Effects of Uncertainties in Numerical Models of Hurricanes

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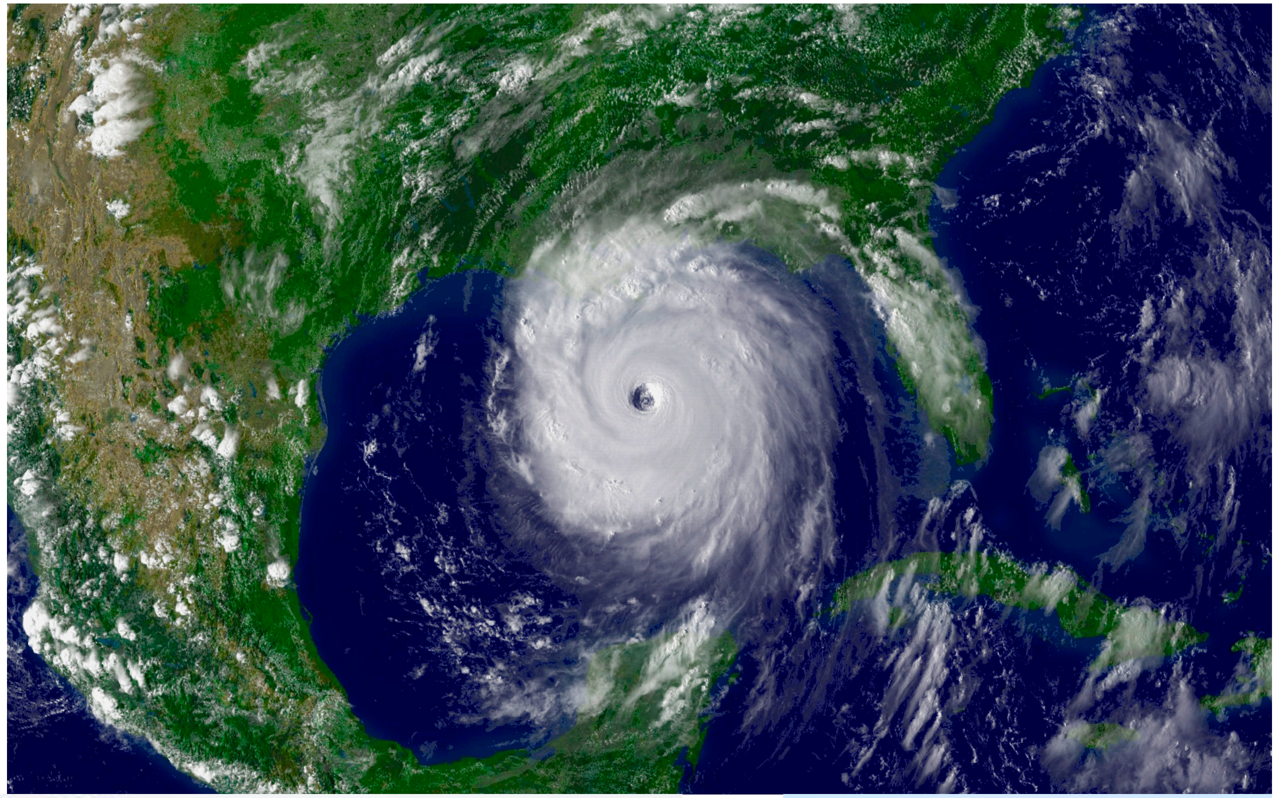
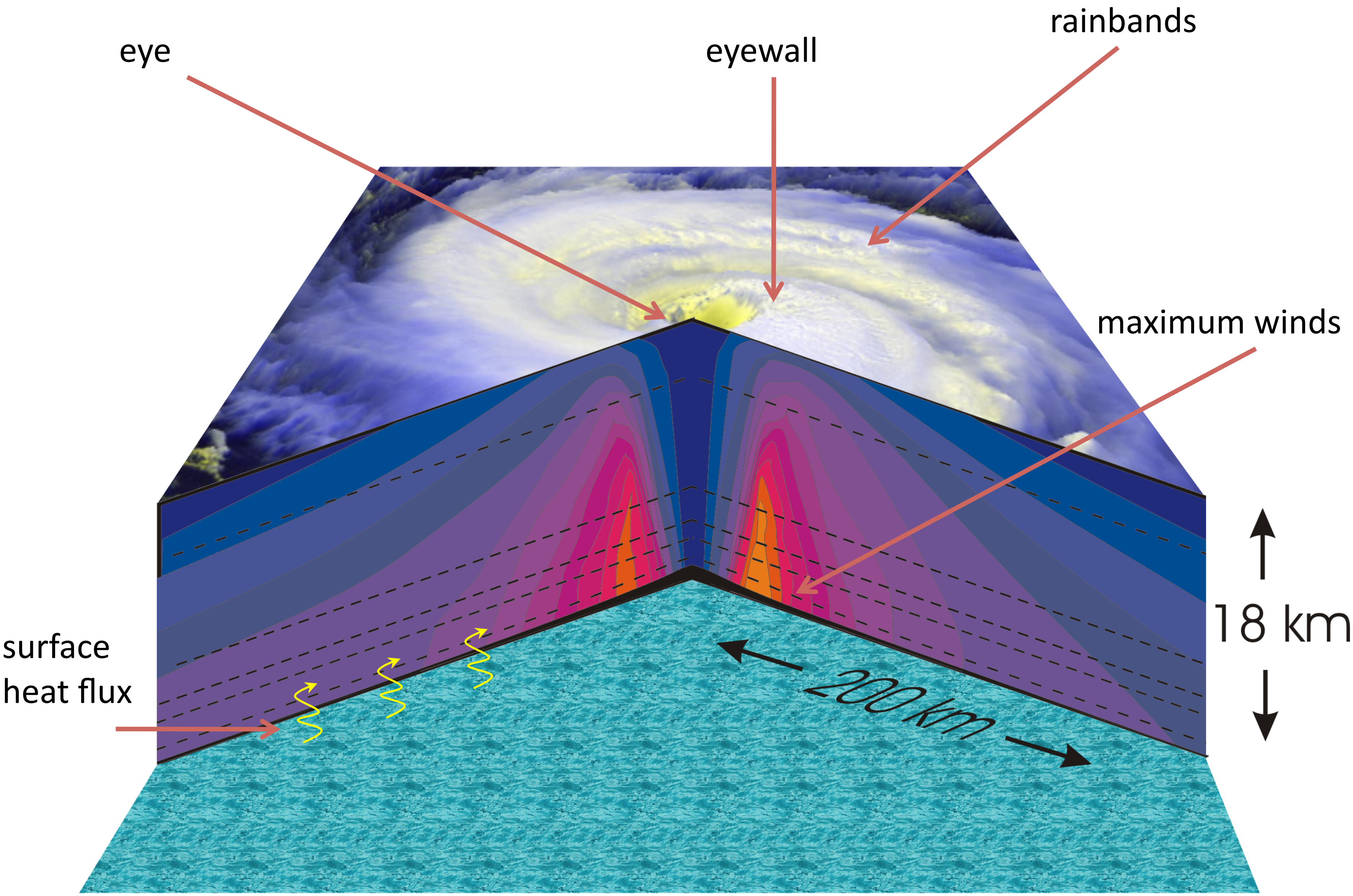
Hurricane Katrina (2005)



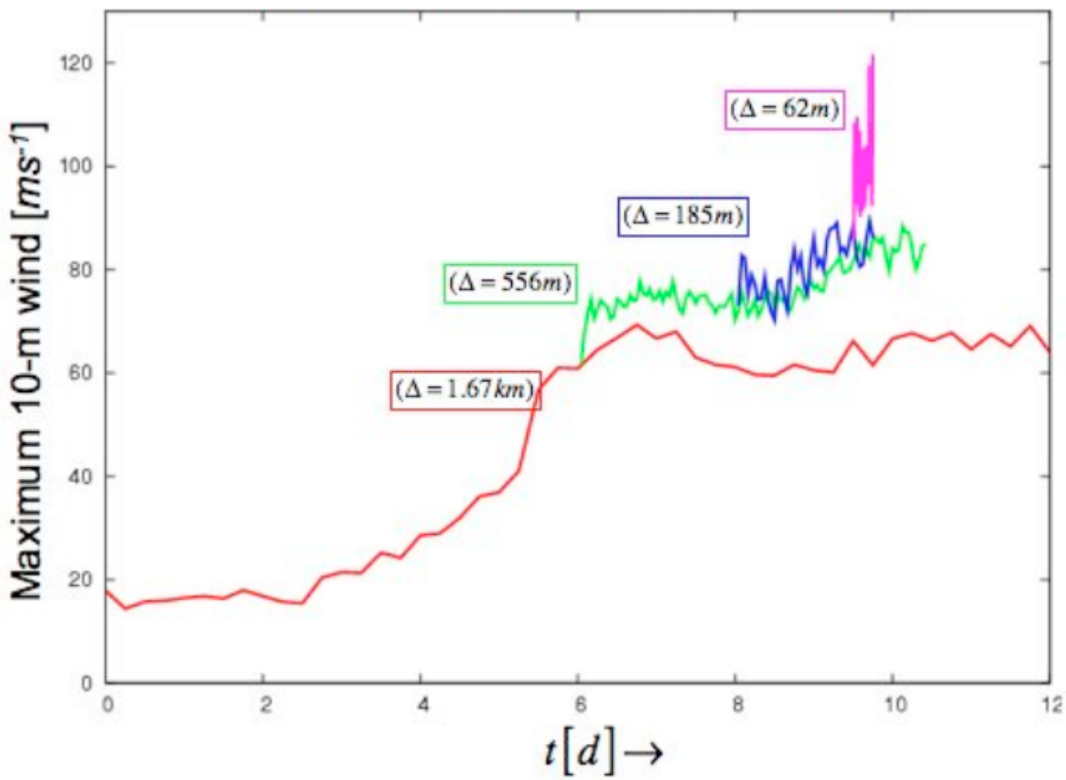
Key components of hurricanes:



Emanuel (2005)

Numerical Simulations of a Hurricane

(3d, WRF/ARW model, SST = 26 °C, C_k/C_d = 0.65)



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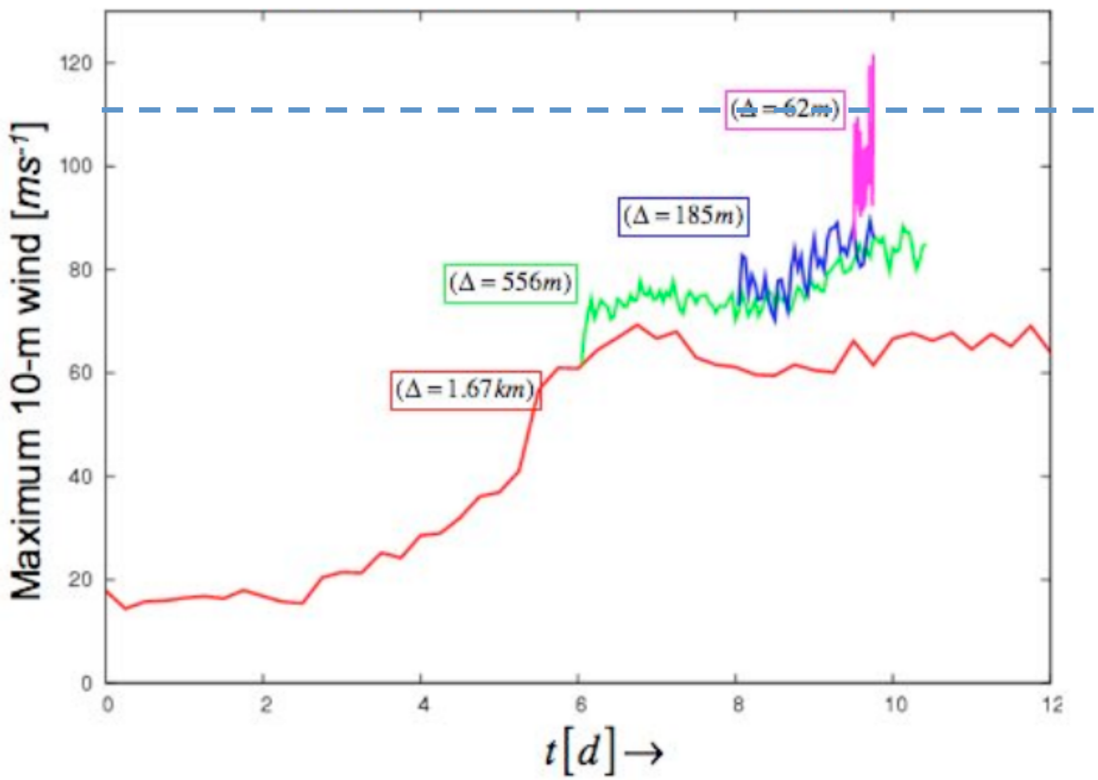
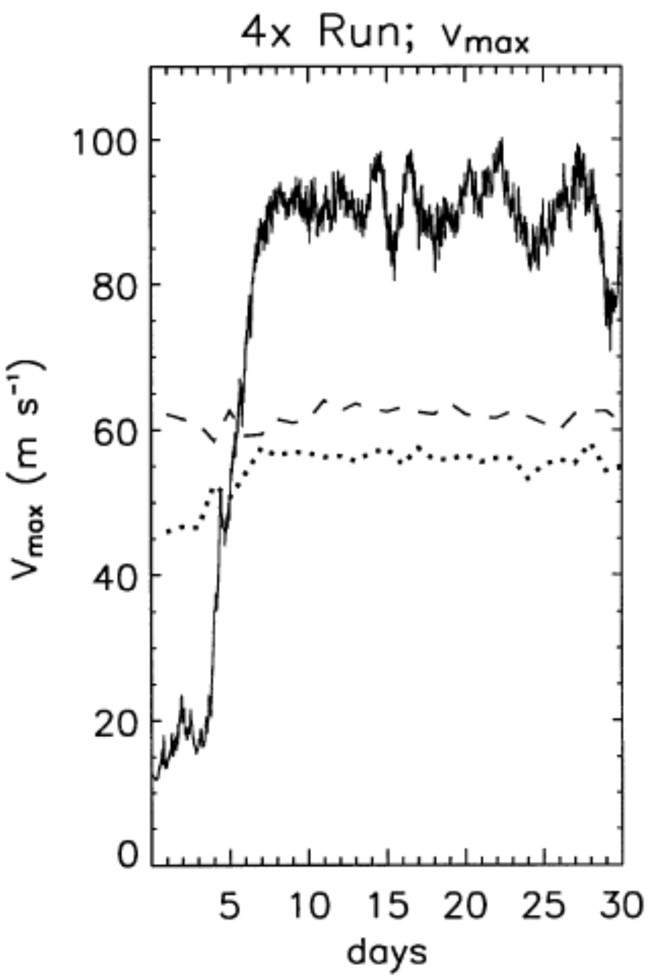


