Do we have the Necessary Ingredients for Hurricane Intensity Forecasting?

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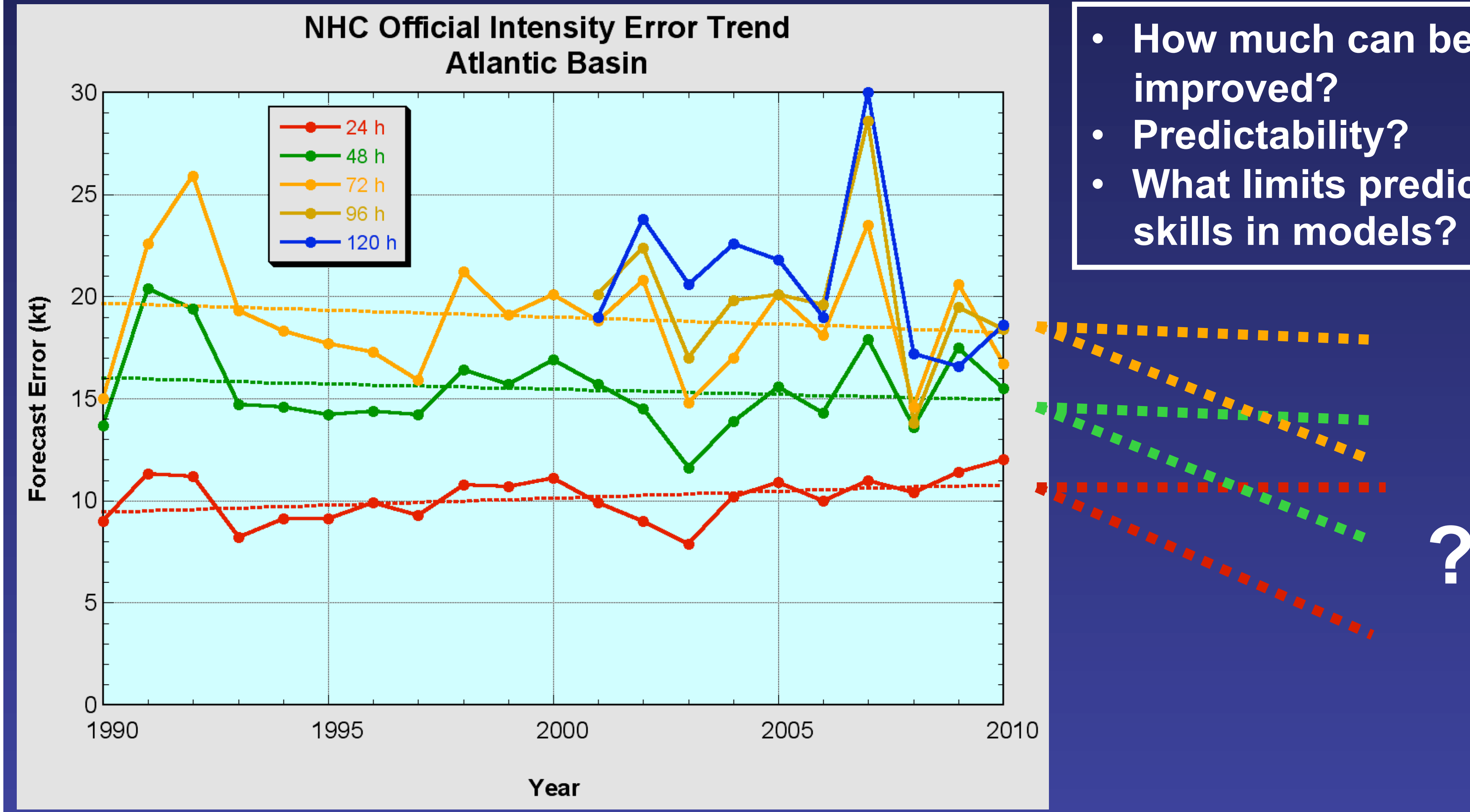
(Seminar at EMC/NCEP/NOAA, 30 September 2011)

In the eye of Katrina

Future of Hurricane Intensity Forecasting



- **How much can be improved?**
- **Predictability?**
- **What limits predictive skills in models?**

NWP Paradigms

1) Baroclinic weather systems (good news)

- Energy sources (thermal gradient) and conversions (potential to kinetic in baroclinic waves) are resolvable
- Life cycle of a few days and observable
- Balanced or quasi-balanced, quasi-2D flow
- Top-down control, large-scale with long predictability (wind adjust to mass). Small scales are in quasi-equilibrium with the large scale, which can be parameterized.

2) Convective weather systems (not so good news)

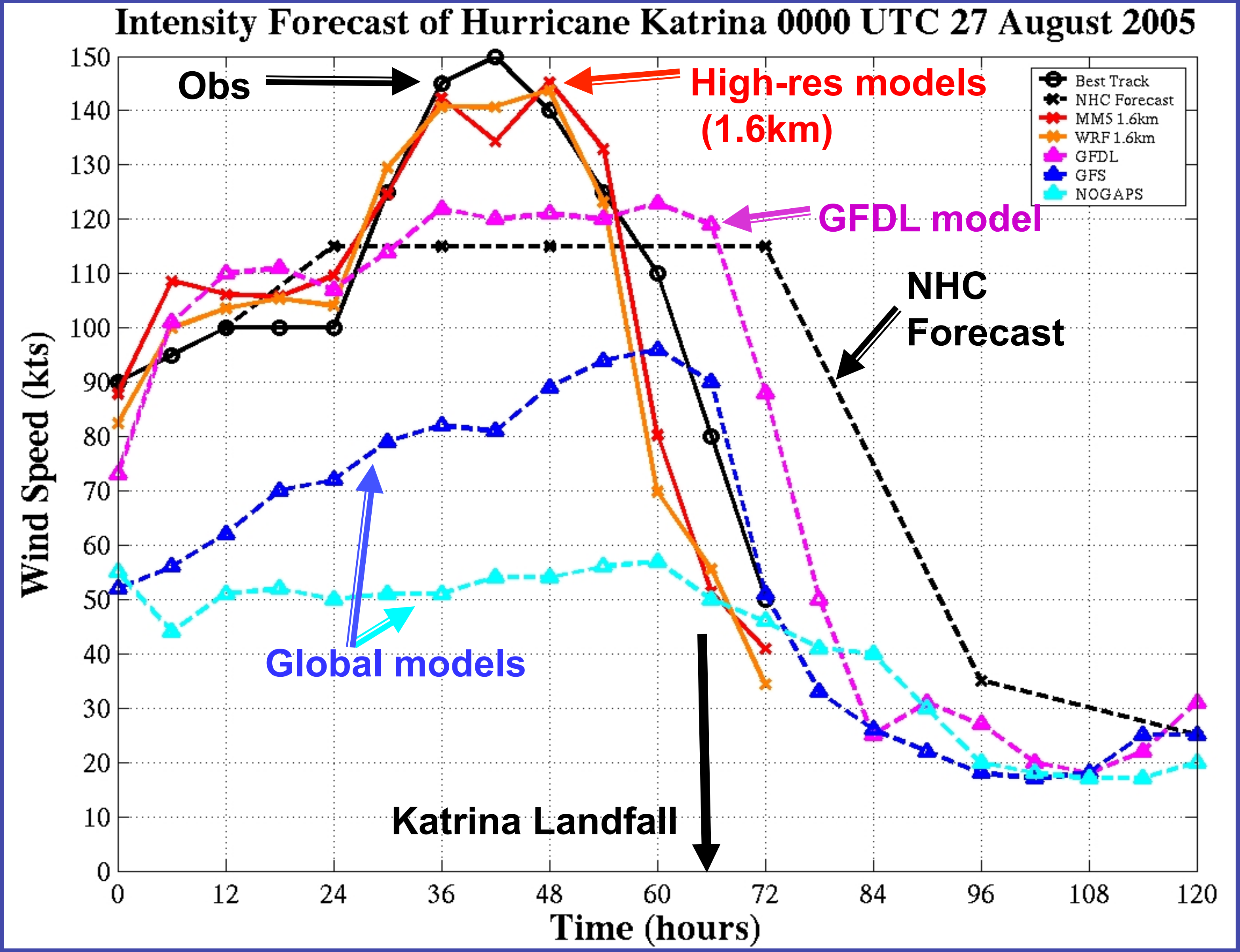
- Energy sources (conditional instability) and conversions (P->K) are in small-scale structures (poorly resolved, not observed)
- Life cycle of minutes to hours
- Unbalanced small scale, highly 3D
- Up-scaling (e.g., convective heating drives the large-scale circulations), short predictability (mass adjust to wind)

- Track prediction is dominated by the large-scale steering flow, mostly Paradigm 1.
- Intensity prediction falls into Paradigm 2. However, because TC vortices are initially stable, TCs are more “predictable” than other convective systems.
- TC genesis is a more complex situation. The large-scale provides a favorable environment for convective systems to develop, while convective upscaling can take days before TC genesis occurs.

Sources of Errors in NWP Models

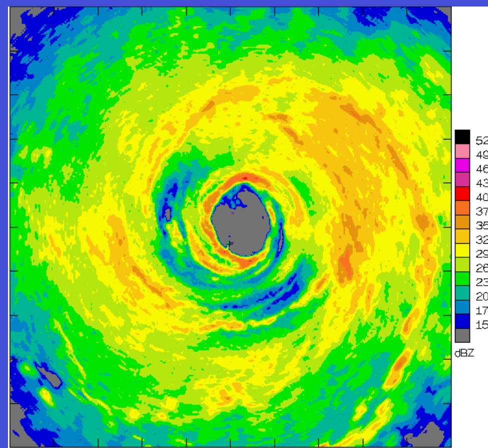
- Initial conditions (lack of observation and data assimilation)
- Model resolution and numerical formulation
- Model physics (both resolvable and subgrid scales: cloud physics, turbulence, air-sea interface, and coupling to the ocean and land, etc.

Model Forecast of Storm Intensity of Hurricane Katrina During RAINEX 2005

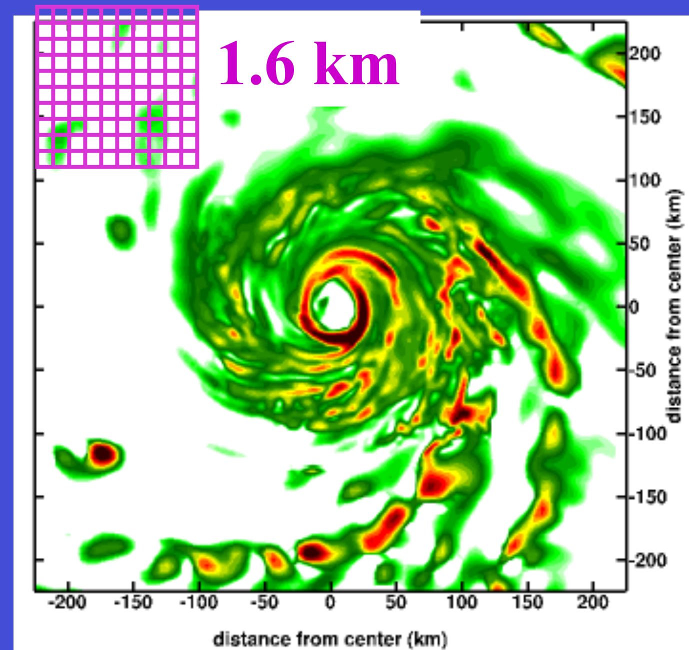


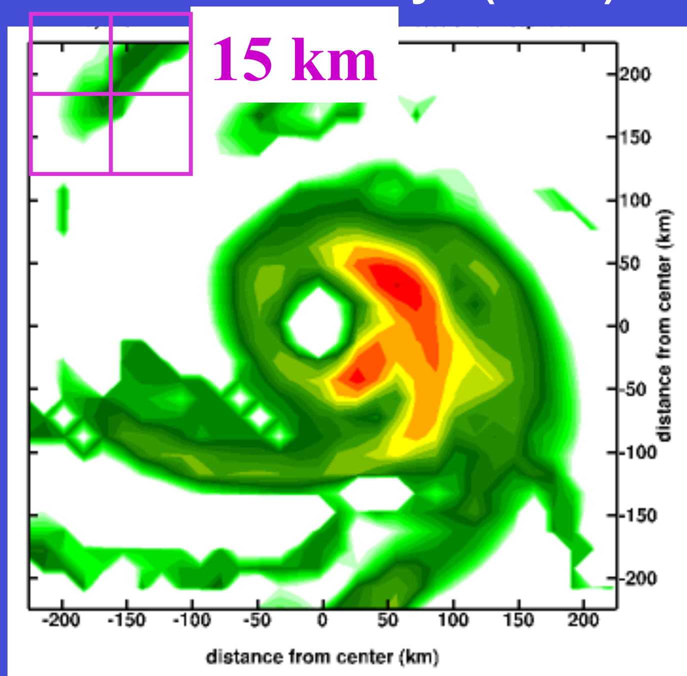
Impact of Model Grid Resolution on Hurricane Forecast

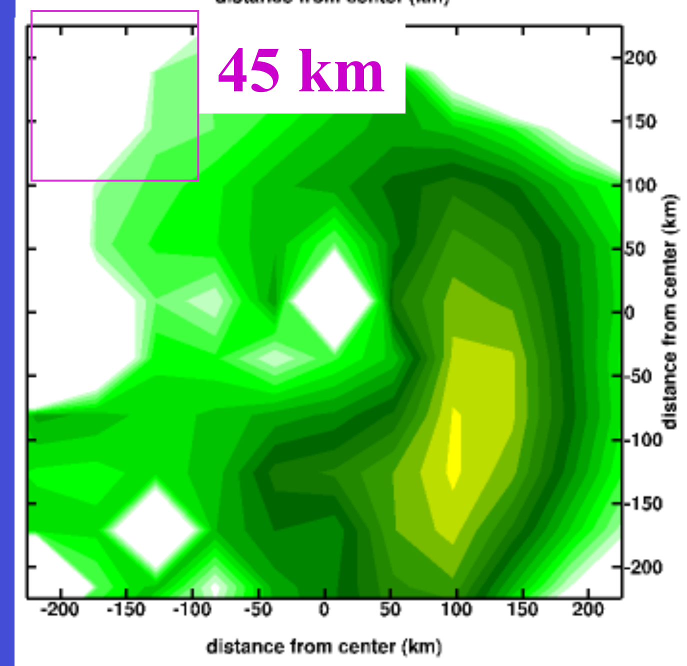
Chen et al (2007)

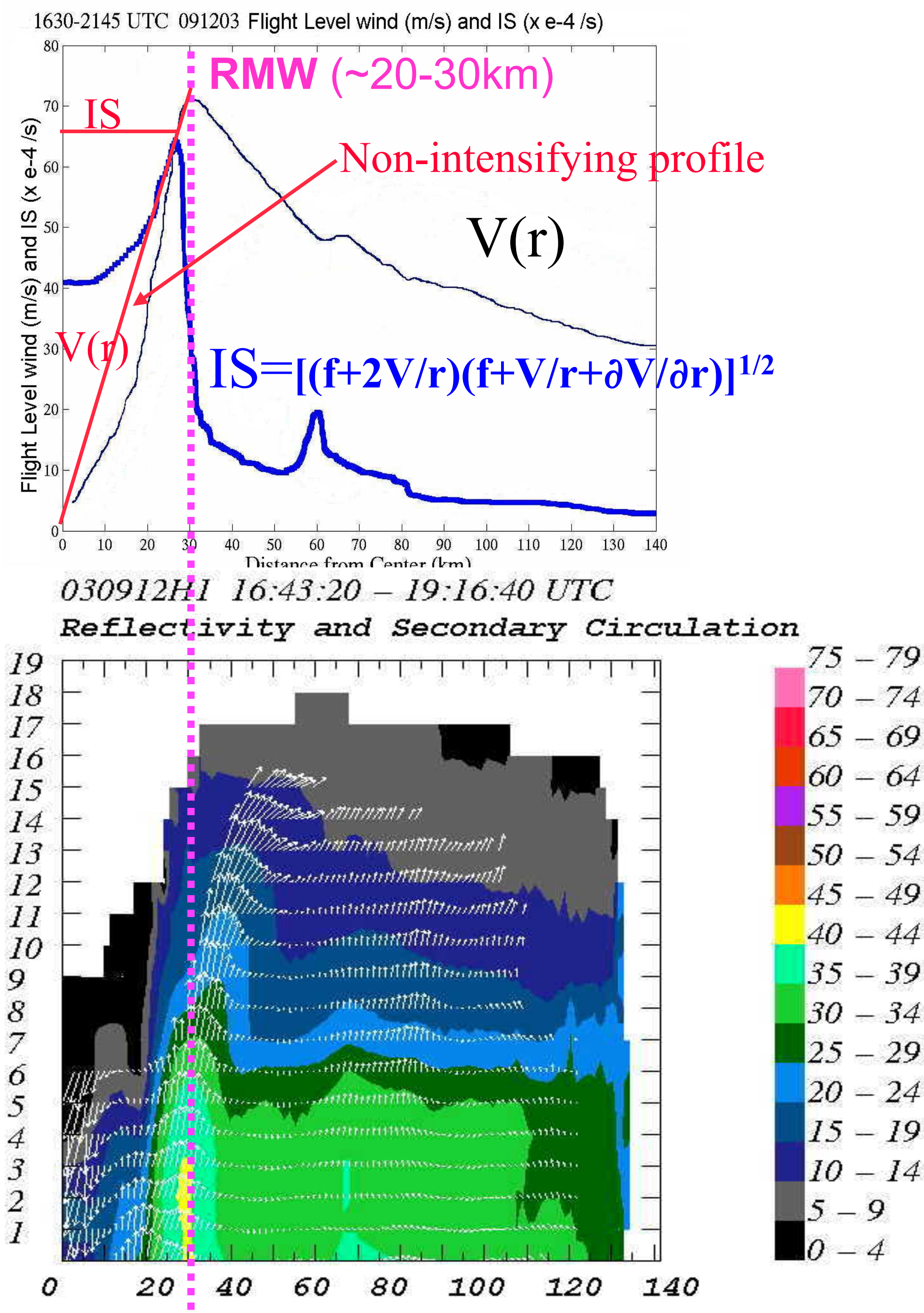


Airborne radar observed rain in Hurricane Floyd (1999)









Hurricane Isabel on 9/12/03

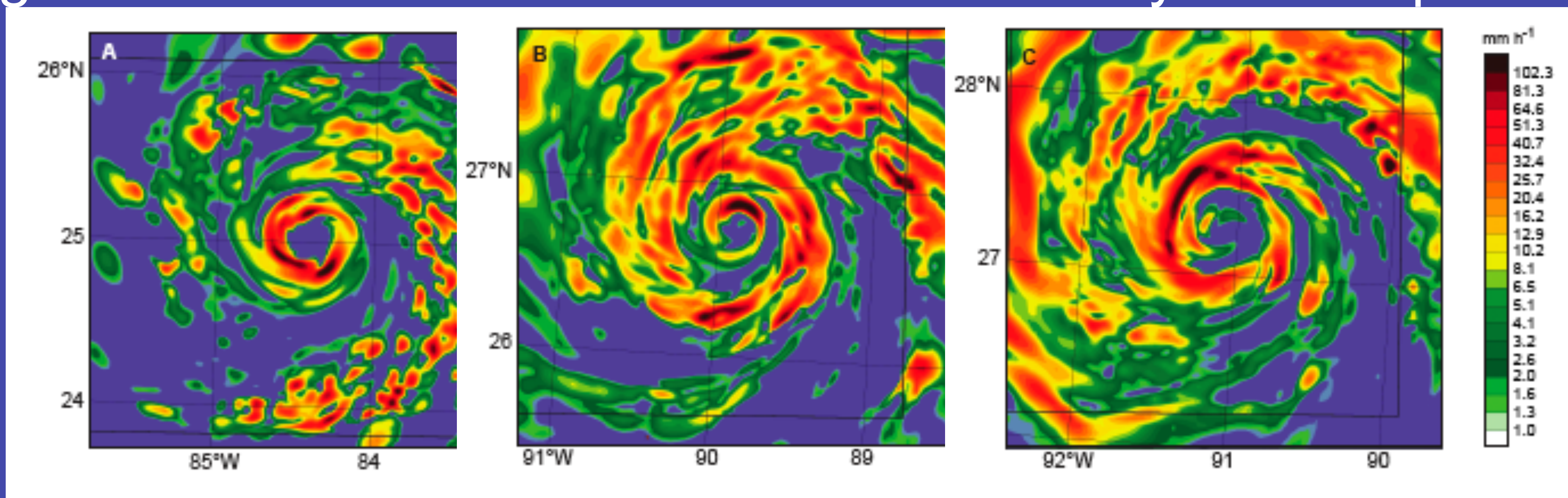
- Intensifying storm
- Highest flight-level winds with a sharp bell-shaped profile
- High inertial stability (IS) inside of the eyewall, where spiral inflow enhances tangential wind
- Strong eyewall updrafts and convection

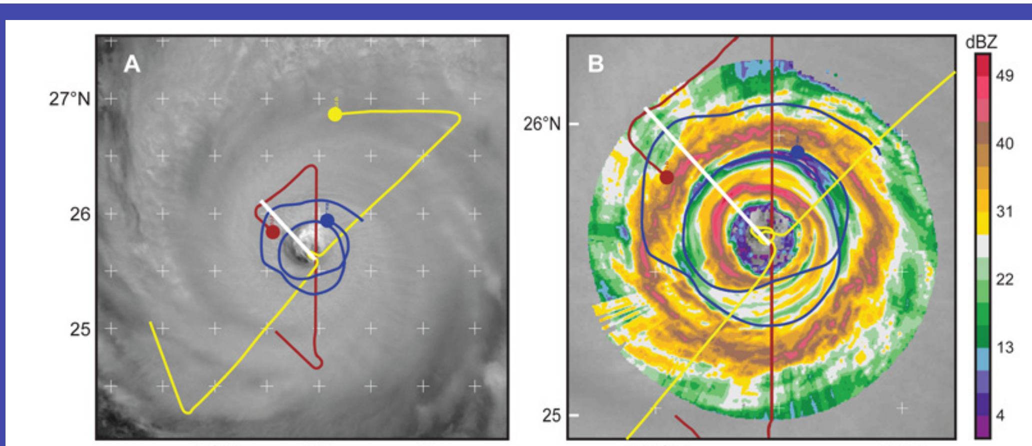
Hurricane Intensity and Eyewall Replacement

Science AAAS

Robert A. Houze Jr.,[1*] Shuyi S. Chen,[2] Bradley F. Smull,[1] Wen-Chau Lee,[3] Michael M. Bell[3]

