Review of Predictability and Model Error Issues Related to Tropical Cyclones

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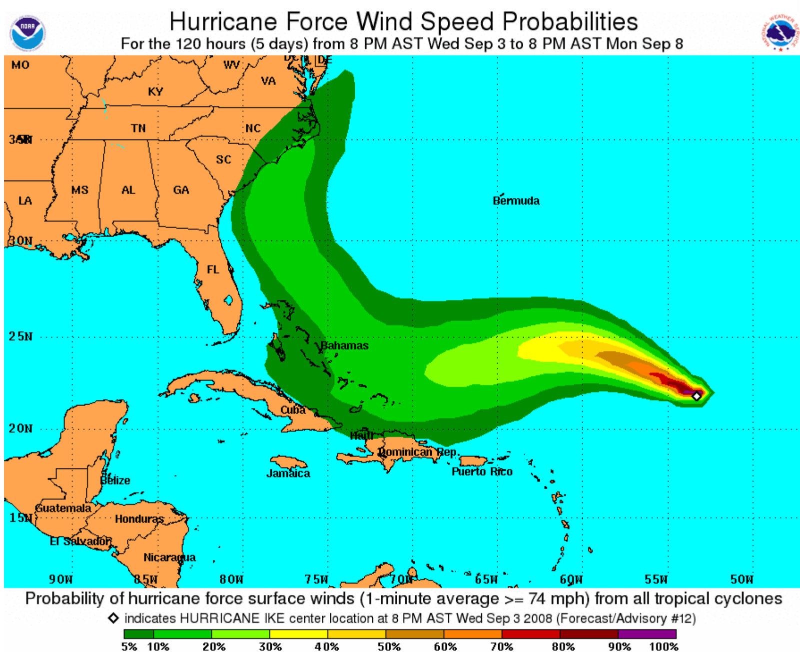
Limitations on Forecast Accuracy

- Fundamental
  - Predictability limitations
  - Definition of intensity; metrics of accuracy
- Addressable error sources
  - Ocean coupling
  - Resolution: resolve eye wall
  - Large-scale environment (shear, etc.)
- Difficult to address
  - Air-sea fluxes (enthalpy flux)
  - Cloud physics (particle sizes)
  - Aerosols
  - Better observations of storm structure

Different Perspectives



Intensity (Maximum Wind Speed) Probability Table
Hurricane Ike Advisory Number 12
11:00 PM AST Sep 3 2008

Wind Range (mph)	Forecast Time: 12 hour for 8 AM Thu	24 hour for 8 PM Thu	36 hour for 8 AM Fri	48 hour for 8 PM Fri	72 hour for 8 PM Sat	96 hour for 8 PM Sun	120 hour for 8 PM Mon
Dissipated	<1%	<1%	<1%	<1%	<1%	1%	2%
Tropical Depression (<39)	<1%	<1%	<1%	<1%	1%	1%	2%
Tropical Storm (39-73)	<1%	1%	2%	5%	10%	8%	11%
Hurricane (all categories)	99%	99%	98%	95%	89%	91%	85%
-- Category 1 (74-95)	<1%	6%	11%	19%	23%	17%	17%
-- Category 2 (96-110)	2%	22%	24%	30%	24%	19%	17%
-- Category 3 (111-130)	54%	57%	45%	32%	27%	31%	26%
-- Category 4 (131-155)	42%	14%	16%	12%	12%	20%	20%
-- Category 5 (>155)	2%	1%	2%	2%	3%	5%	5%
Forecast Maximum Wind	135 mph	120 mph	120 mph	115 mph	115 mph	125 mph	135 mph

Ground relative, probabilistic

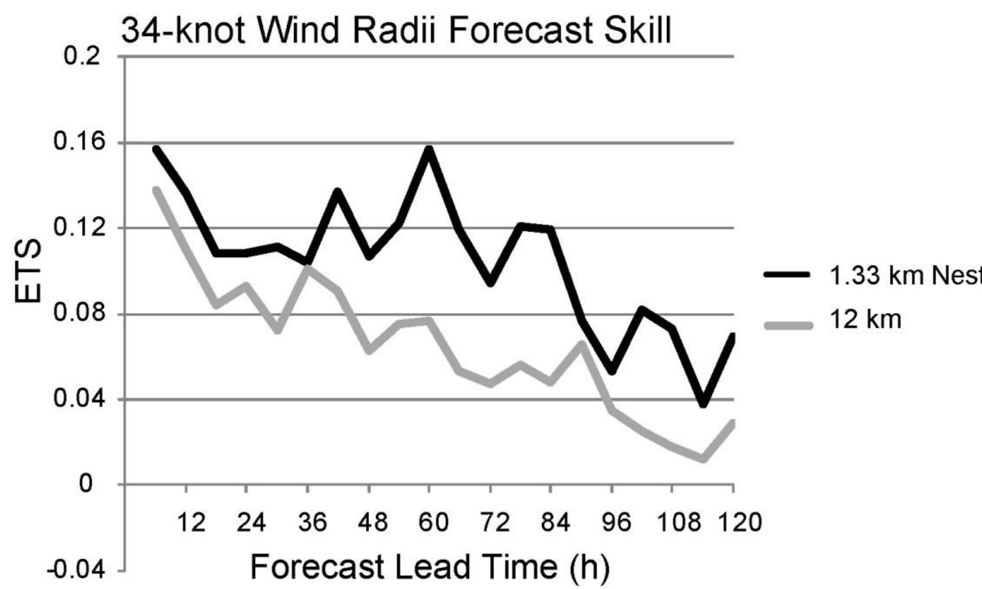
Storm relative, deterministic

Predictability

- Three time scales
  - Convection: H/w ~ 10^3 s
  - Vortex: R/V ~ 10^4 s
  - Synoptic-scale: L/U ~ 10^5 s.
- Implications
  - Convective elements unpredictable
  - Vortex Rossby waves, inner rainbands very hard to predict (rapid intensification)
  - Nearly everything we can predict is on the synoptic scale

What is included in large scale?

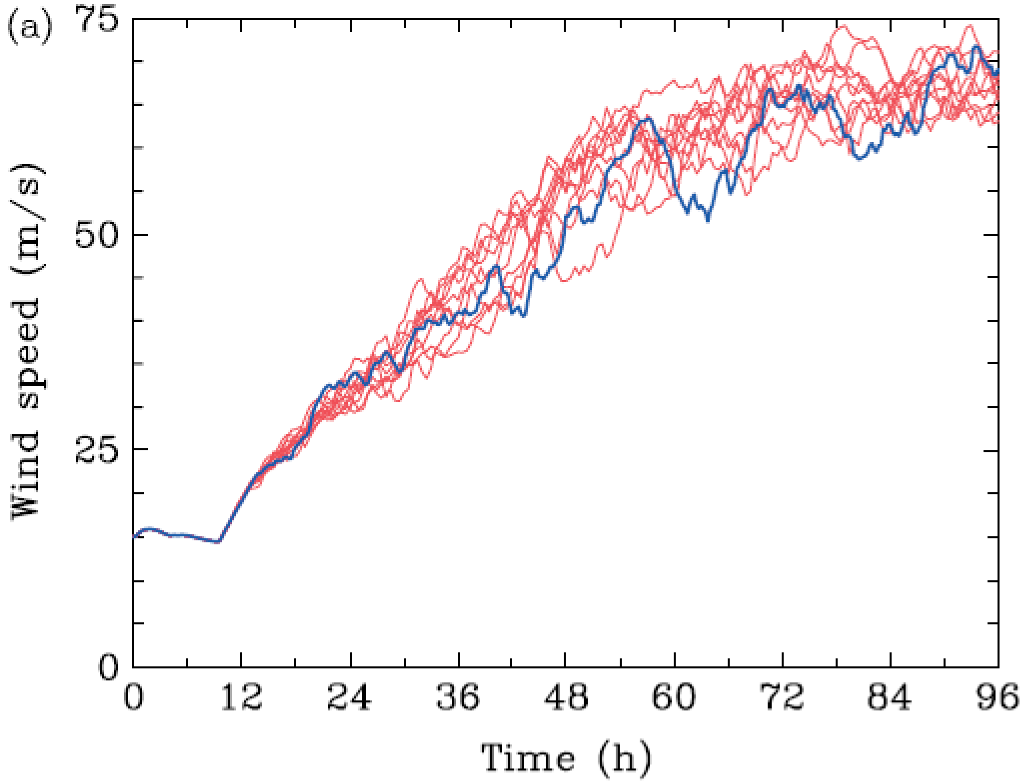
- Steering flow
- Lower-boundary conditions
- Vertical wind shear
- Outer wind radii
  - Forecasts from NCAR Advanced Hurricane Research WRF (AHW) show long time-scale decay of skill