Official (WMO) peak wind: 113 m s^{-1}, Olivia (1996)

Simulated intensity can exceed theoretical maximum intensity

Axisymmetric model:
(Δx = 3.75 km)



Persing and Montgomery (2003)

3D WRF (ARW):

Δx (m):	v_{max}/Potential intensity (m s^{-1})
1700	50/50
556	71/55
185	74/57
62	67/56

Rotunno et al. (2009)

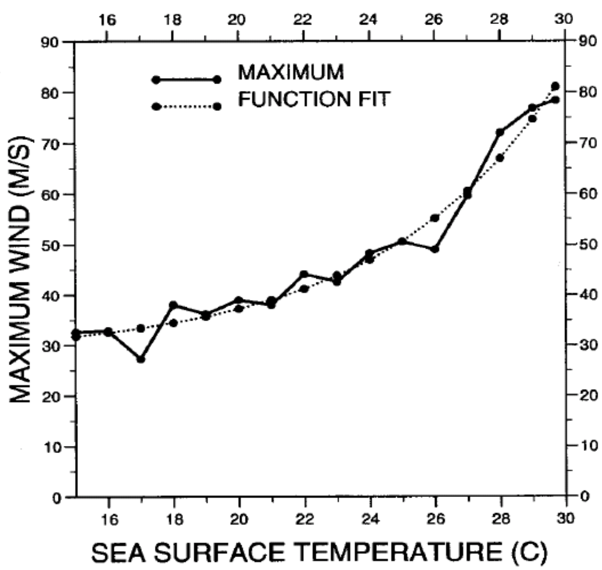
Motivation:

- Much can be learned about hurricane intensity by studying the maximum possible intensity
  - A specific question: What does it take … in terms of resolution, physical processes, etc … for numerical models to reproduce the strongest hurricanes?

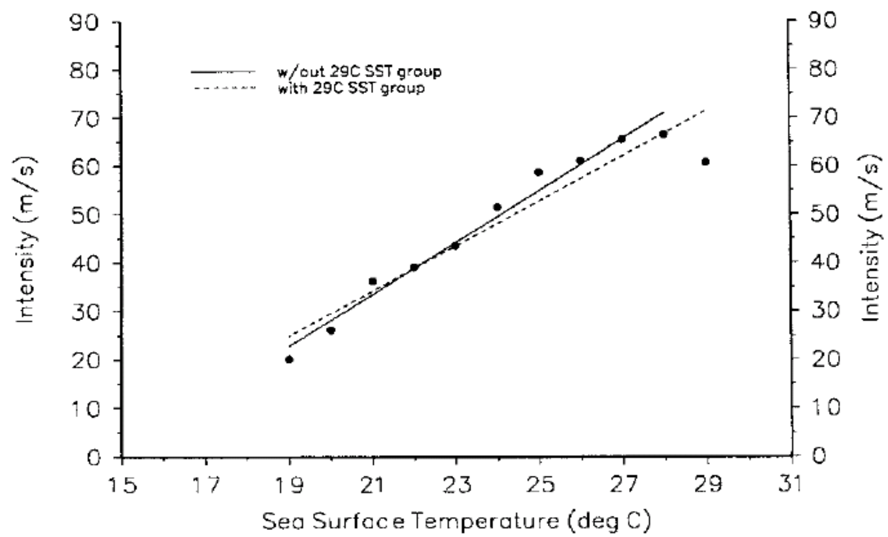
- Knowledge of maximum intensity comes from three general methods …

Method 1: Observations

- Collect as much data as possible
- Choose a relevant environmental parameter: e.g., sea-surface temperature



Atlantic: DeMaria and Kaplan (1994)



East Pacific: Whitney and Hobgood (1997)

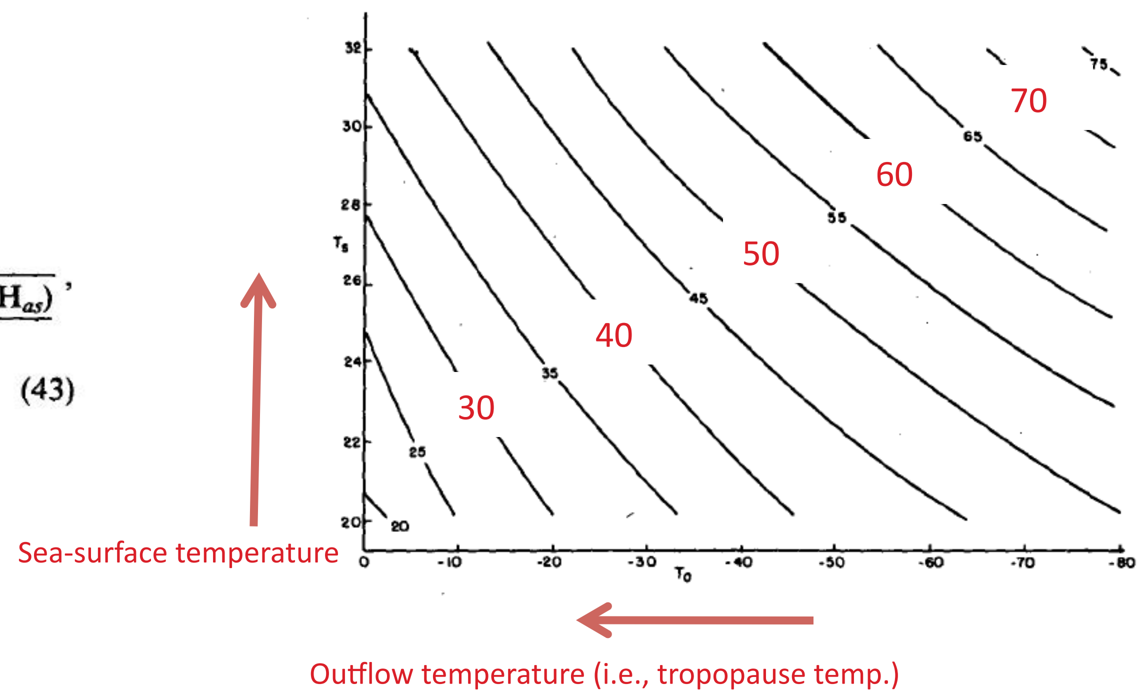
- Advantages: accurate (especially in Atlantic; airplane reconnaissance)
- Drawbacks: limited physical insight, not useful for some applications (future climate)

Method 2: Theoretical Models

– Use governing equations and assumptions about the important processes in tropical cyclones

$$V_{\max}^2 = \frac{C_\theta}{C_D}\epsilon L q_a^*(1-\mathrm{RH}_{as})\frac{1-\frac{1}{4}\frac{f^2 r_0^2}{\beta R T_B}}{1-\frac{1}{2}\frac{C_\theta}{C_D}\epsilon\frac{L q_a^*(1-\mathrm{RH}_{as})}{\beta R T_s}}, \quad (43)$$

Emanuel (1986)

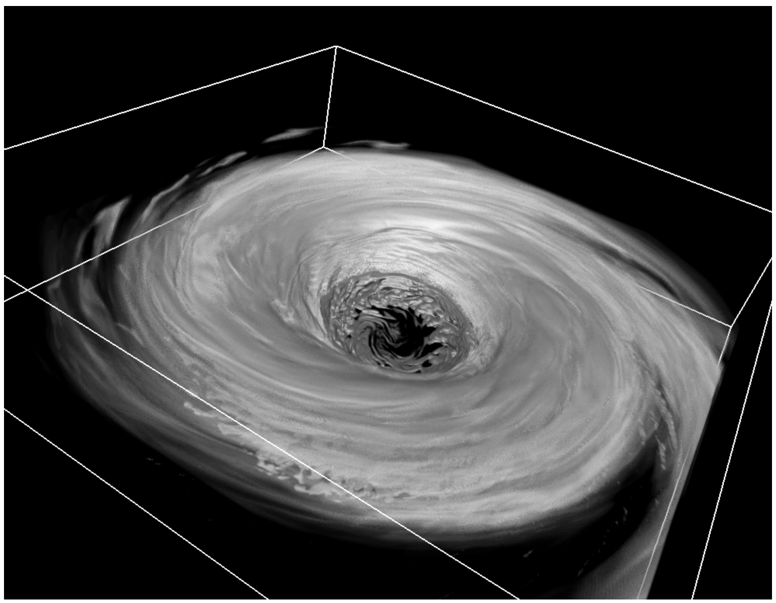


– Advantages: excellent physical insight, adapts to different conditions (e.g., future climate)

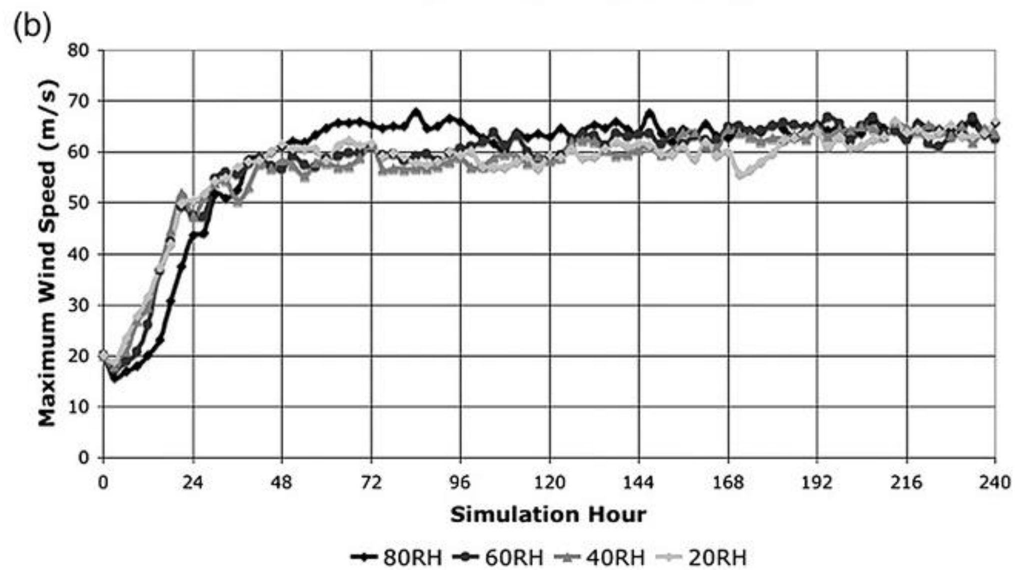
– Drawbacks: requires a great deal of knowledge about tropical cyclones and many approximations; tends to underpredict maximum intensity

Method 3: Numerical models

– Use a time-dependent numerical modeling system



WRF simulation (Yongsheng Chen)

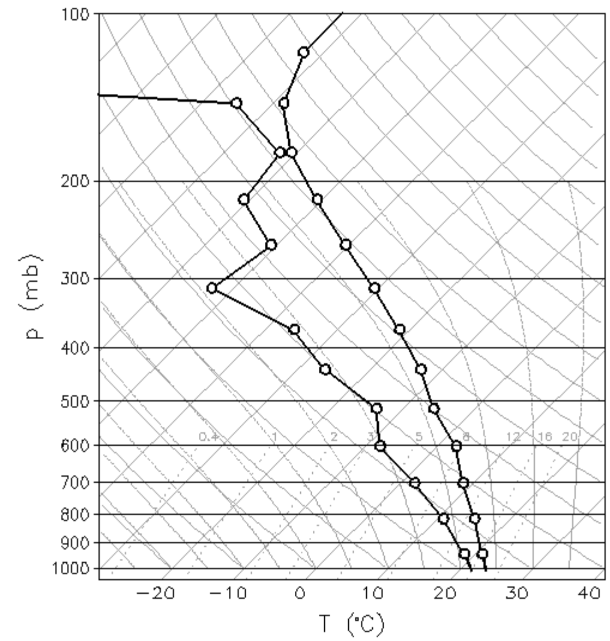


Hill and Lackmann (2009)

