Realistic Simulations of Intense Hurricanes with the NCEP/NCAR WRF Modeling System

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Motivation

- Hurricane intensity forecasts
  - Have improved little in 30+ years
  - Dependent on inner-core dynamics
- New, high-resolution models (WRF) that resolve the hurricane core and fine structures
- Explore what this model can do
  - Real-time prediction
  - Exploratory simulations
    - Extremely fine scale, approaching Large-Eddy Simulation
    - New methods for initialization

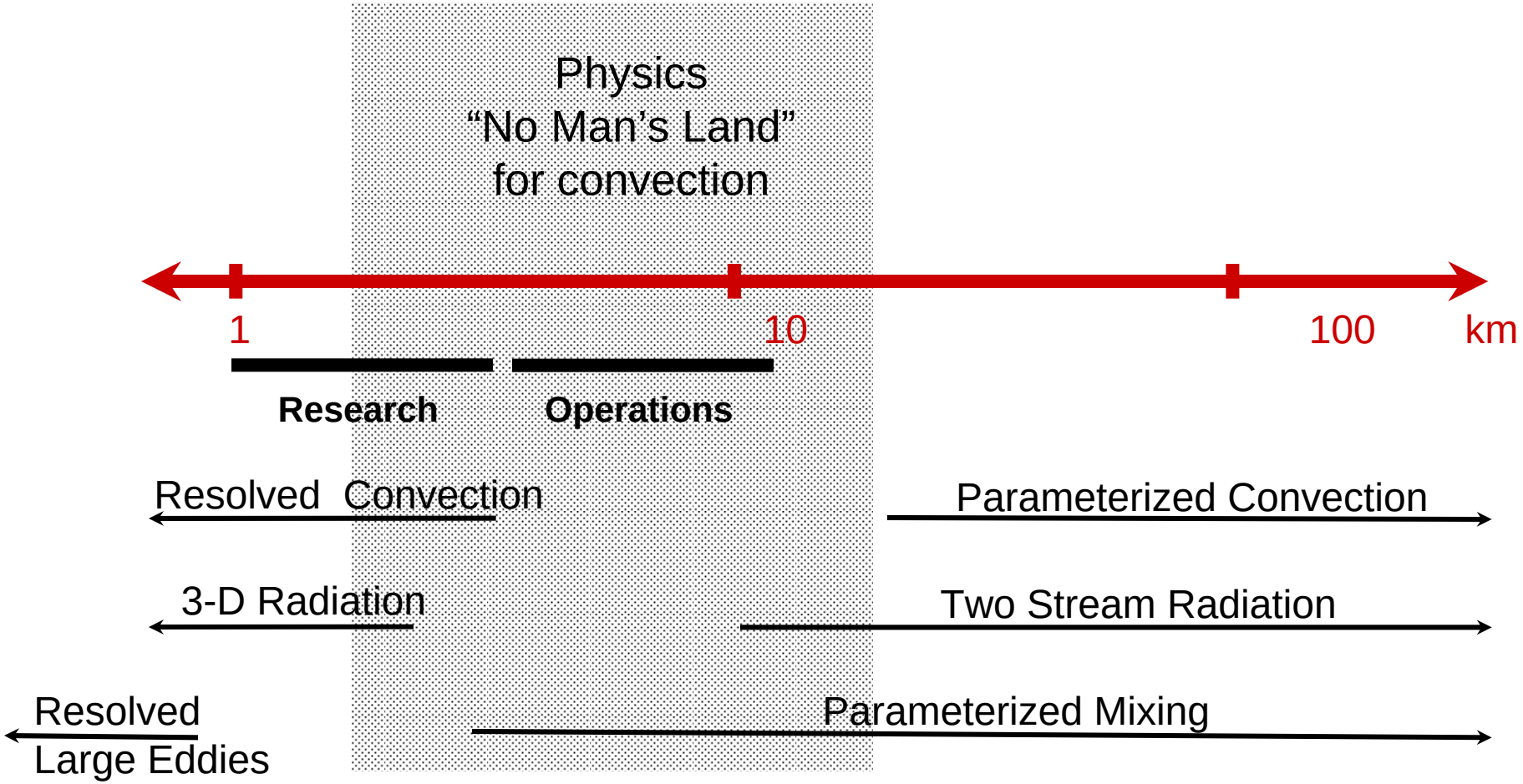
Methodology

- Real-time forecasts for 4 Atlantic hurricane seasons
  - Hurricane model derived from Advanced Research WRF
  - Moving nested grids, finest horizontal increment 1.33 km
  - Forecasts out to 5 days
- Alternative initialization methods
  - Variation assimilation of airborne Doppler radar
  - Ensemble data assimilation
- “LES-scale” idealized simulations
  - Understand behavior of “coarse” resolution (1-2 km grid)
  - Finest grid 62 m

Conclusions

- Real-time forecasts
  - Distinguish strong versus weak storms
  - Realistic structures (not well quantified yet)
  - Indications of initialization deficiencies
- Alternative initialization methods
  - Radar data improves intensity prediction out to 1.5 days
  - Ensemble assimilation: promising blend of data assimilation and probabilistic prediction
- “LES-scale” idealized simulations
  - Intensification with decreasing grid spacing
  - turbulence erupts at ~100 m; halts intensification