Vortex-scale Fluctuations

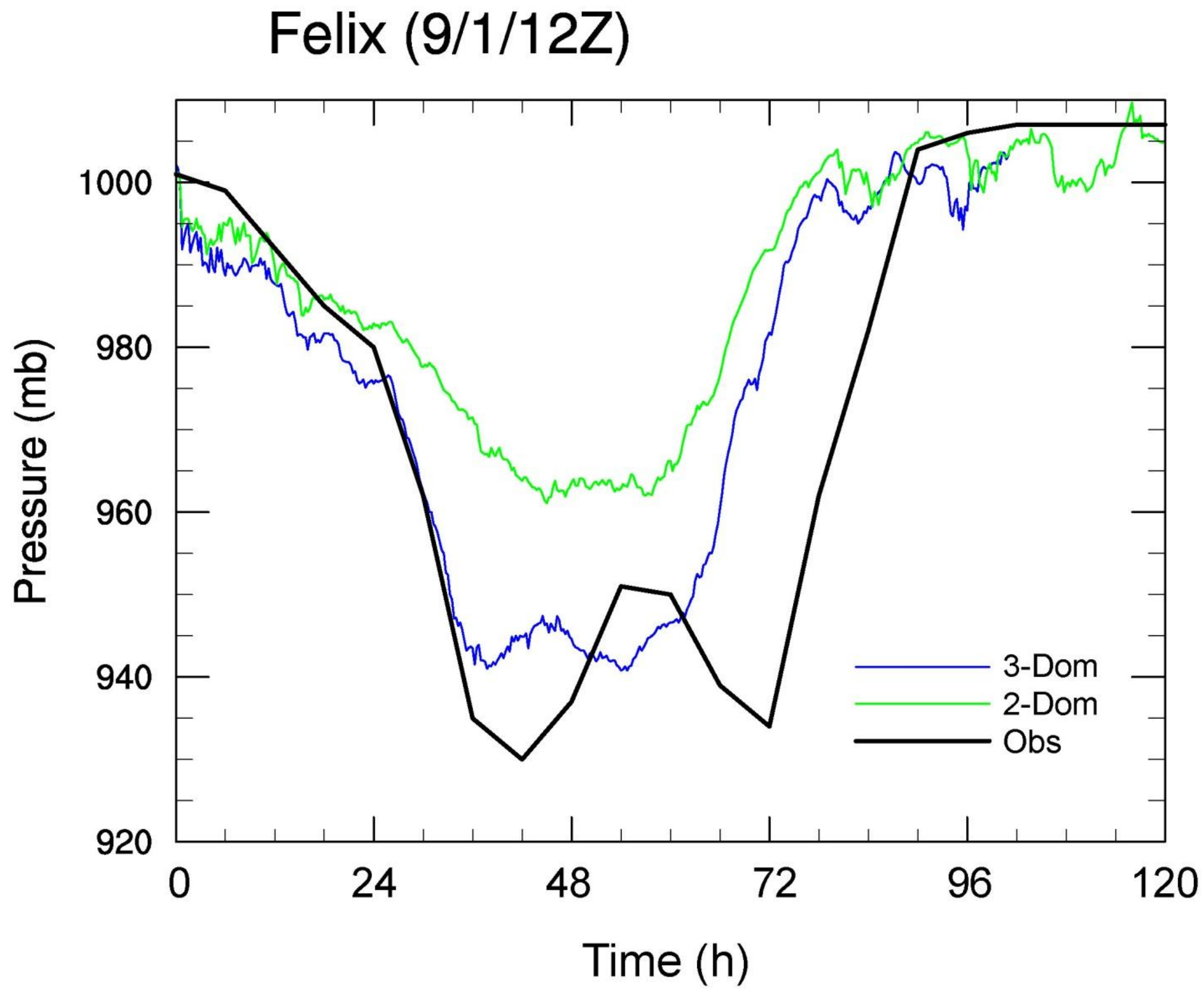
MM5 Simulations, dx=5km

Intrinsic fluctuations of inner core of idealized hurricane ~10 m/s.



Van Sang et al, 2008: QJRMS

Intensity Fluctuations

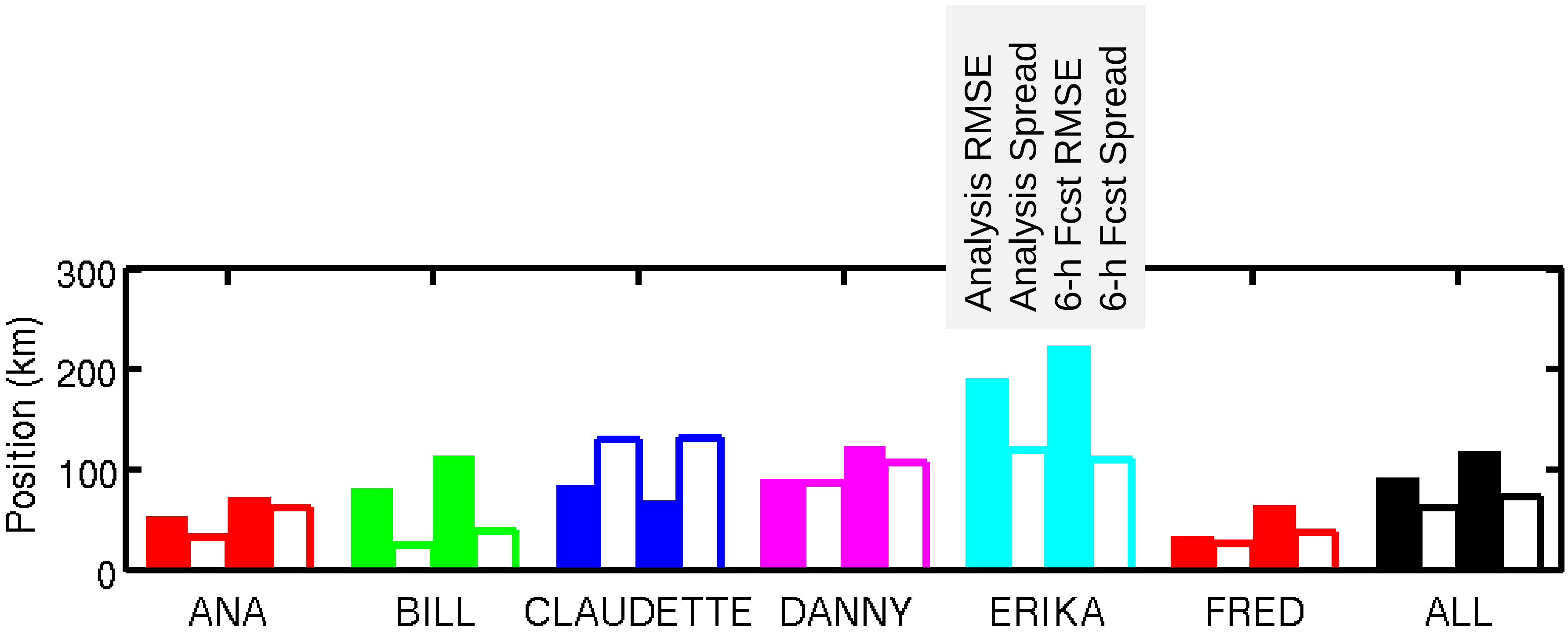


Handled better at high-resolution, but still essentially no skill

Verification of Forecasts: Errors in Observations

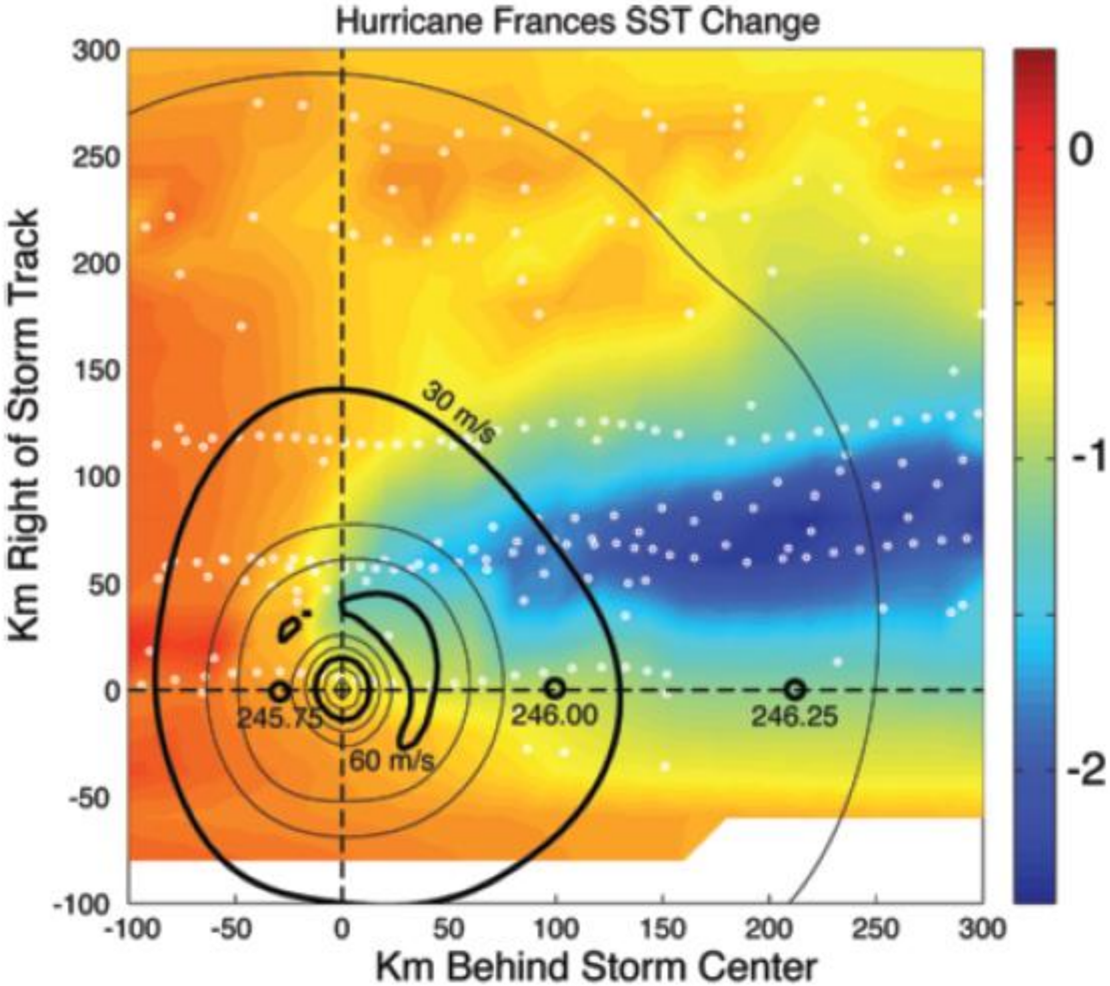
- Maximum 1-m sustained 10-m wind
  - Highly localized quantity
  - Uncertainty: Reconnaissance vs. no recon.
  - 5 knot binning (NHC) probably best case
- Minimum sea-level pressure
  - Errors scale as v^2: large for strong storms (nearly 20 mb for Cat 5)
- Storm position
  - Essentially zero error for strong storms
  - Surprisingly large uncertainties in weak systems (depressions or strongly sheared storms)