– Advantages: it's easy! (don't need a great deal of obs, don't need to assume much about TC structure)
– Drawbacks: uncertainties in physical parameterizations (turbulence, air-sea exchange, moist processes, etc); can overpredict maximum intensity

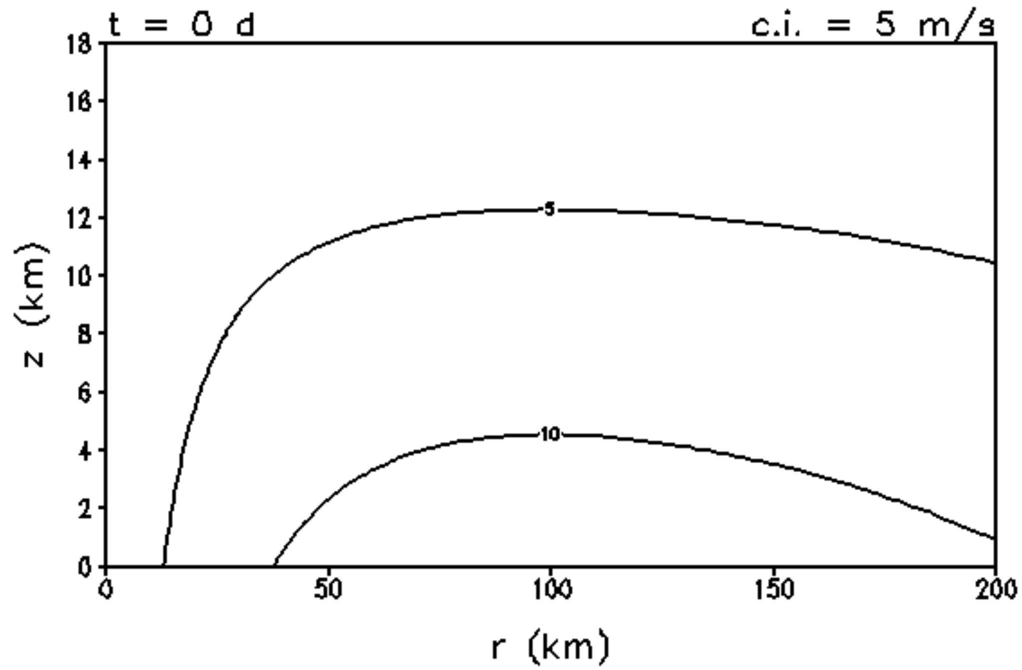
What controls maximum intensity in numerical models?

- Nonhydrostatic, cloud-resolving model (CM1)
  - Bryan and Rotunno (2009, MWR)
  - Same numerical techniques as WRF (ARW)
  - Height coordinate, energy-conserving equations
- Setup:
  - Axisymmetric (r,z) … (now 3d)
  - Homogeneous environment
  - Constant SST (26.1 °C)
  - Initialize with weak vortex
  - Δr = 1 km, Δz = 250 m
  - C_k / C_d = 1
  - Simple liquid-only microphysics
  - Simple radiation



Bryan and Rotunno (2009)

Initial conditions:

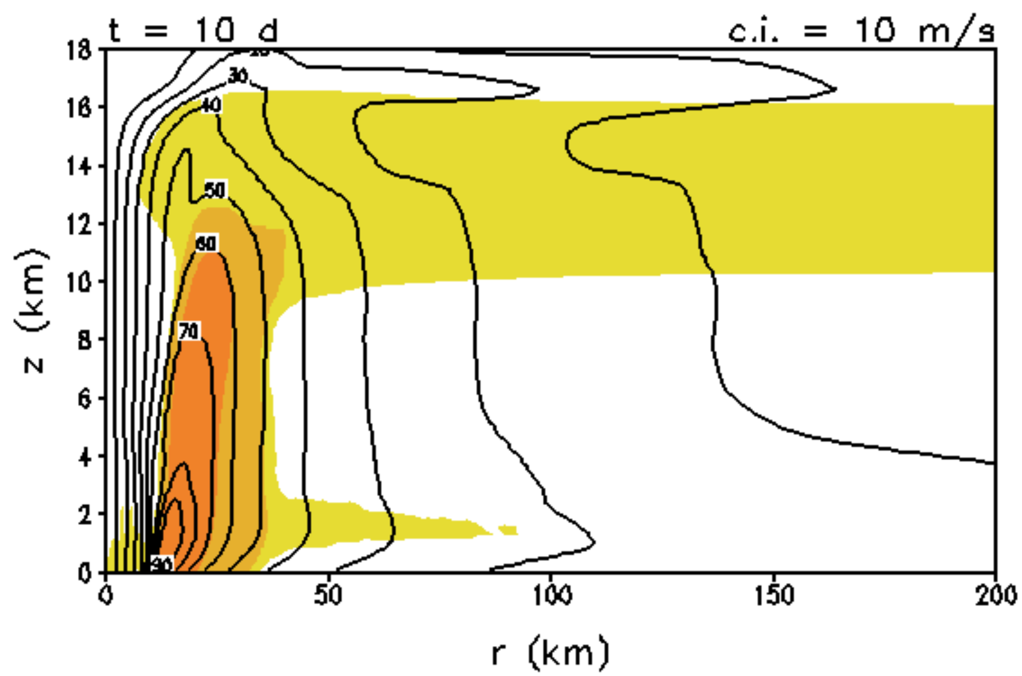


yellow = cloud

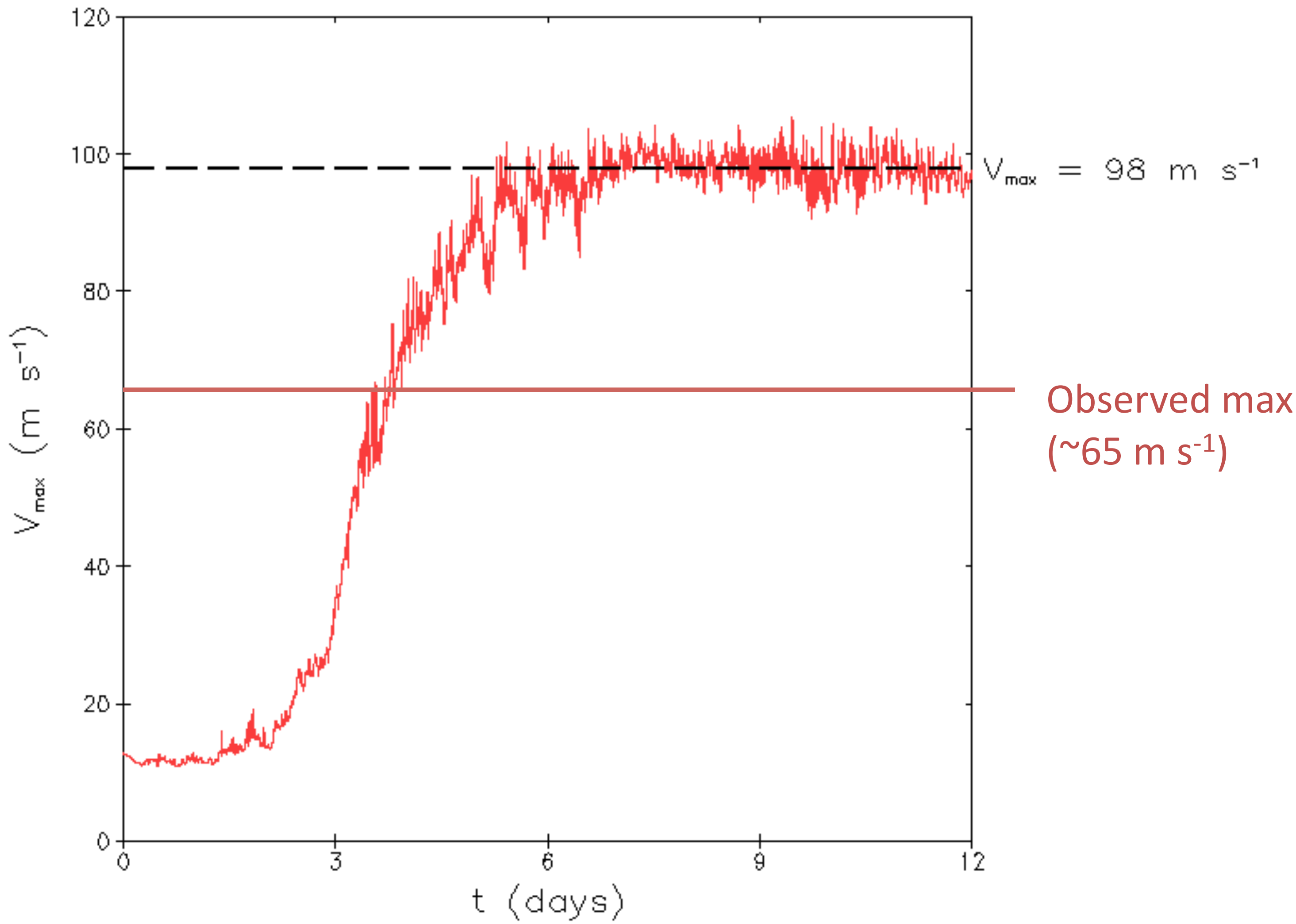
orange = rain

contours = v (m s^{-1})

t = 10 days:



Time series of v_{max} (m s^{-1})



Model components investigated:

[see Bryan and Rotunno (2009, MWR) for details]

- Resolution* (as long as $\Delta r < 8$ km, $\Delta z < 500$ m)
- Numerics (e.g., advection scheme)
- Initial vortex (affects size more than intensity)
- Governing equations (energy-conserving equations change V_{max} by ~10%)
- Microphysics (fall velocity of condensate matters most)
- **Surface exchange coefficients** (but not as much as theory says they should)
- **Turbulence** (relatively unexplored topic until recently)

Turbulence in mesoscale models
(including this axisymmetric model):

Turbulence eddy viscosities:

horizontal: $$\nu_h = l_h^2 S_h,$$

vertical: $$\nu_v = l_v^2 \left(S_v^2 - N_m^2 \right)^{1/2}.$$

Where: S is deformation

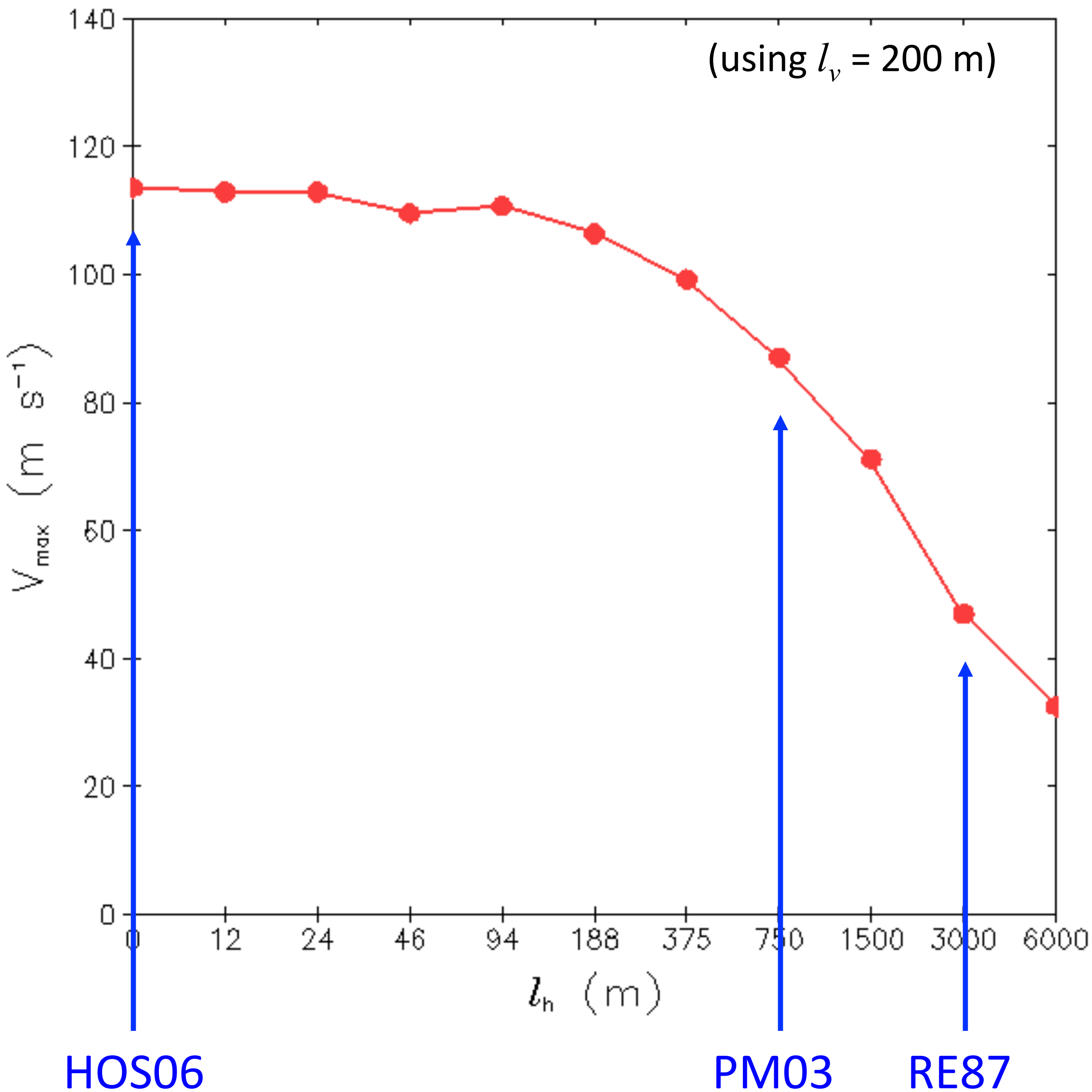
N_m^2 is squared Brunt-Vaisala frequency

l_h is a horizontal length scale (unknown; specified here)

l_v is a vertical length scale (unknown; specified here)