High Resolution Model Forecasts for Rita's Eyewall Replacement

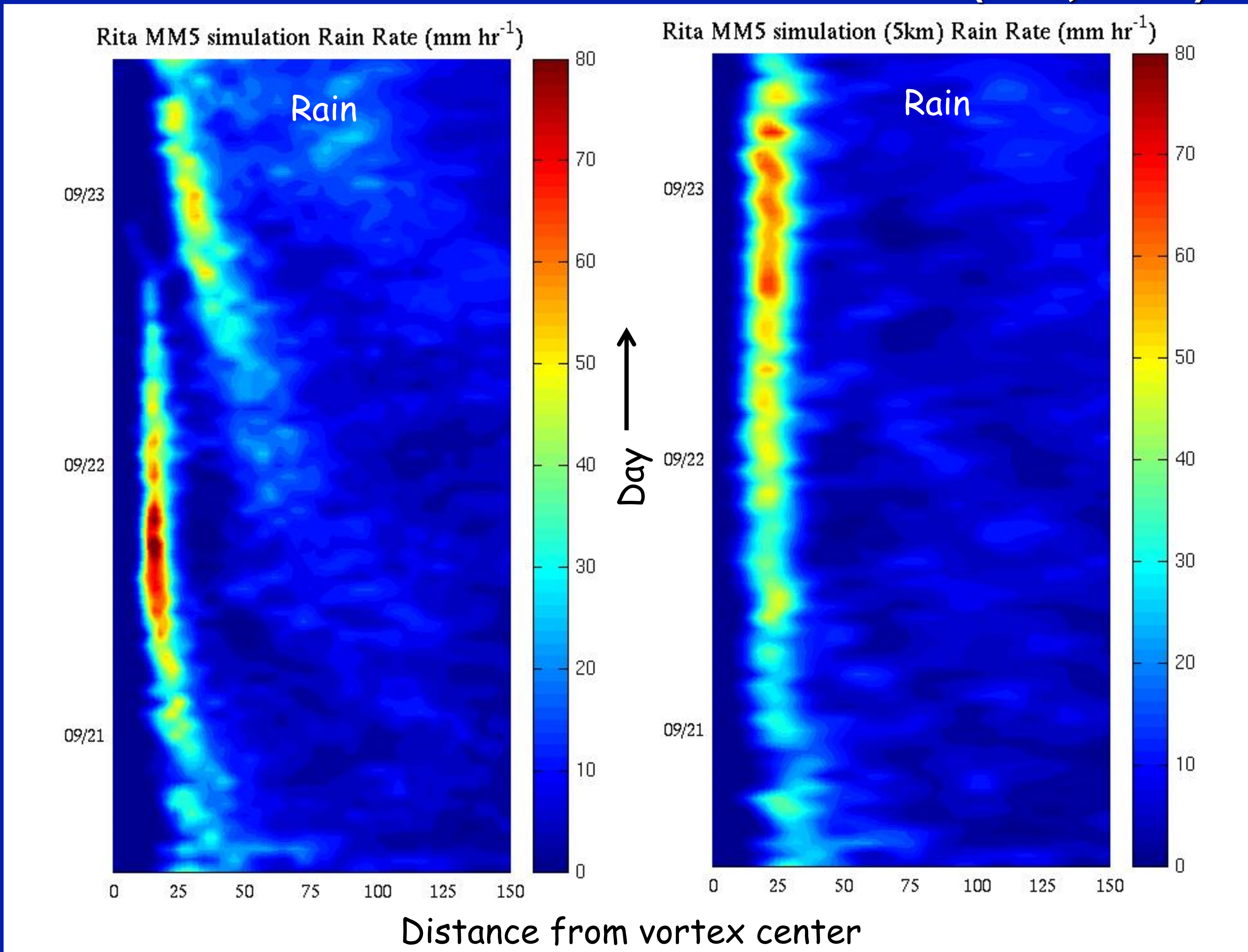




Airborne Radar Observed Rita's Concentric Eyewalls

Hurricane Rita

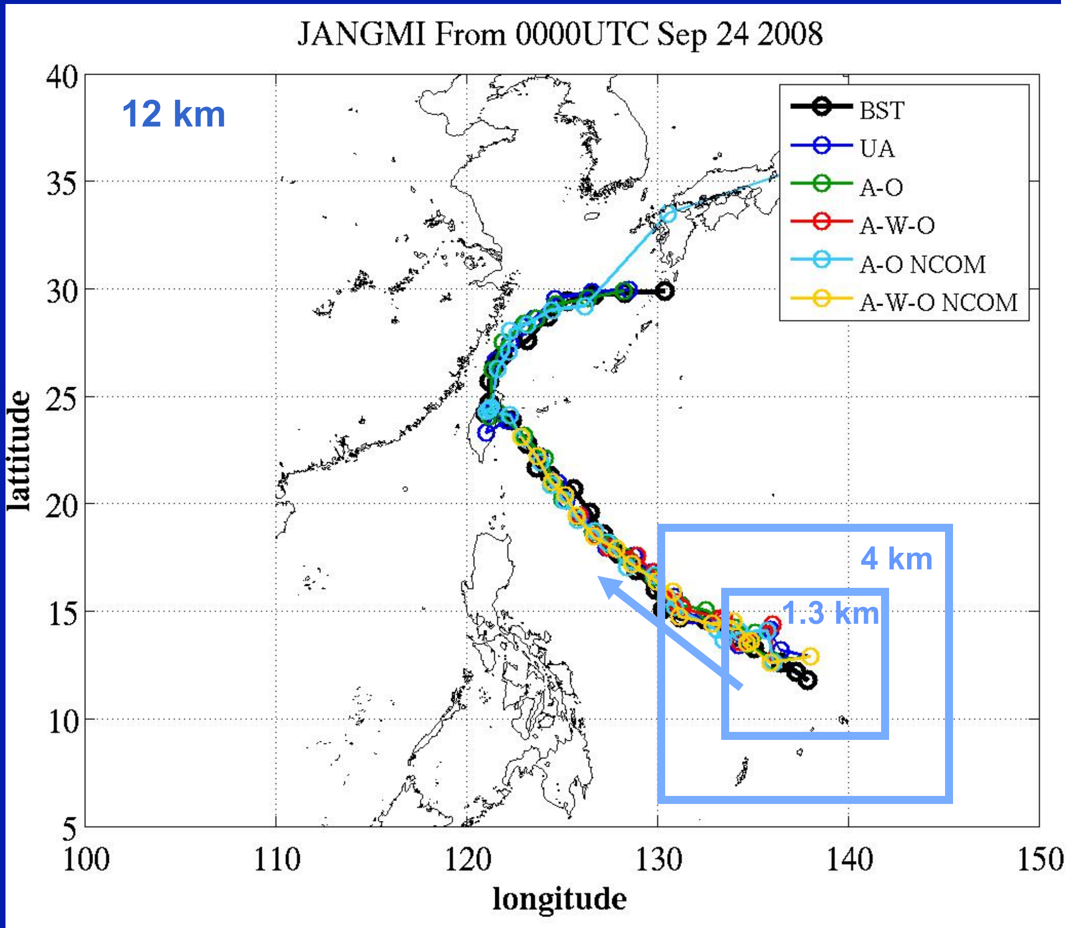
Judt and Chen (JAS, 2010)



Multi-Model, High-Resolution, Coupled Modeling System at University of Miami:

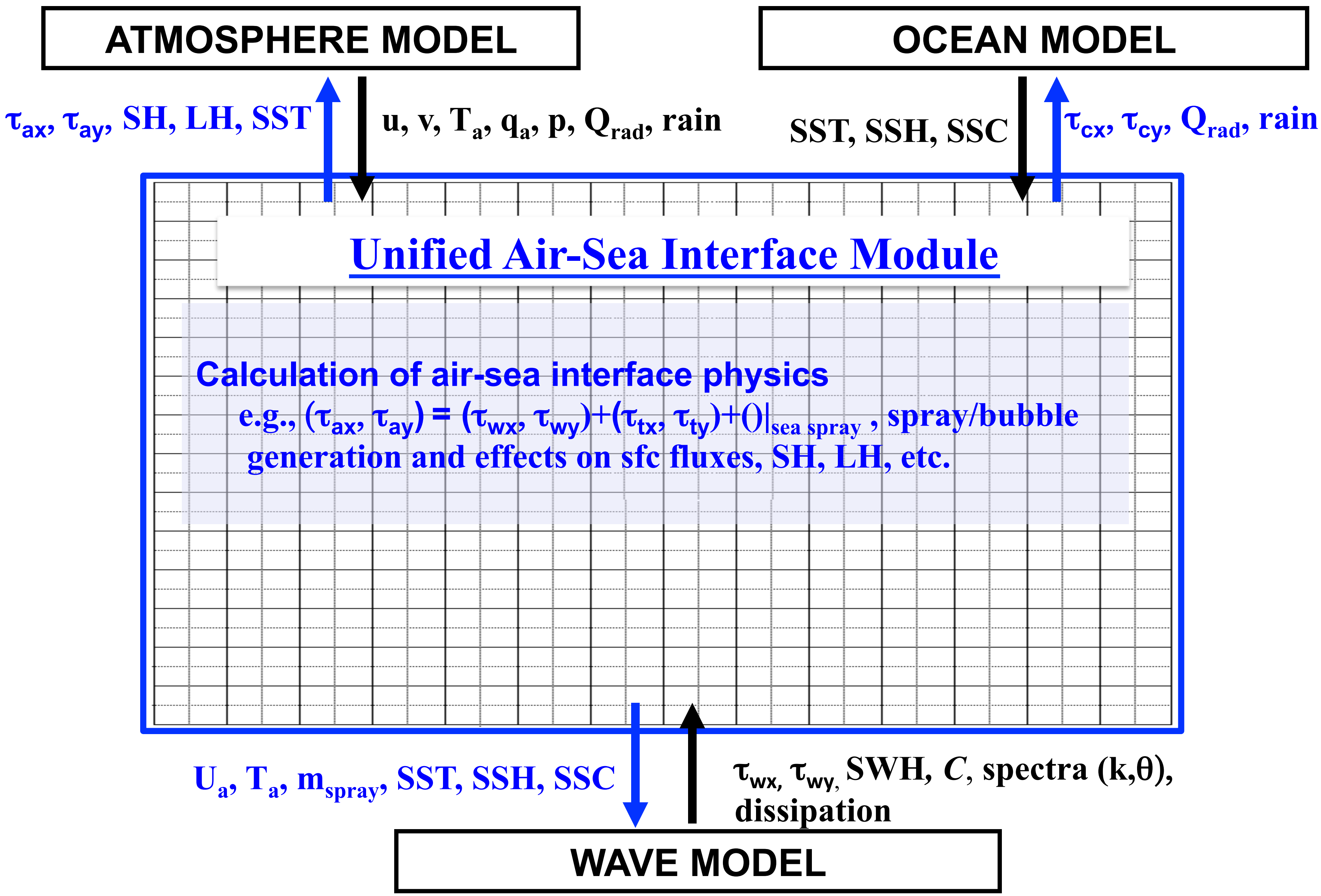
- UM Coupled Atmos-Wave-Ocean Model (UMCM)
- Coupled WRF (CWRF)
- WAVEWATCH III
- HYCOM
- 3DPWP ocean model – initialized with satellite SST + Obs profiles, and NCOM or HYCOM data assimilation
- Mini ensemble UMCM, MM5 CWRF, & WRF forecasts using GFS, GFDL, NOGAPS, CMC, JMA, and ECMWF forecast fields as initial and lateral boundary conditions

- Real-time support for ITOP 2010
- Virtual experiments for research
- Understanding TCs and improve perditions

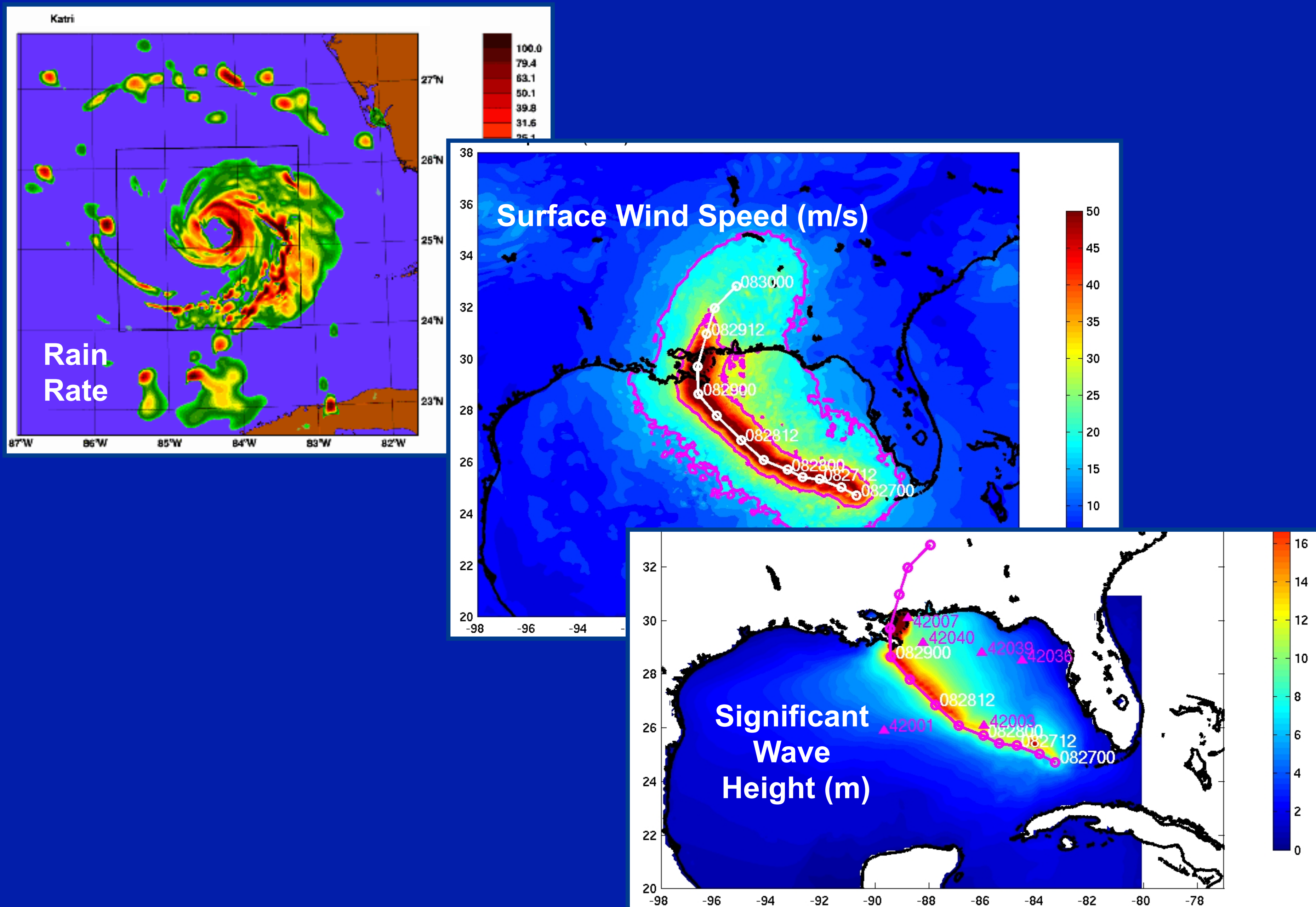


Most challenging Issues:

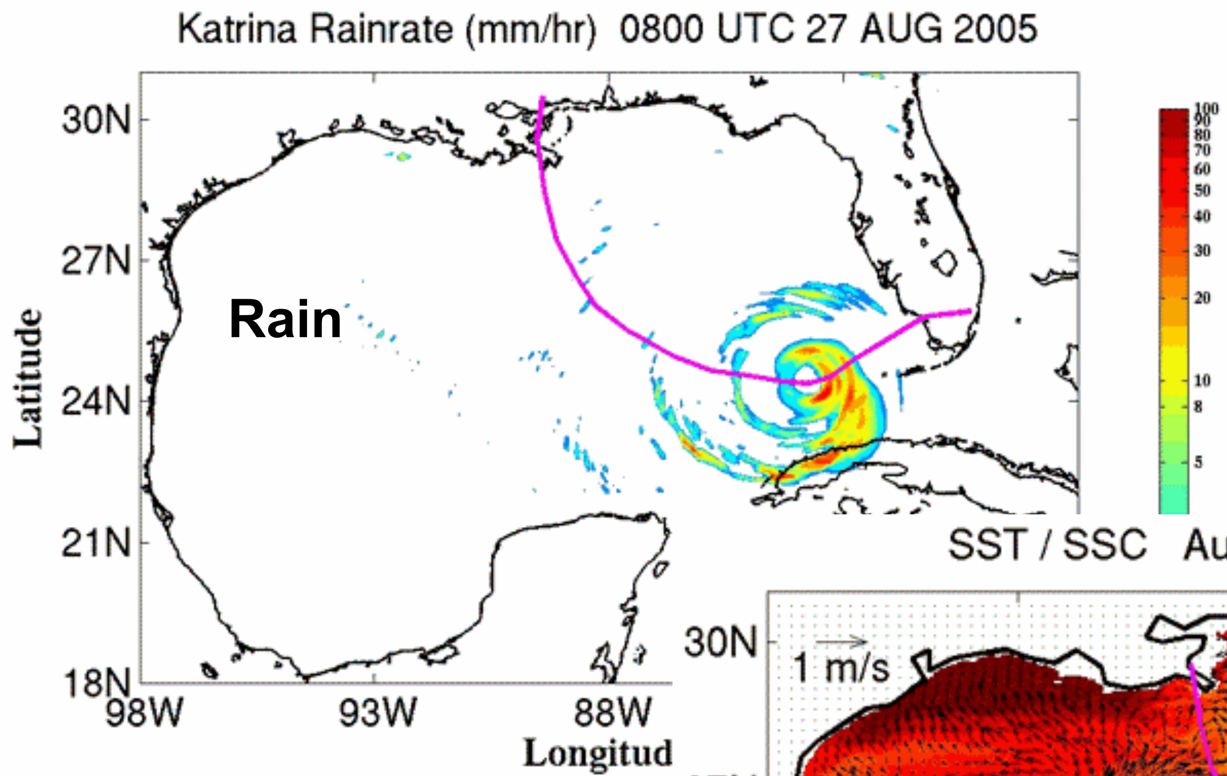
- coupled model initialization, data assimilations, and evaluation/verifications.

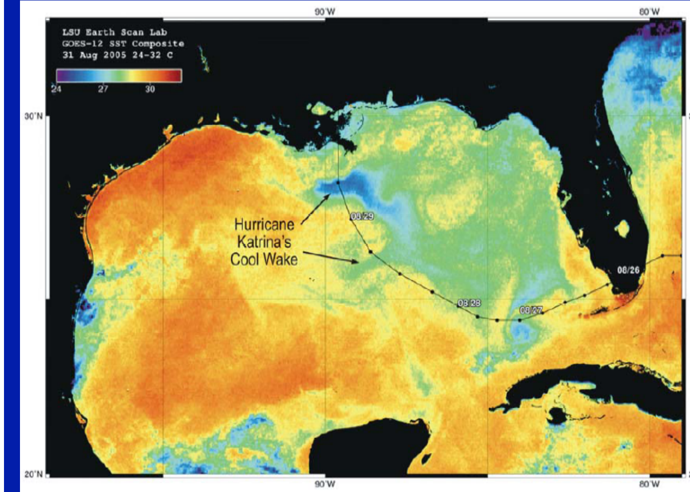

ATMOSPHERE MODEL
OCEAN MODEL
τ_{ax}, τ_{ay}, SH, LH, SST
u, v, T_a, q_a, p, Q_{rad}, rain
SST, SSH, SSC
τ_{cx}, τ_{cy}, Q_{rad}, rain
Unified Air-Sea Interface Module
Calculation of air-sea interface physics
e.g., $(\tau_{ax}, \tau_{ay}) = (\tau_{wx}, \tau_{wy})+(\tau_{tx}, \tau_{ty})+()|_{sea\ spray}$, spray/bubble generation and effects on sfc fluxes, SH, LH, etc.
U_a, T_a, m_{spray}, SST, SSH, SSC
τ_{wx}, τ_{wy}, SWH, *C*, spectra (k,θ), dissipation
WAVE MODEL

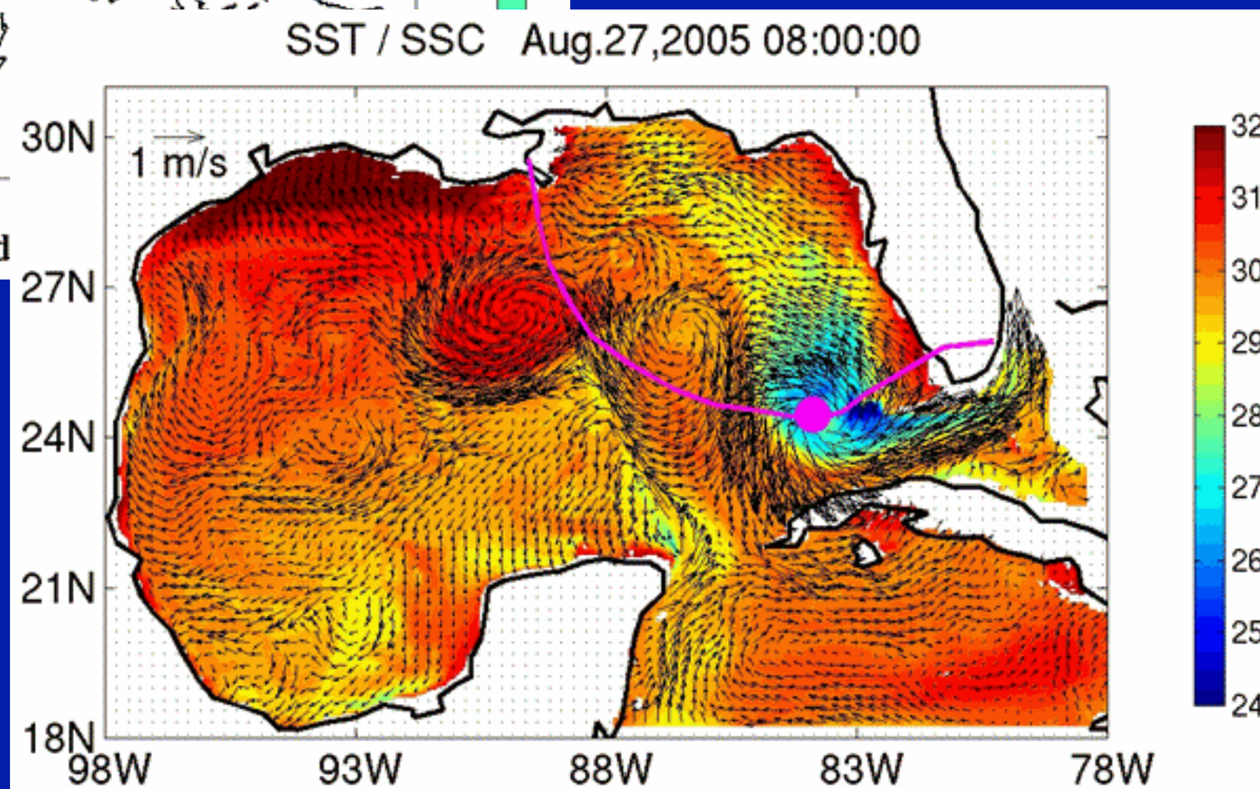
High-resolution Coupled Model Forecast of Hurricane Katrina