Ensemble Error and Spread in Position



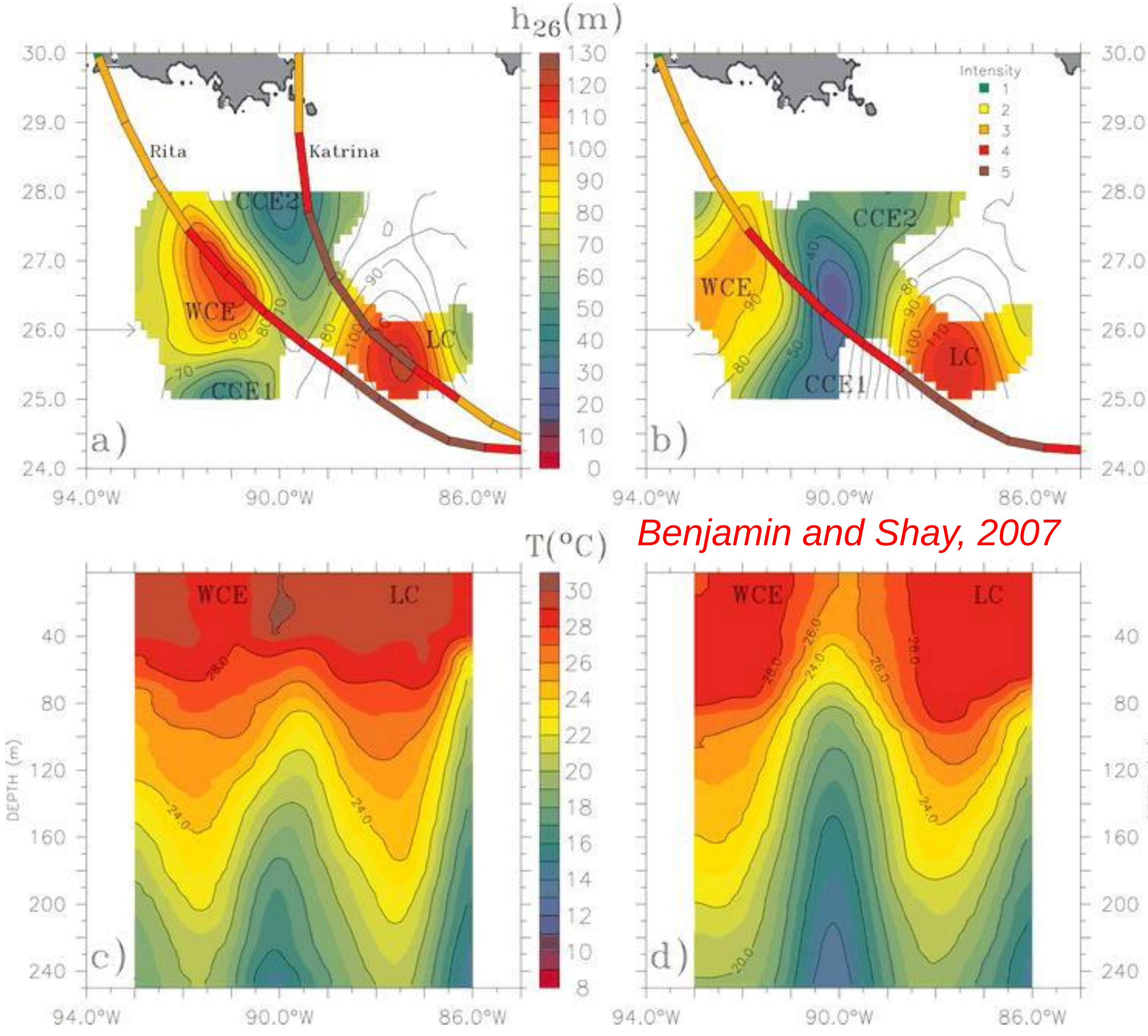
From Ryan Torn, U. Albany, SUNY

Cool wake behind hurricane:
How much cooling under eye wall?



