How to make simulated hurricanes look like observed hurricanes

George Bryan

National Center for Atmospheric Research

Seminar at NOAA/HRD

15 November 2011

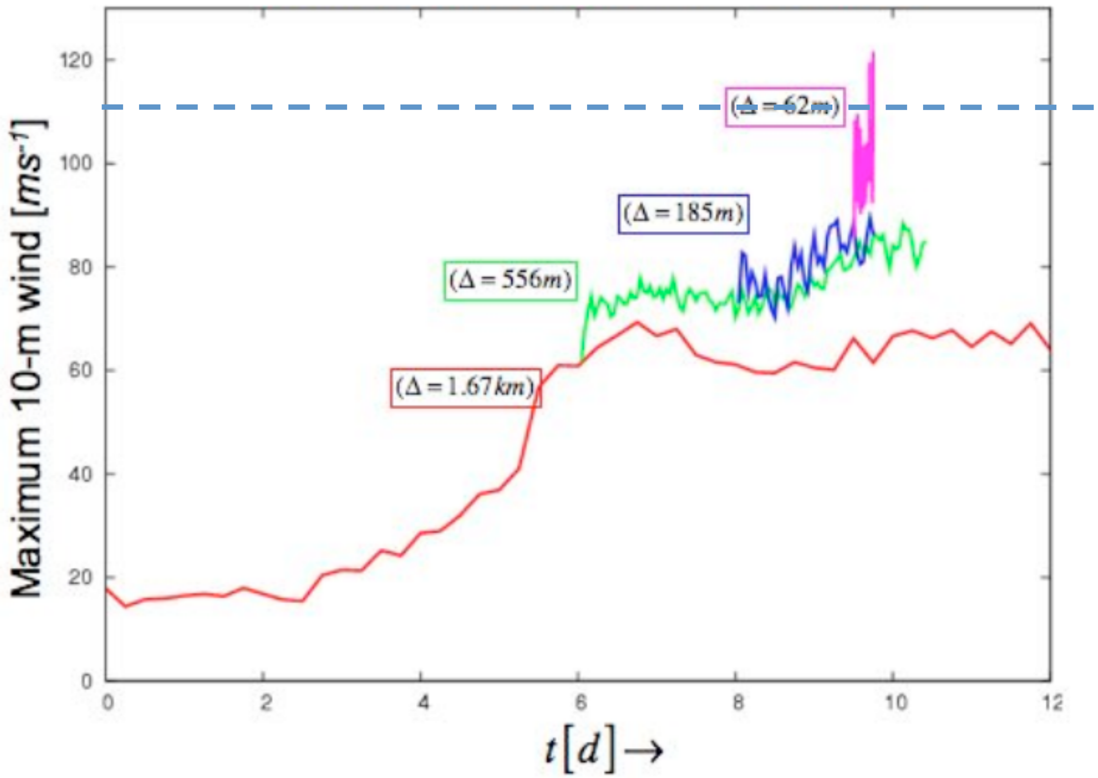
Acknowledgments:

NOPP/ONR (N00014-10-1-0148)