High-resolution Coupled Model Forecast of Hurricane Katrina



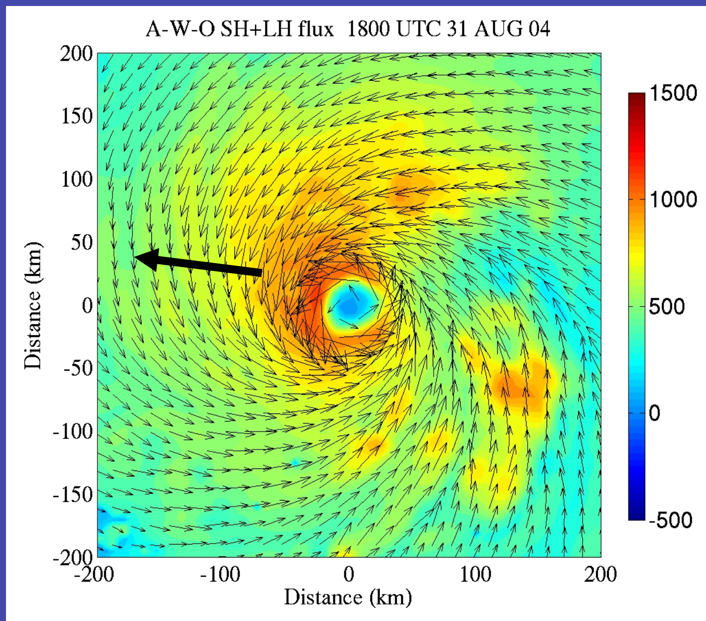




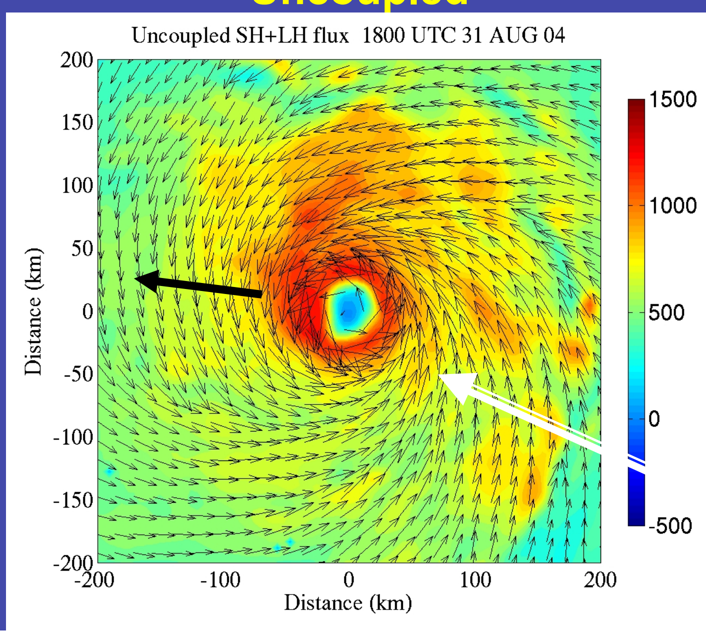
SST and ocean surface current

Total Surface Heat Flux

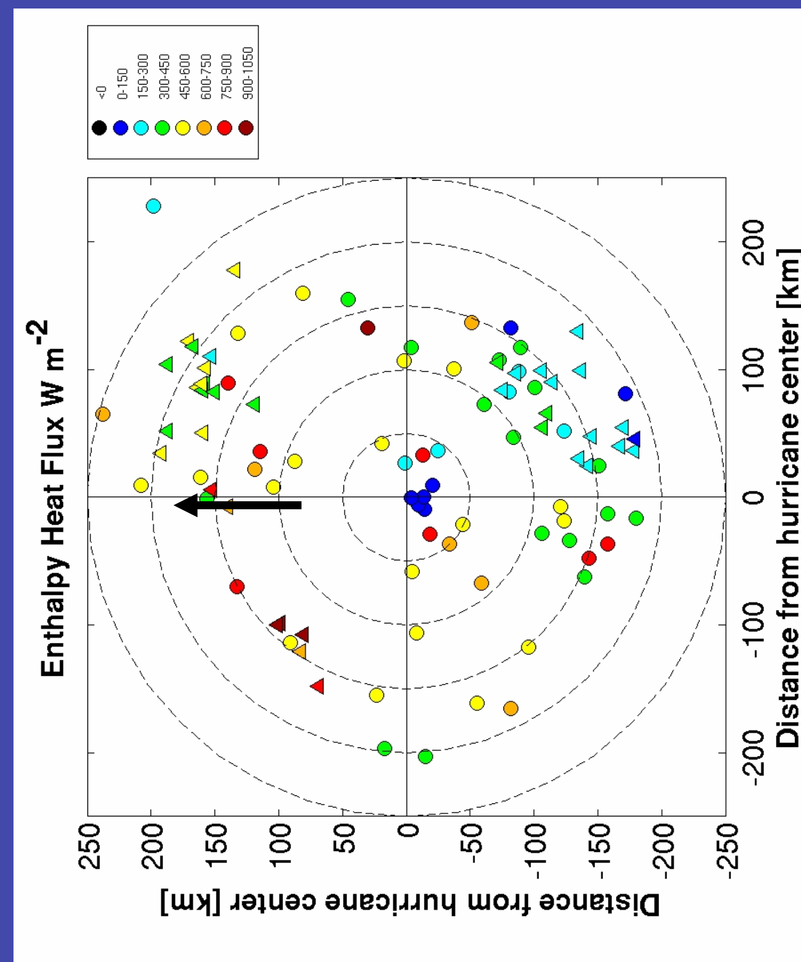
Coupled Atmos-Wave-Ocean



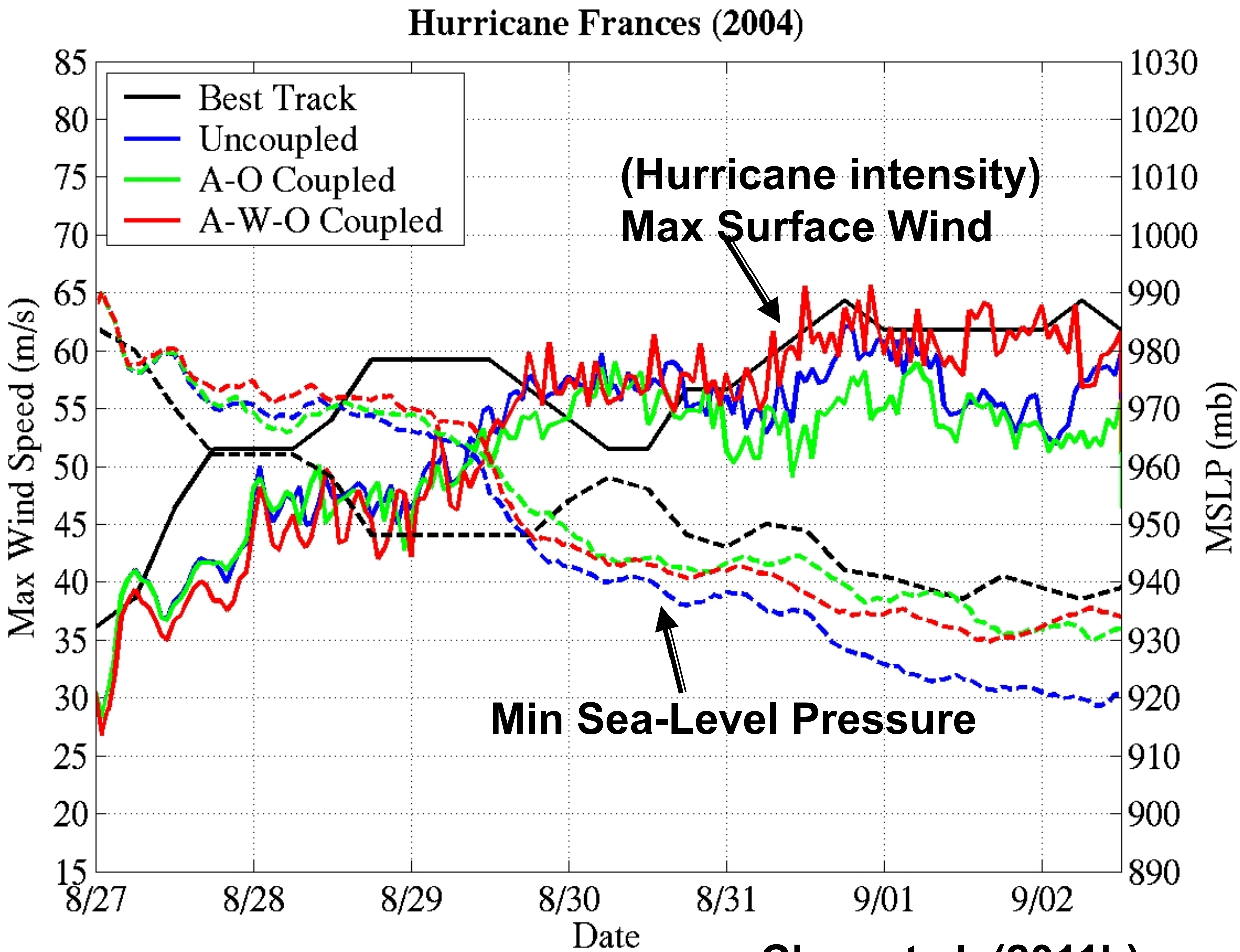
Uncoupled



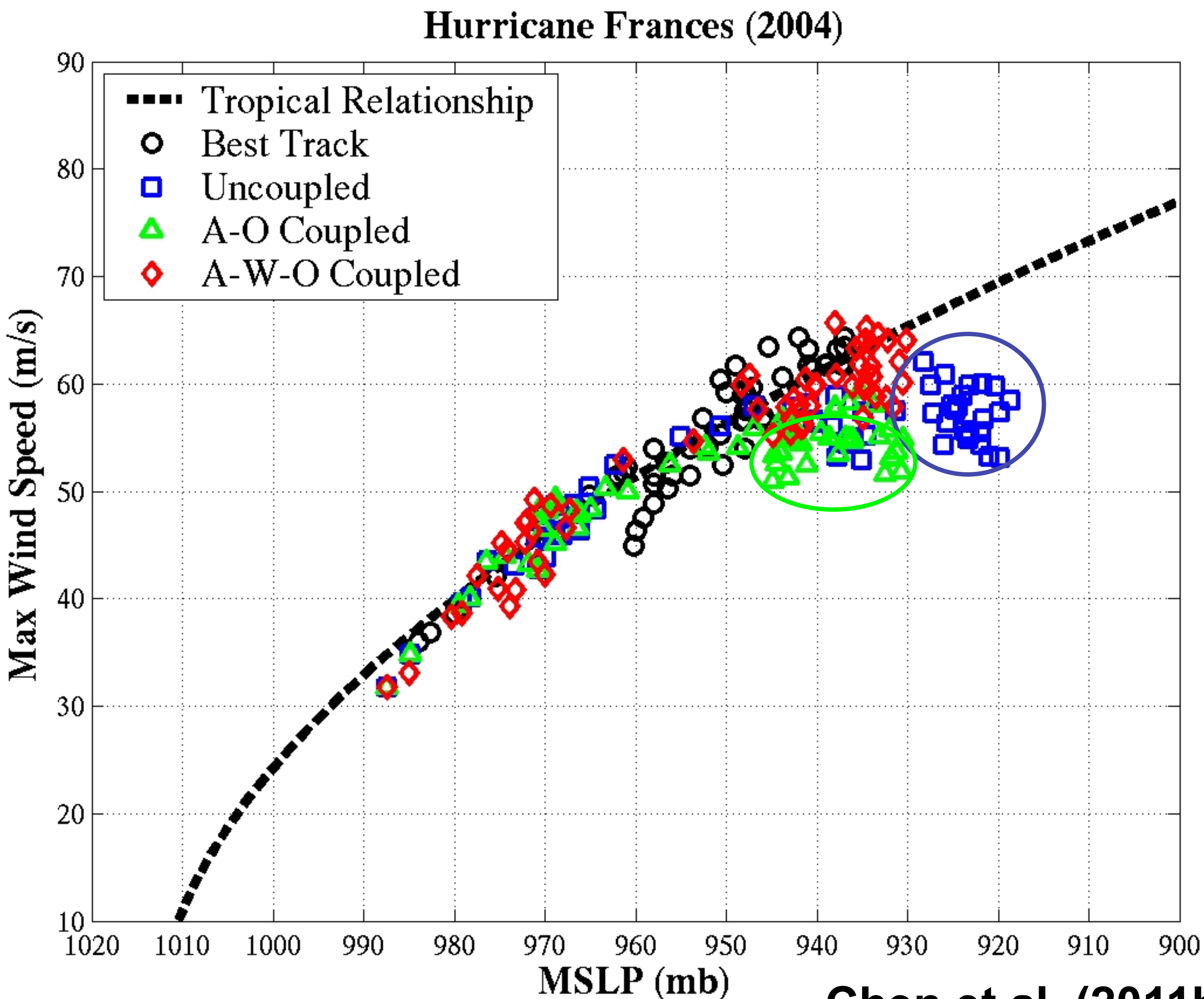
Observed form 6 hurricanes using GPS dropsondes plus 2 from CBLAST turbulence flux measurement (triangles)



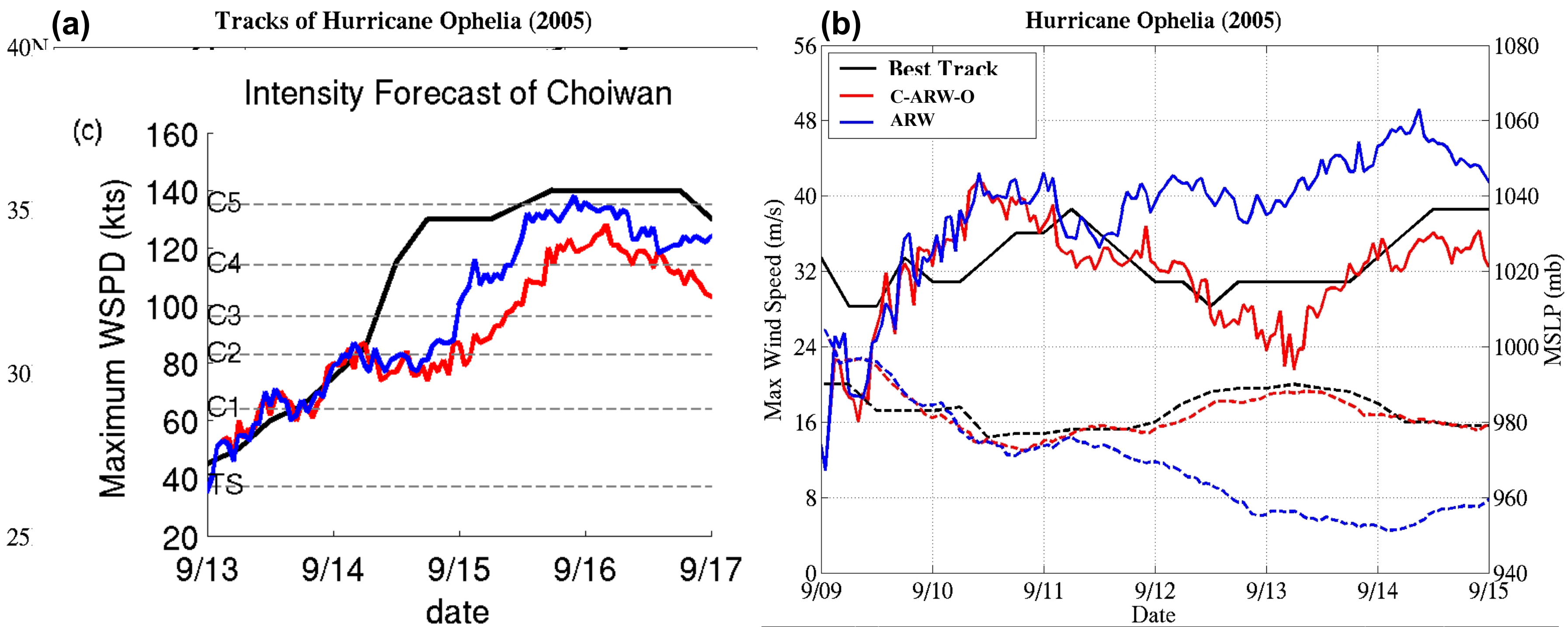
~30% greater than observed



Chen et al. (2011b)



Chen et al. (2011b)



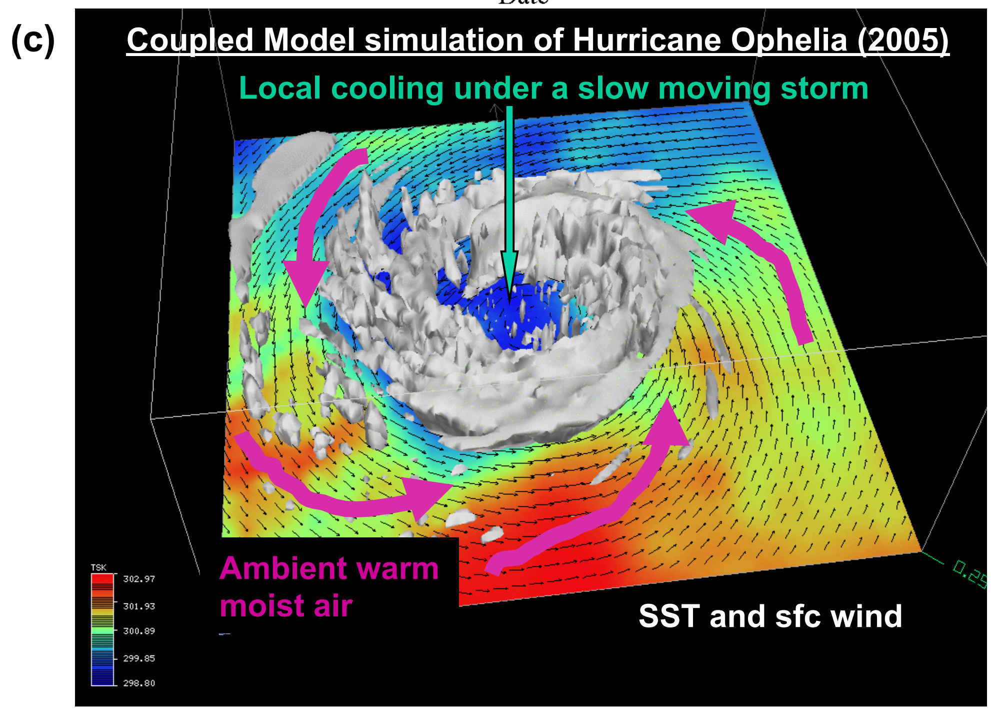
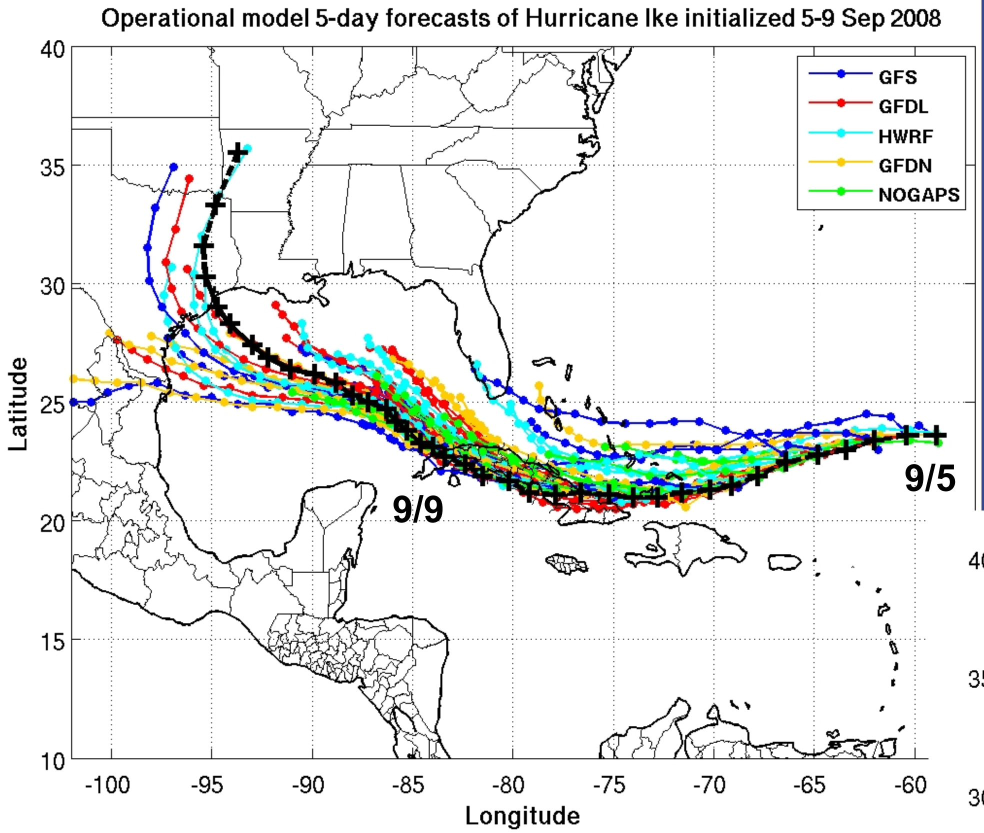
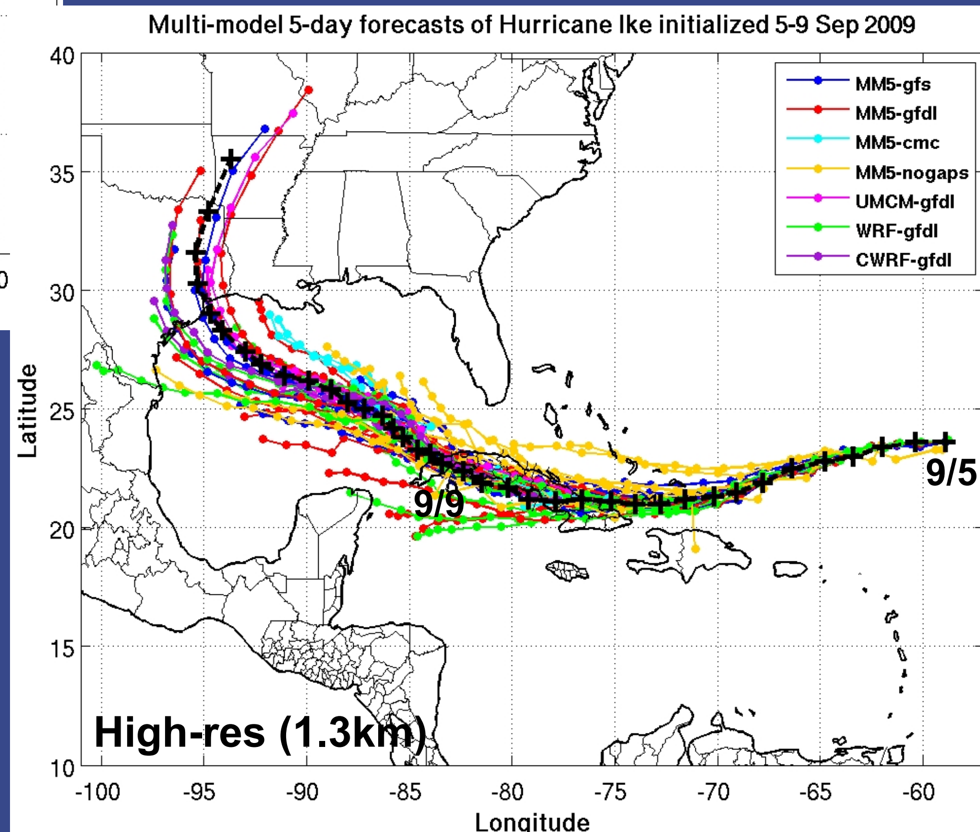


Fig. 1 (a) Uncoupled ARW (blue) and coupled ARW-Ocean model (red) simulated storm tracks, (b) MSLP (dashed) and maximum wind speed (solid) of Hurricane Ophelia (2005) compared with the NHC best track (black) data, and (c) SST, surface wind, cloud water+ice of Ophelia at 0000 UTC Sept 13. The models were initialized at 0000 UTC Sept 9 with the NCEP analysis fields as initial and lateral boundary conditions for ARW and HYCOM Atlantic data assimilation fields for the coupled model.

