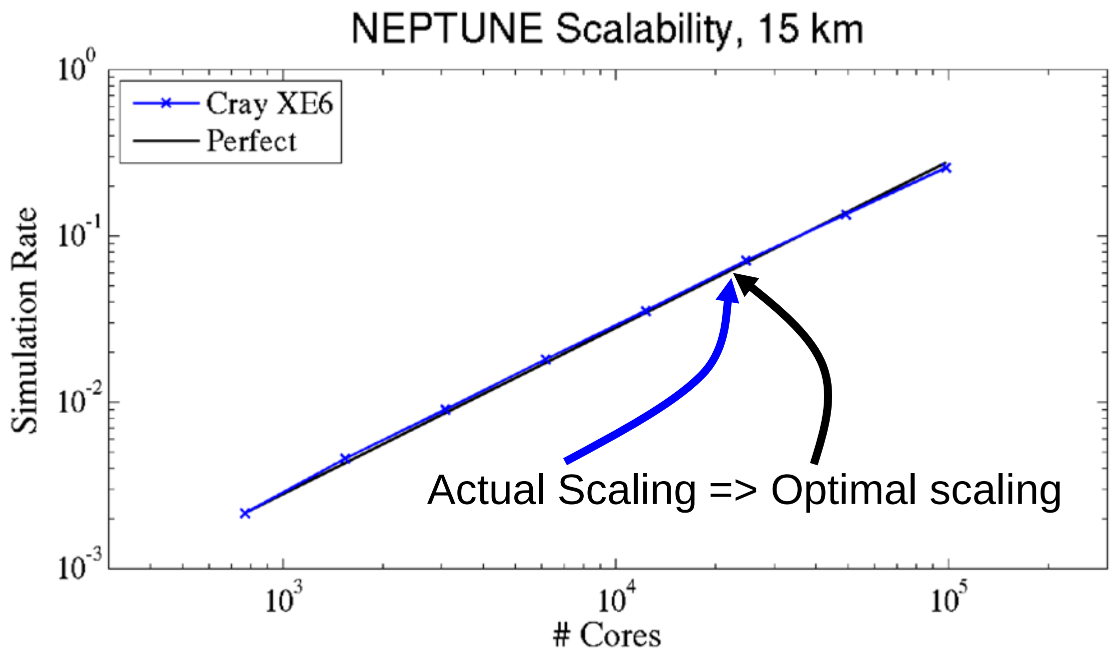
6. Next-Generation Models

Navy's NEPTUNE

Take full advantage of next-generation computer architectures (100K+ cores)

- Next-generation TC codes need to be highly scalable





NEPTUNE has a small communication volume and scales extremely well

Often with models that require large communication volumes, the cost of communication dominates the cost of computation as core count increases.