NCAR is sponsored by the National Science Foundation

Numerical Simulations of a Hurricane

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

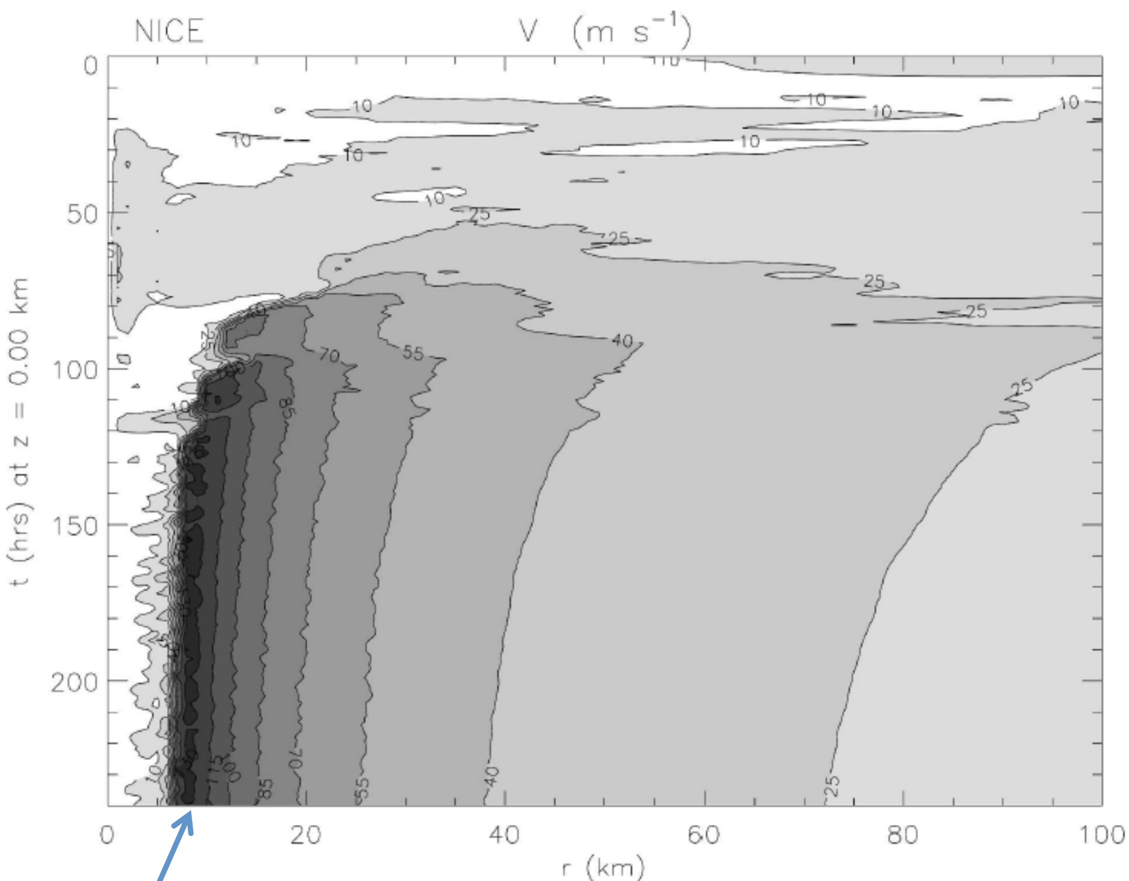


Official (WMO) peak wind: 113 m s^{-1}, Olivia (1996)

Rotunno et al (2009)

Numerical Simulations of a Hurricane

(axisymmetric model, SST = 28 °C, $C_k/C_d = 1$)



V > 130 m s^{-1}

Hausman et al (2006)

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 terms 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)

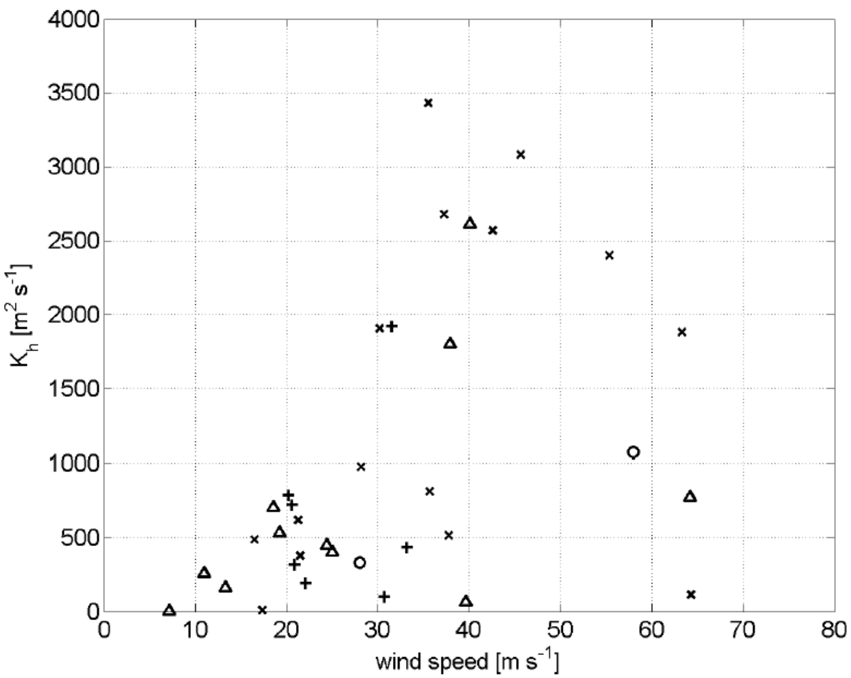
l_v is a vertical length scale (unknown; specified here)

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

- Typical settings:
  - l_h: 3000 m (Rotunno and Emanuel 1987) to 0 (Hausman et al 2006)
  - l_v: 200 m (Rotunno and Emanuel 1987) to 40 m (MM5 "bulk PBL" scheme)

Estimated eddy diffusivity (K) from flight-level observations (roughly 500 m MSL)

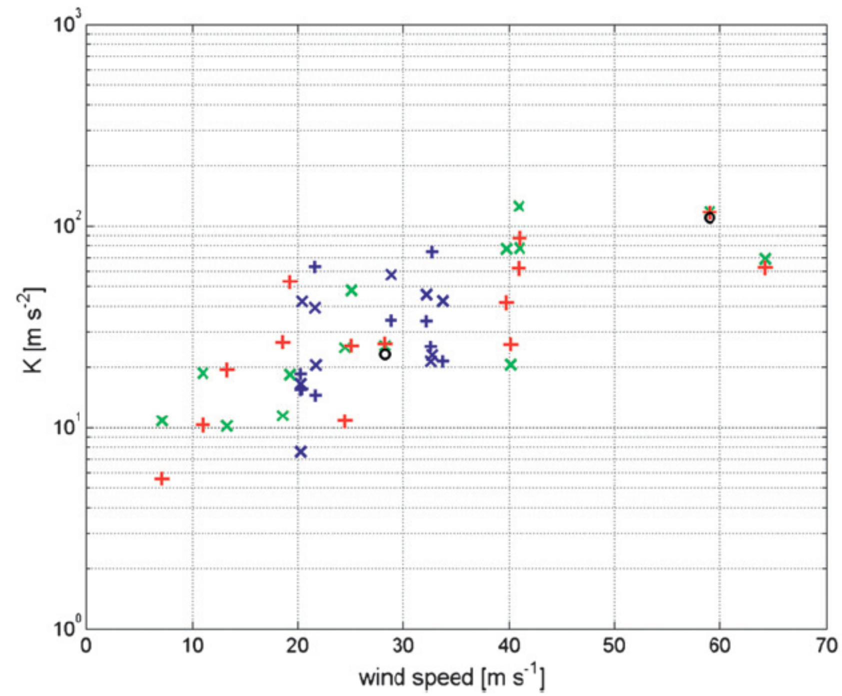
horizontal (K_h)