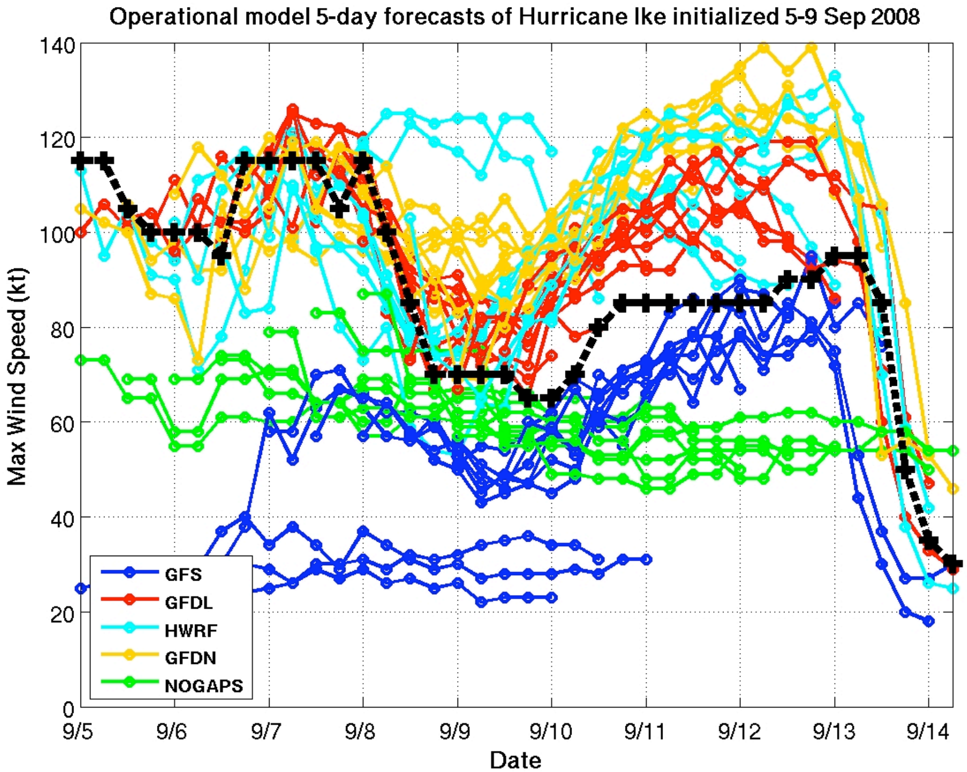
Model Verification Methods

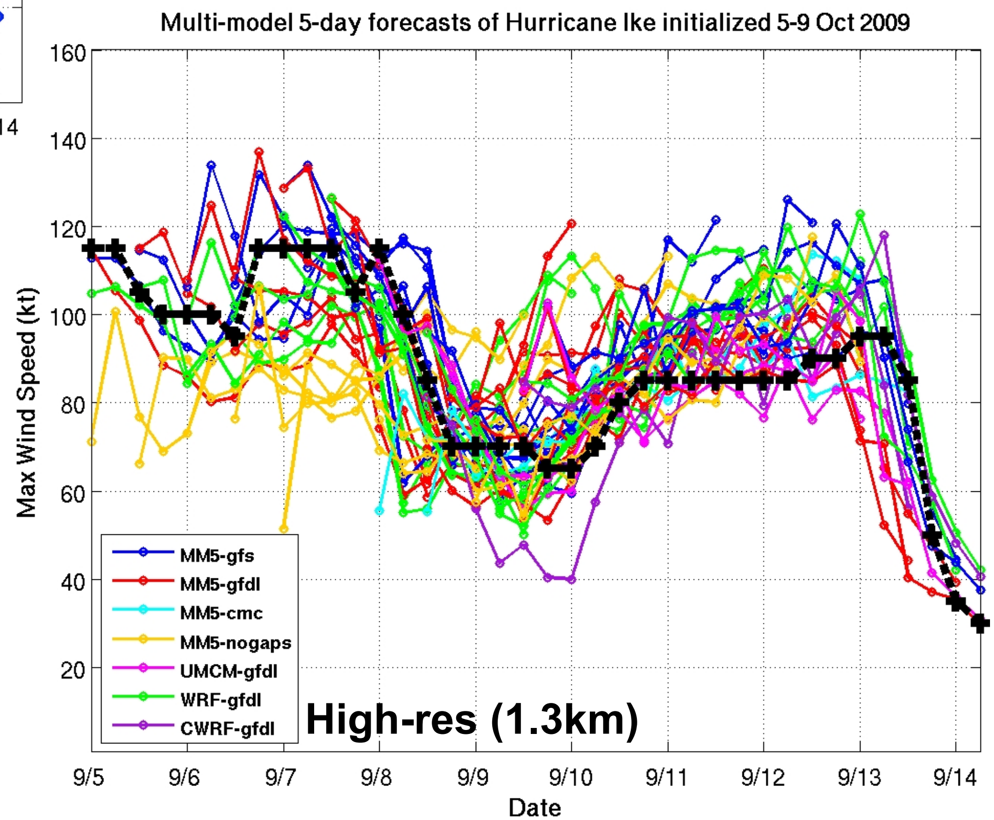


Hurricane Ike (2008) track forecasts and verification (NHC Best Track data in black) from September 5-9th (ten model forecasts at 12-h intervals)

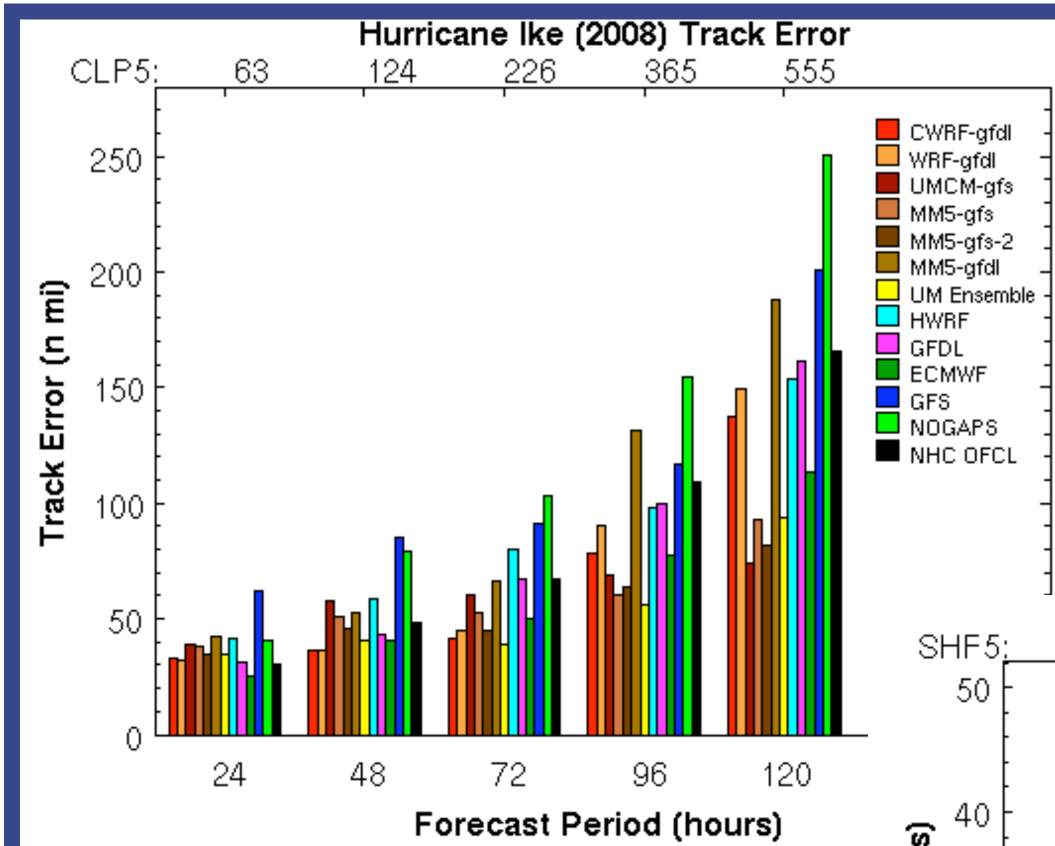


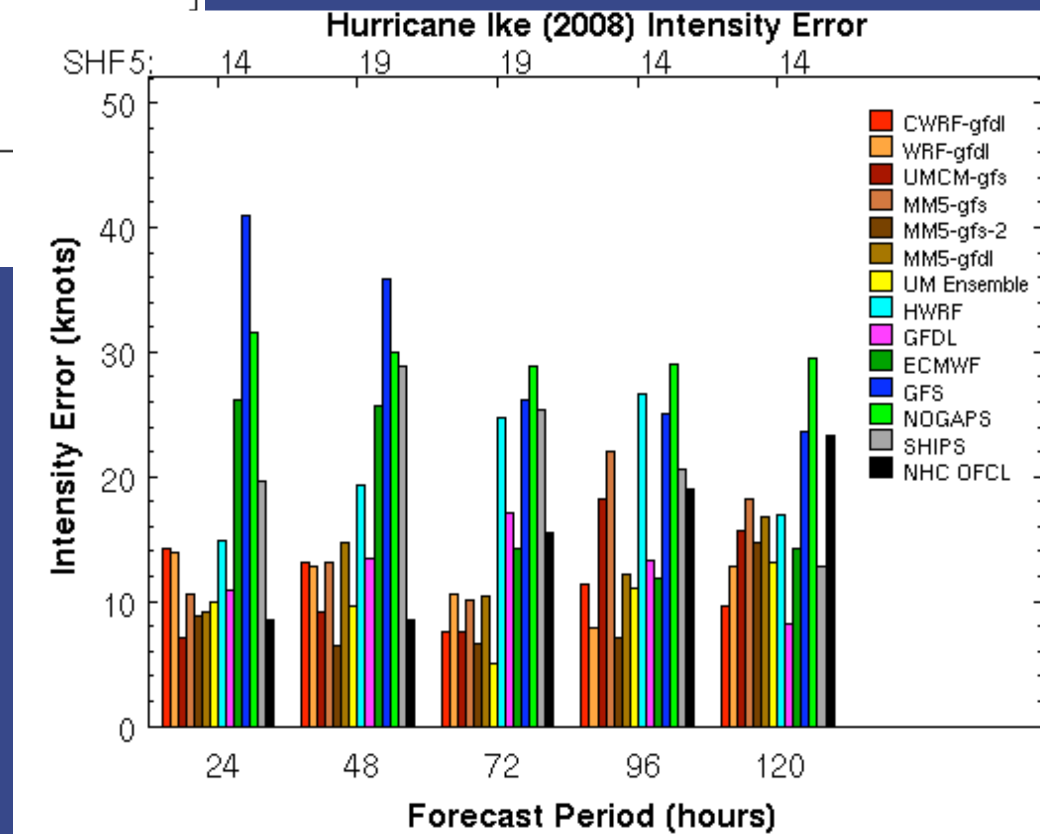
Hurricane Ike (2008) intensity forecasts and verification (NHC Best Track data in black) from September 5-9th (ten model forecasts at 12-h intervals)



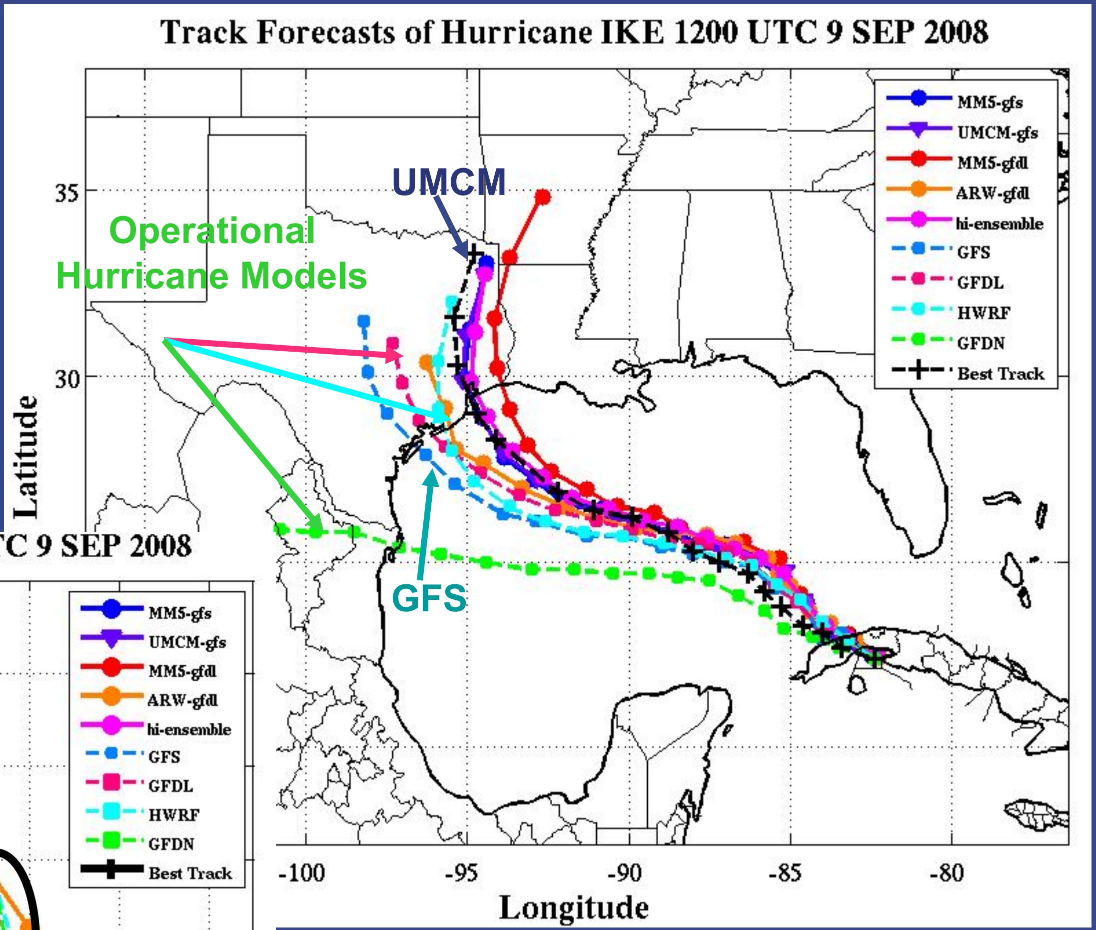


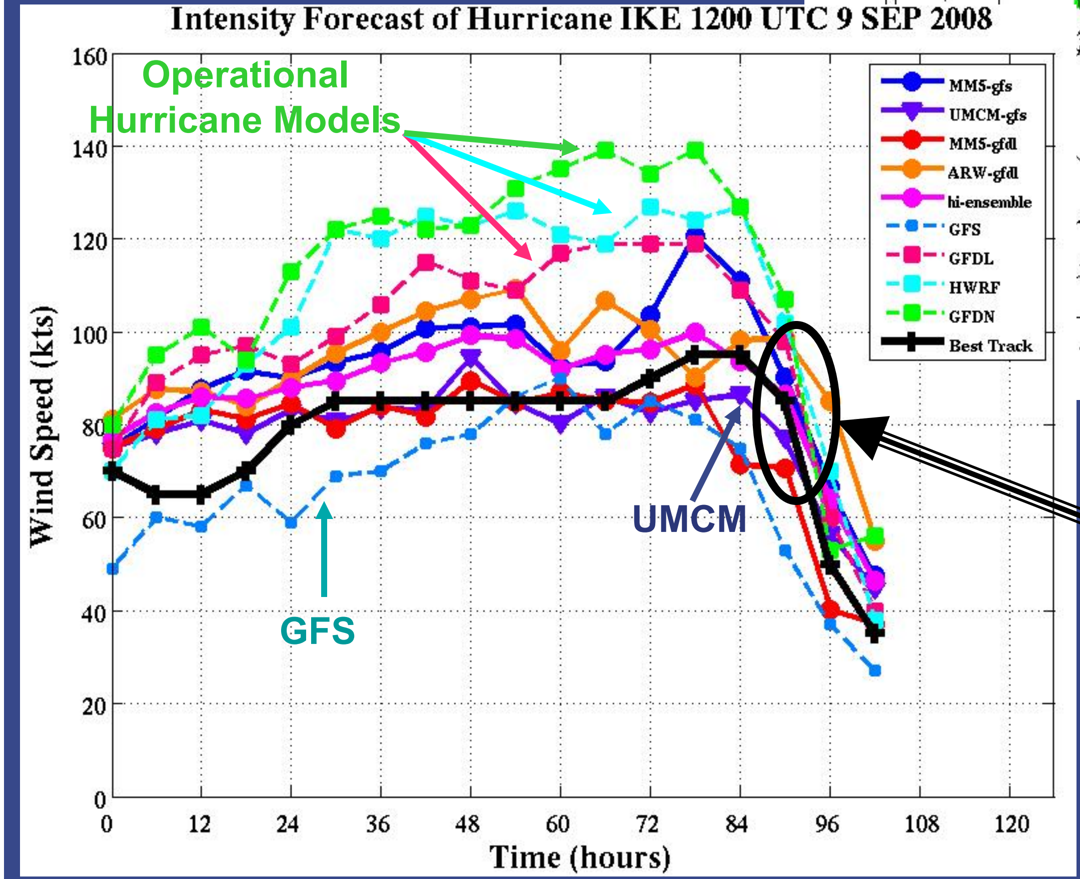
Traditional TC Forecast Verification





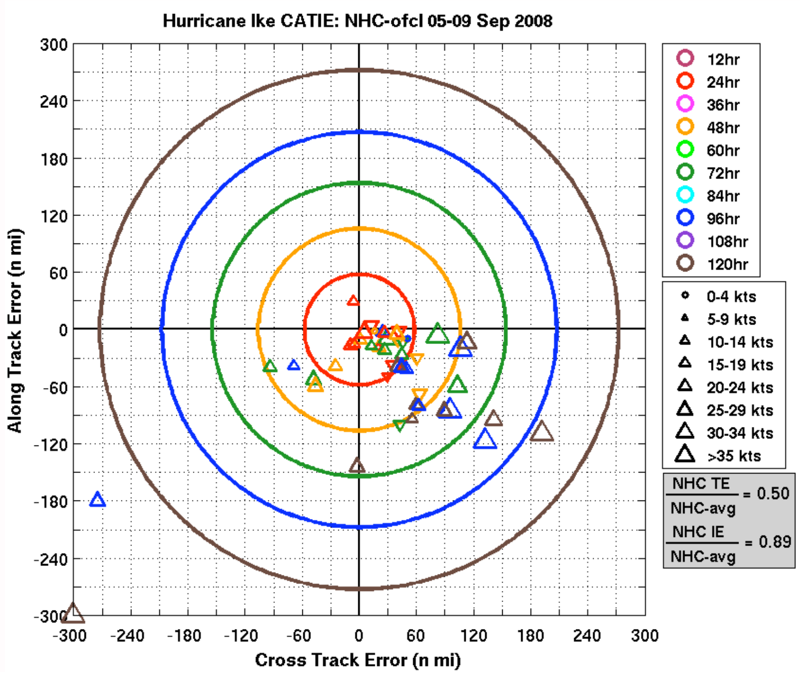
Mini-ensemble forecast of Hurricane Ike

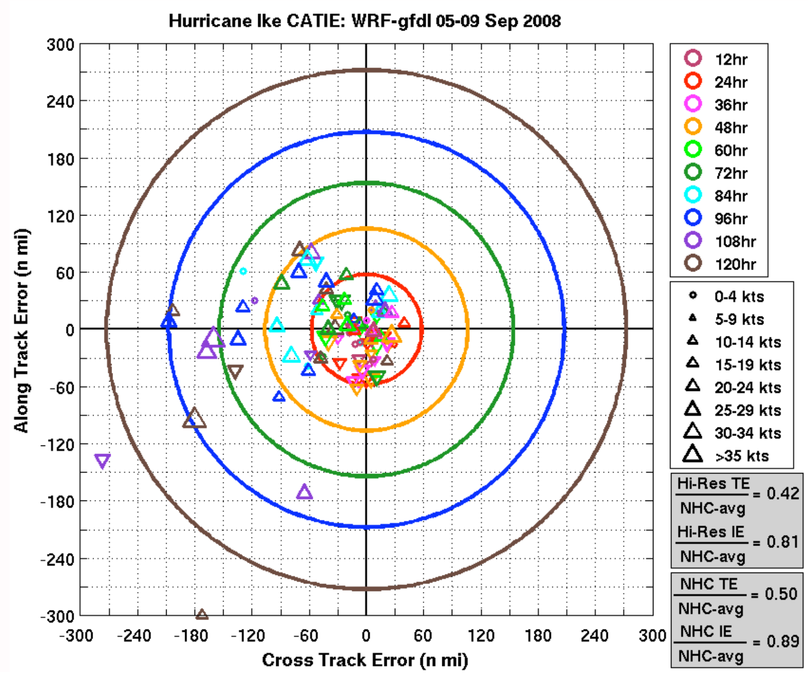


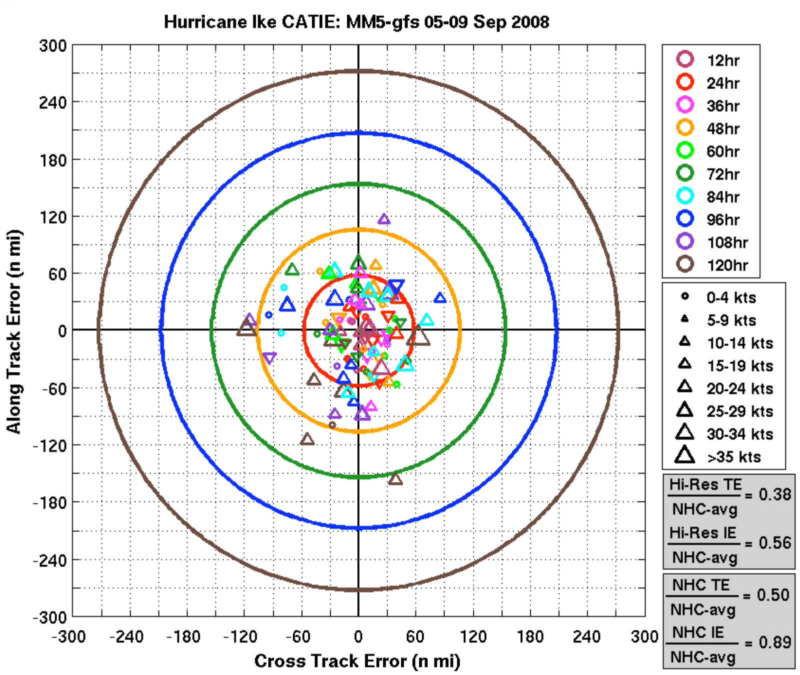


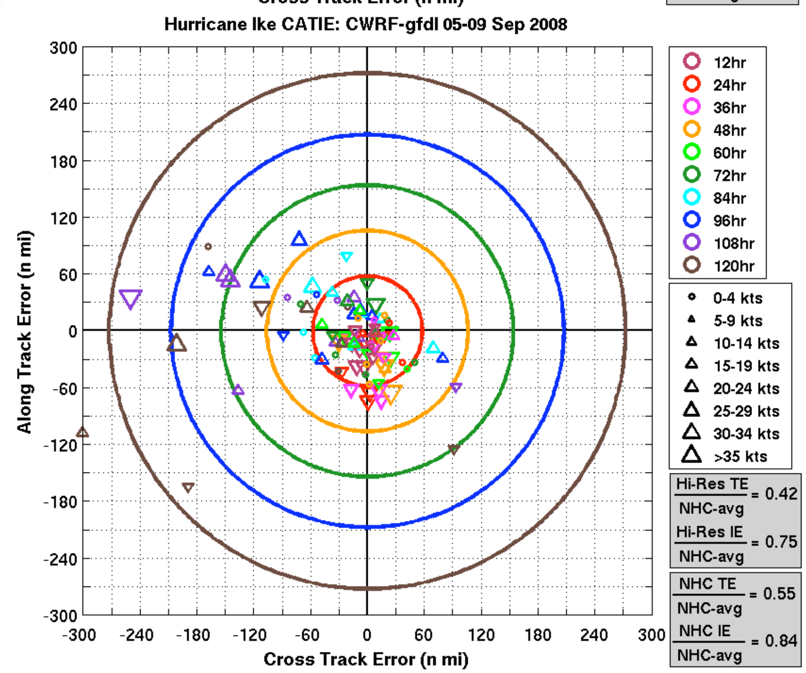
"Good" landfall intensity forecasts?