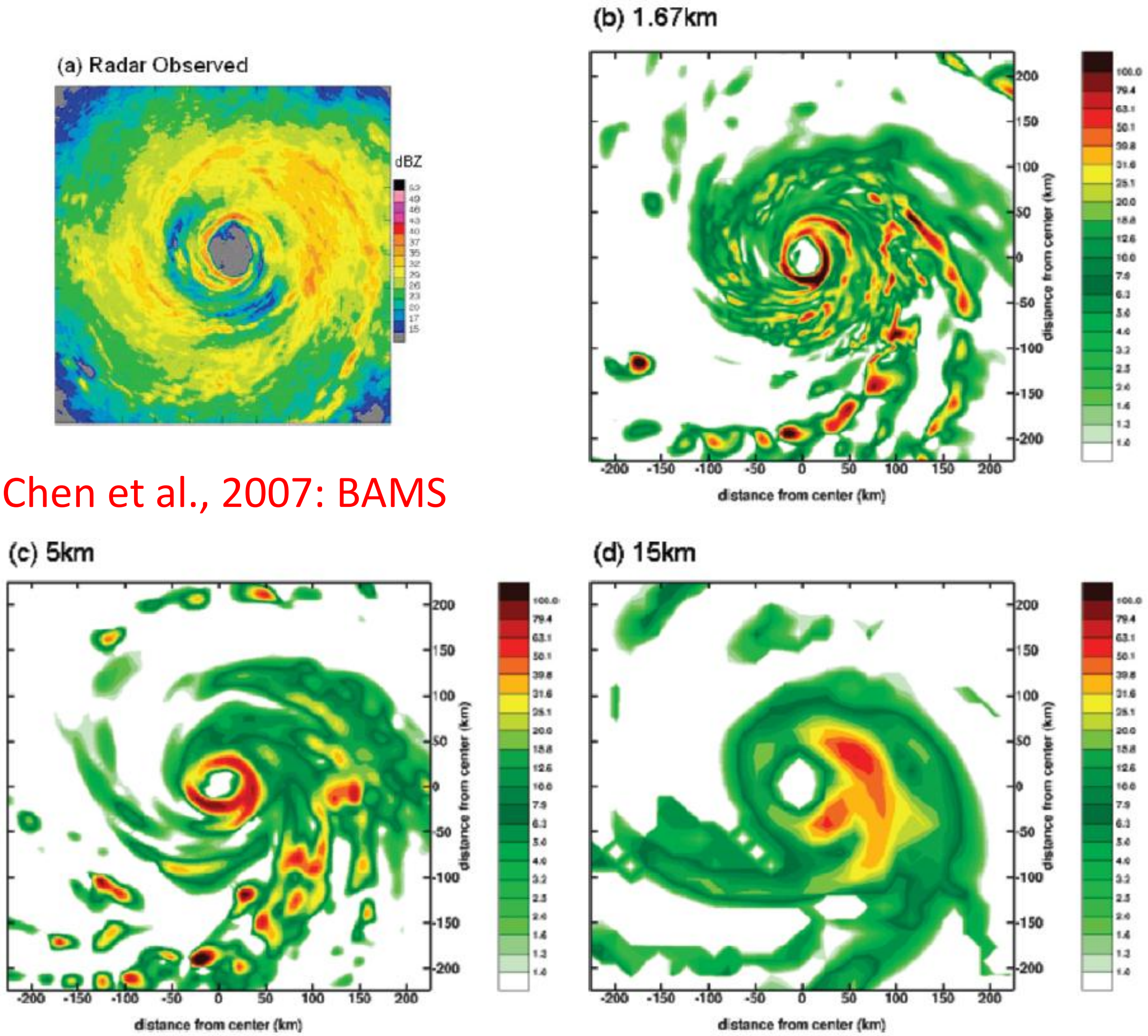
Black et al., 2007: BAMS

Upper Ocean Structure



Benjamin and Shay, 2007

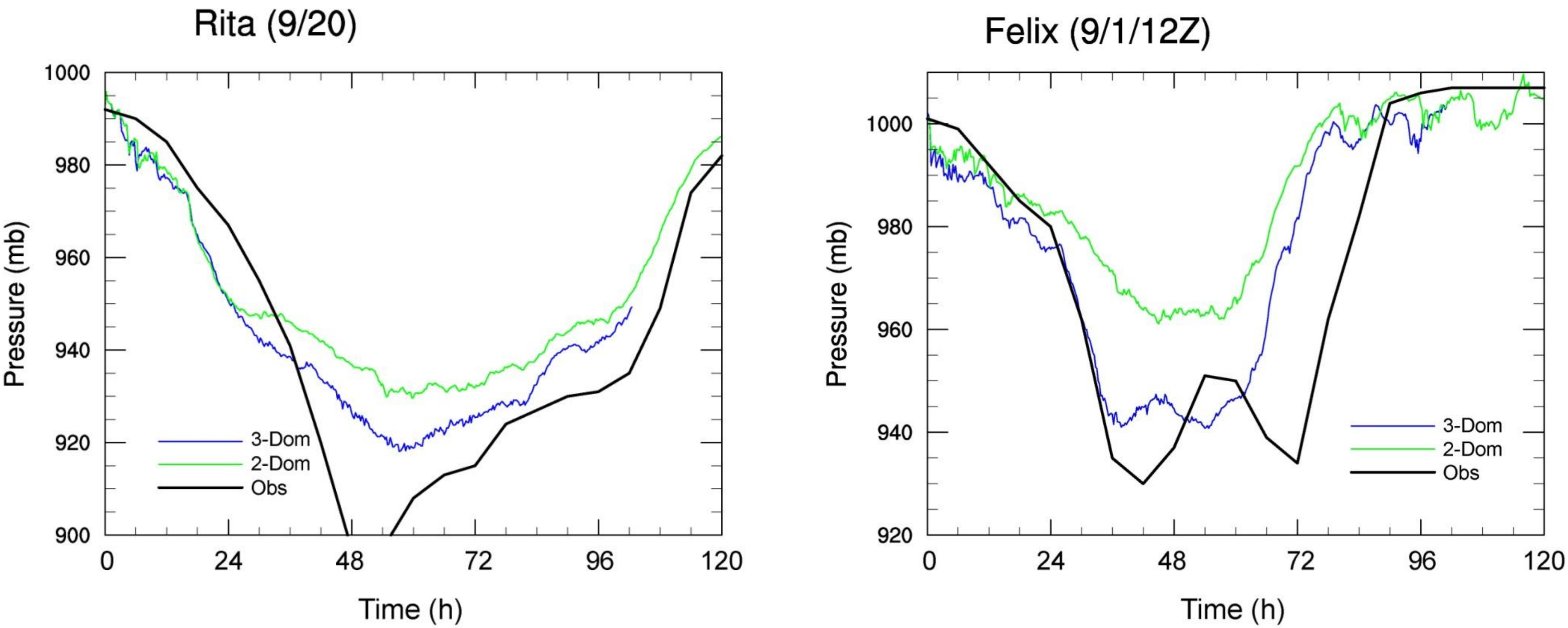
Varying Horizontal Grid Spacing



Chen et al., 2007: BAMS

Fig. 2. (a) The NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML)/HRD airborne radar-observed reflectivity (dBZ, over an area of 360 km x 360 km) and the MM5-simulated rain rate (mm h^{-1}) using (b) 1.67-, (c) 5-, and (d) 15-km grid resolution in Hurricane Floyd at 0000 UTC 14 Sep 1999.

Varying Horizontal Grid Spacing



AHW forecasts of Rita and Felix with 4-km and 1.33-km innermost nests: more difference for smaller storm (Felix).

Turbulent Mixing

Bryan and Rotunno, 2010

Intensity highly dependent on horizontal mixing length (not vertical), 2-D and 3-D.