Zhang and Montgomery (submitted)

further analysis shows $l_h \approx 700$ m

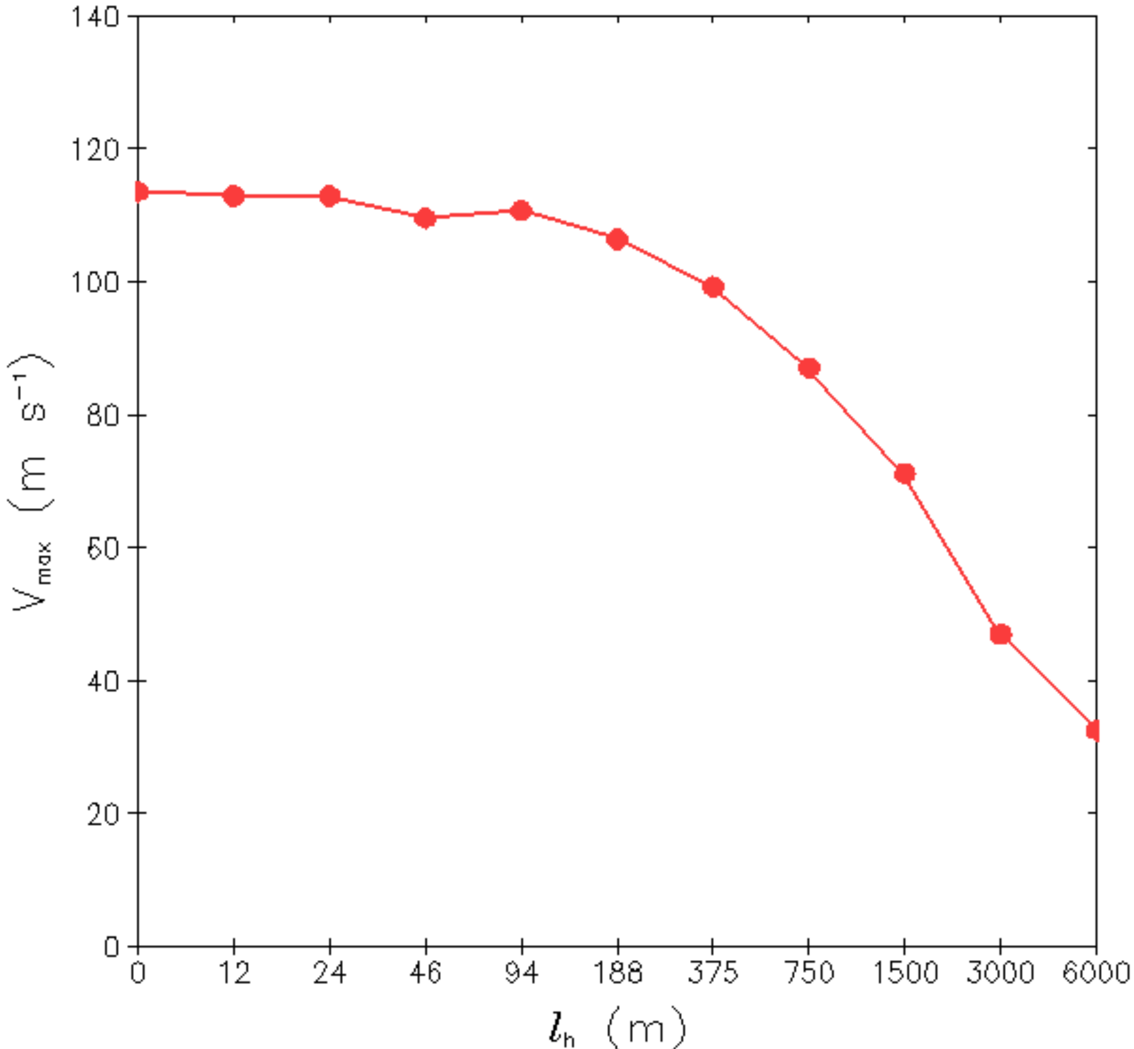
vertical (K_v)



Zhang et al (2011)

further analysis shows $l_v \approx 100$ m sensitivity of V_{max} to horizontal turbulence:

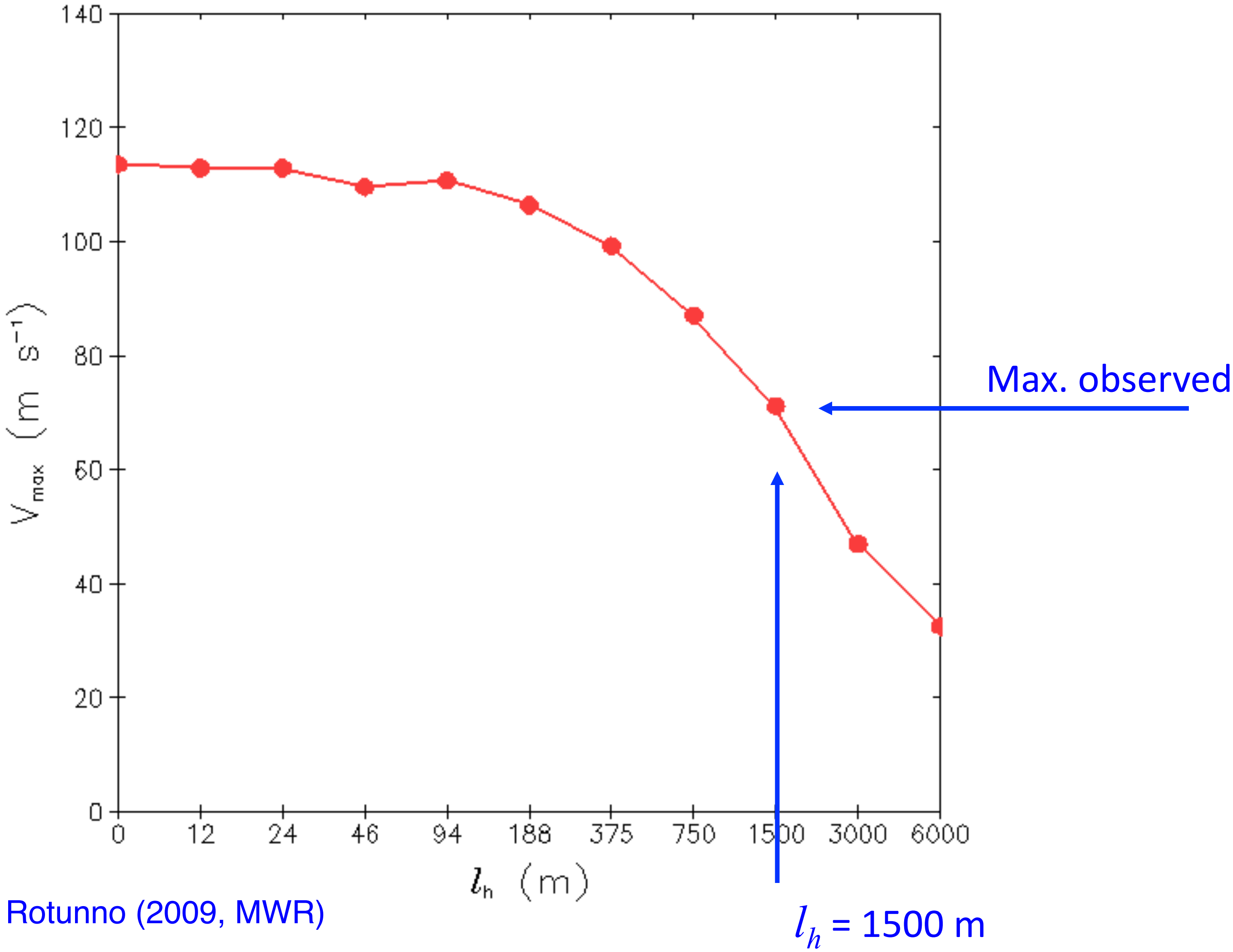
axisymmetric model simulations (CM1, SST = 26 °C, C_k/C_d = 1, l_v = 200 m)



Bryan and Rotunno (2009, MWR)

sensitivity of V_{max} to horizontal turbulence:

axisymmetric model simulations (CM1, SST = 26 °C, $C_k/C_d = 1$, l_v = 200 m)