Cross-Along Track and Intensity Error (CATIE) Diagram

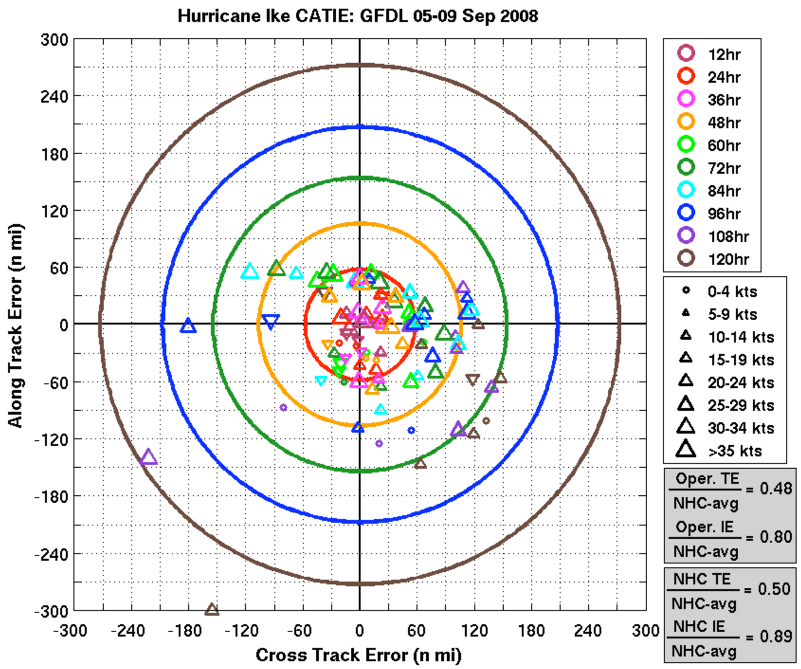


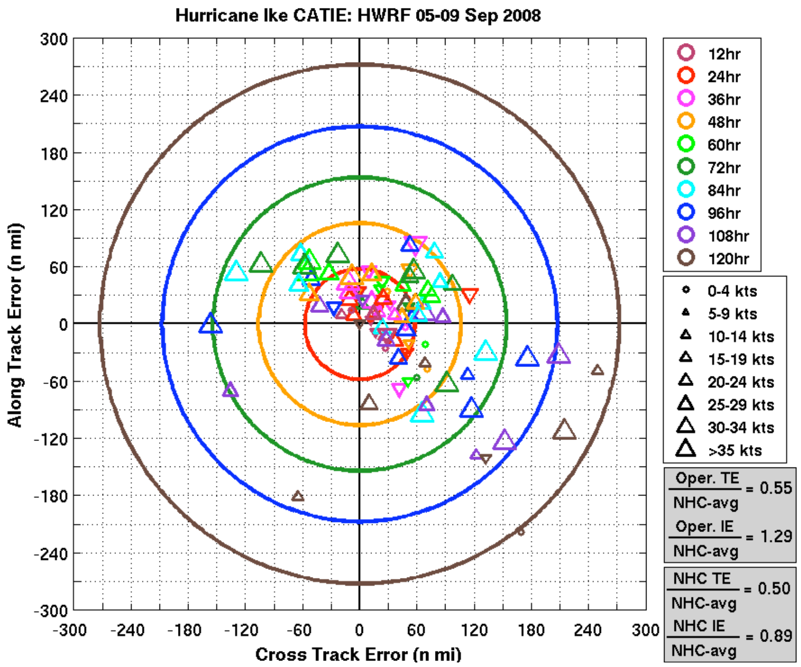


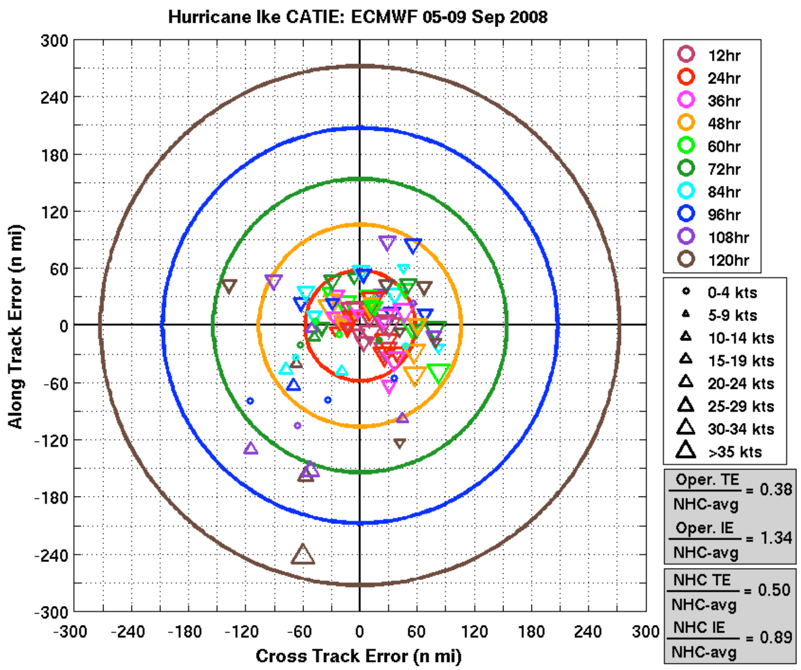


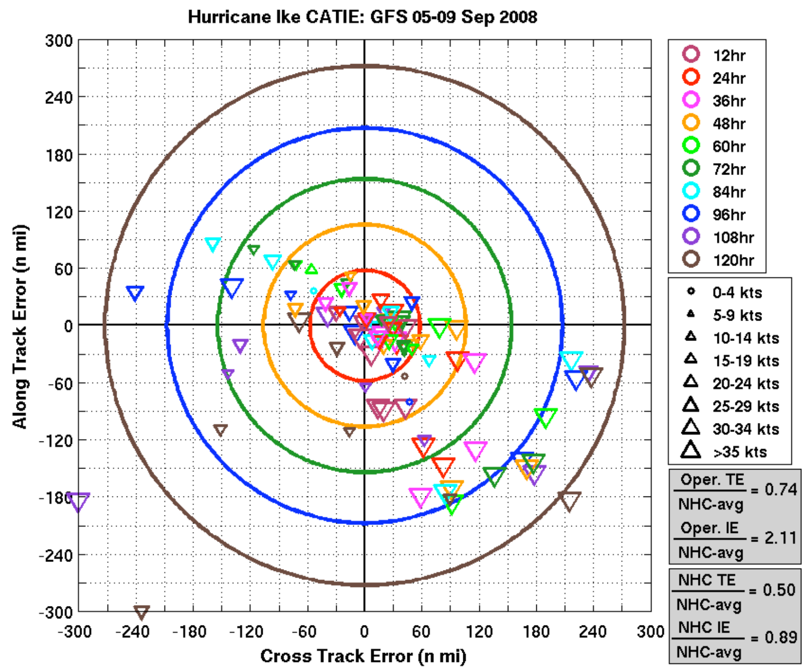


Cross-Along Track and Intensity Error (CATIE) Diagram



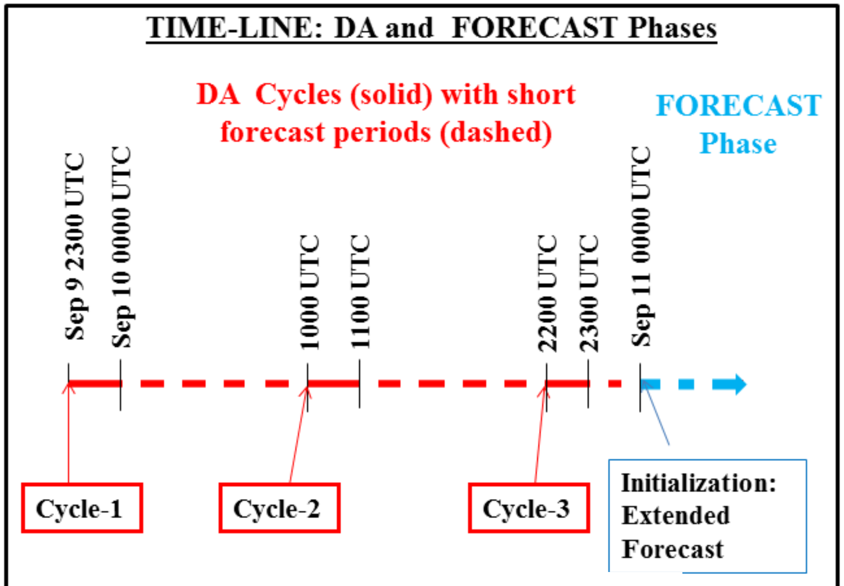


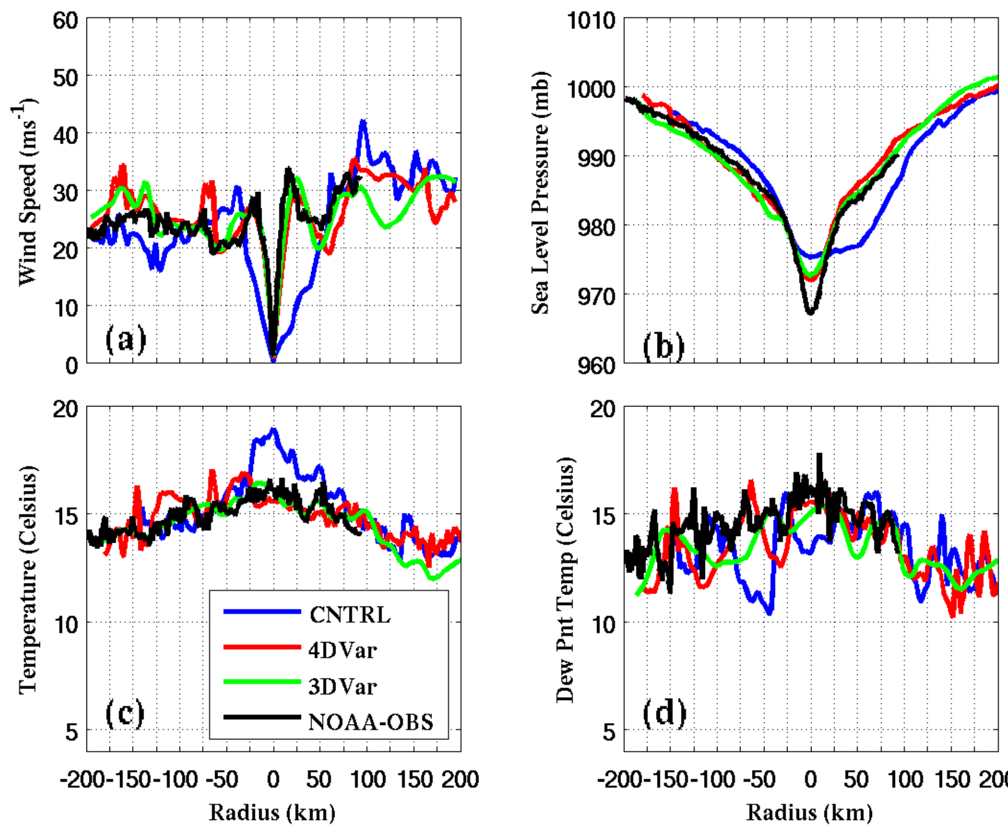


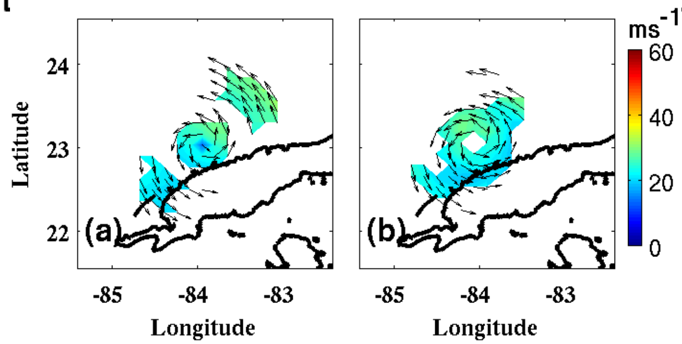


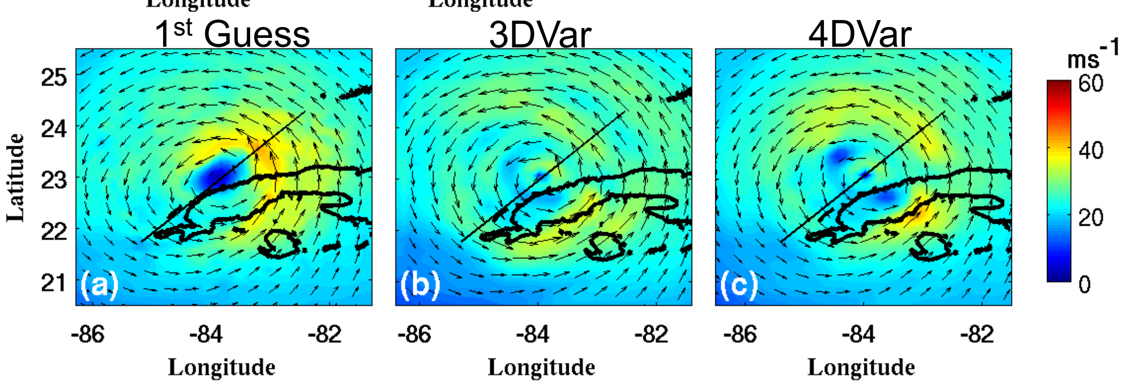
IMPACT OF ASSIMILATING AIRBORNE DOPPLER RADAR WINDS ON THE INNER-CORE STRUCTURE AND INTENSITY OF HURRICANE IKE (2008)

Gordon and Chen (2011)

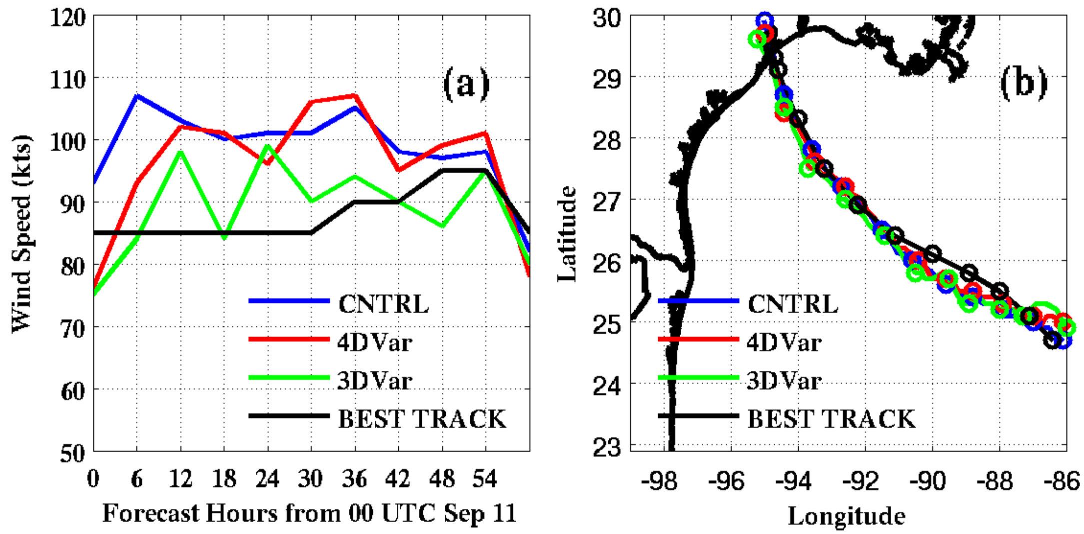


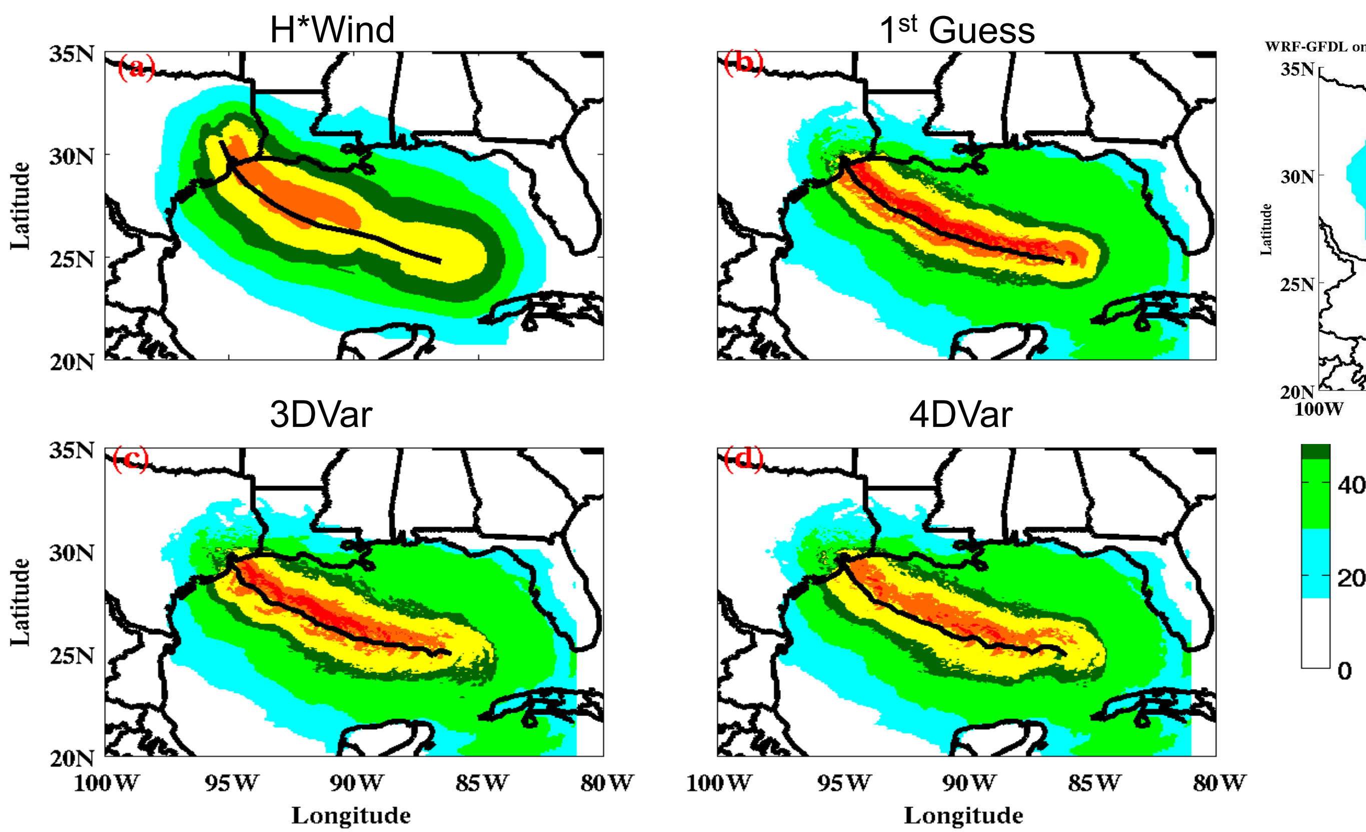


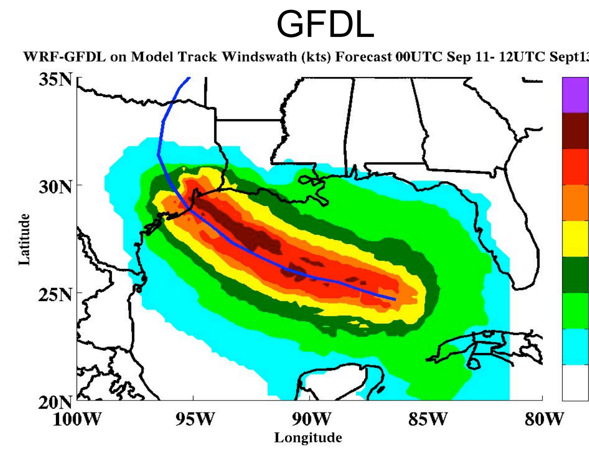




Gordon and Chen (2011)