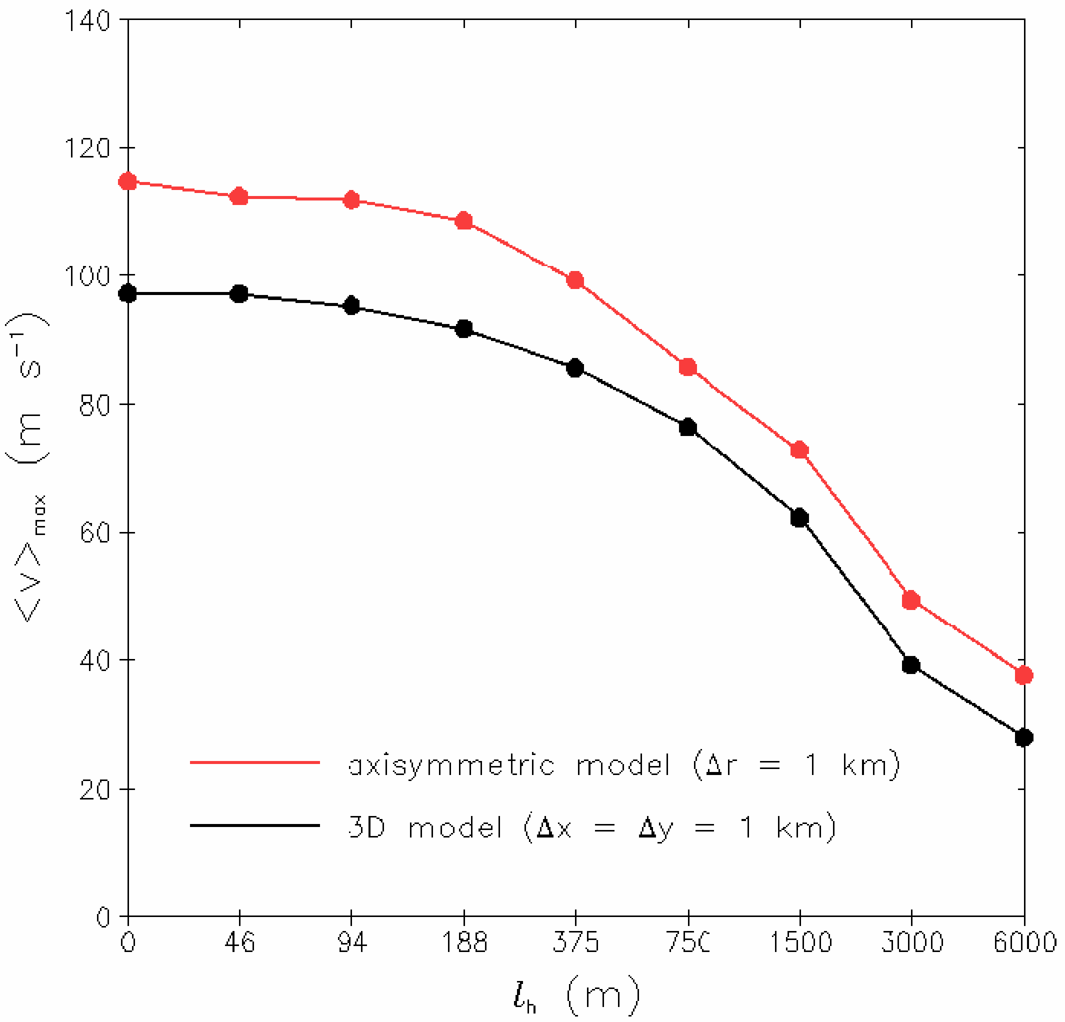


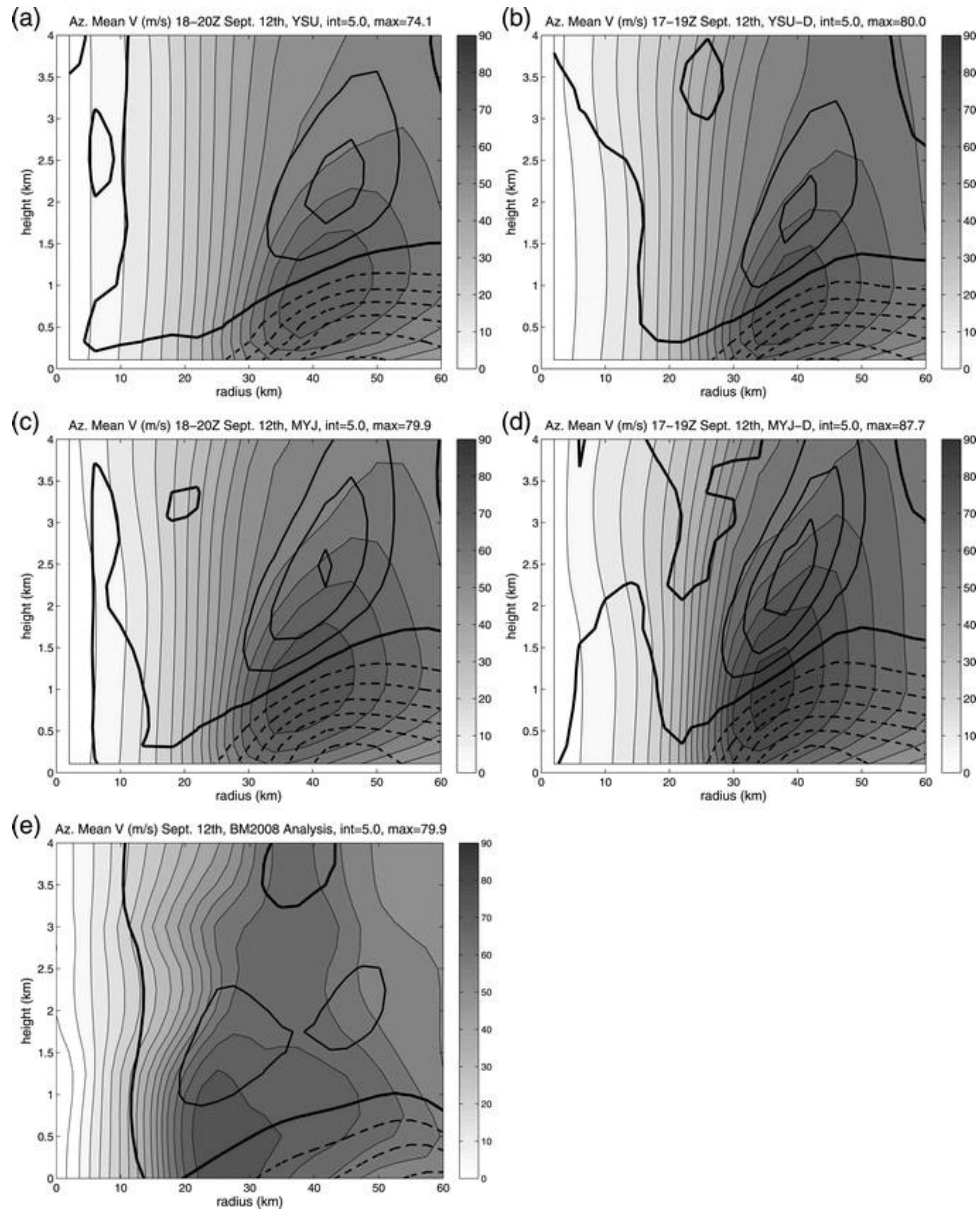
FIG. 2: Maximum azimuthally averaged azimuthal velocity, $\langle v \rangle_{max}$, from the axisymmetric model (red) and the three-dimensional model (black). All simulations use l_v = 200 m.

PBL

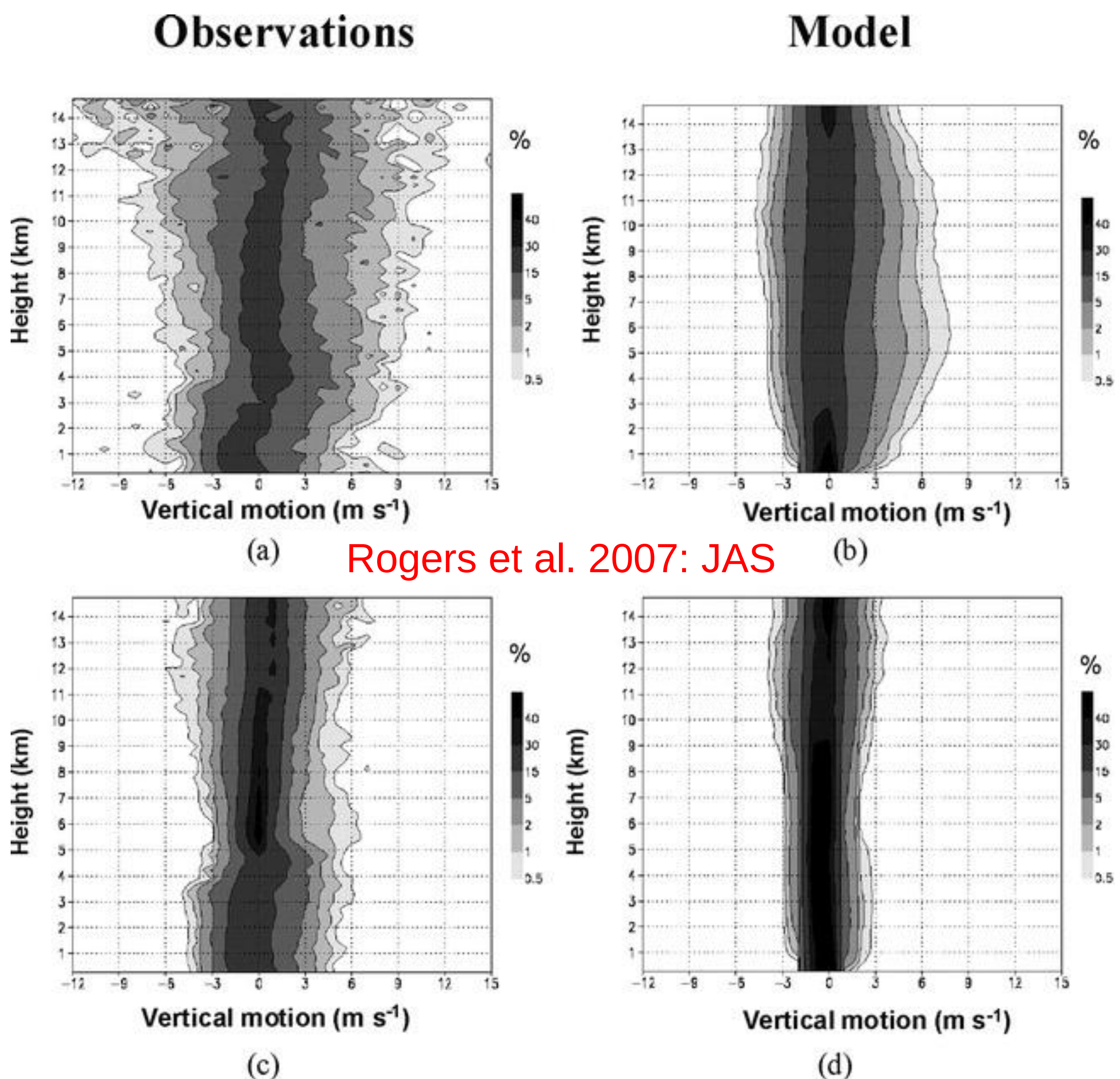
Nolan et al., 2009:

Max winds not affected too much by PBL

Results more like each other than the real storm:
however, could be many reasons for this.