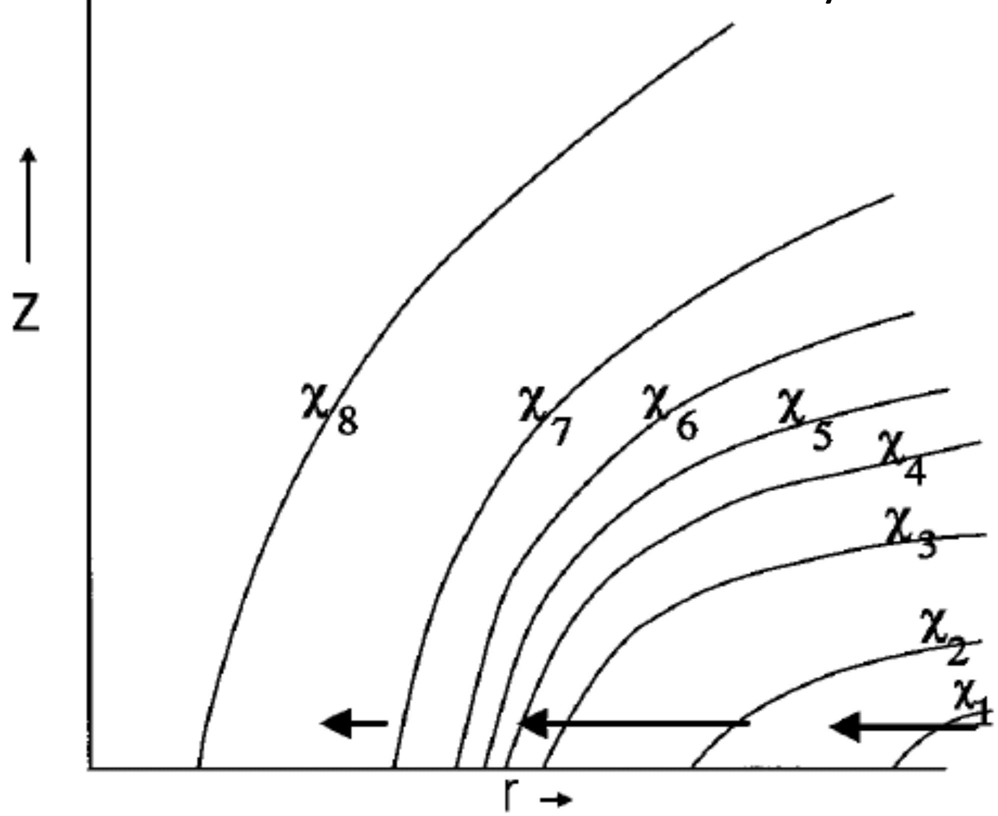


Bryan and Rotunno (2009, MWR)

Frontogenesis in hurricane eyewalls:

χ = entropy (θ_e), or M

Arrows: radial velocity

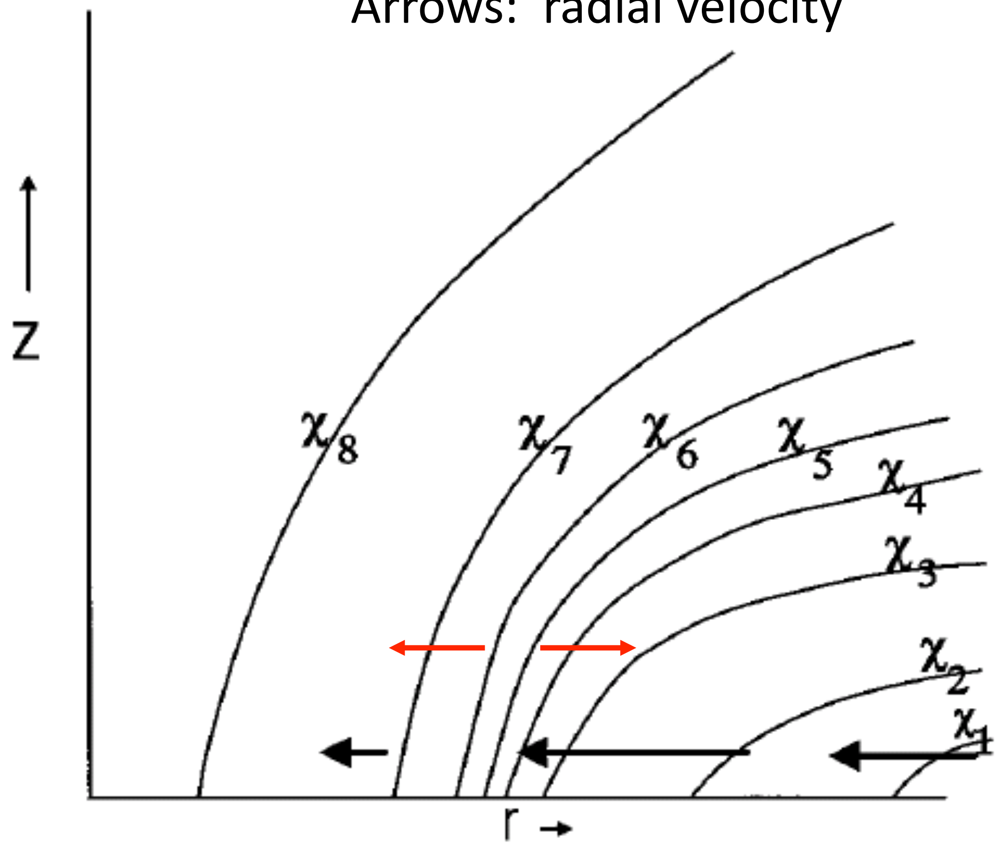


Emanuel (1997)

Frontogenesis in hurricane eyewalls:

χ = entropy (θ_e), or M

Arrows: radial velocity



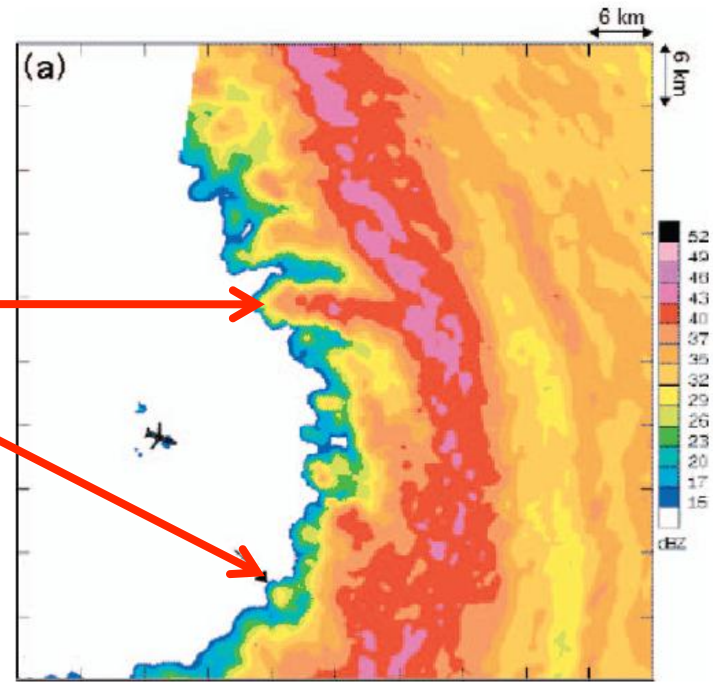
Emanuel (1997)

diffusion is frontolytic! (limits frontal collapse)

Mesoscale turbulence in hurricane eyewalls:

reflectivity, z ≈ 2.5 km MSL

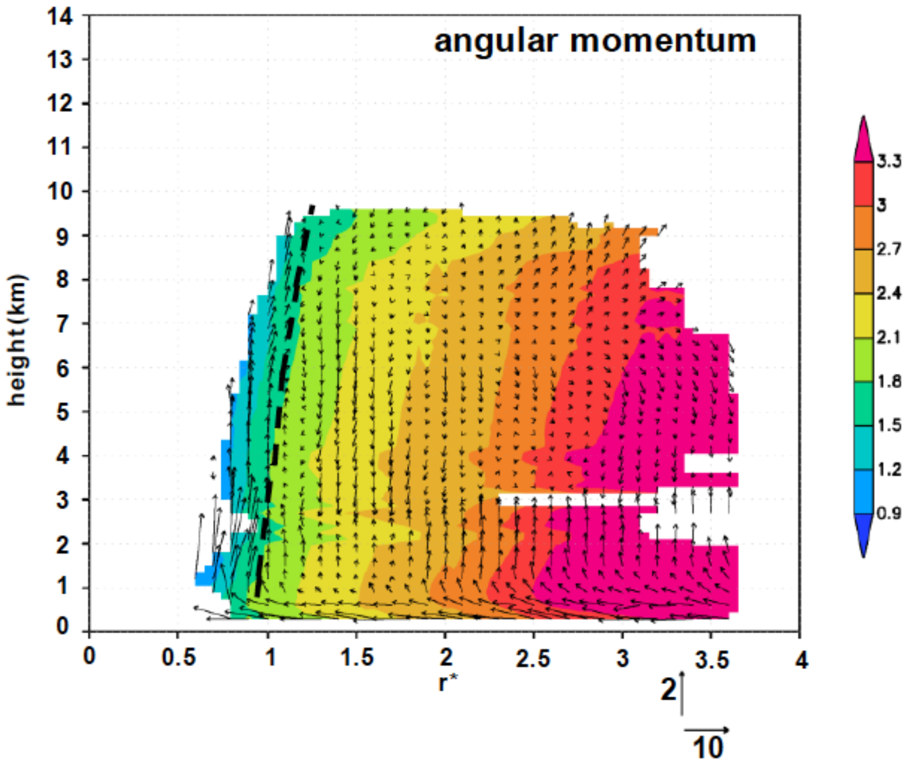
mesovortices at eye/eyewall interface

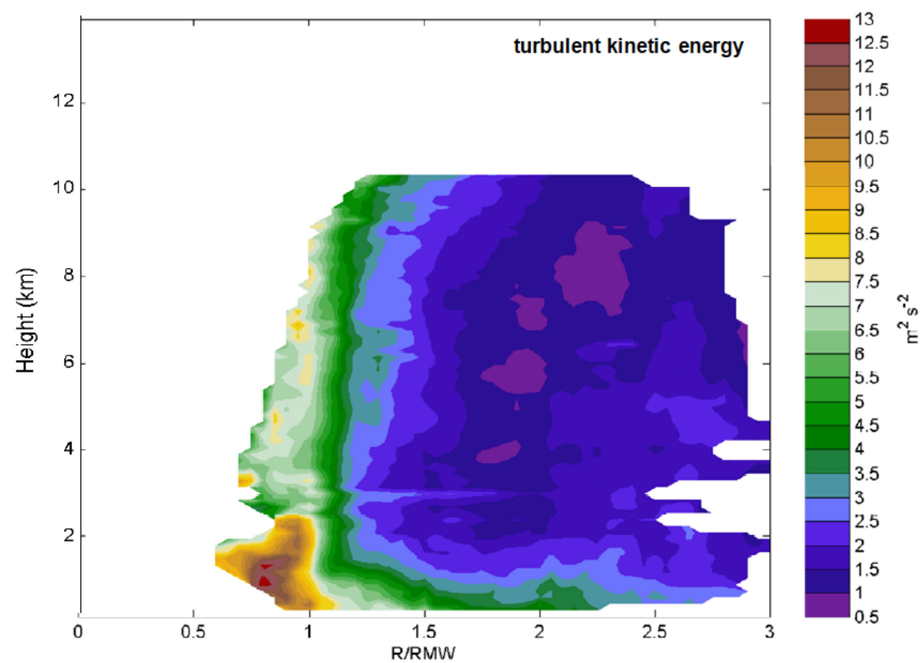


Aberson et al. (2006)