Resolution Dependence of “Physics” in Atmospheric Prediction Models

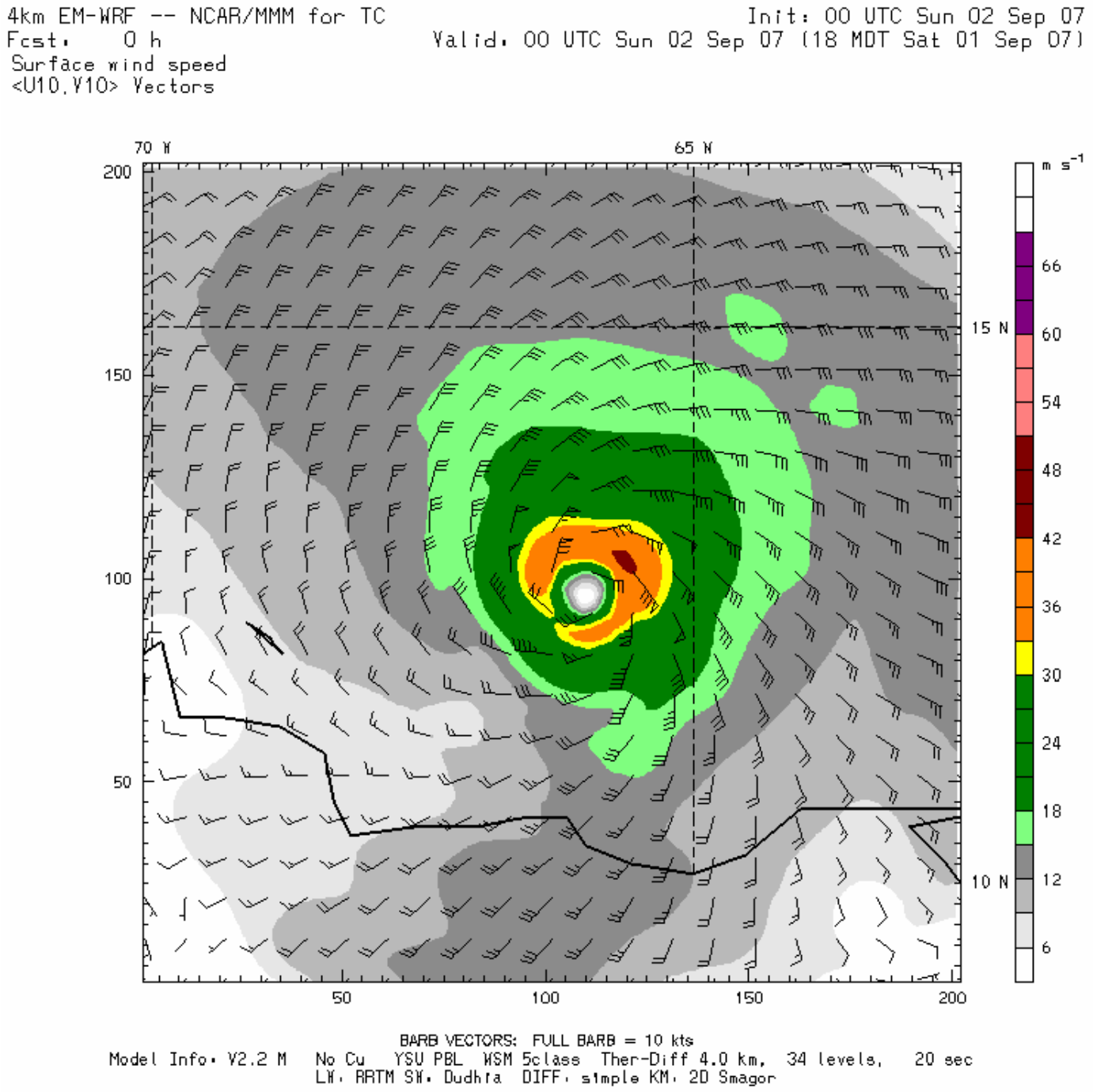


Real-time Forecasts

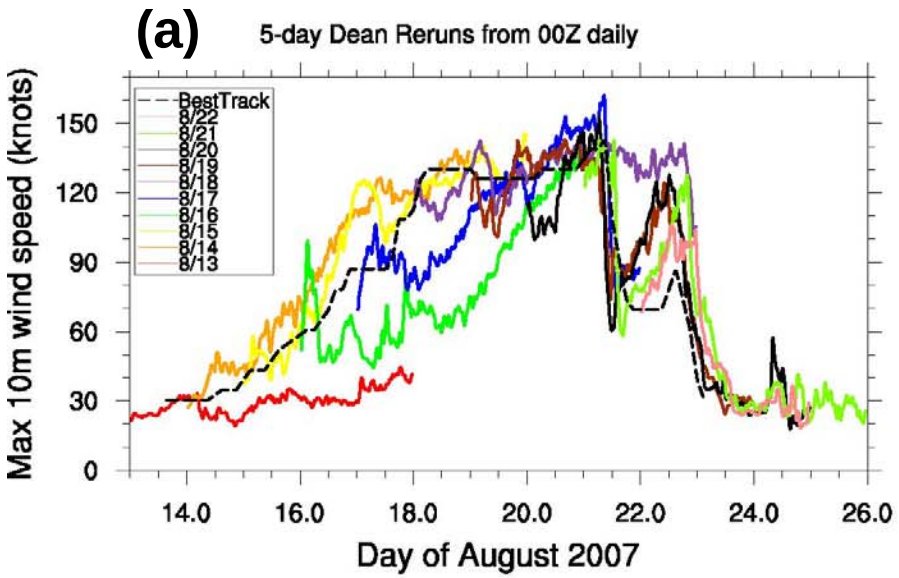
- AHW is ARW for hurricanes (Advanced Hurricane WRF)
  - Community model, 5000+ users worldwide
  - Non-hydrostatic; time splitting for acoustic modes
  - Stretched vertical coordinate (35-50 layers)
  - Top is ~20 km
- Atmosphere initialized with GFDL analysis
- GFS model lateral boundary conditions
- 2 moving nests (4 km, 1.33 km) inside 12-km grid
- Explicit treatment of precipitation

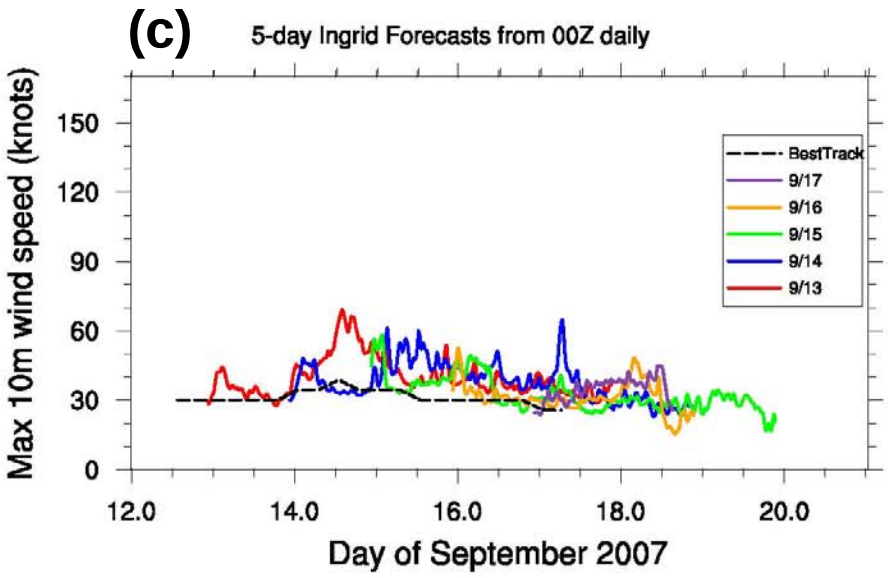
Felix:

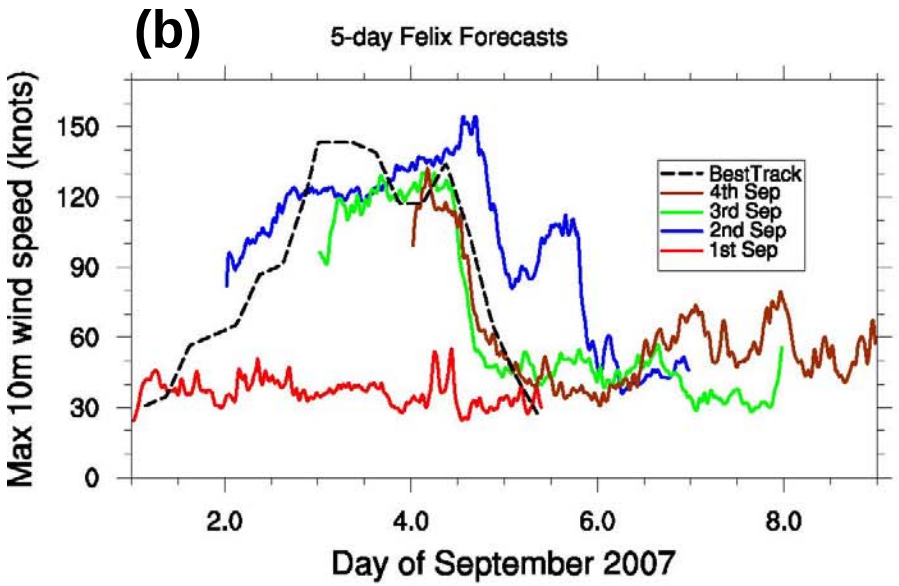
Forecast from 00Z 2 Sept.