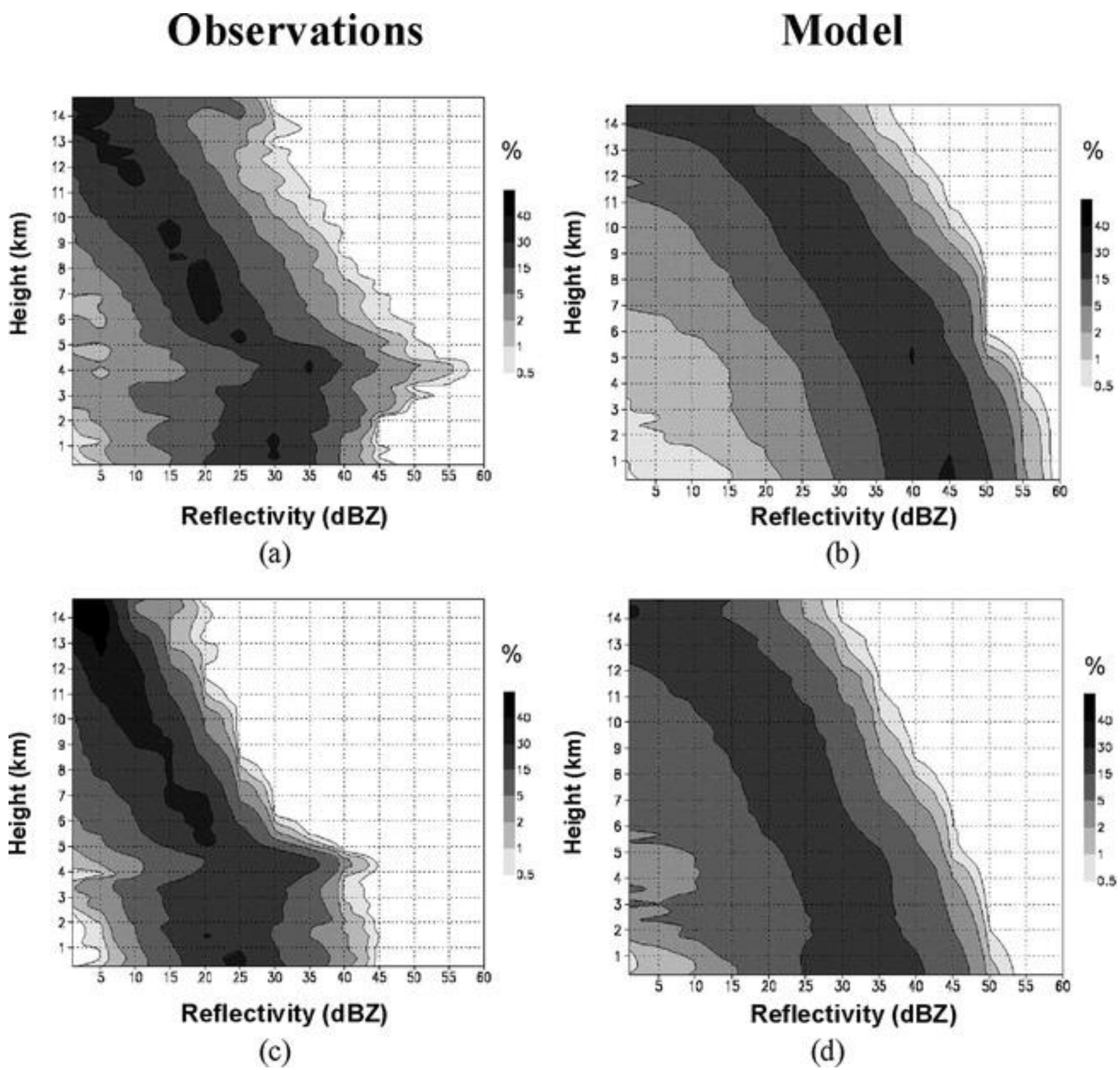


Contoured Frequency by Altitude Diagrams (CFADS)

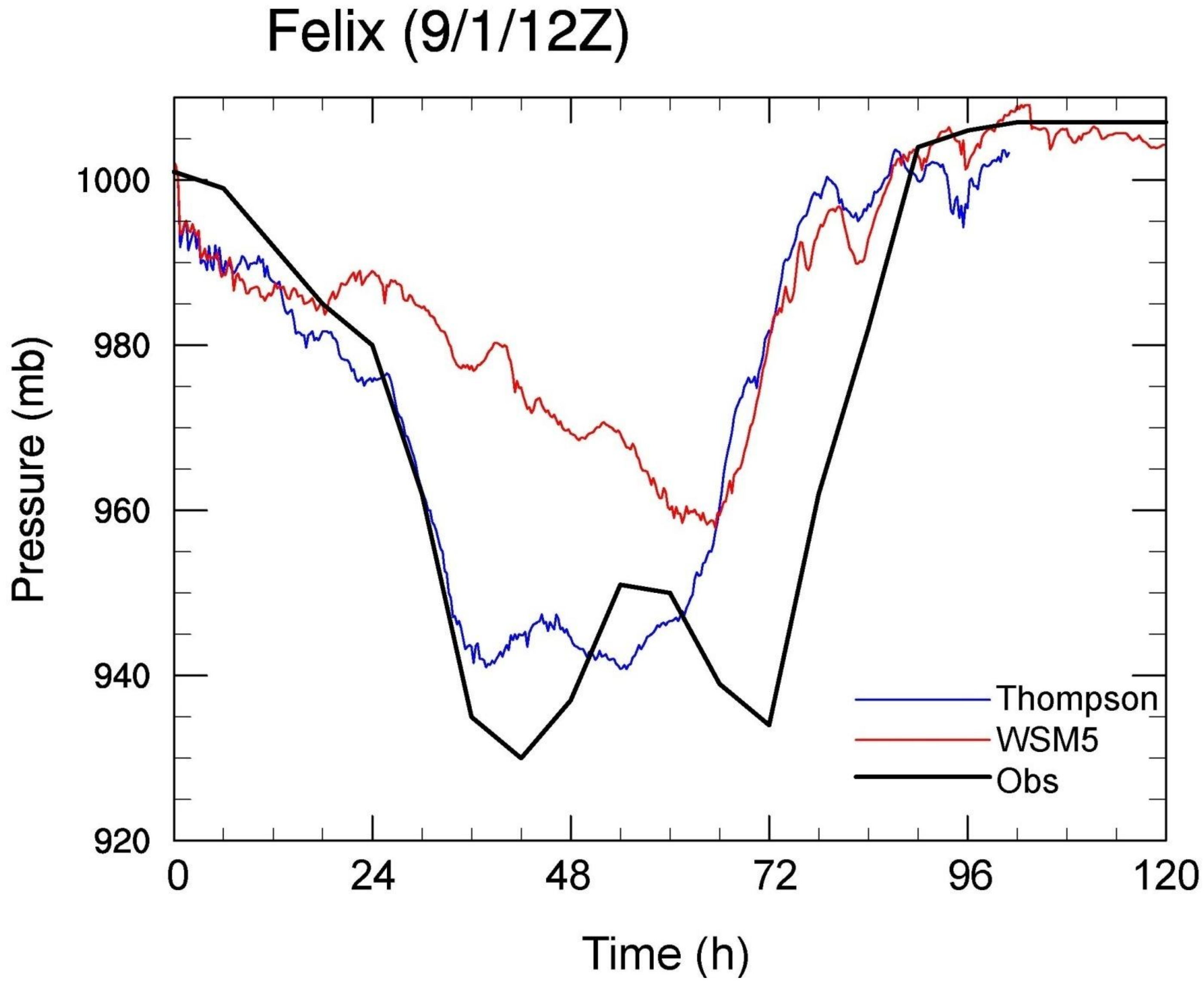


Rogers et al. 2007: JAS

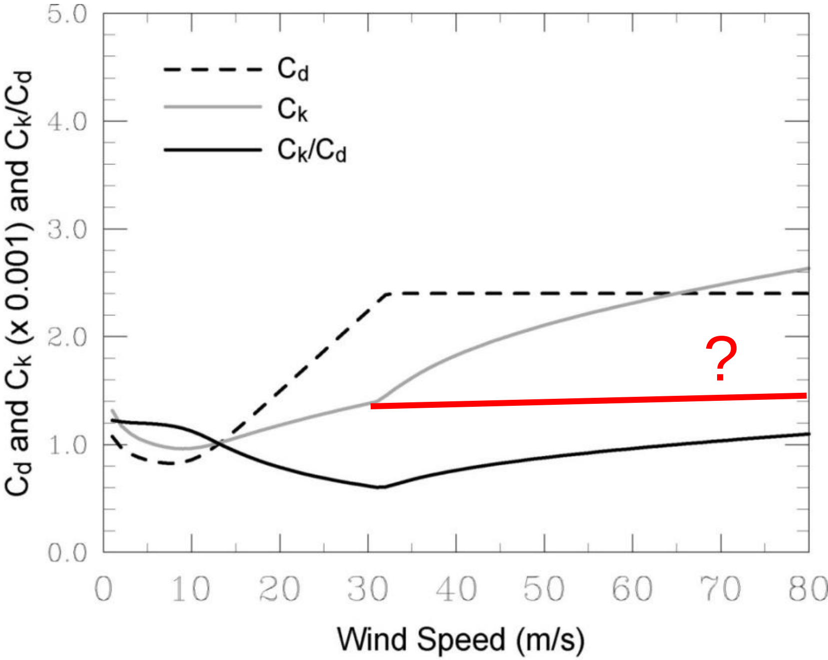
Contoured Frequency by Altitude Diagrams (CFADS)