Experience with 3d models: Δx must be O(100 m) to produce these features

Composite analyses from airborne Doppler radar





Rogers et al (2011)

Uncertainties in surface exchange coefficients

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

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

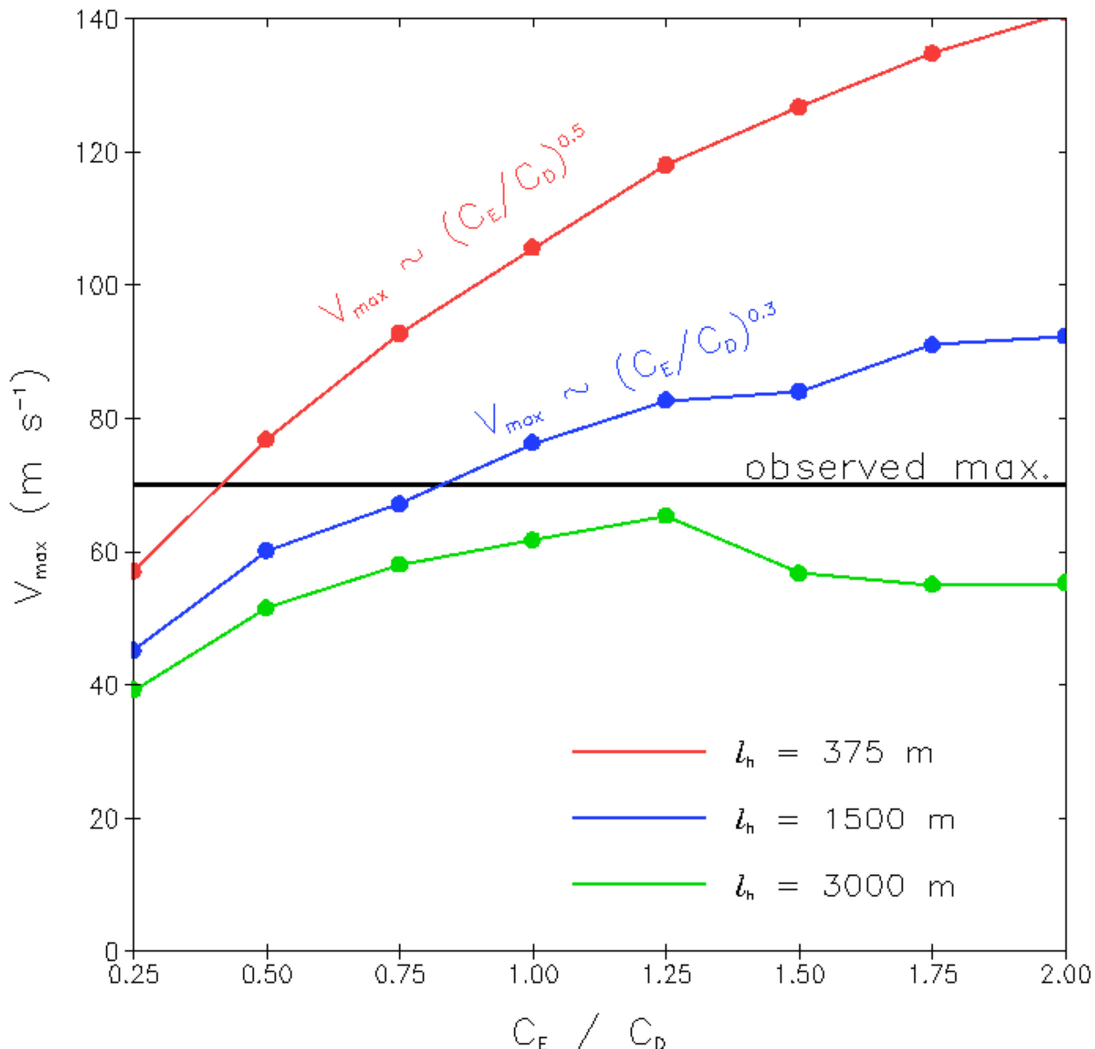
Theoretical models (see review by Emanuel 2004):