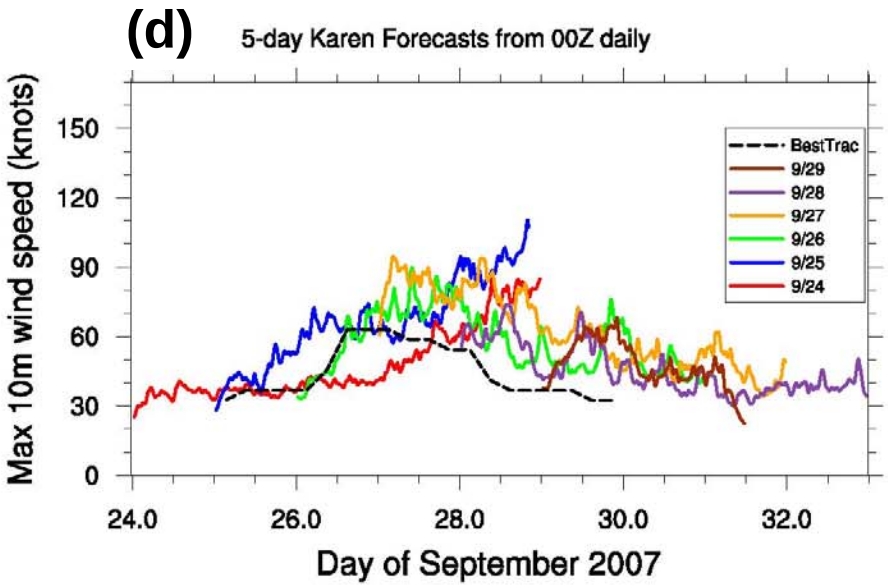


Time Series of Maximum Wind

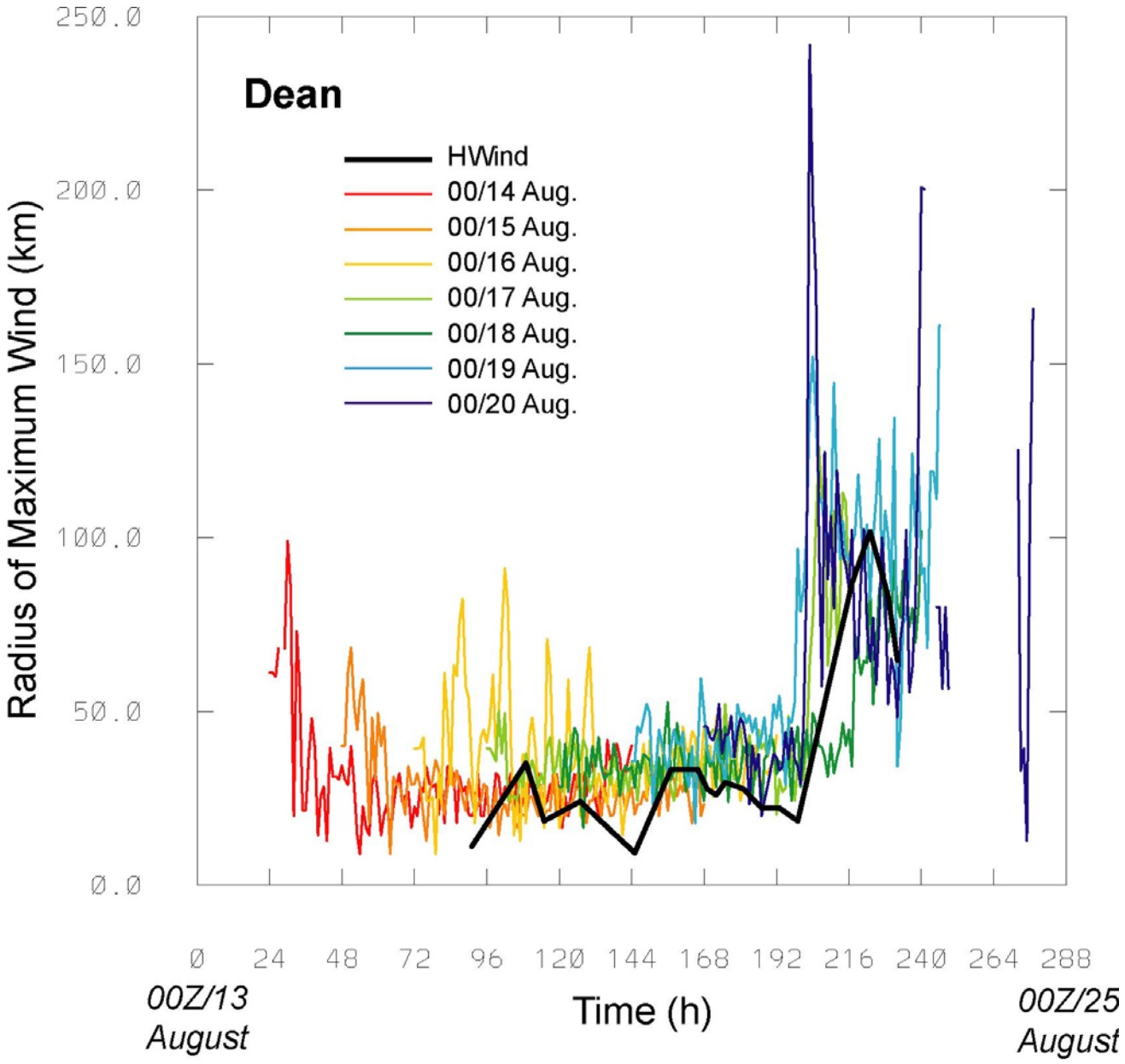








Radius of Maximum Wind



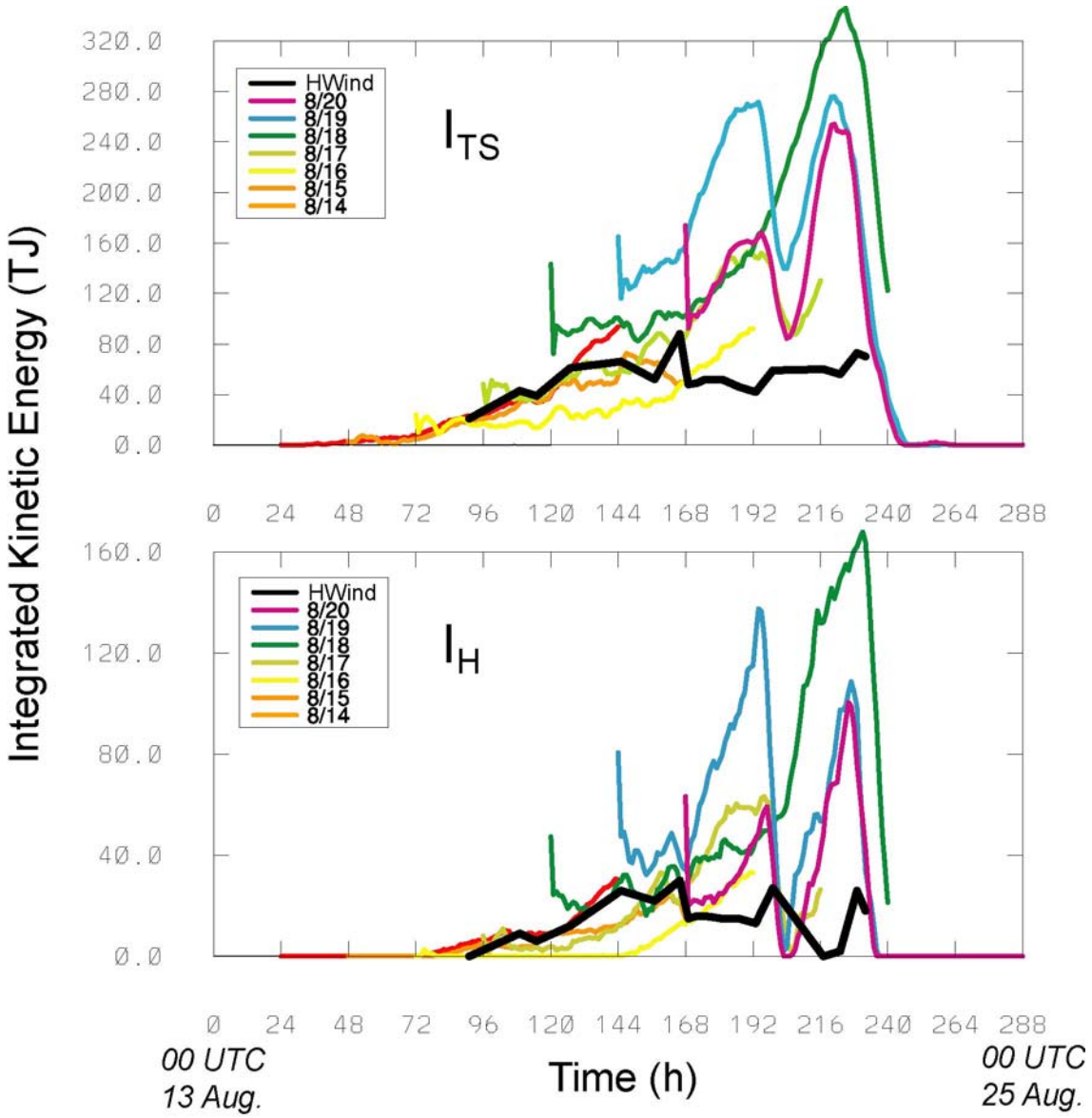
Integrated Kinetic Energy: Dean