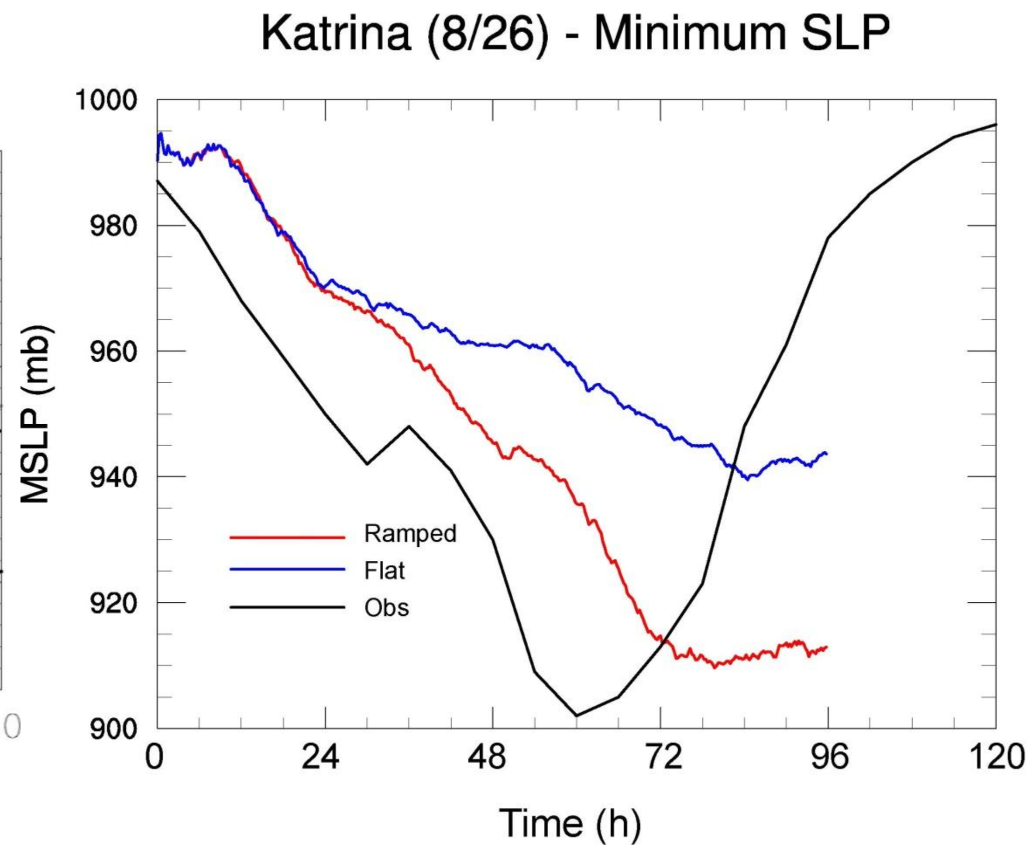


Microphysical Influence on Intensity

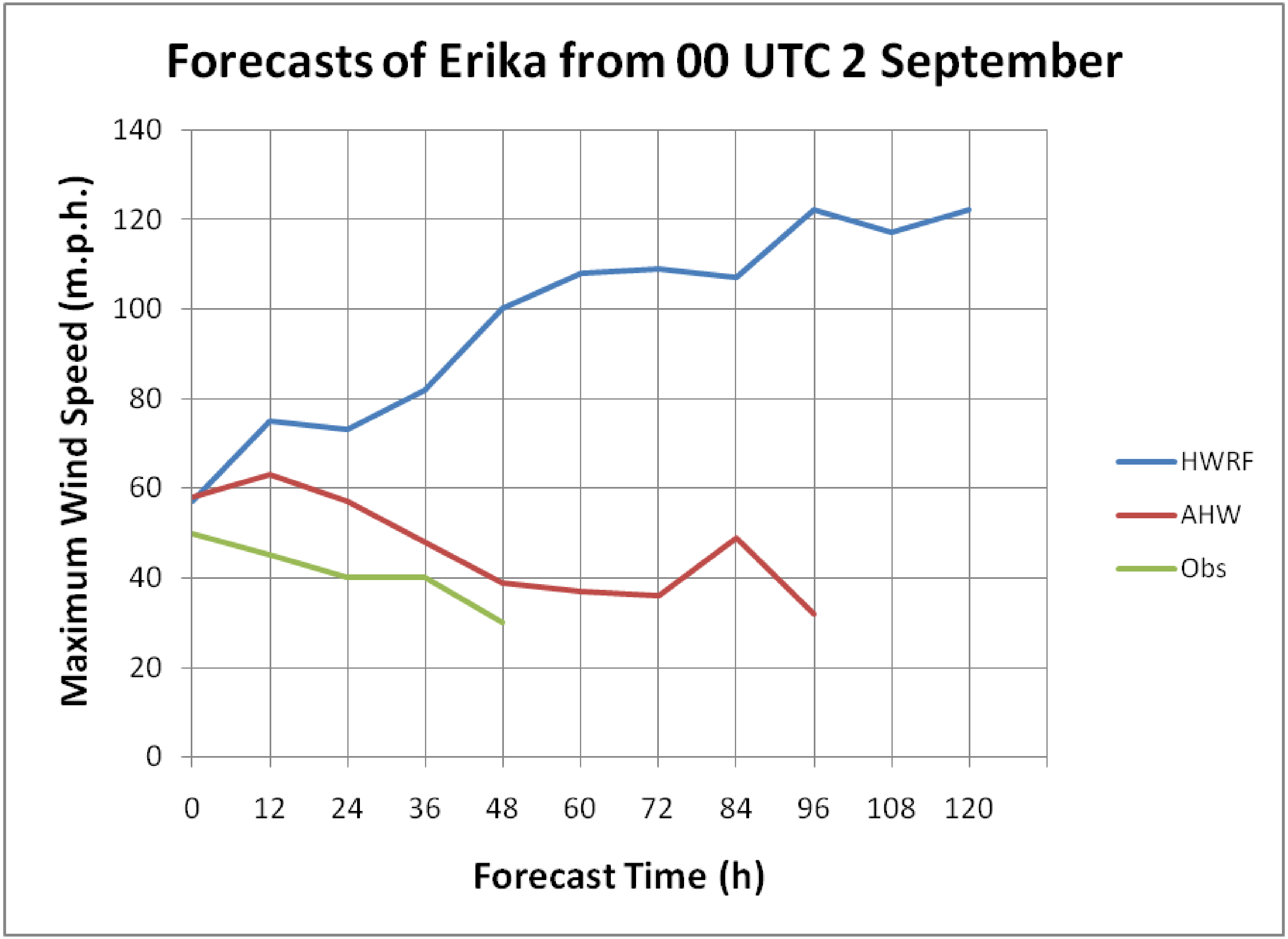


Air-sea Exchange



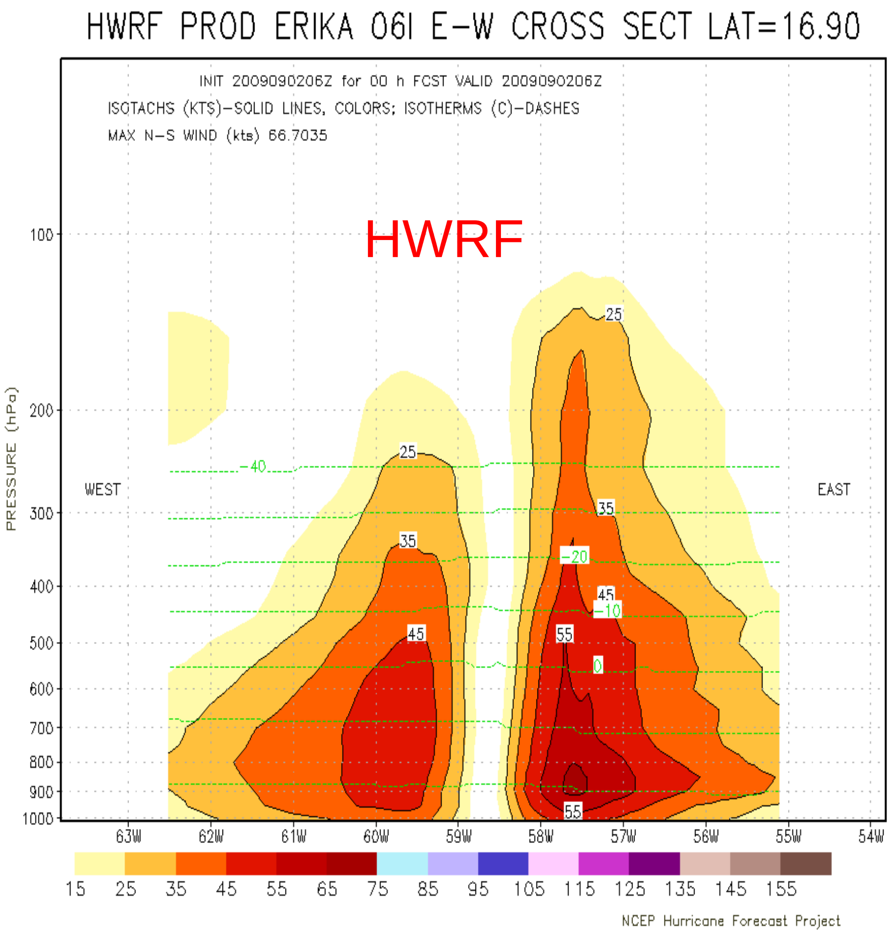


On the coupling of initial condition and physics errors

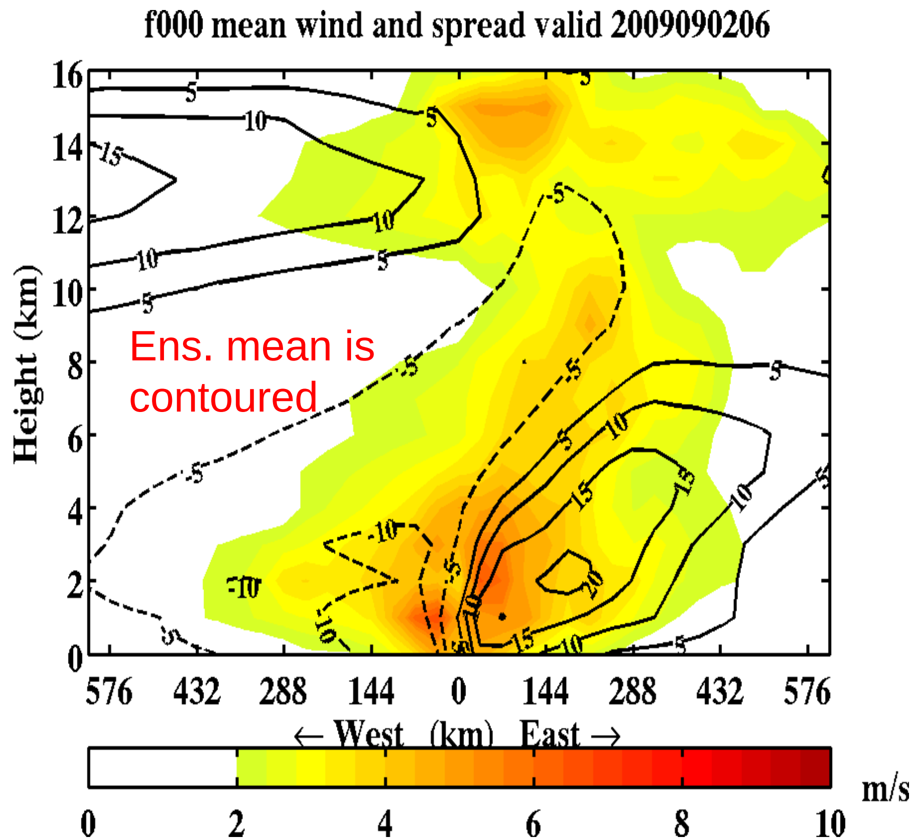


Initial Conditions for Erika 0902/06Z

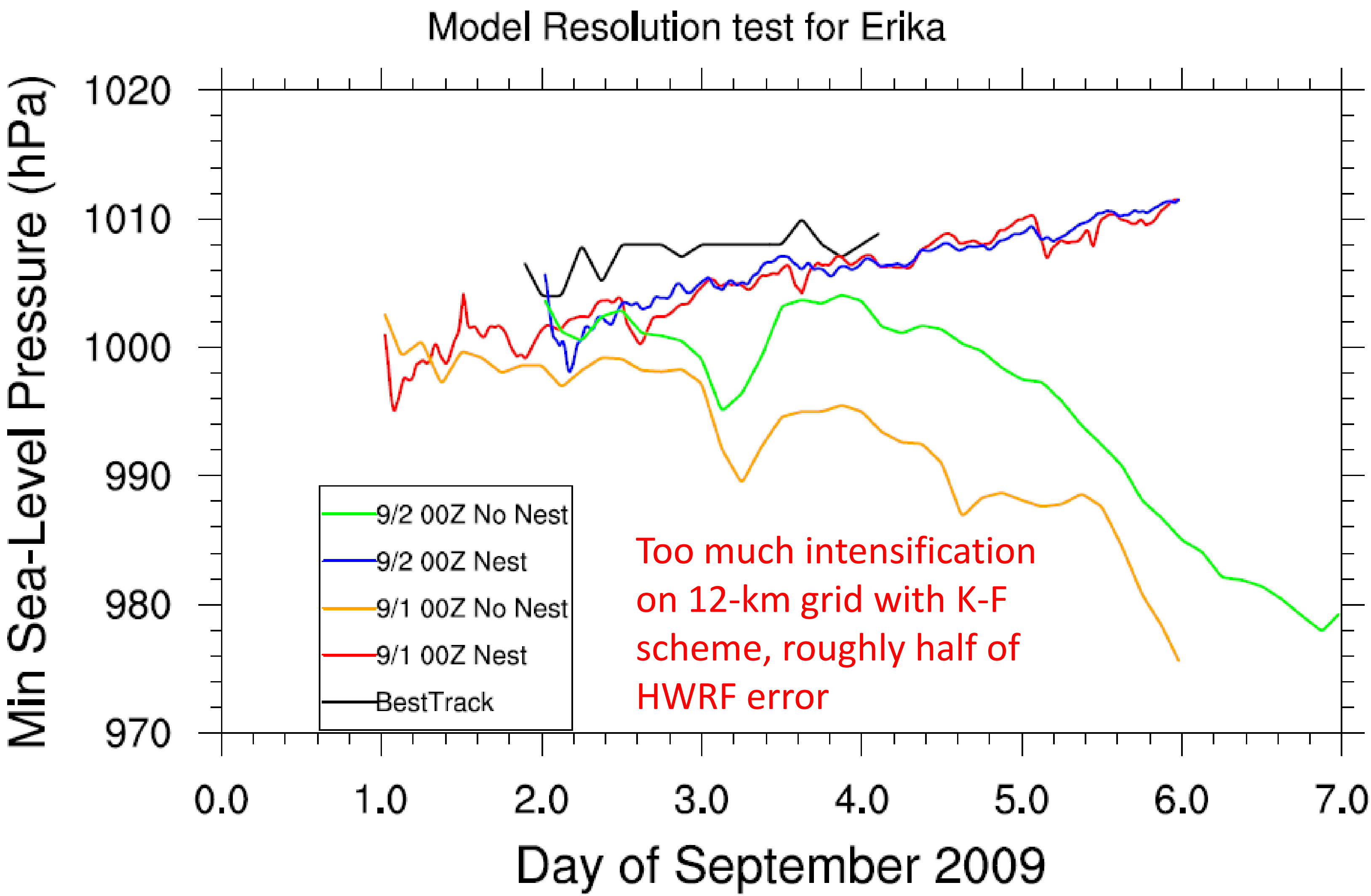
(cross section of meridional velocity)



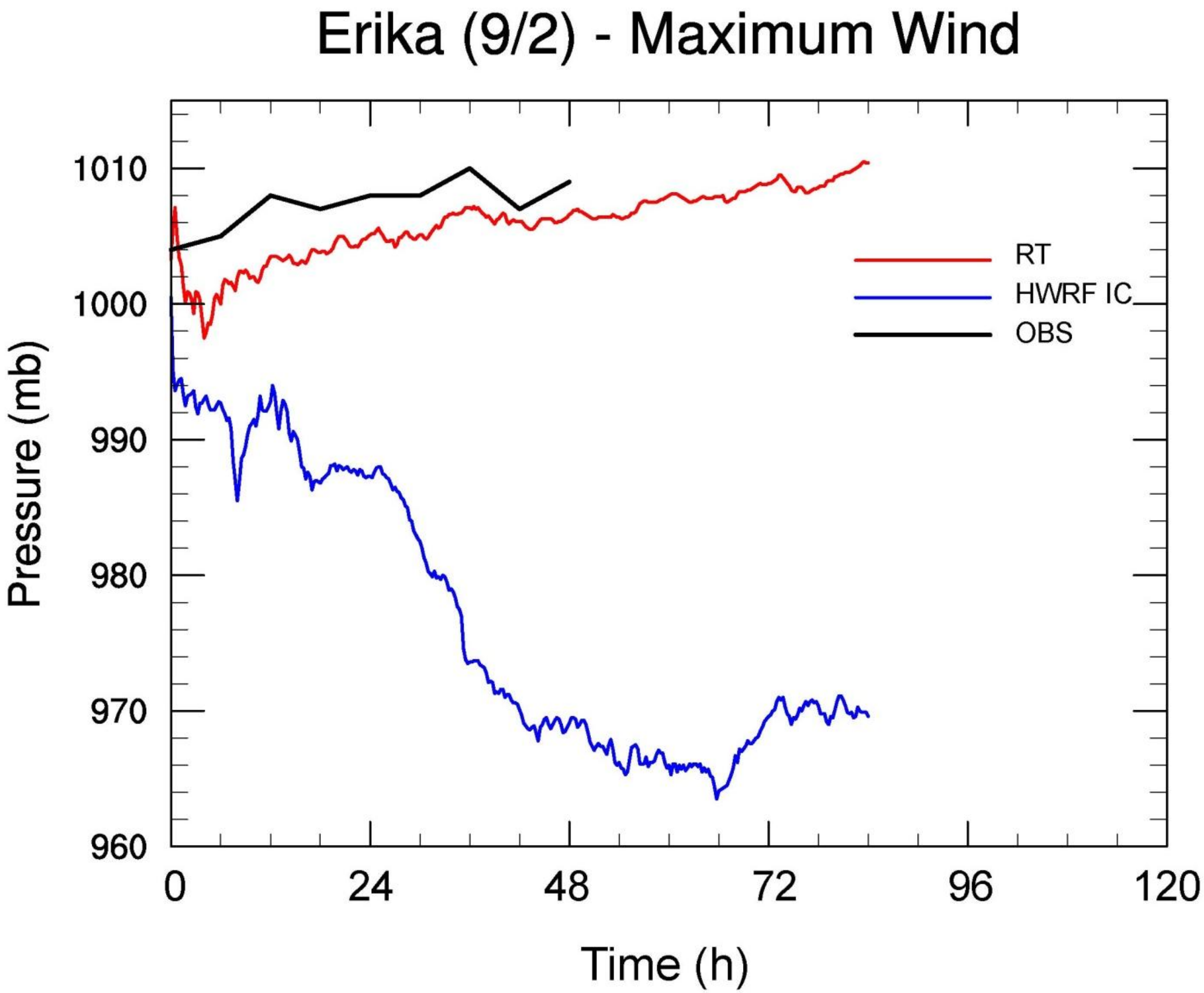
No tilt (HWRF) vs. tilt (AHW)



Erika 12-km vs. 1.33-km nest: Min SLP



Initial Conditions vs. Physics



Concluding Remarks

- Significant predictability limits to intensity forecasts
  - Inner core fluctuations vs. external influences
- Large uncertainty to microphysics, air-sea interaction and turbulence: inter-relationships?
  - Turbulence effects entrainment; transport of aerosol
  - Details of fluxes dependent on many unknowns or complex processes (spray, ocean waves, etc)
- Well-defined tests needed to unravel sources of physical errors versus initial conditions: not always possible