- This turbulence model is used because it has only one free parameter (a length scale l) that is intuitive and obtainable from measurements

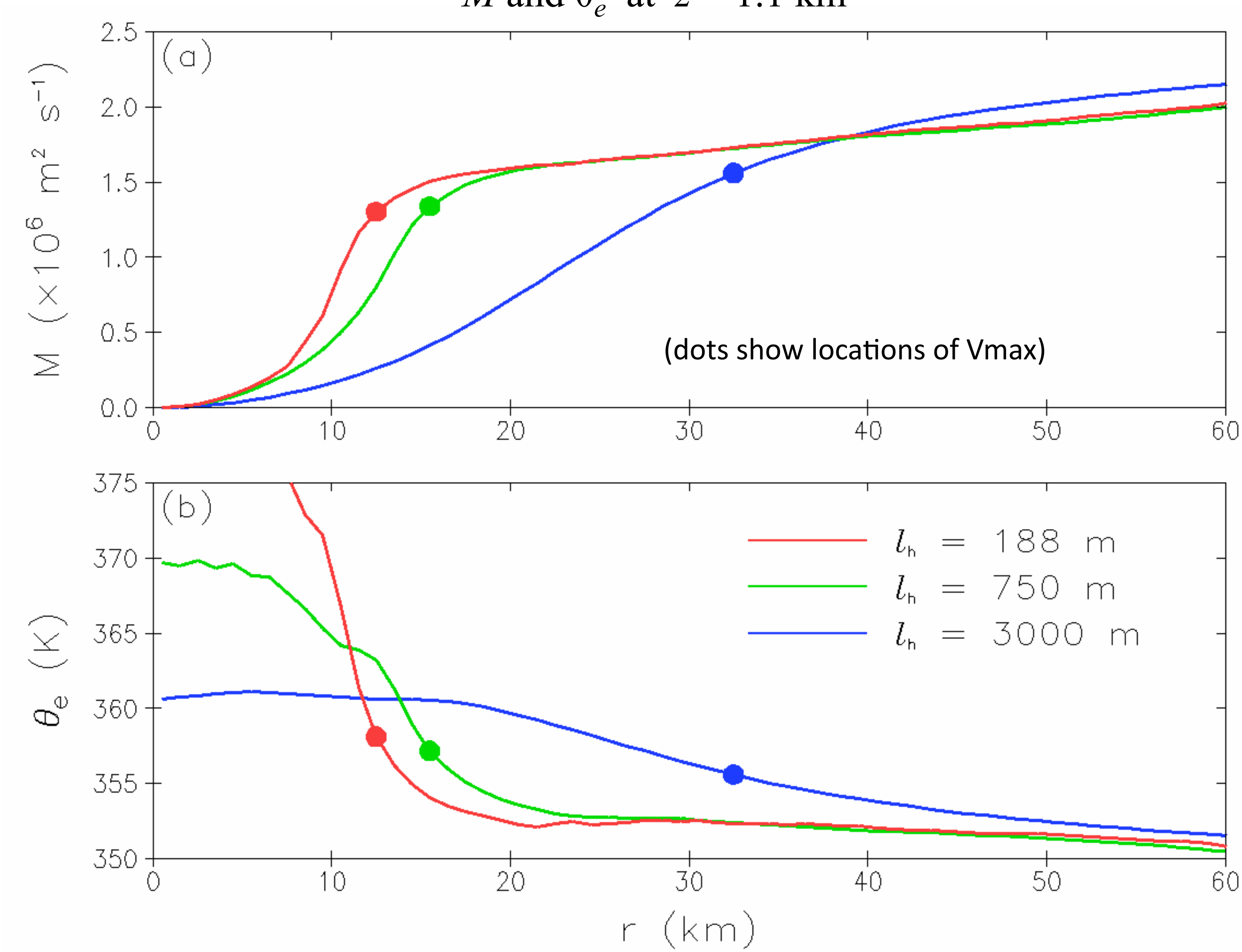
Sensitivity to horizontal turbulence length scale:



Bryan and Rotunno (2009, MWR)

Output from axisymmetric model:

M and θ_e at $z = 1.1$ km

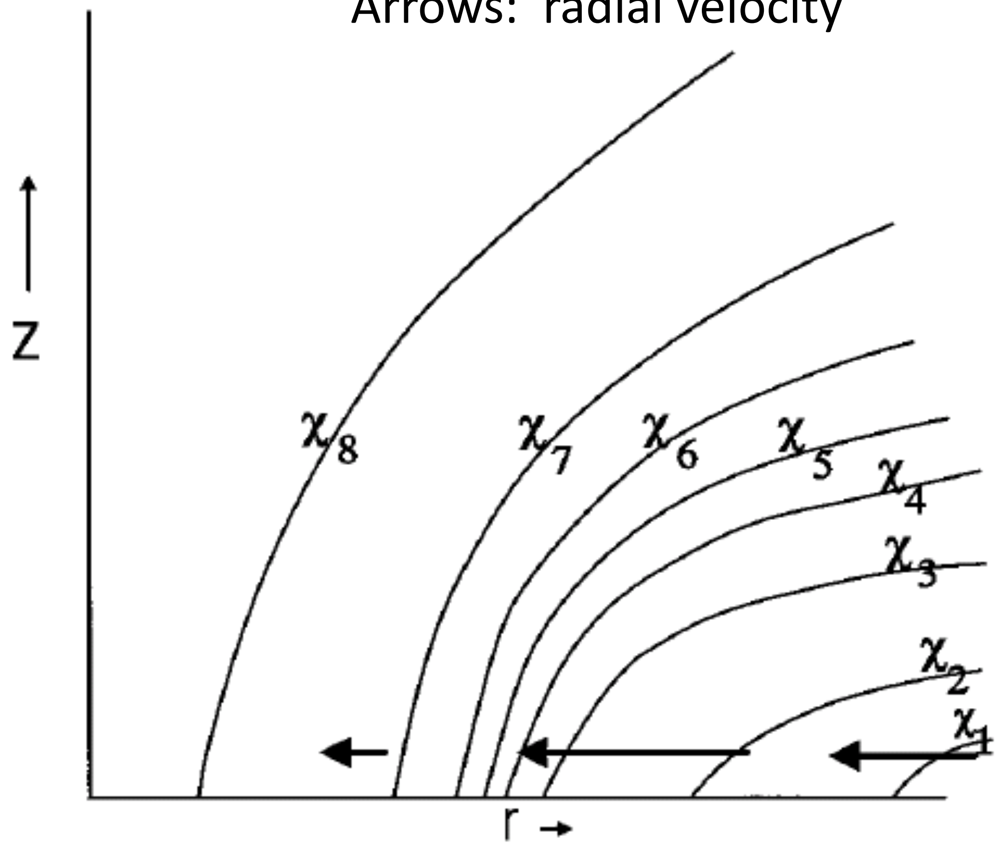


Bryan and Rotunno (2009, MWR)

Strong frontogenesis is a fundamental characteristic of hurricane eyewalls:

χ = entropy (θ_e), or M

Arrows: radial velocity



Emanuel (1997)

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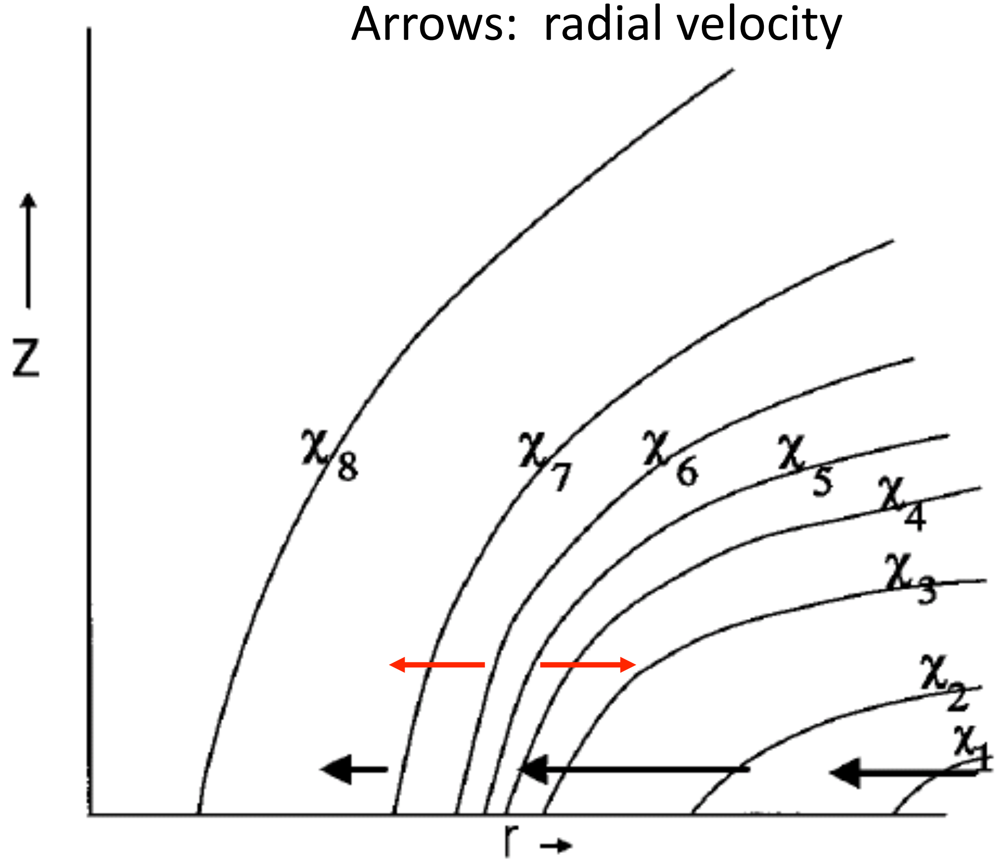
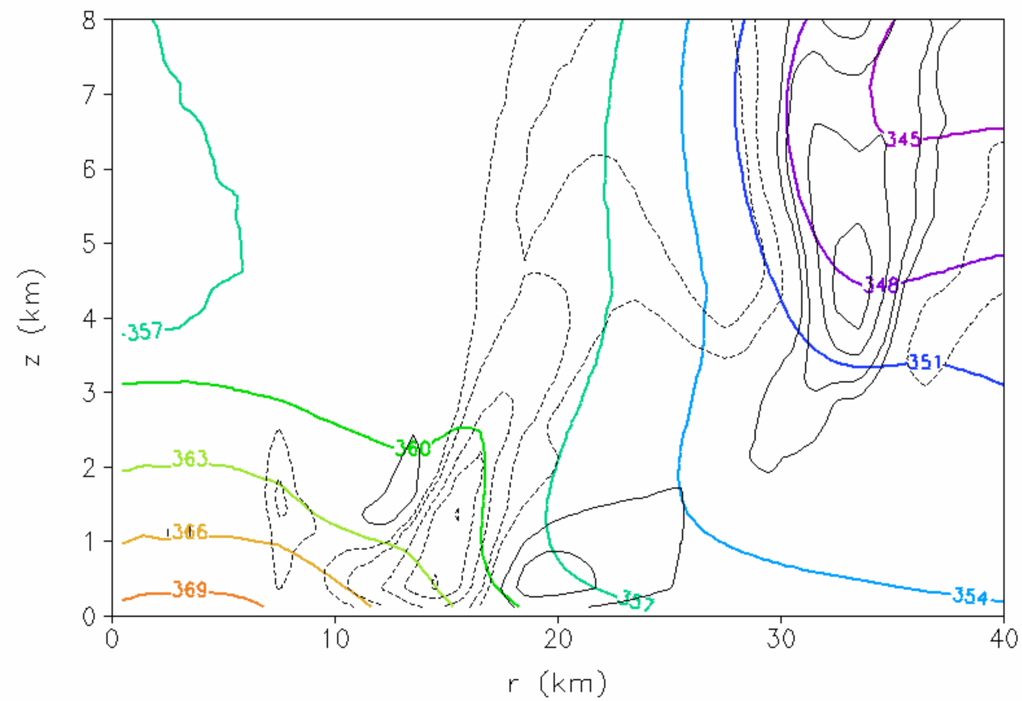


Emanuel (1997)