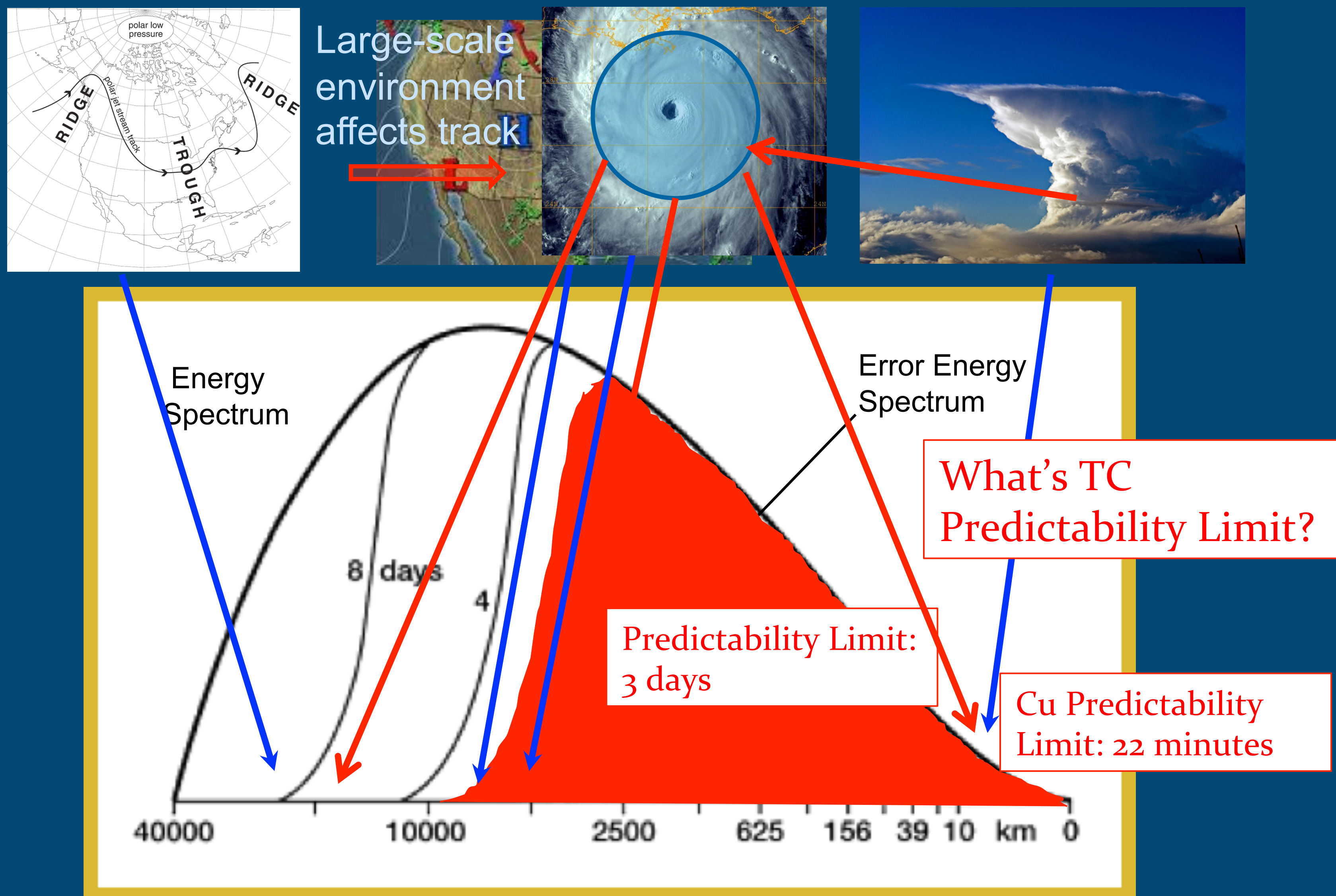




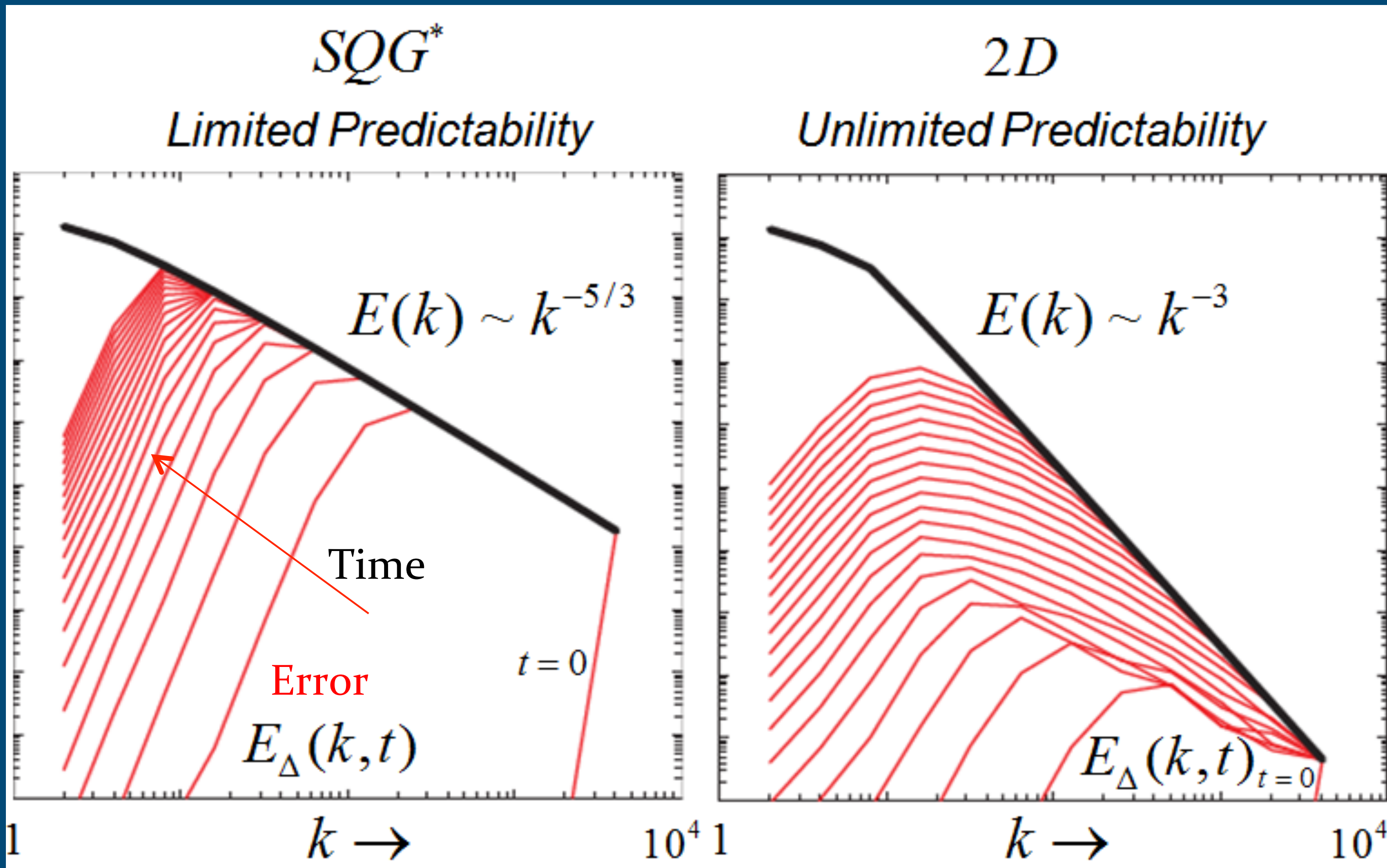


What is “predictability”?

- “The extent to which future states of a system may be predicted based on knowledge of current and past states of the system.” (AMS Glossary)
- Even with arbitrarily accurate models and observations, there may still be limits to the predictability of a physical system.
- Complex non-linear dynamical systems (e.g. the atmosphere) possess an inherent predictability limit.



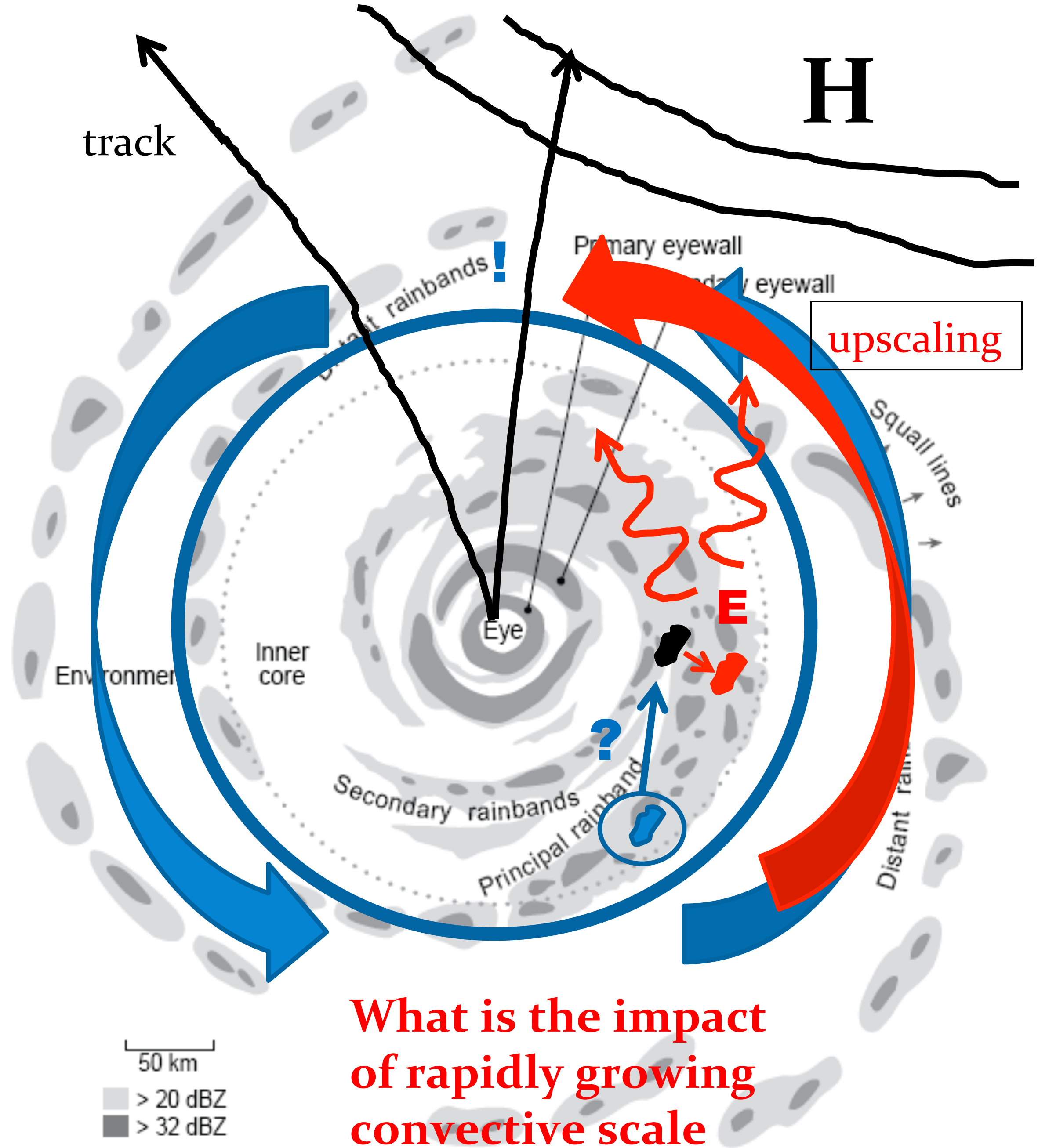
Lorenz (*Tellus*, 1969)



Rapid error growth at smallest scales

Error growth independent of scale

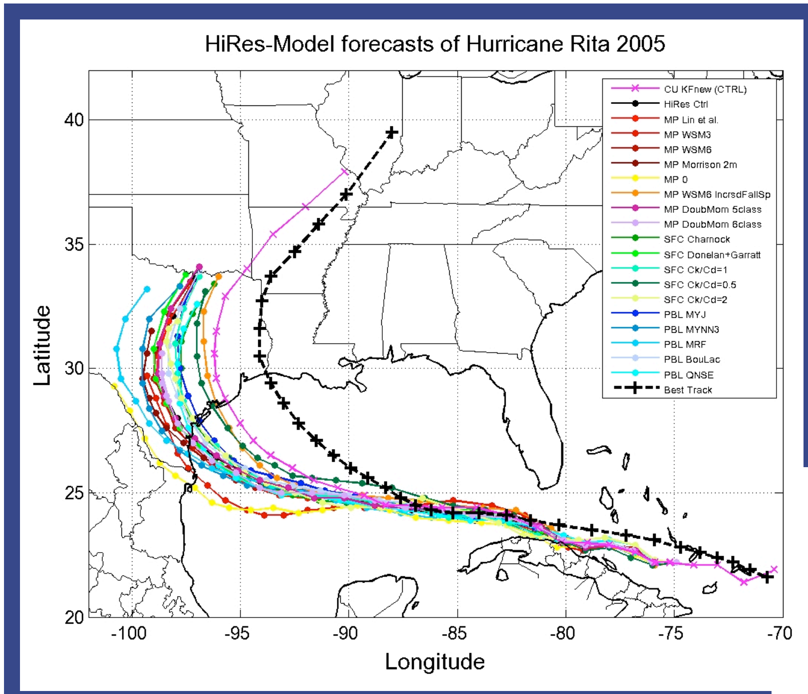
Rotunno and Snyder (*JAS*, 2008)

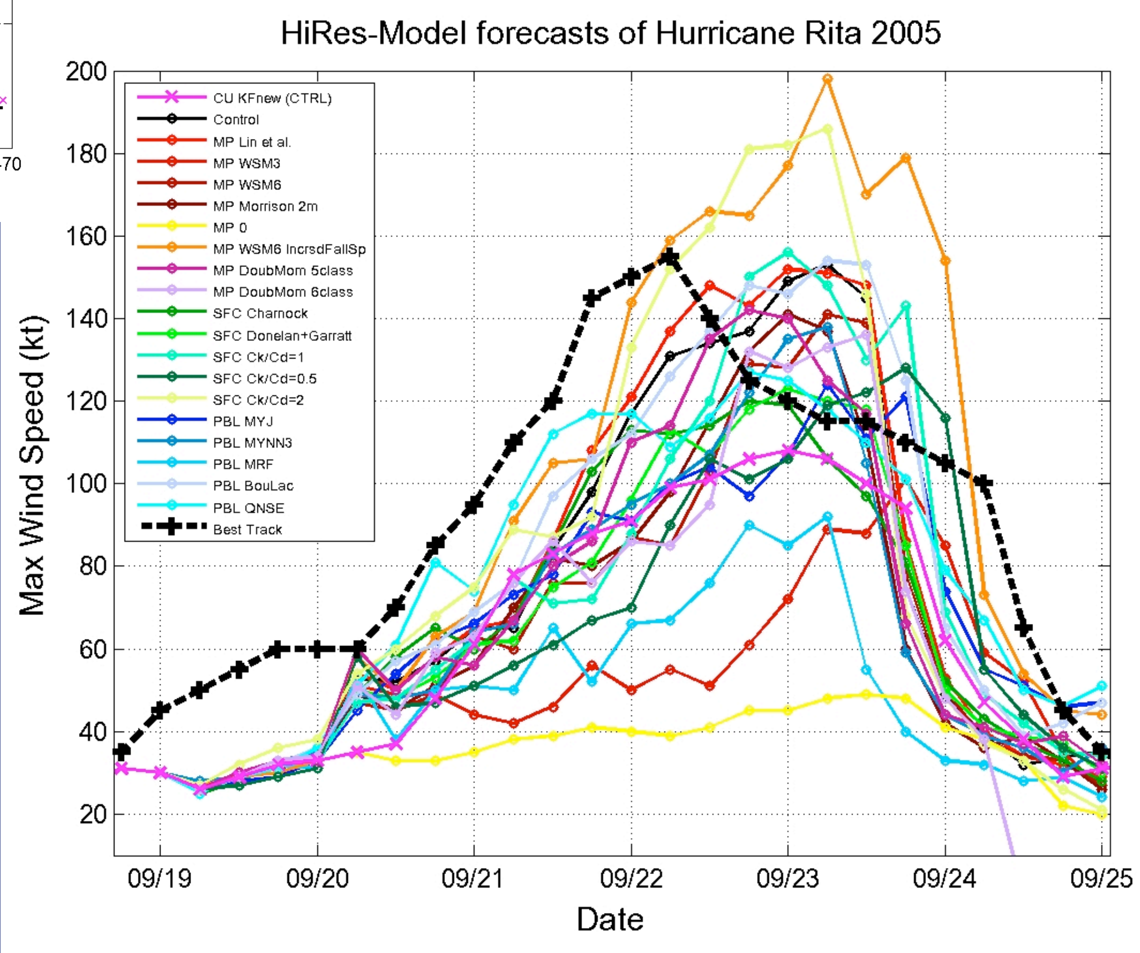


What is the impact of rapidly growing convective scale errors on TC vortex?

Houze (2010)

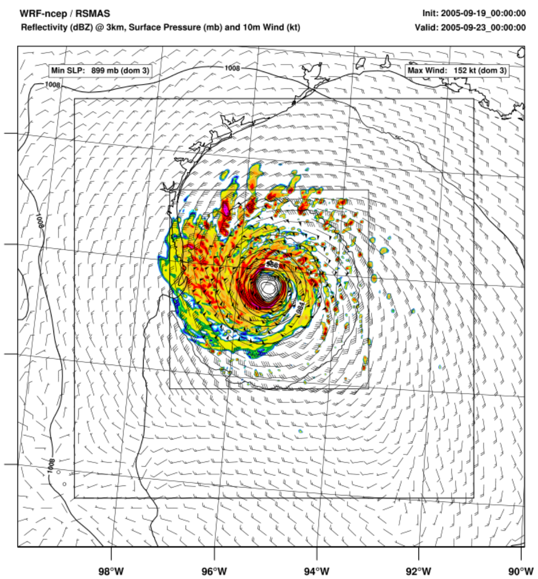
WRF-ARW Physics Ensemble (12/4/1.3 km grids)



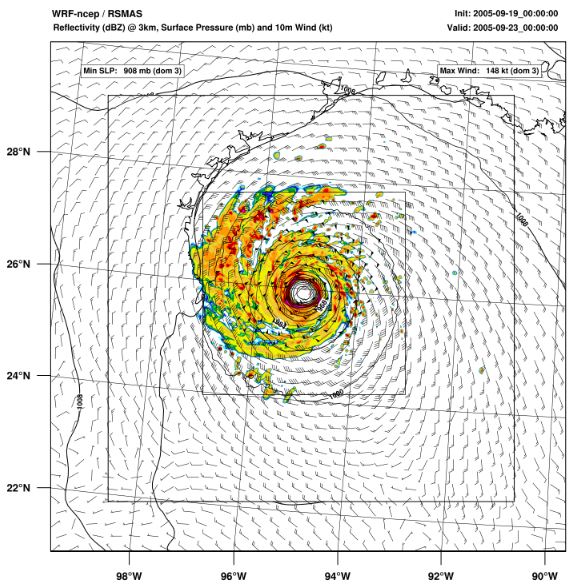


3-km level dBZ

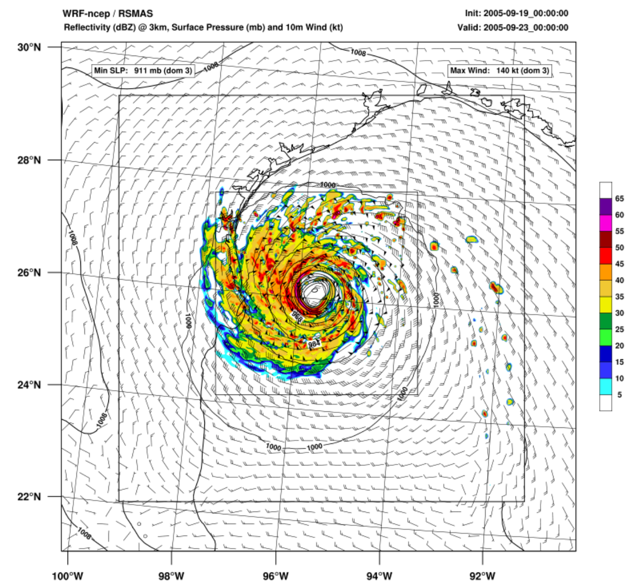
Lin et al.



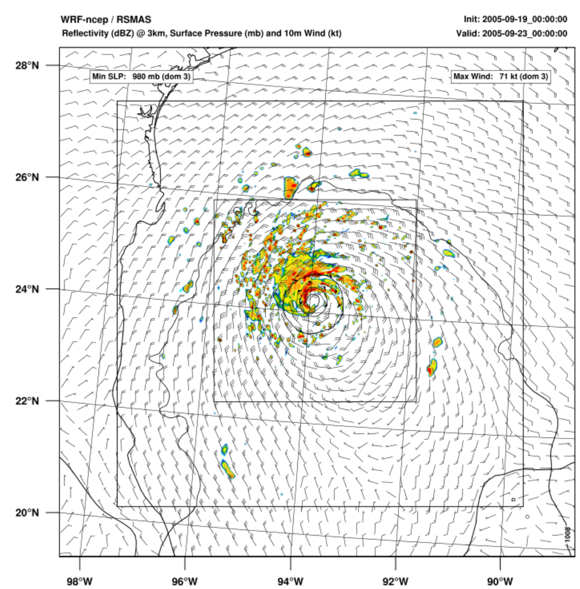
WSM5



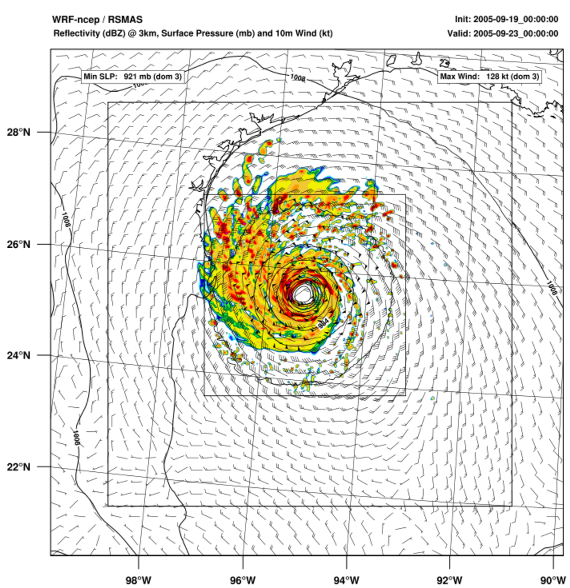
Morrison



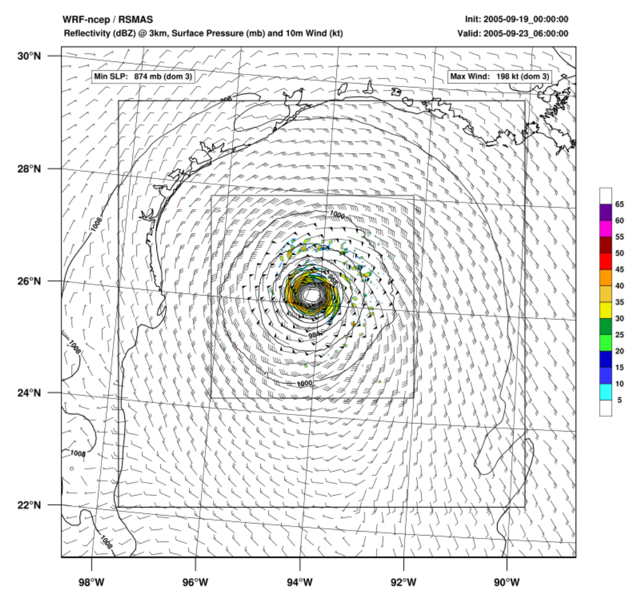
WSM3



WSM6

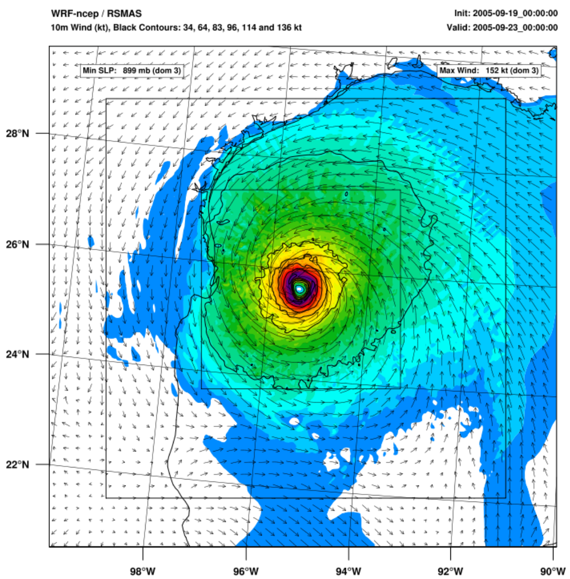


WSM6 – doubled fall speed

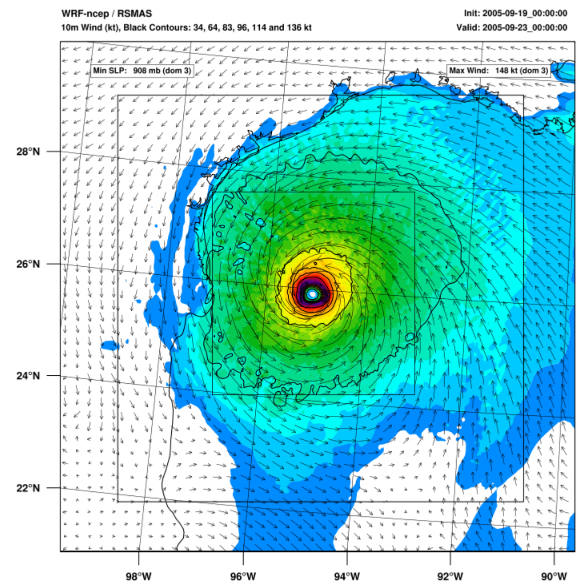


[10-m Wind]

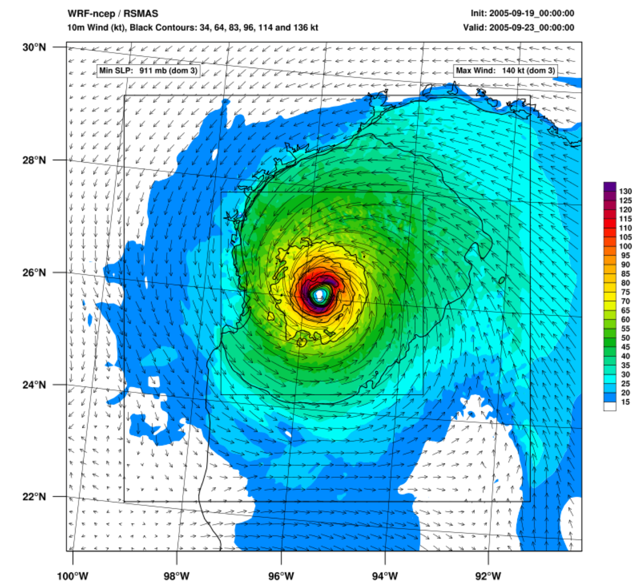
Lin et al.