$$I = \int_{dV} \rho U^2, \text{ for } U > U_0$$

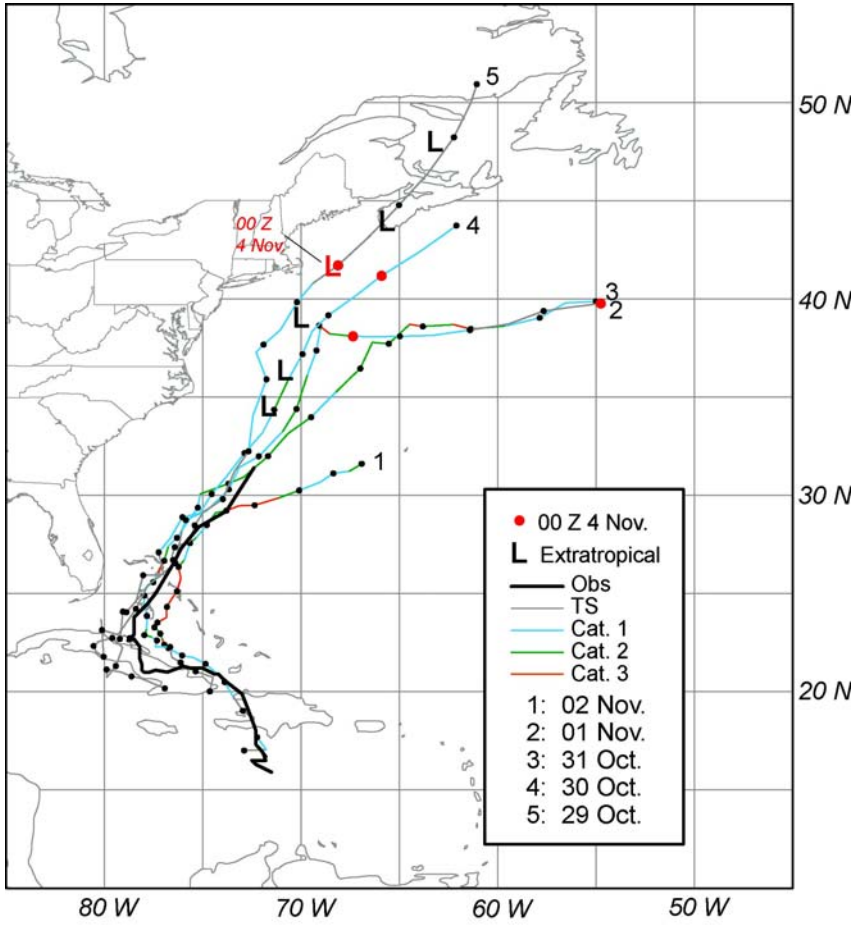
I_{TS}: U_0=34 knots

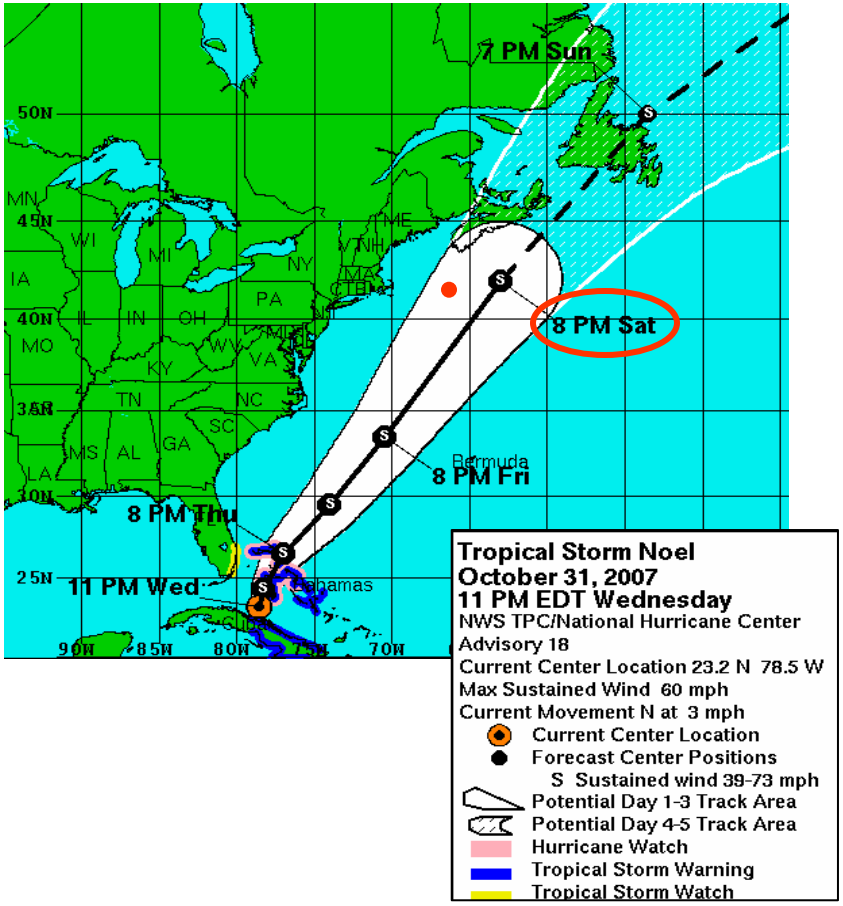
I_H: U_0=64 knots

Despite reasonable V_{max} and R_{max}, both I_{TS} and I_H are overestimated in mature stage.