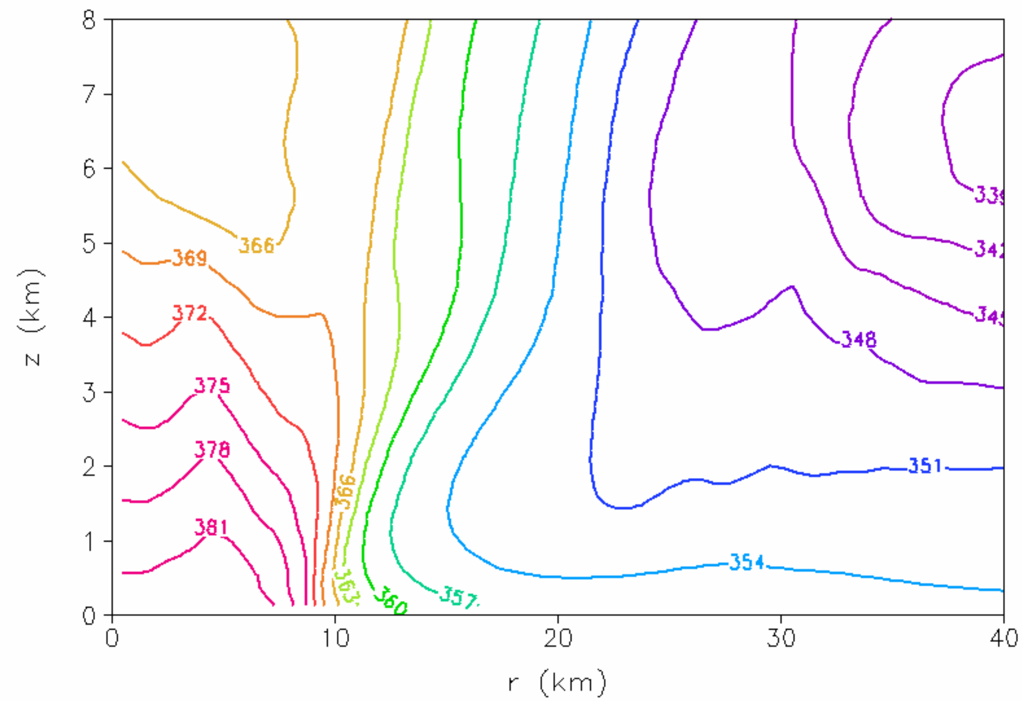
diffusion is frontolytic! (limits frontal collapse)

Simulations that vary *only* in <u>horizontal</u> turbulence:

l_h = 1500 m



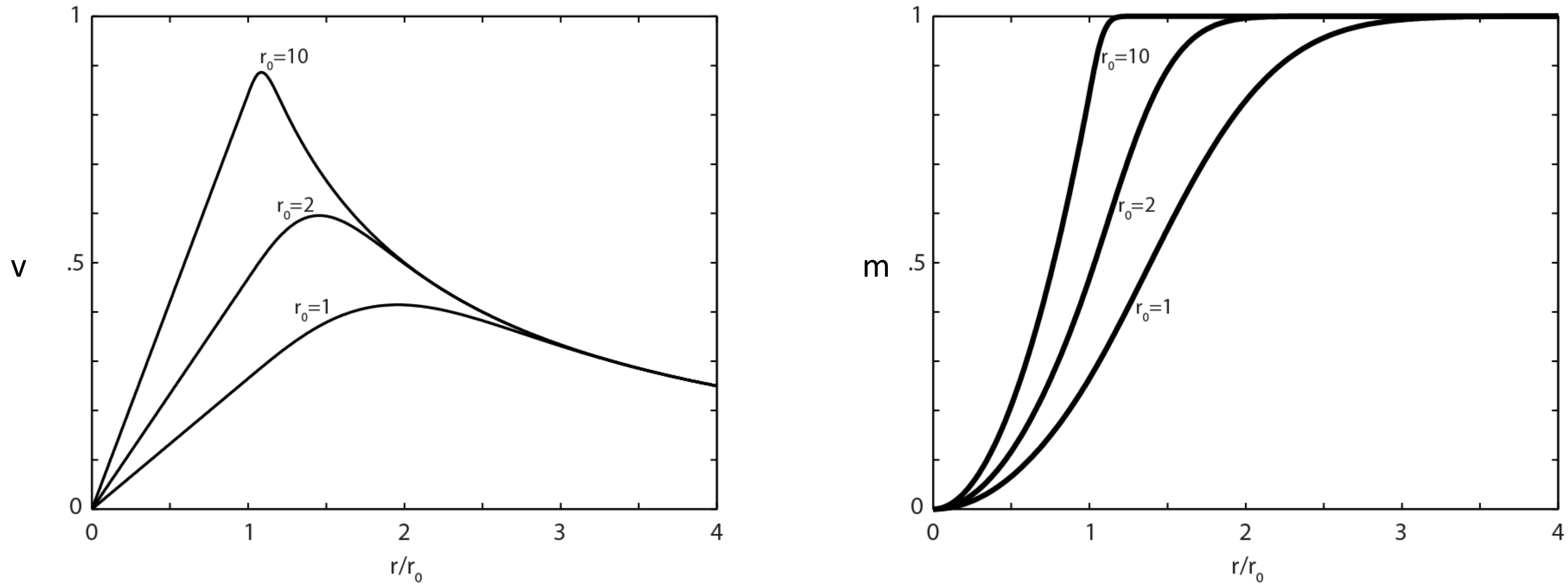
l_h = 0 m



Color contours = θ_e

Black contours = diffusive tendency

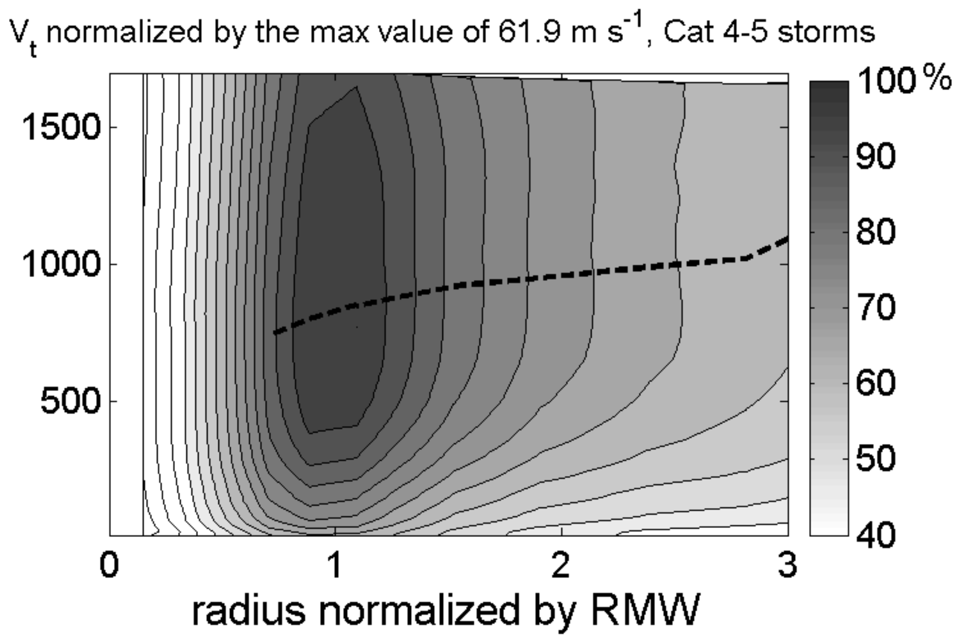
Analytic solutions to advection/diffusion equation:



Rotunno and Bryan (2011; under review)

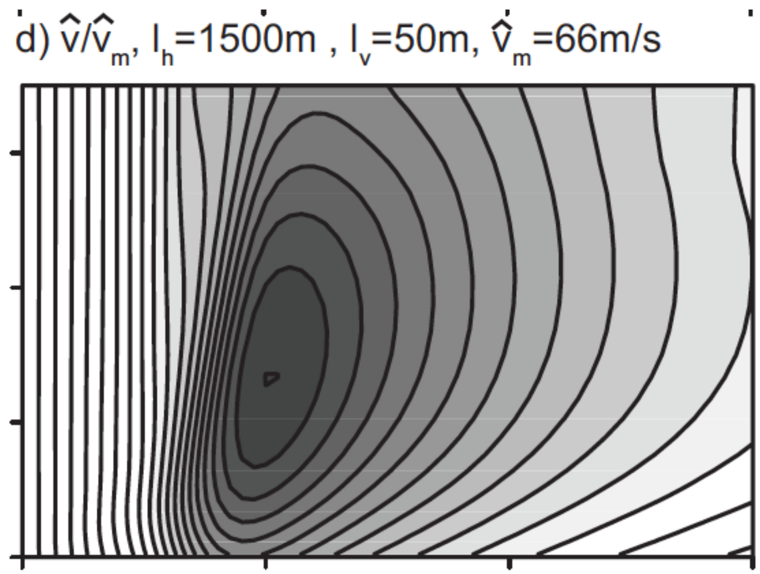
Comparison of simulations to observations: azimuthal velocity (v)

Observations
(dropsonde data)



Zhang et al (2011)

Idealized simulations



Rotunno and Bryan (2011; under review)

Comparison of simulations to observations: radial velocity (u)

Observations
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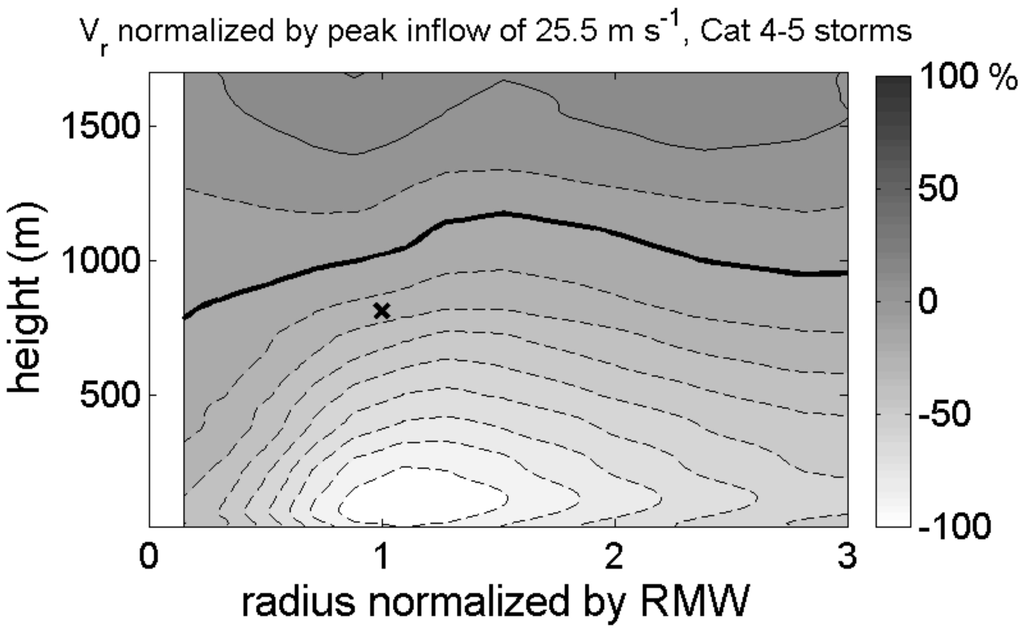

Zhang et al (2011)

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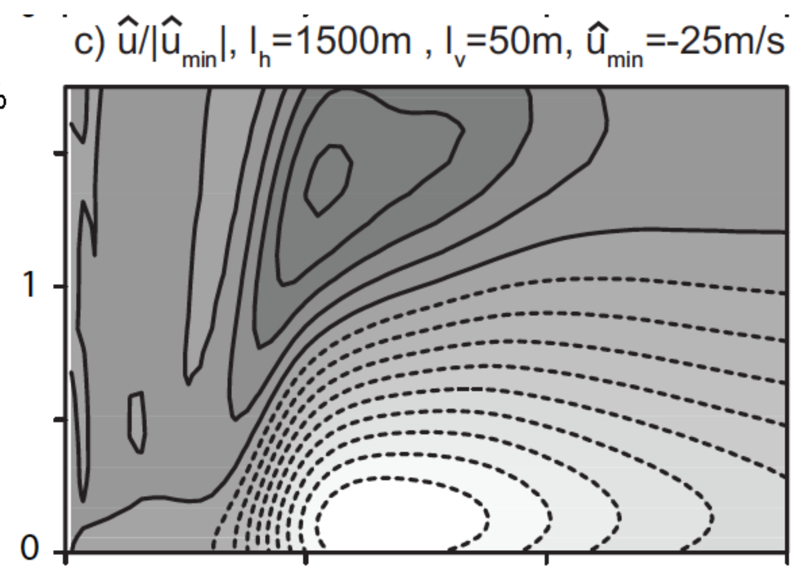


Rotunno and Bryan (2011; under review)

Historical Context

- Why hasn't this importance to horizontal diffusion in numerical models been identified before?

- Hardware: computers are more powerful
  - $\Delta x \approx 1$ km is now common
  - (collapsing onto grid at $\Delta x \approx 10$ km produces reasonable solution!)