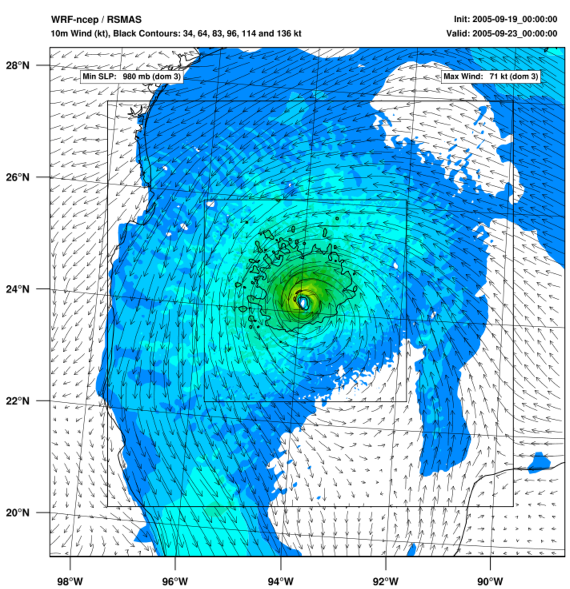
WSM5



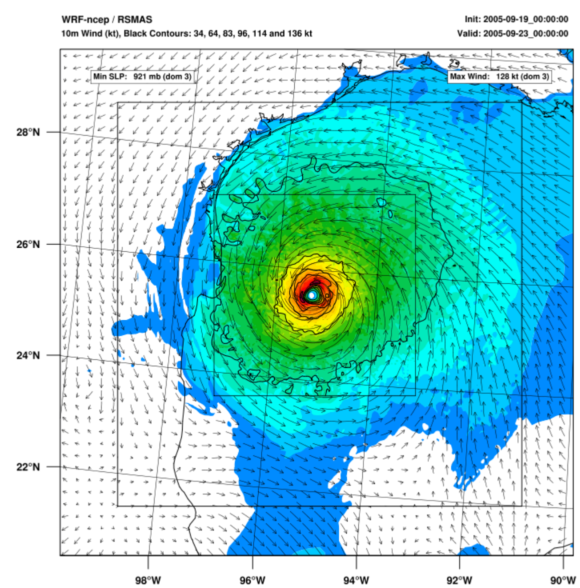
Morrison



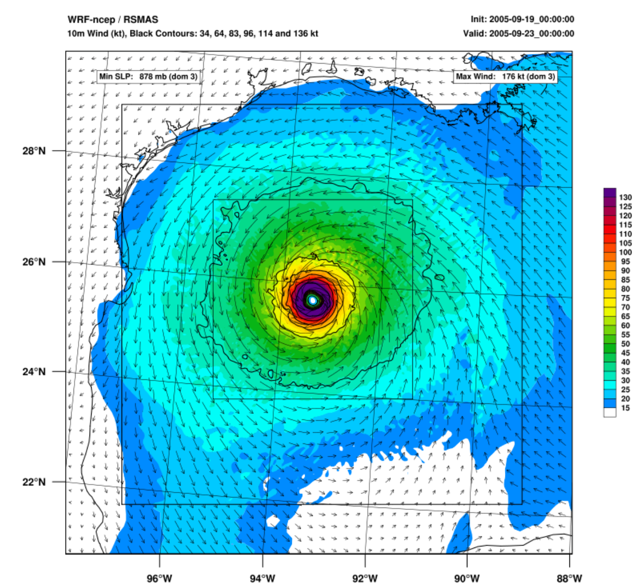
WSM3



WSM6



WSM6 – doubled fall speed



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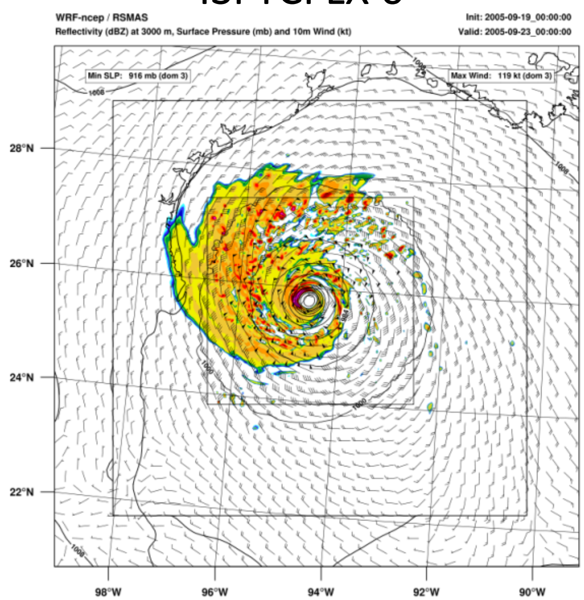

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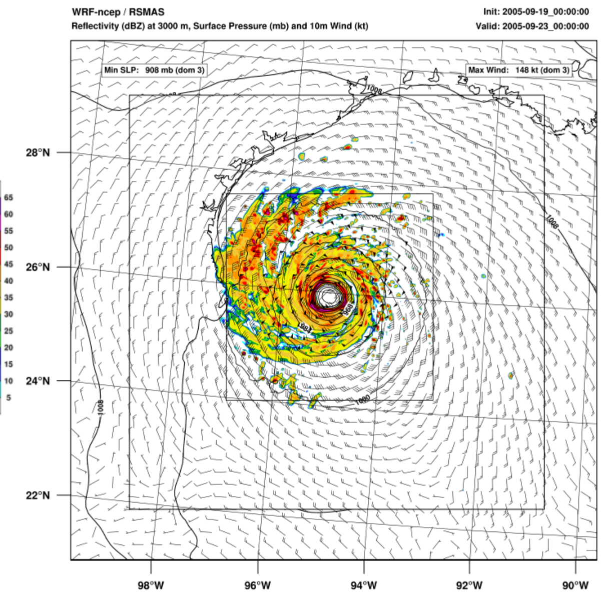

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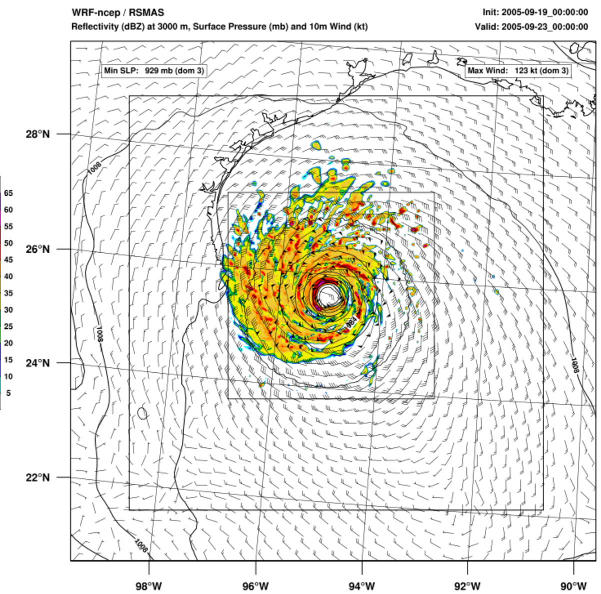

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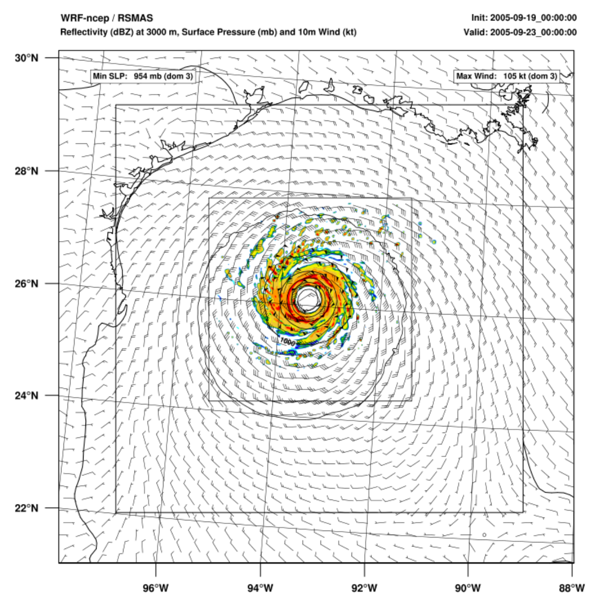

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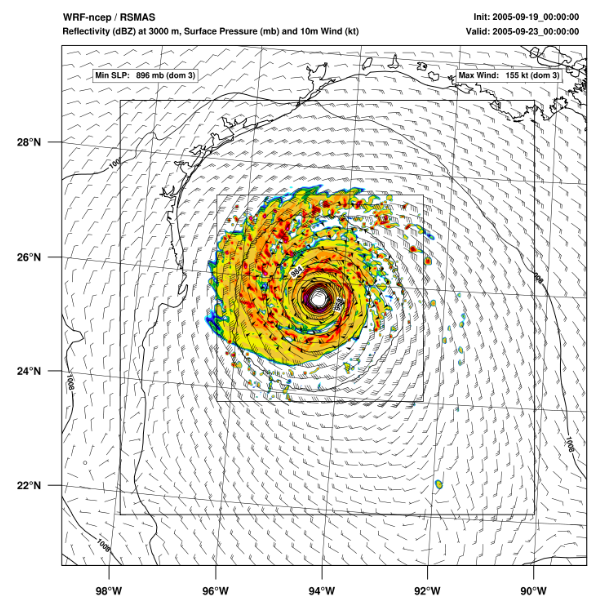

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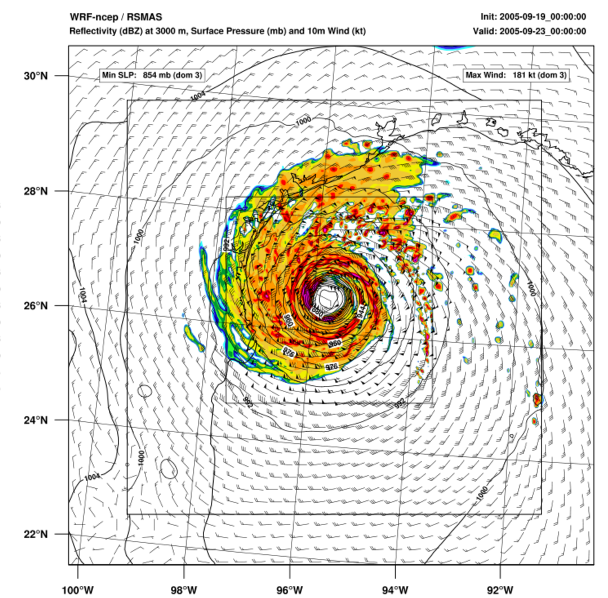

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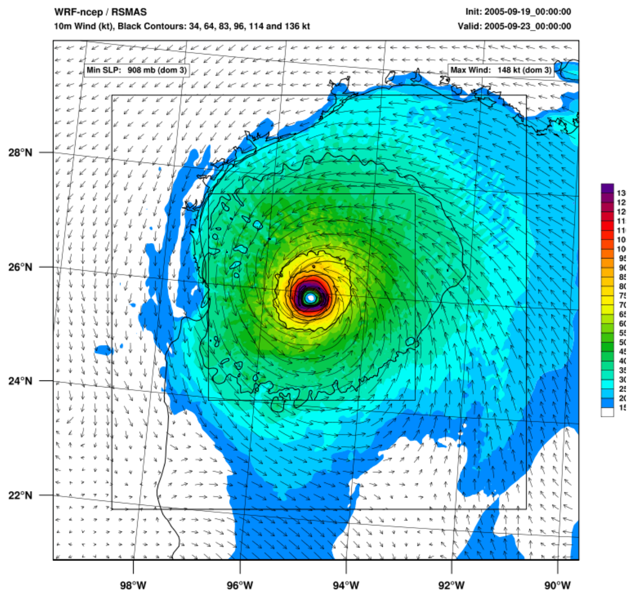

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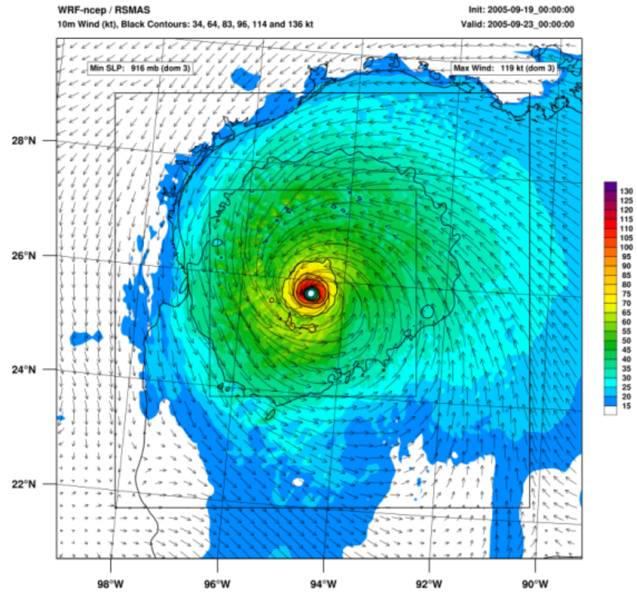

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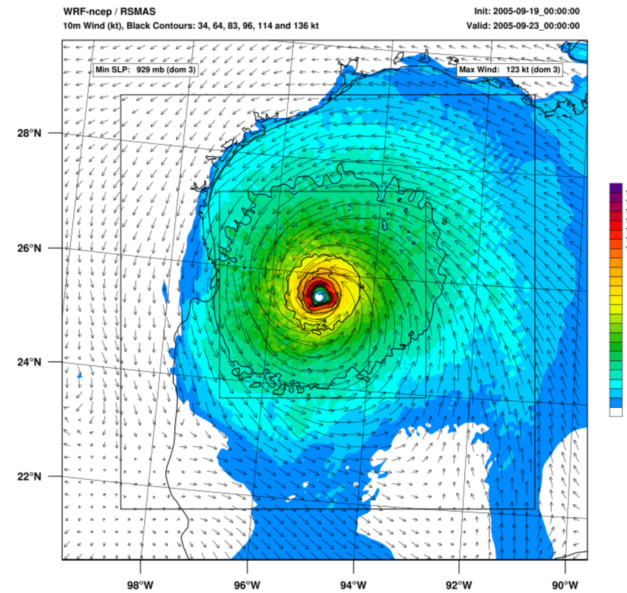

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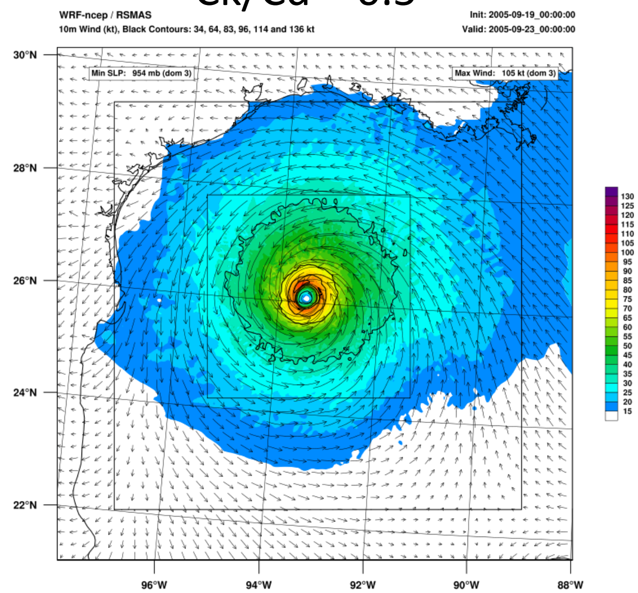

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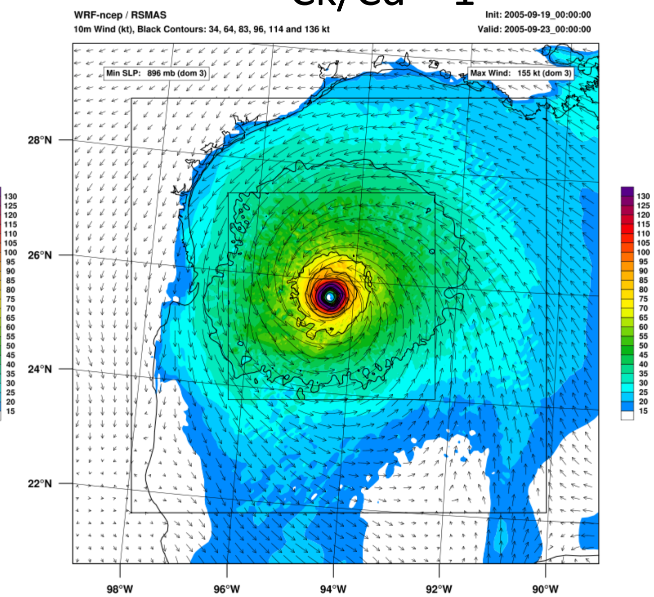

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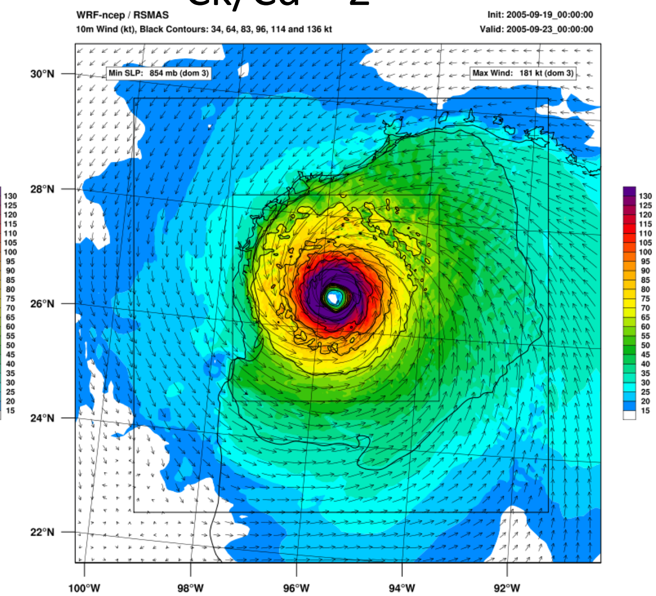
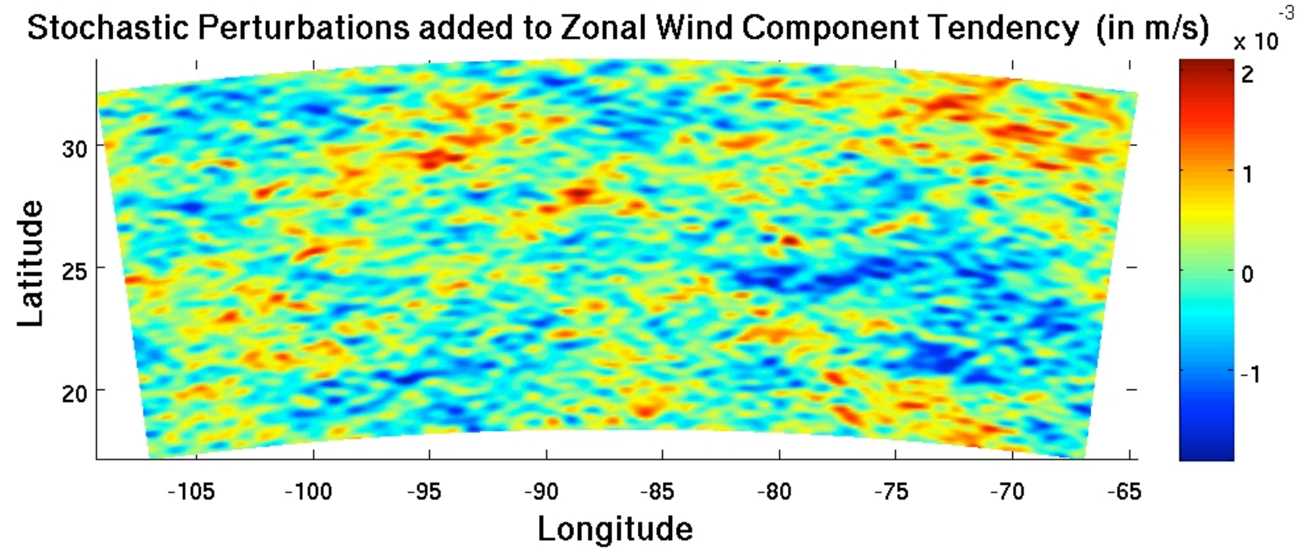
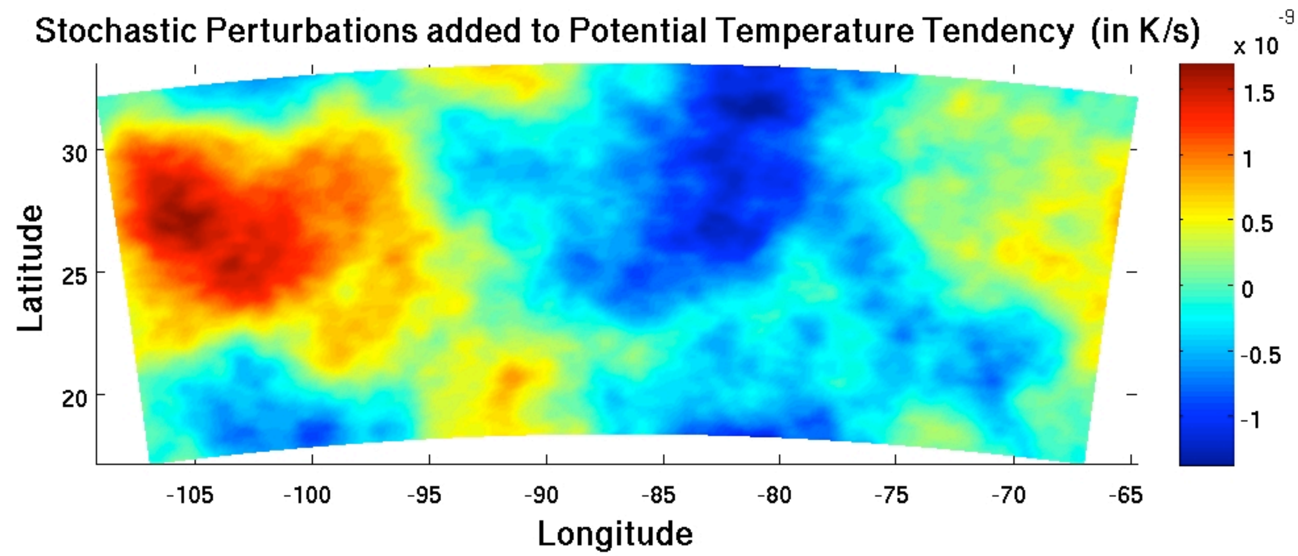


Stochastic Kinetic-Energy Backscatter Scheme in WRF-ARW
(Berner et al. (2010)