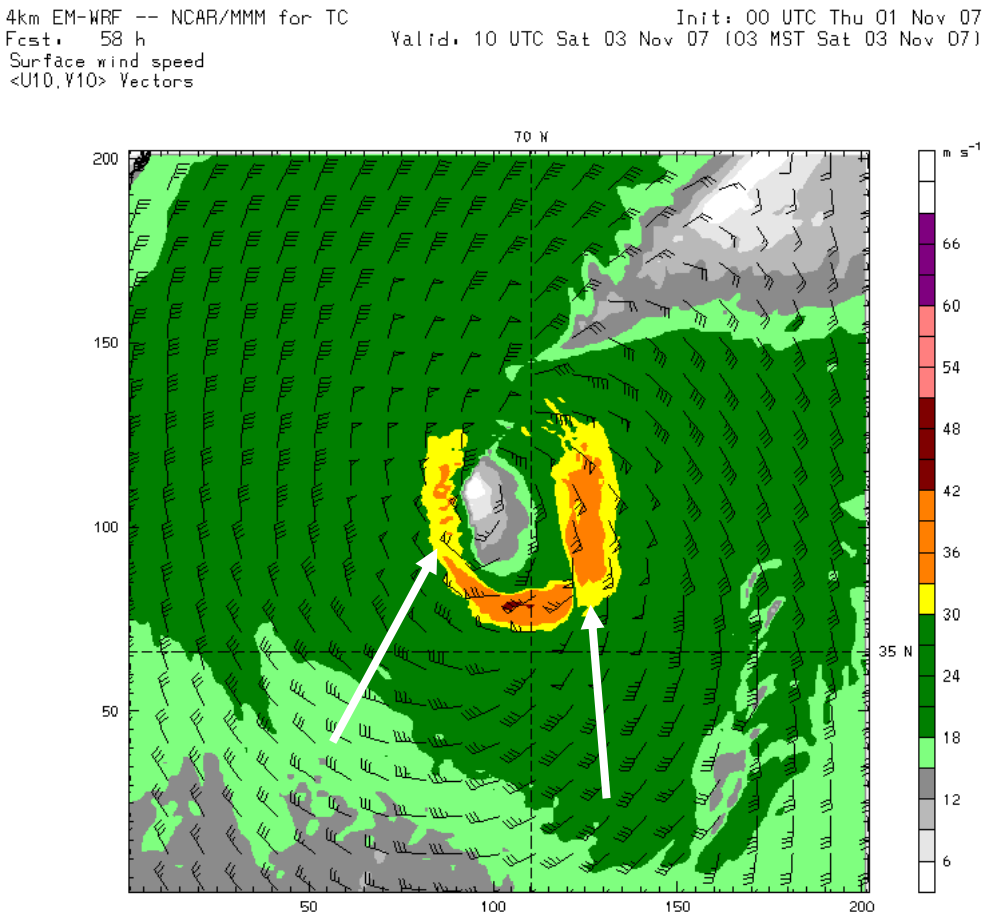


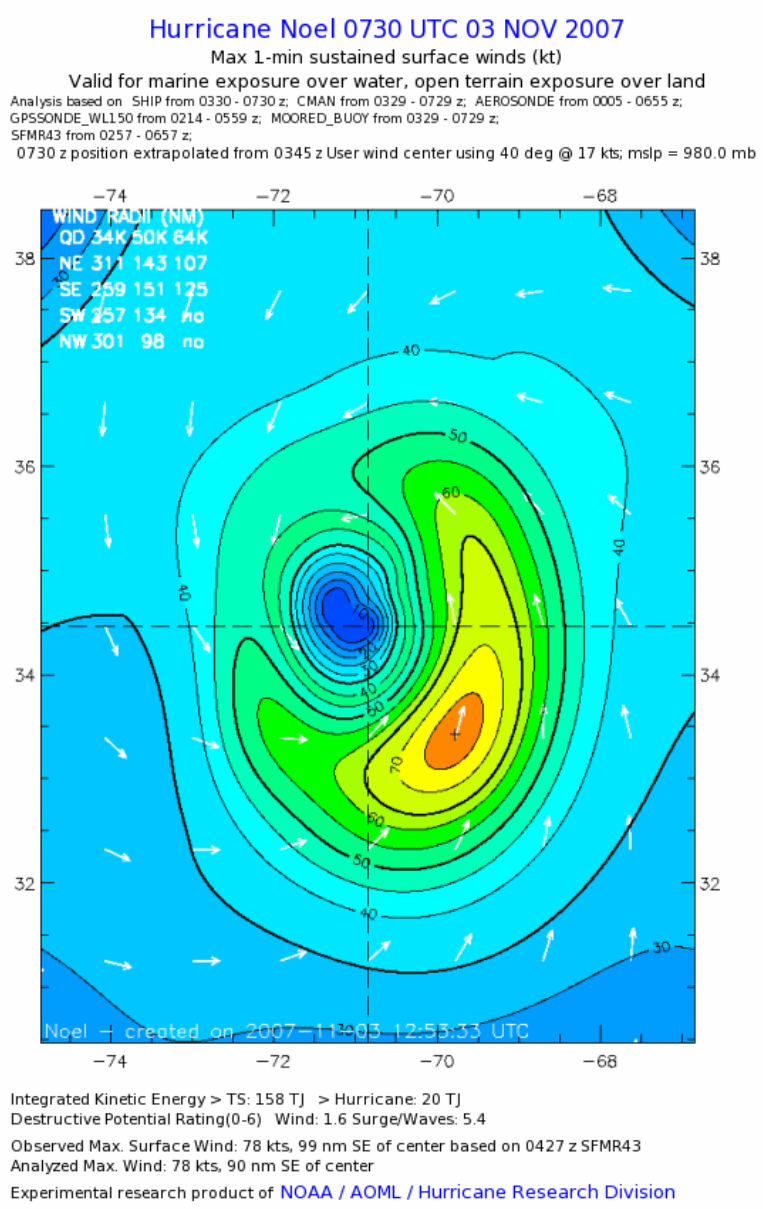
Extratropical Transition: Noel 2007





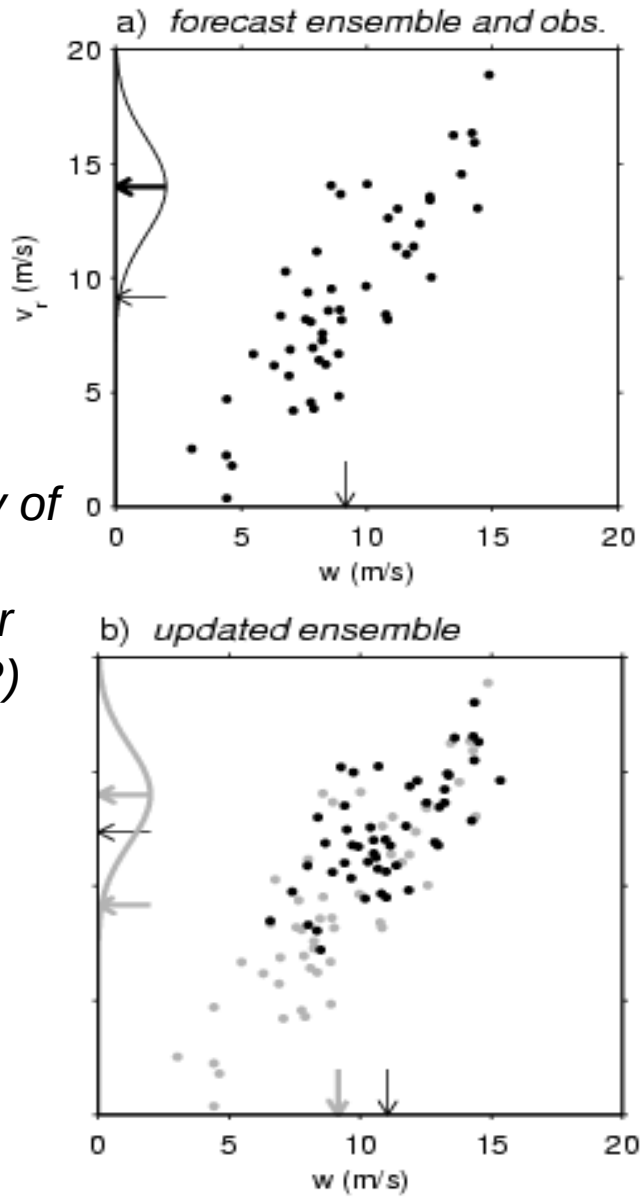
Noel



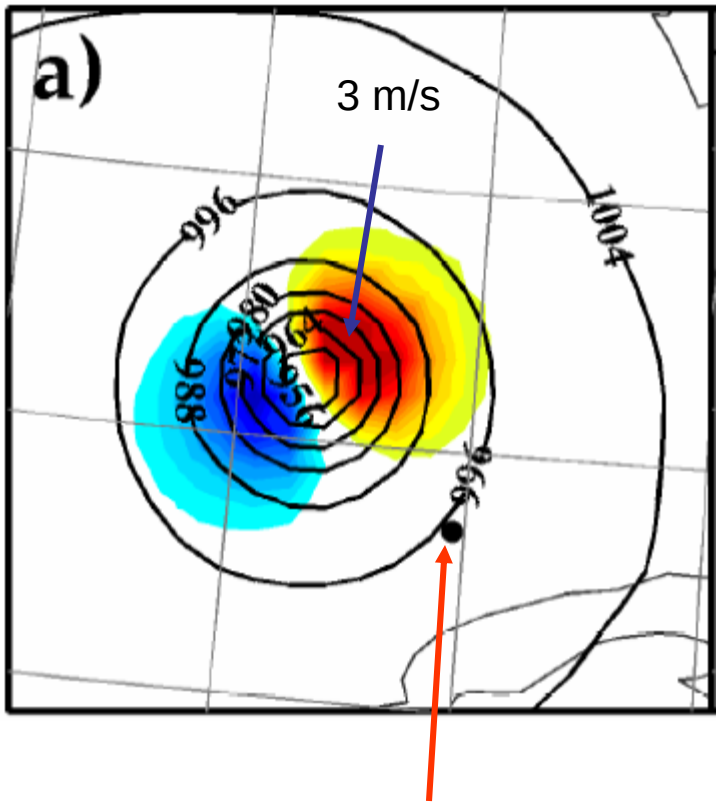


- Max. wind rotates to SE side as observed
- Still strong winds on west side

Ensemble Data Assimilation



Courtesy of Chris Snyder (NCAR)



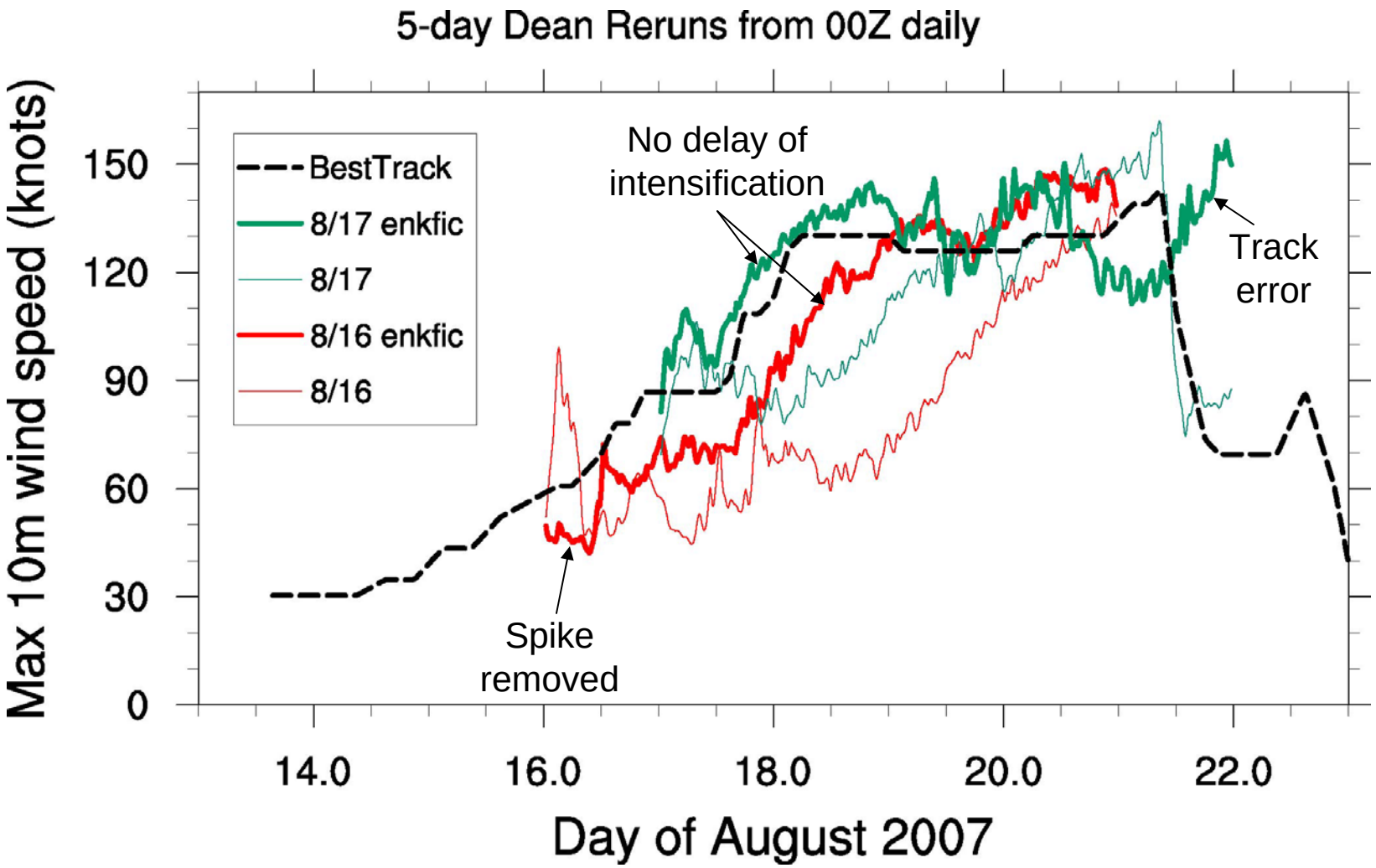
Largest changes to analysis can be displaced from observation location.

Courtesy of Ryan Torn (U. Washington, NCAR)

Practical Use of Ensemble Kalman Filter (EnKF)

- Long assimilation period prior to forecast
- Start prior at tropical depression stage
- Assimilate position, minimum pressure and synoptic data
- 96 members, coarse (36-km) grid
- Launch high-resolution forecast at any time (random member close to mean)
- Would like a REALLY big computer

Results Using EnKF



Hurricane Intensity:
Sources Model Error or Uncertainty

- Air-sea exchange and ocean feedback
- Cloud Physics
- **Turbulence**

l_H (m)	V_{max}(m/s)
3000	48
1500	72
750	86
375	98
188	105
94	108
47	111

Axisymmetric model results courtesy of G. Bryan:

Dr=1 km; dz=0.25 km

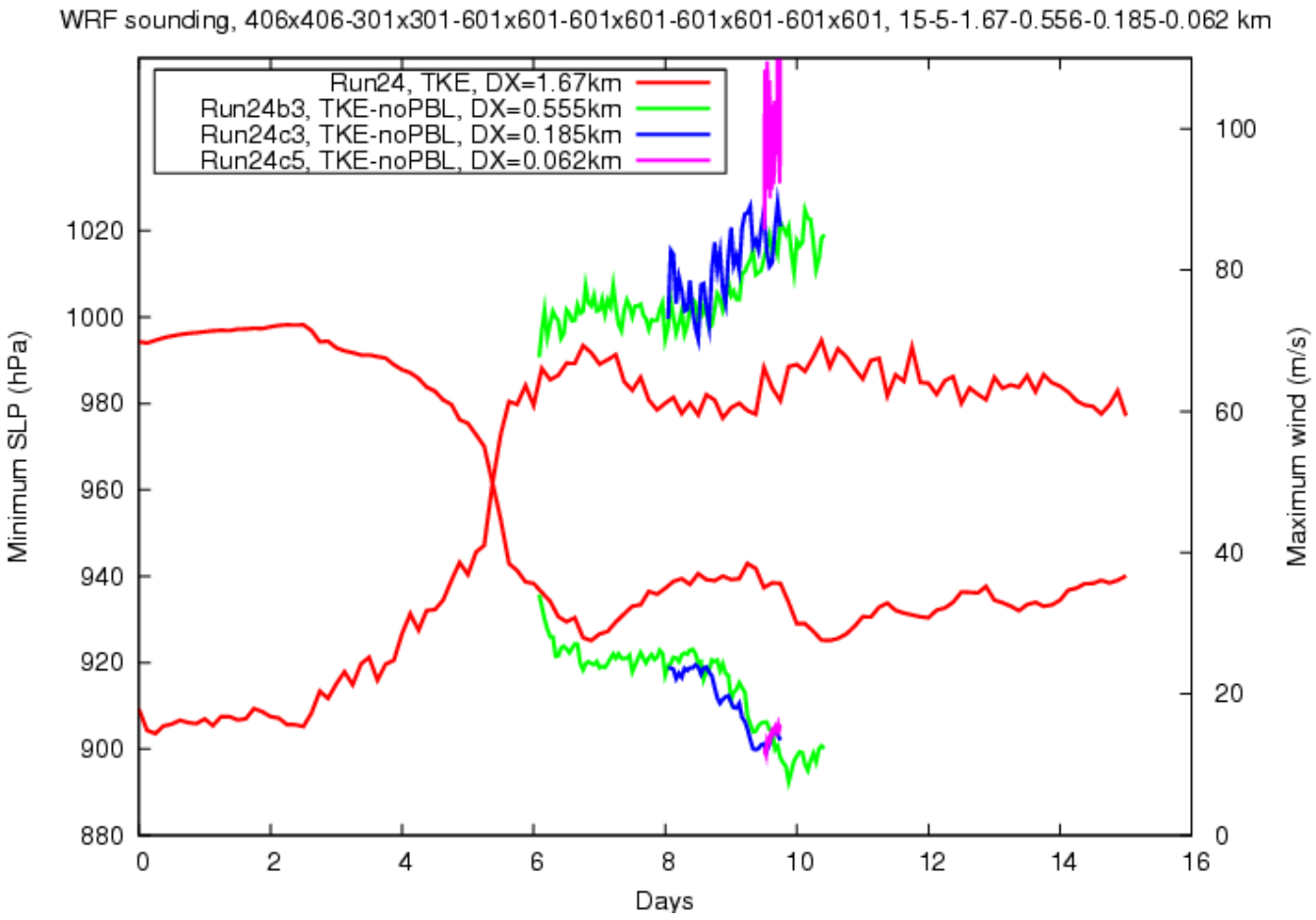
$$\left(\langle u'\theta'\rangle, \langle w'\theta'\rangle\right) = -K\left(\frac{\partial\langle\theta\rangle}{\partial r}, \frac{\partial\langle\theta\rangle}{\partial z}\right) \quad ; \quad K = l^2\left|Def\right|$$

Idealized Simulations: Toward LES scales

(Thanks to R. Rotunno, Y. Chen, G. Bryan and W. Wang)

- Idealized vortex on f-plane, no environmental wind
- 6 domains, 5 concentric nests:
  - 15-5-1.67-0.556-0.185-0.062 km
  - 50 levels from surface to 15 hPa
- Initial moist-neutral environment
- WRF model Physics:
  - Two-phase hydrometeor scheme
  - no radiation
  - Prediction of turbulent kinetic energy (determines viscosity)
  - Newtonian Relaxation to Initial Temperature (relaxation time=36h)

Intensity v. Resolution



Red: dx = 1.67 km

Green: dx = 0.556 km

Blue: dx = 0.185 km

Magenta: dx = 0.062 km

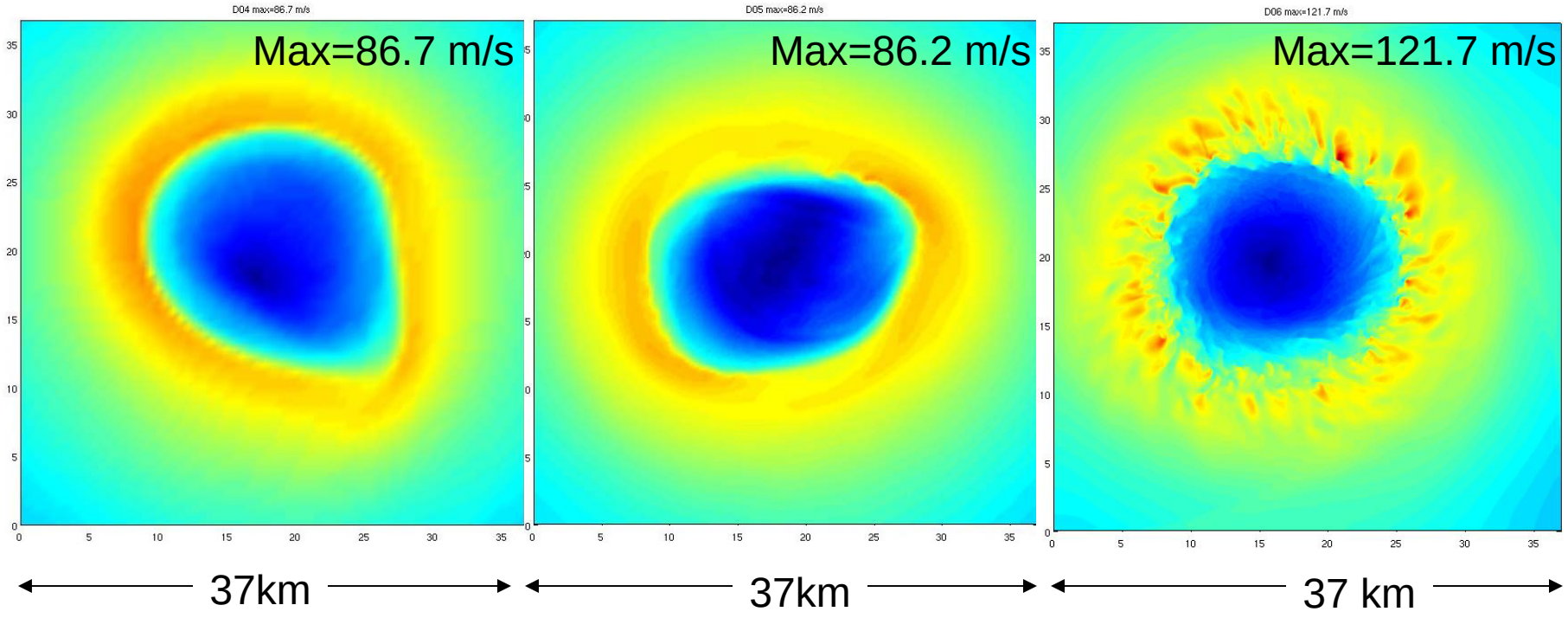
10-m Wind (zoom)