- Software: numerical models are becoming more accurate
  - MM5: 2nd-order transport scheme
  - WRF (ARW): 5th/6th-order transport scheme (retains smaller-scale structure)

- Theory: "classical" boundary layer theory assumes isotropic diffusion (e.g., Batchelor 1967)
  - There appear to be different mechanisms for horizontal/vertical turbulent processes in hurricanes (at least in the eyewall)

Uncertainties in surface exchange coefficients

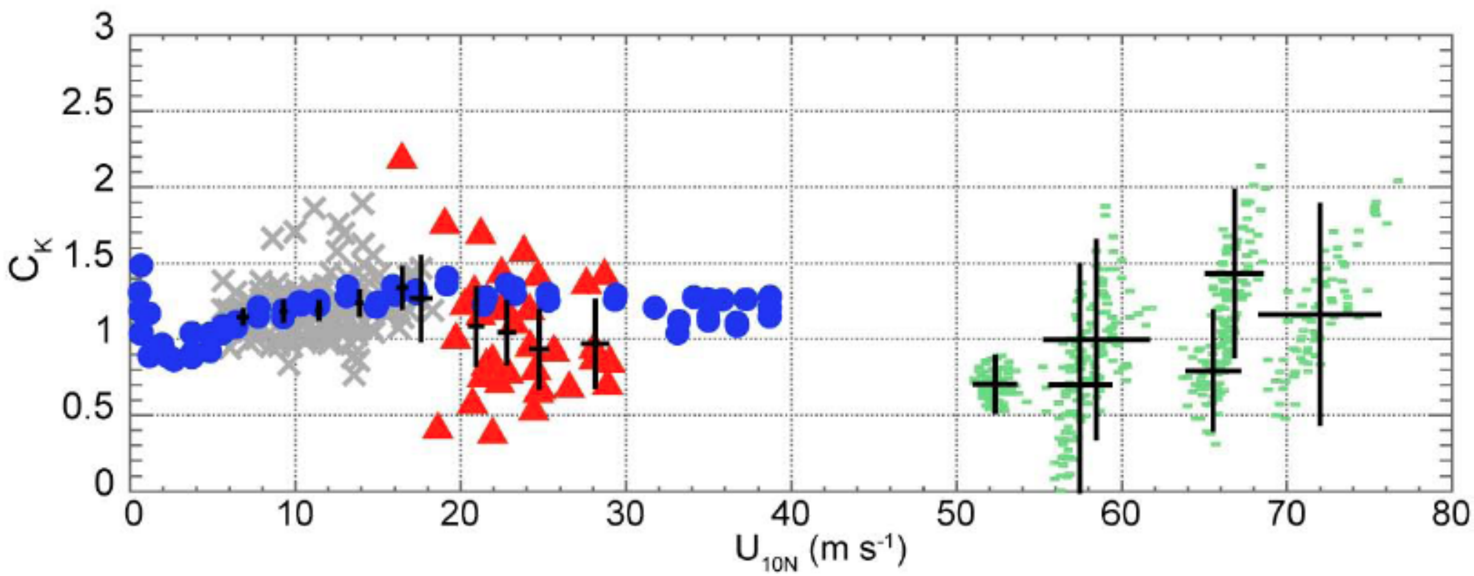
The exchange of energy and momentum between the surface (ocean) and the atmosphere is parameterized by bulk aerodynamic formulae:

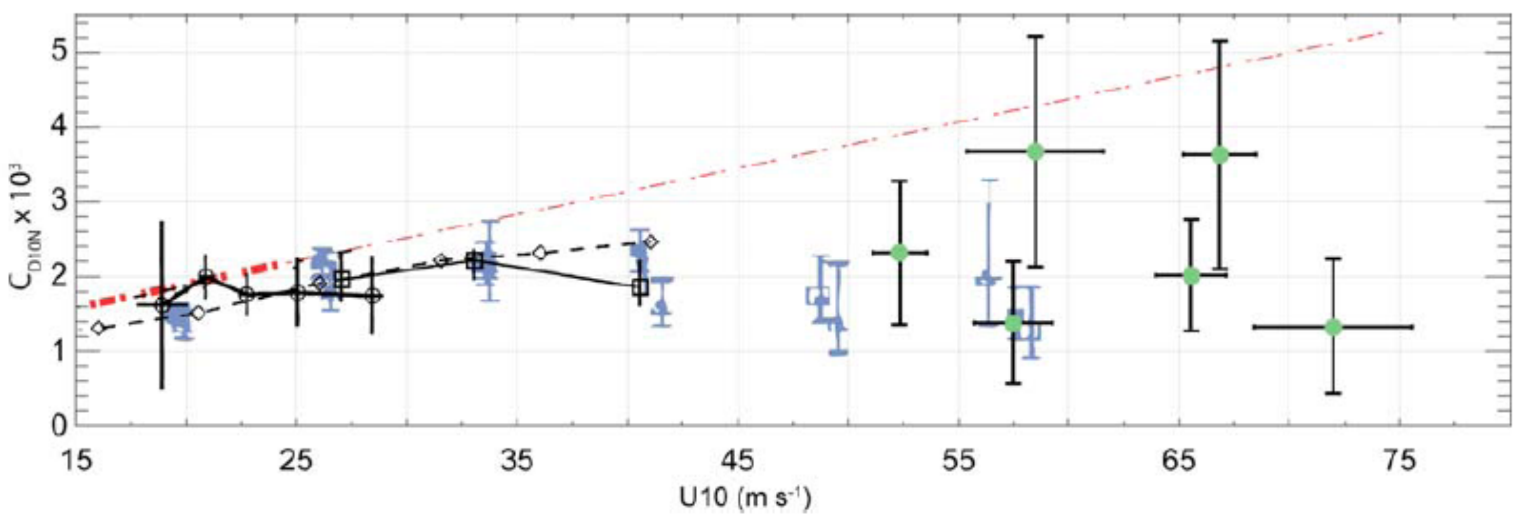
$$\tau_{rz} = C_d V u$$
$$\tau_{rz} = C_d V v$$
$$\tau_{z\theta} = C_k V \left(\theta_{\mathrm{surf}} - \theta\right)$$

Theoretical models (see review by Emanuel 2004) find that Vmax varies as follows:

$$V_{\max} \sim \left(\frac{C_k}{C_d}\right)^{\frac{1}{2}}$$

Observed/diagnosed/retrieved exchange coefficients



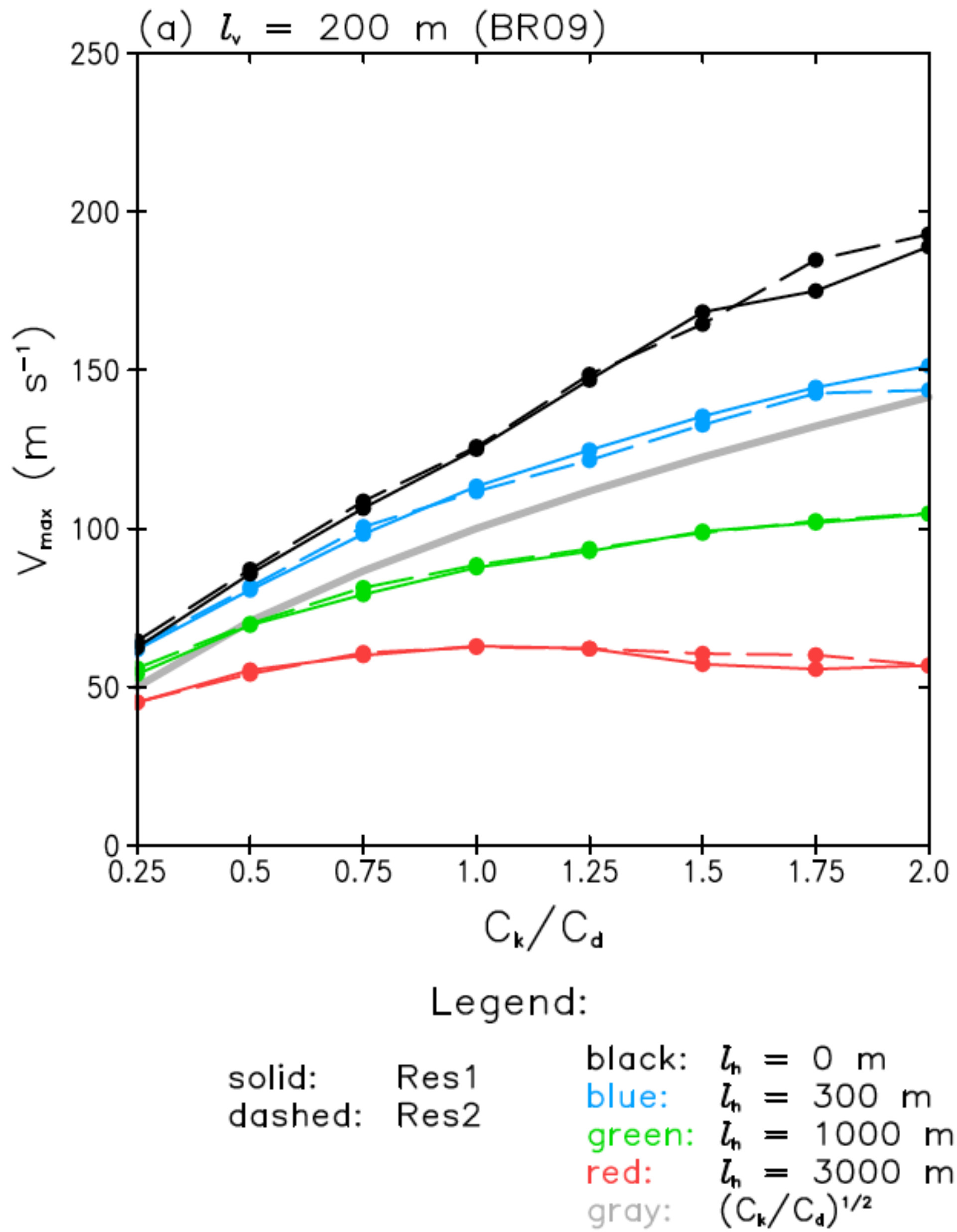


Bell (2010)

Model Setup

- Axisymmetric model: Δr = 1 km (some 3d results later)
- Δz varies (20 m to 250 m); 17 levels below 1 km
- Two environments considered:
  - Rotunno and Emanuel (1987): T_s = 26 C, CAPE = 400 J/kg
  - Dunion (2011) "moist tropical" sounding: T_s = 29 C, CAPE = 2400 J/kg
- Two microphysical schemes:
  - Rotunno and Emanuel (1987) liquid-only scheme
  - Morrison et al (2009) double-moment mixed-phase scheme
- Nominal setup: C_k = constant = 1.2×10^{-3}, C_d = constant
- Following results presented in terms of C_k/C_d

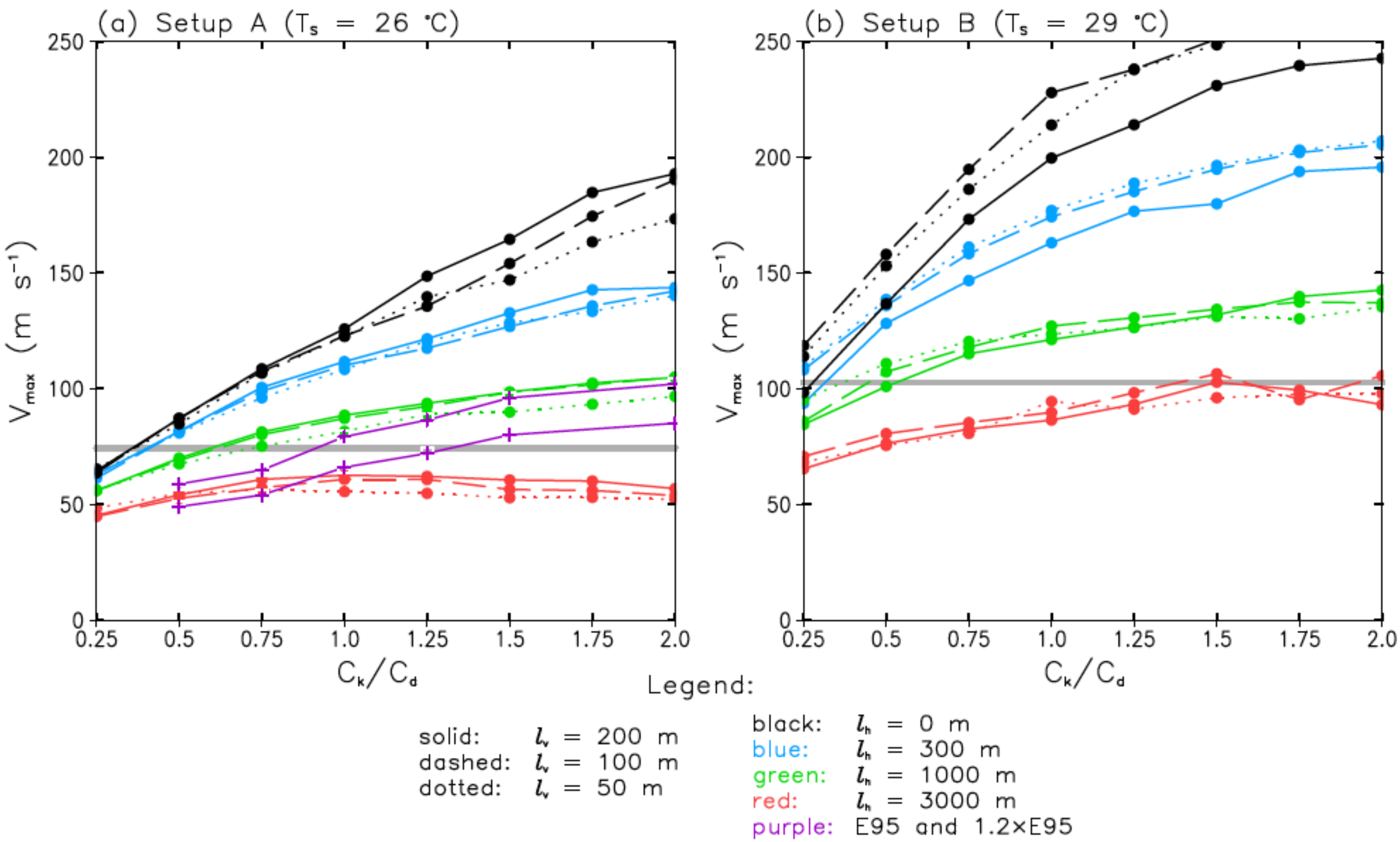
  (recall that obs/lab results are finding $C_k/C_d \approx 0.5$)
- See Bryan (2011, MWR, in press) for more details