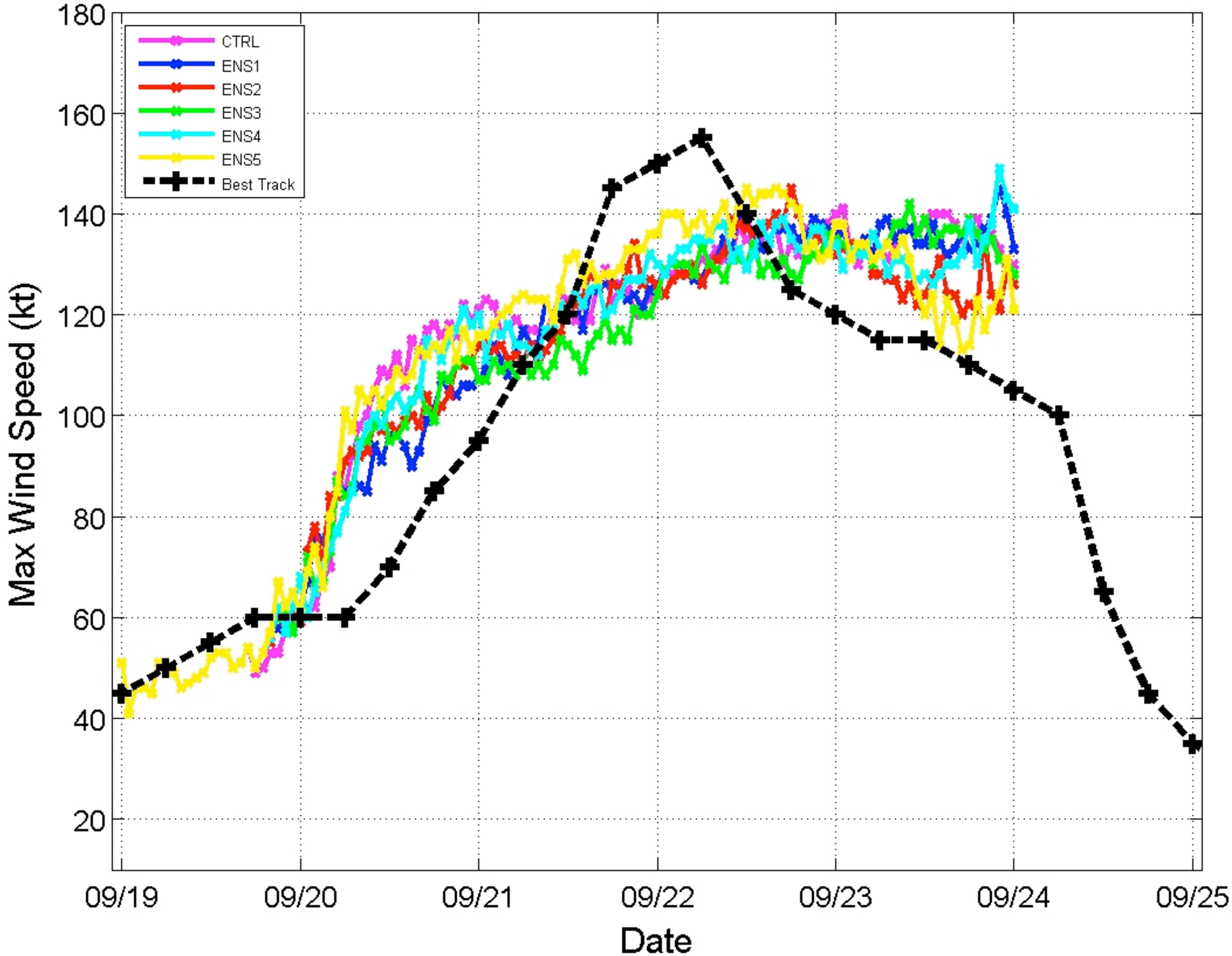


0.001 m/s

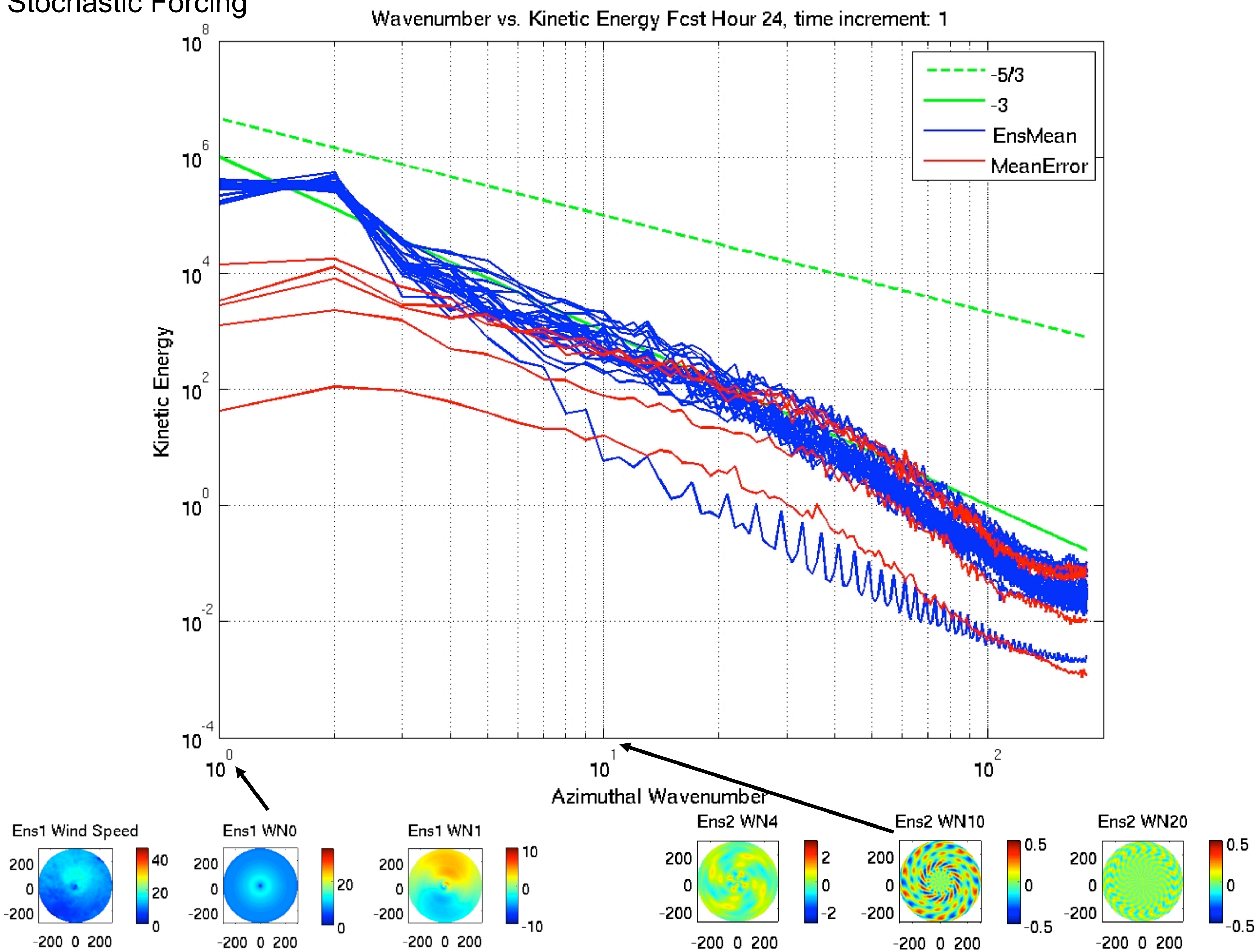


10^{-9} K/s

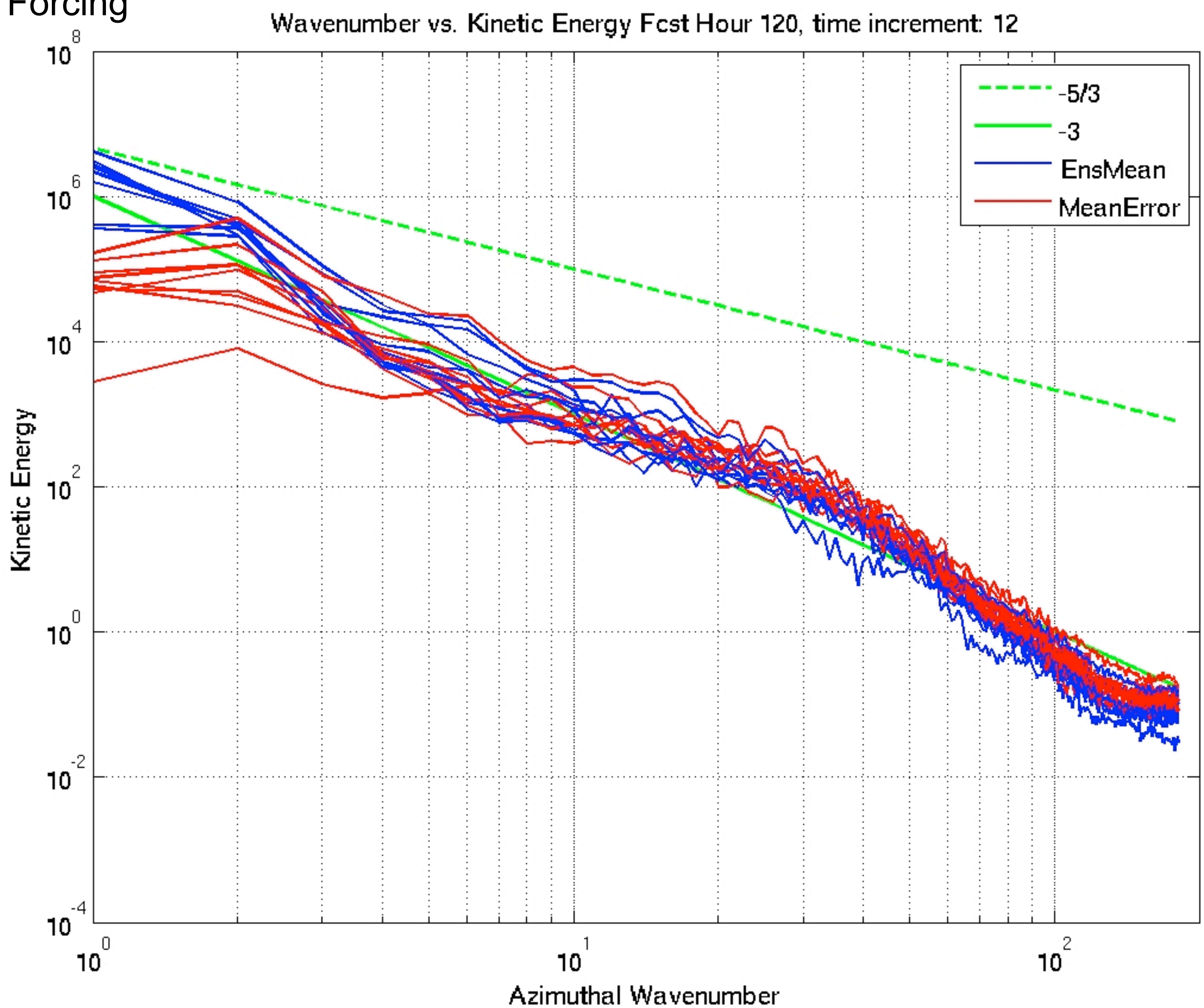
WRF-ARW Stochastic Kinetic-Energy Backscatter Ensemble

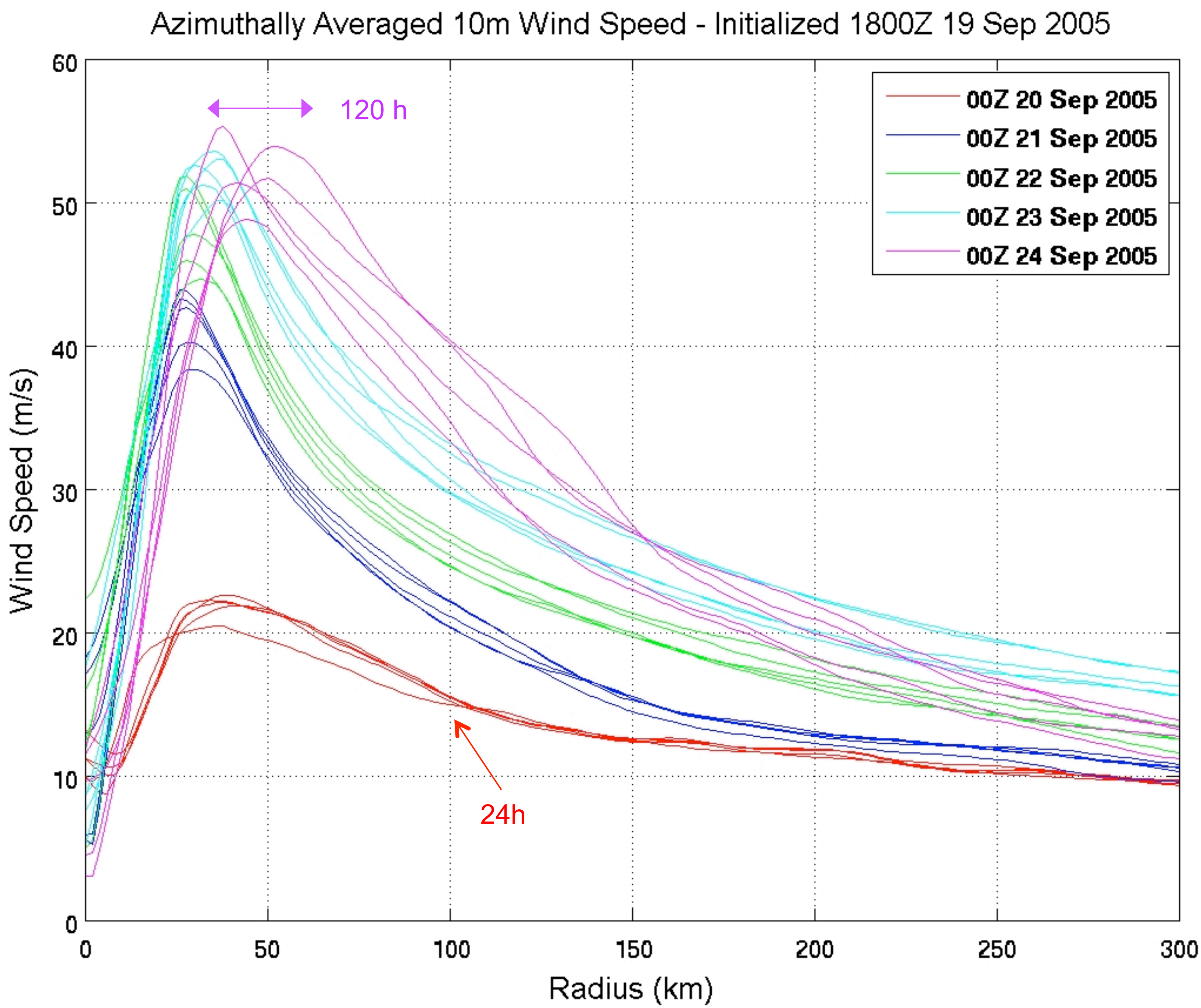


Stochastic Forcing



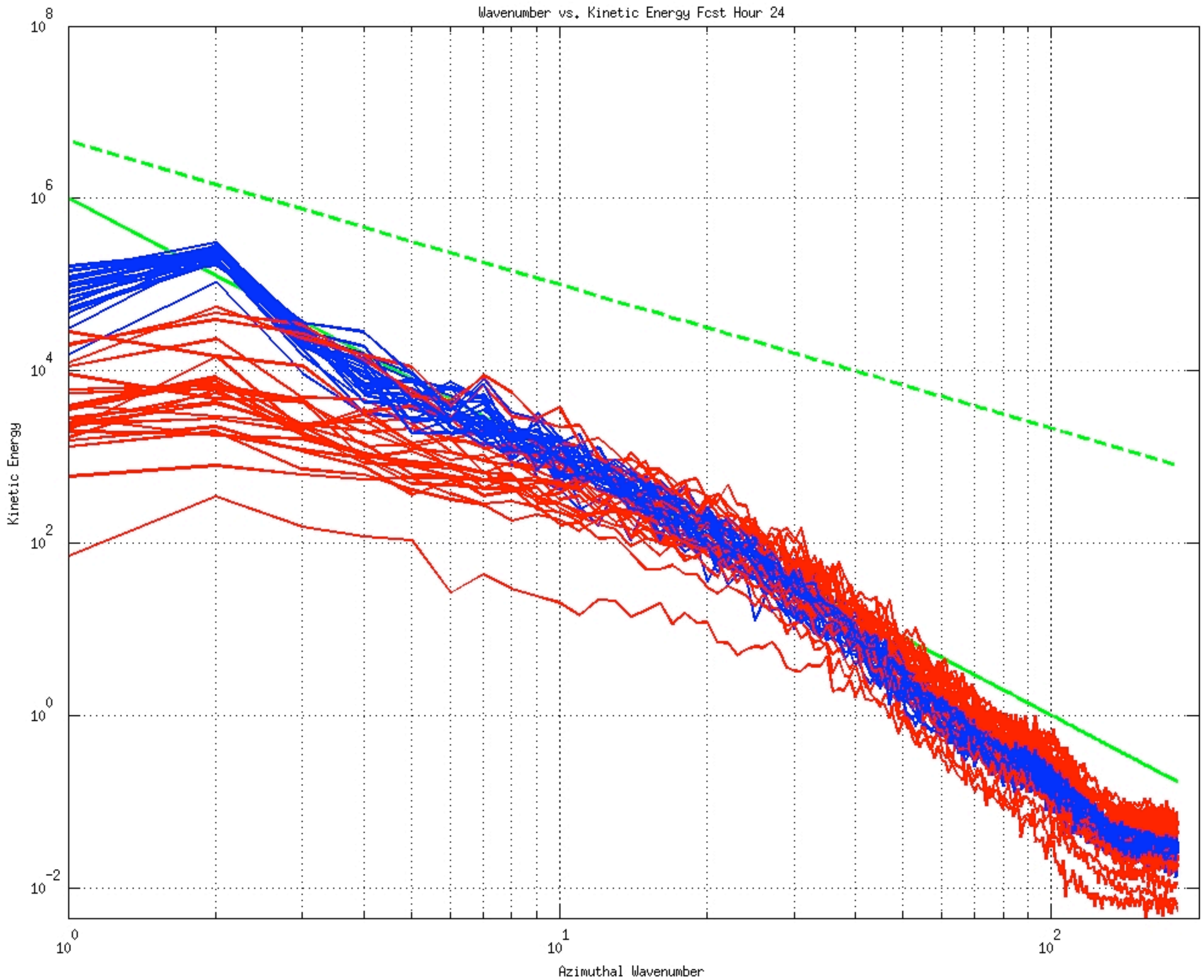
Stochastic Forcing




Azimuthally Averaged 10m Wind Speed - Initialized 1800Z 19 Sep 2005
00Z 20 Sep 2005
00Z 21 Sep 2005
00Z 22 Sep 2005
00Z 23 Sep 2005
00Z 24 Sep 2005
120 h
24h
Wind Speed (m/s)
Radius (km)
0
10
20
30
40
50
60
0
50
100
150
200
250
300

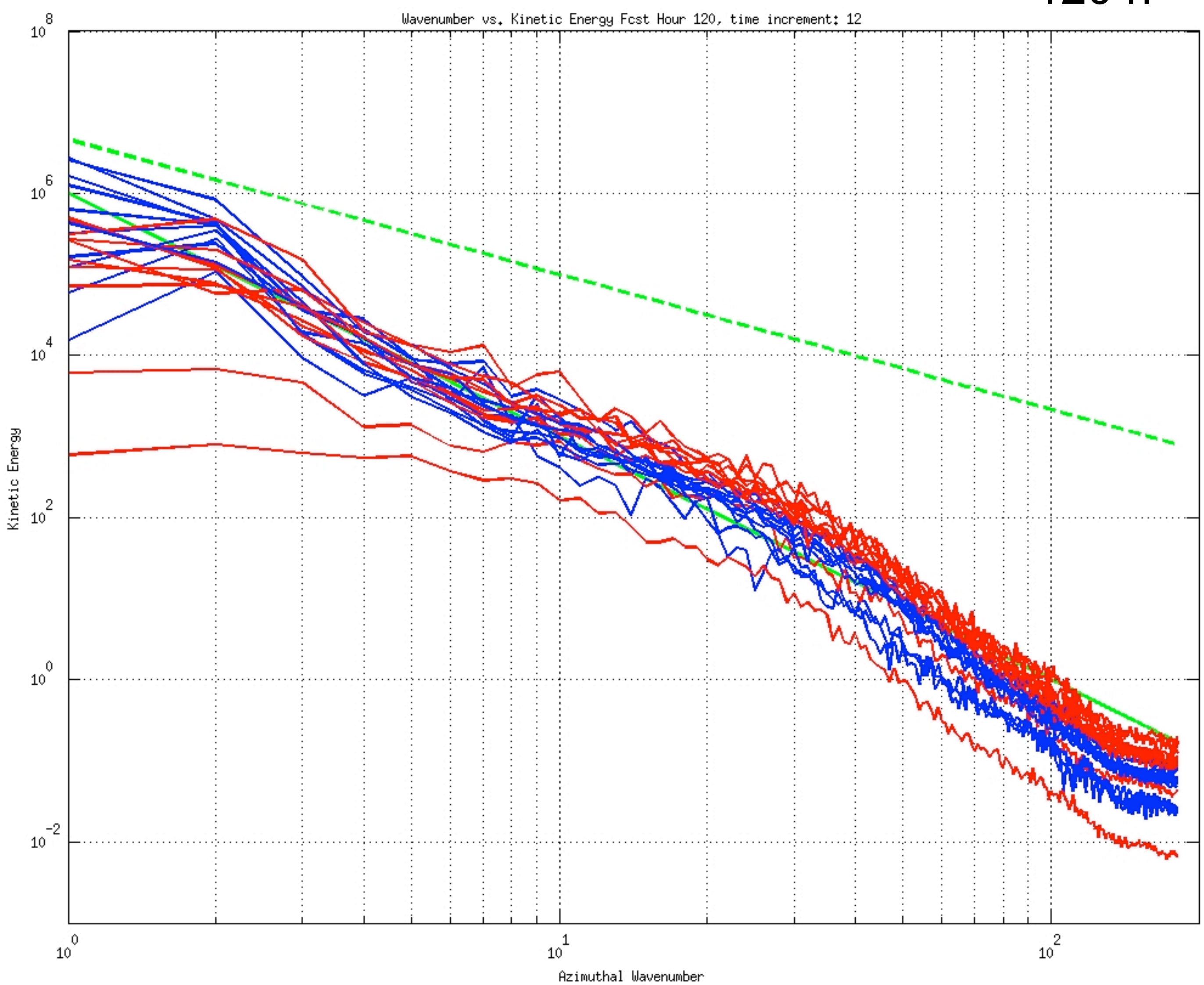
Physics Ensemble

24 h



Physics Ensemble

120 h



SUMMARY

To improve hurricane intensity forecasts:

- High-resolution, cloud-resolving, fully coupled models are a must!
- Model physics for cloud-resolving resolution
- Better verification metrics for high-resolution coupled models
- Model physics ensemble has the largest uncertainly and faster upscaling error growth
- Size of a hurricane is more sensitive to surface parameterization (air-sea fluxes)
- Stochastic kinetic-energy backscatter forcing ensemble is a valuable tool for quantifying subgrid model error
- Hurricane vortex (e.g., wavenumber 0 and 1: symmetric and asymmetric structure) is more predictable than convective elements in rainbands