Day 9 18Z

4-domain, dx=556m

5-domain, dx=185m

6-domain, dx=62m



10-m Wind

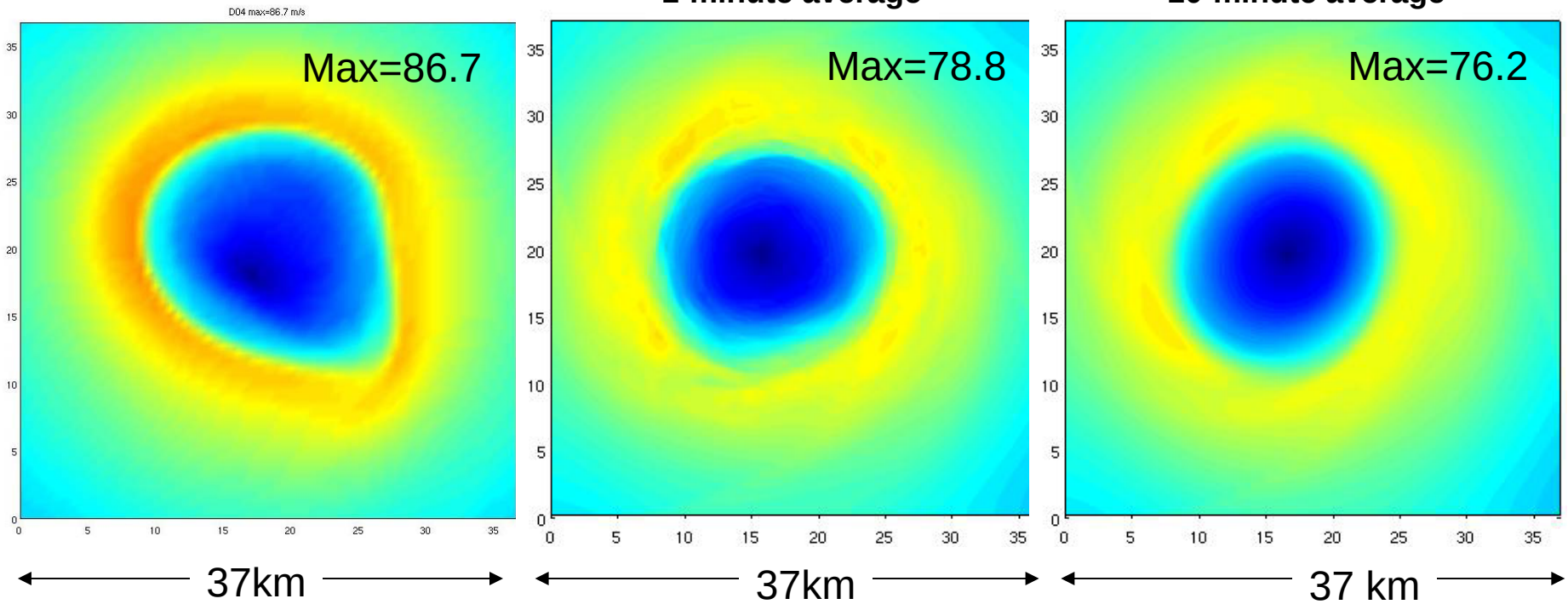
Day 9 18Z

4-domain, dx=556m

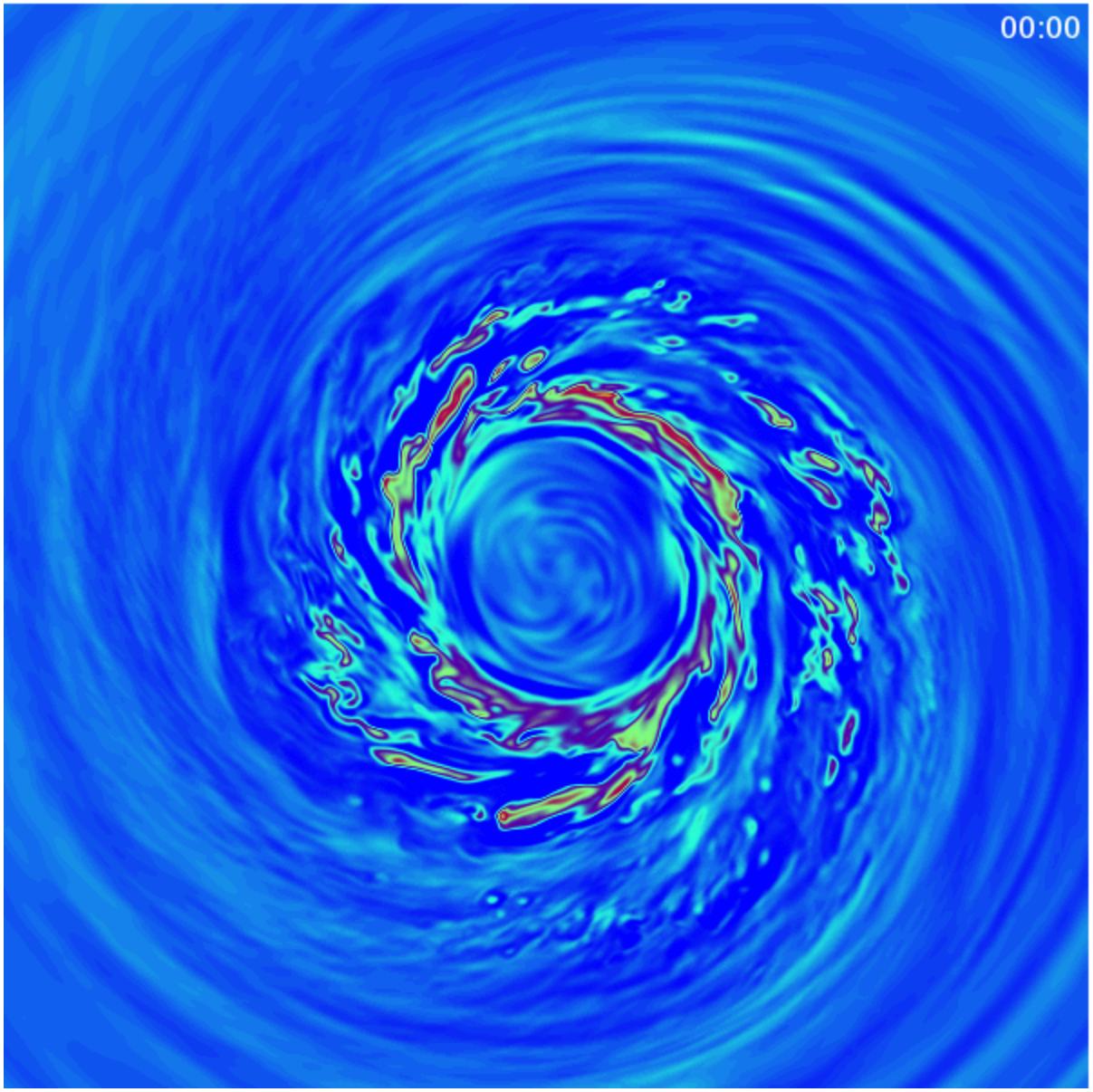
6-domain, dx=62m

1-minute average

10-minute average



Vertical Velocity at 4 km (dx=185 m)



Concluding Remarks

- Determinism versus stochasticism
  - Initialization improvement lost at 1-2 days
  - Environmental factors determine intensity on “decision” time scales (3+ days, fluctuations may be random)
  - Forecasts from depression stage lower in skill
  - Importance of realistic (unbiased) core representation
- Intensity versus resolution
  - O(10 km), eye-wall not resolved, meaning of V_{max}?
  - O(<1 km), turbulence not explicit, storm too intense
  - O(100 m), turbulence emerges as break on intensity
  - May use 3-D results to estimate parameters for 2-D