(a) l_v = 200 m (BR09)
250
200
150
100
50
0
V_{max} (m s^{-1})
0.25
0.5
0.75
1.0
1.25
1.5
1.75
2.0
C_k/C_d
Legend:
solid: Res1
dashed: Res2
black: l_h = 0 m
blue: l_h = 300 m
green: l_h = 1000 m
red: l_h = 3000 m
gray: $(C_k/C_d)^{1/2}$

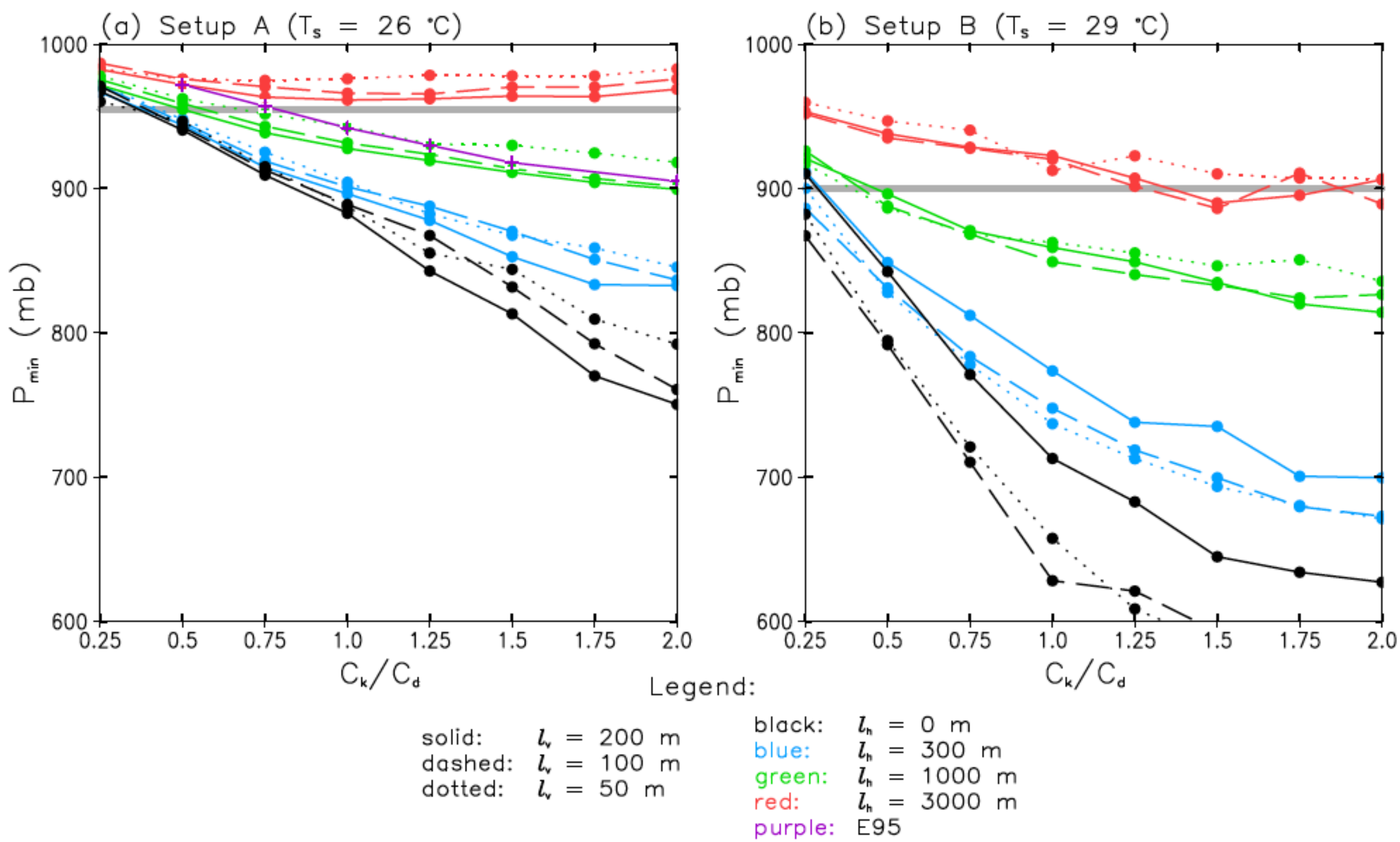
Maximum tangential windspeed (note: *above surface*)

---> Horizontal gray line: observed V_{max} (see Bryan 2011 for details)



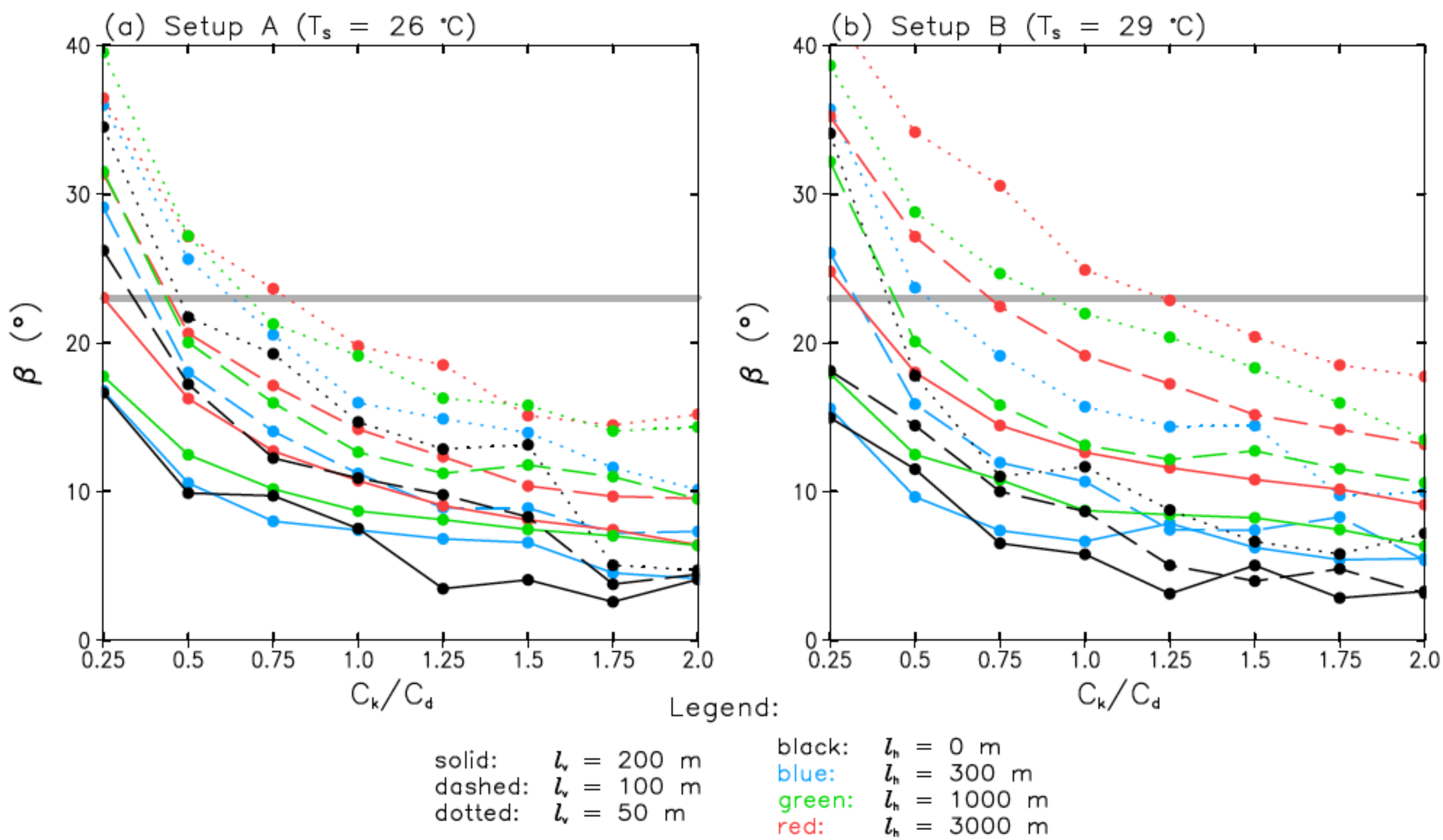
Minimum Surface Pressure

---> Horizontal gray line: observed P_{min}



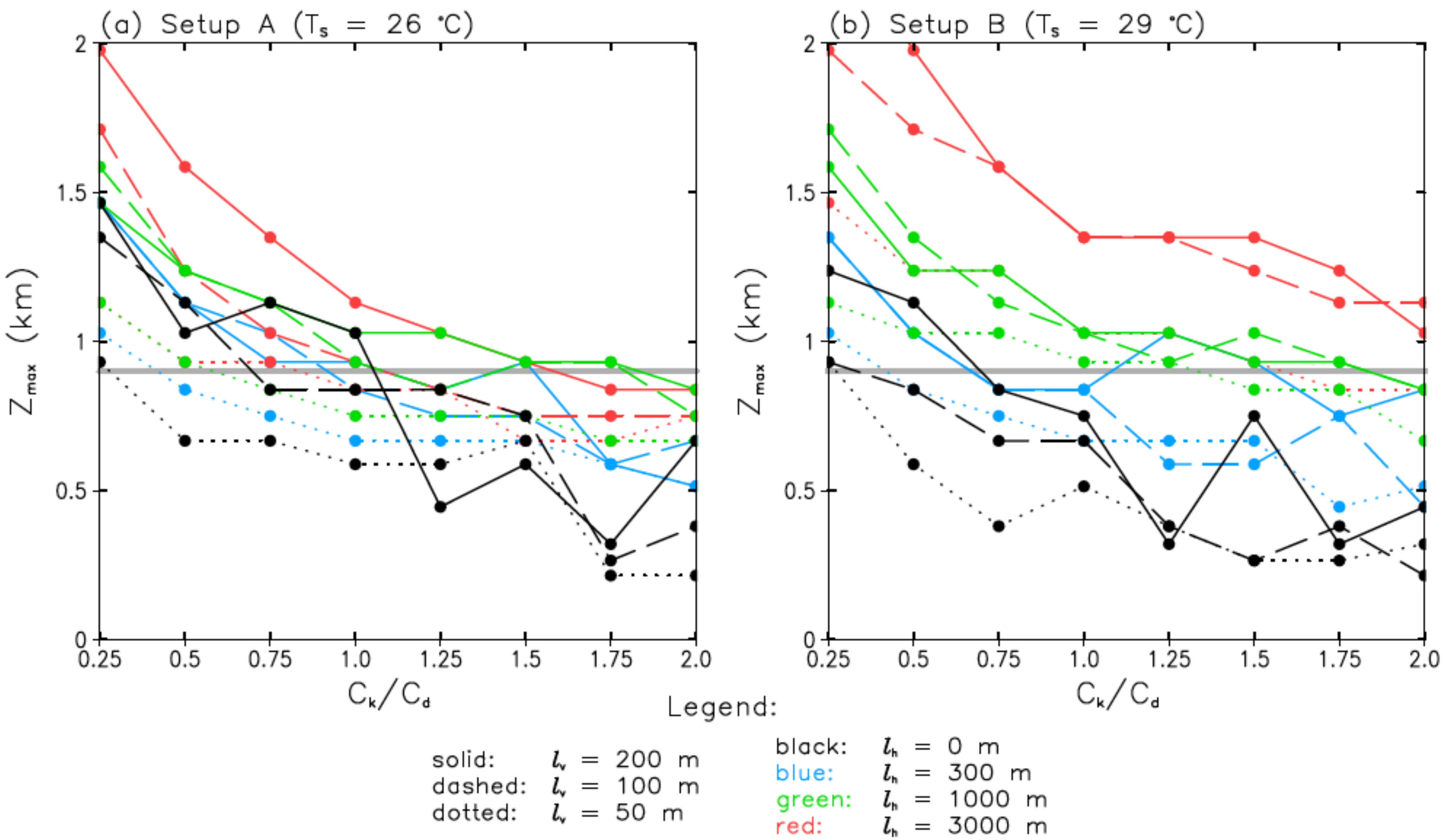
Surface (10-m) inflow angle

---> Horizontal gray line: average value from dropsonde observations (Powell et al 2009)



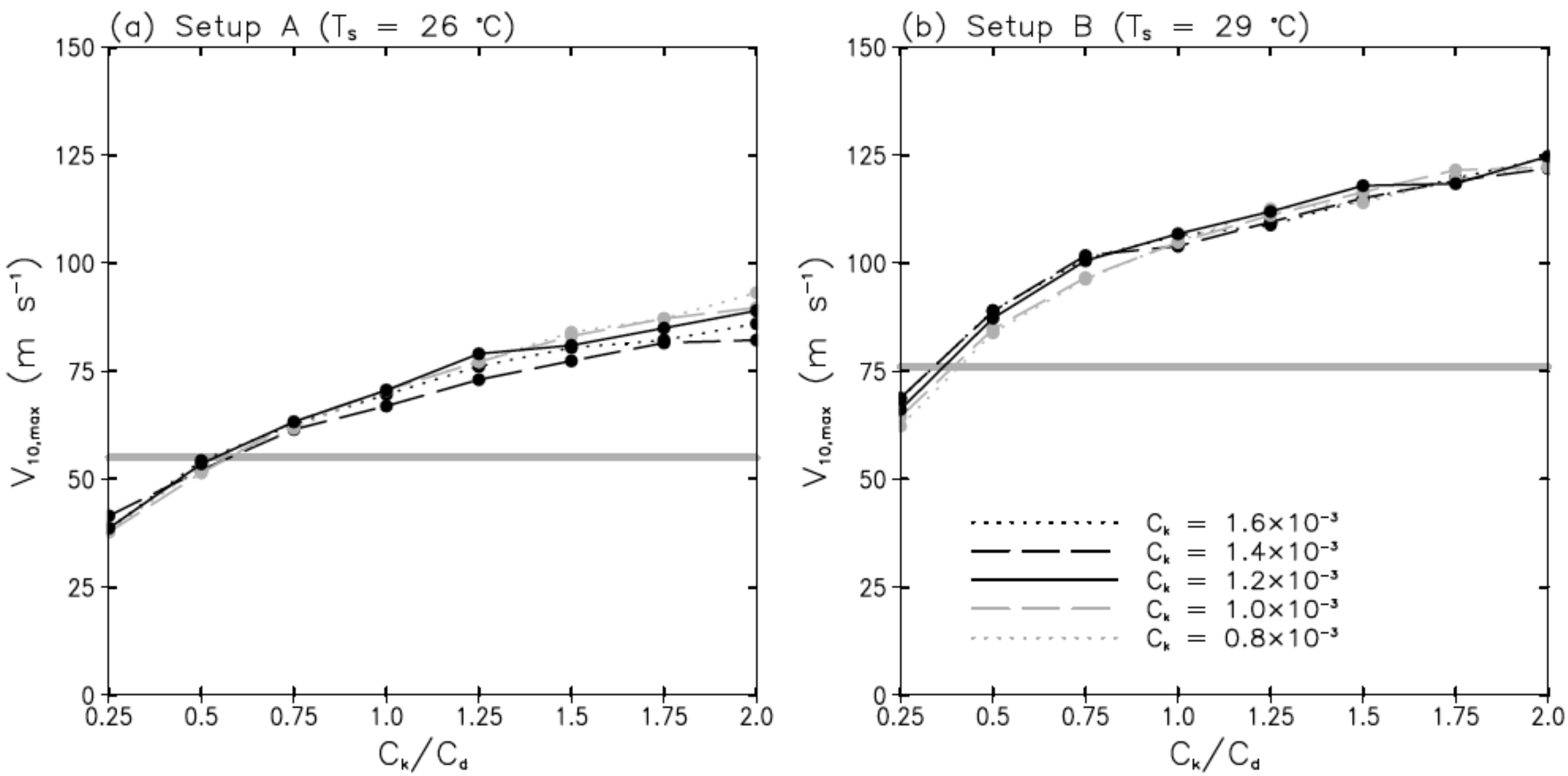
Height of V_{max}

---> Horizontal gray line: value from composite analysis of dropsonde data (Zhang et al 2011)



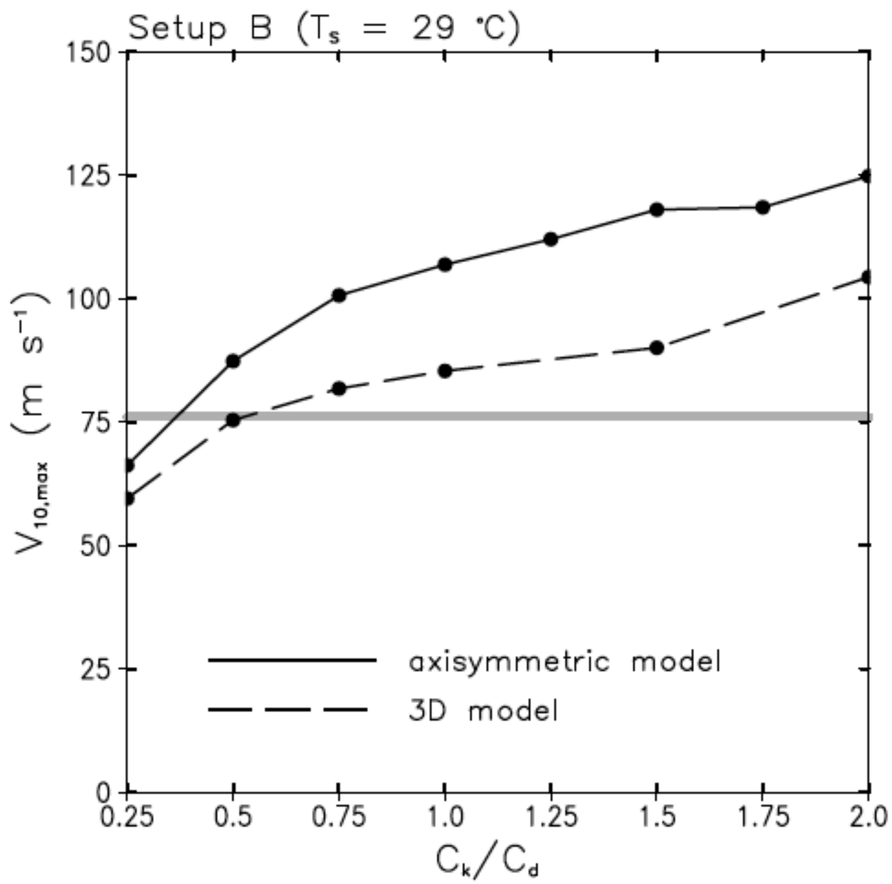
Results using different C_k

(here, showing only simulations with l_h=1000m and l_v=50m)



Comparison of axisymmetric model and 3D model

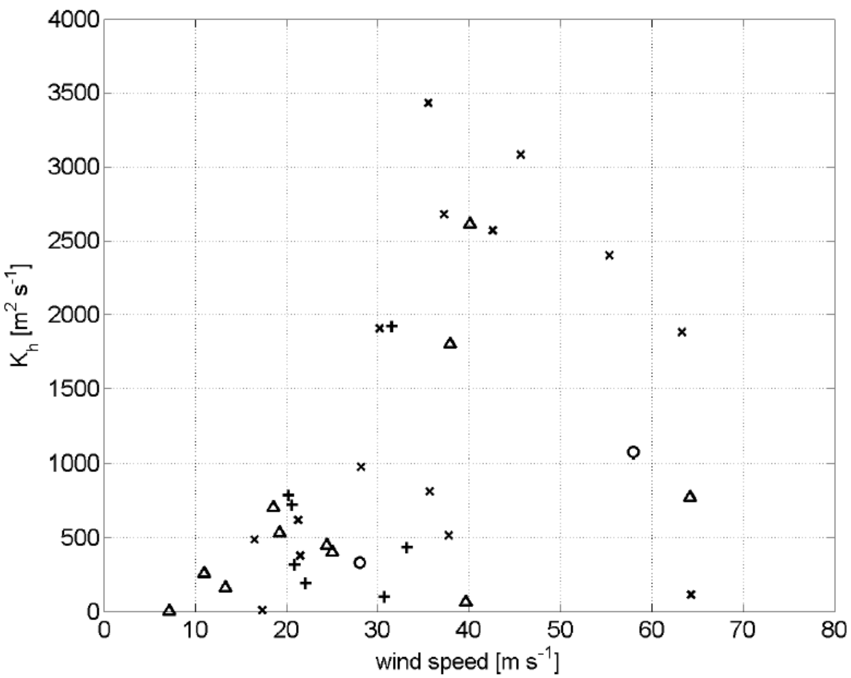
(here, showing only simulations with l_h=1000m and l_v=50m)



(azimuthally averaged)

Estimated eddy diffusivity (K) from flight-level observations

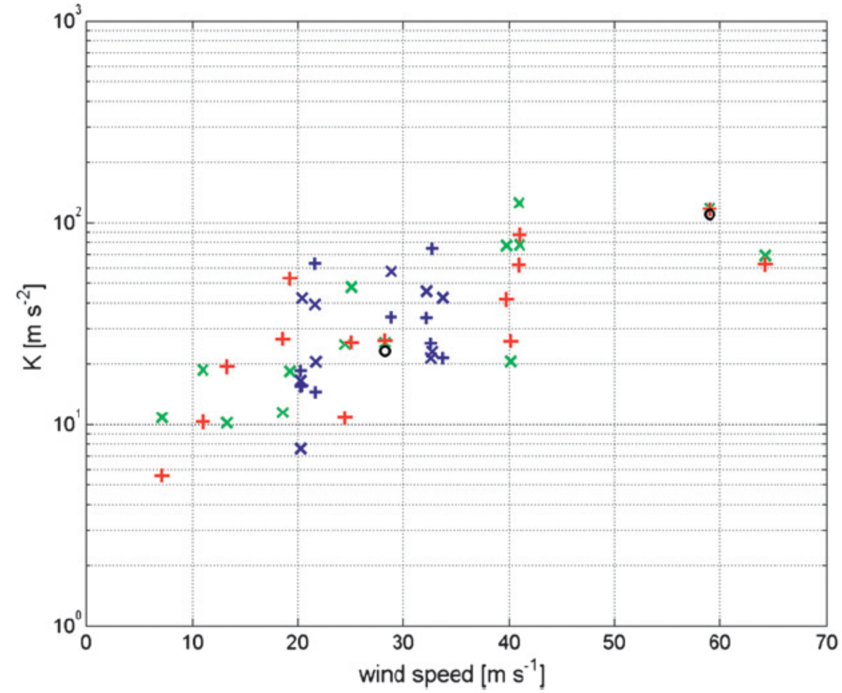
horizontal (K_h)



Zhang and Montgomery (submitted)

further analysis shows $l_h \approx 750$ m

vertical (K_v)

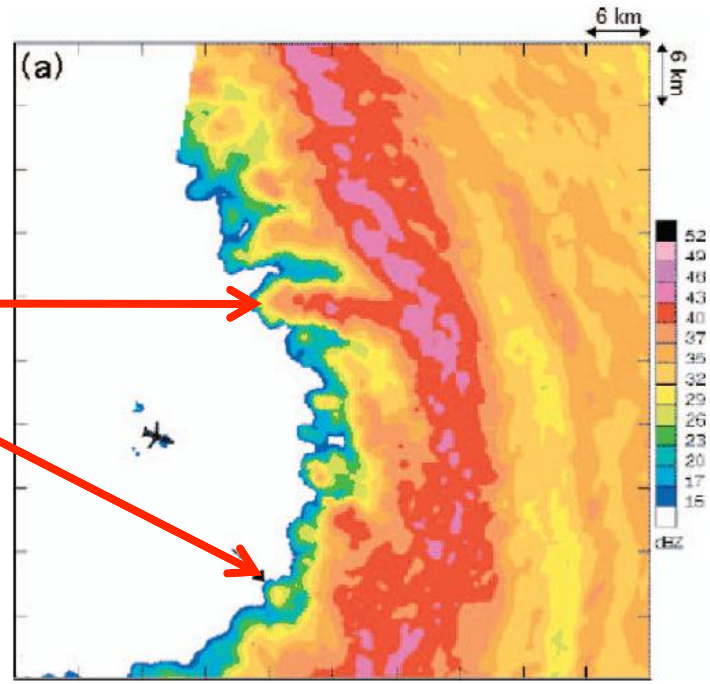


Zhang et al (2011)

further analysis shows $l_v \approx 100$ m

Quasi-2D turbulence probably caused be shearing instability
(or combined baroclinic/barotropic instability)

mesovortices at
eye/eyewall interface



Aberson et al. (2006)

Summary

- Horizontal turbulence processes are an important component of hurricane dynamics
  - in the boundary layer (z < 1 km)
  - primarily in the eyewall (near max winds)

- Best estimates for Category 4-5 storms:
  - $l_h \approx 1000$ m (although, axisymmetric models need larger l_h)
  - $l_v \approx 50$ m
  - $C_k/C_d \approx 0.5$