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

Typical numerical model settings: $C_k/C_d \approx 0.5$ to 1

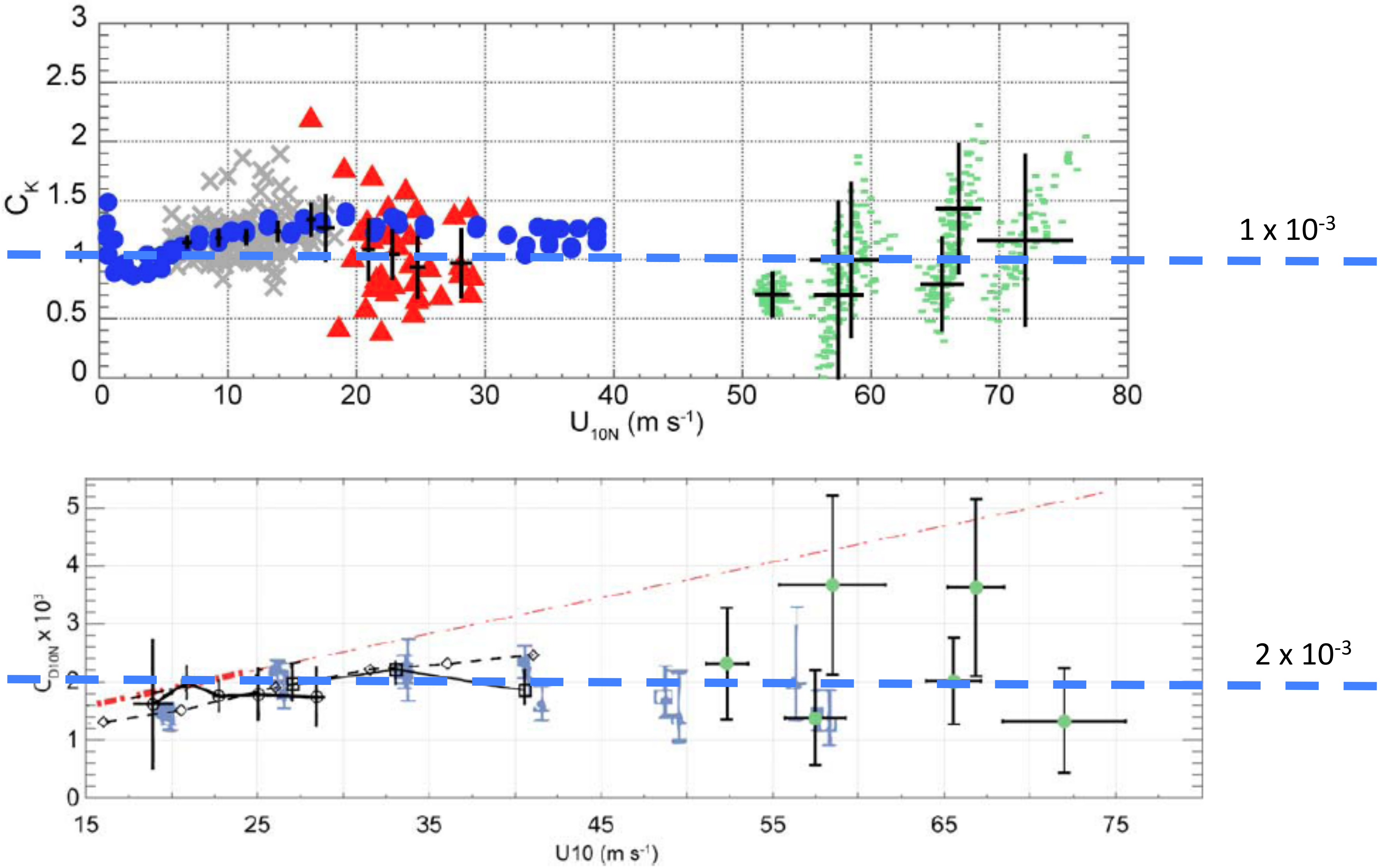
sensitivity of V_{max} to surface exchange coefficients:

axisymmetric model simulations (CM1, SST = 26 °C, l_v = 200 m)



Bryan and Rotunno (2009, MWR)

Observed/diagnosed exchange coefficients



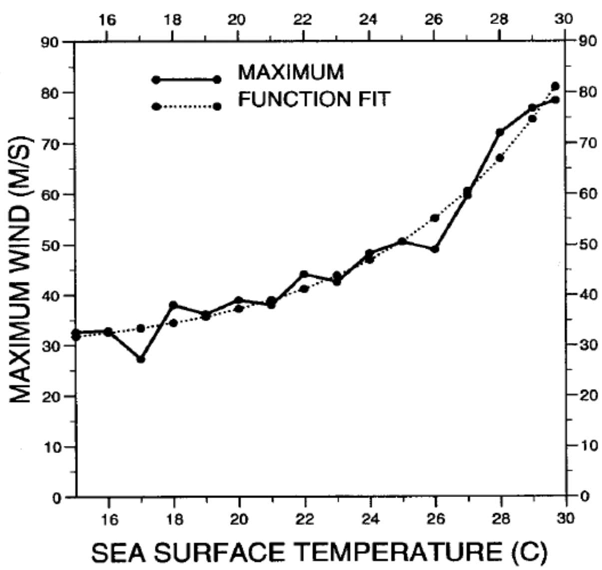
Bell (2010)

- Goal of this study: Determine which combination of parameters l_h, l_v, C_k, and C_d yield reasonable TC intensity *and* structure

- Methodology: Use relatively simple and well-observed metrics of intensity and structure …

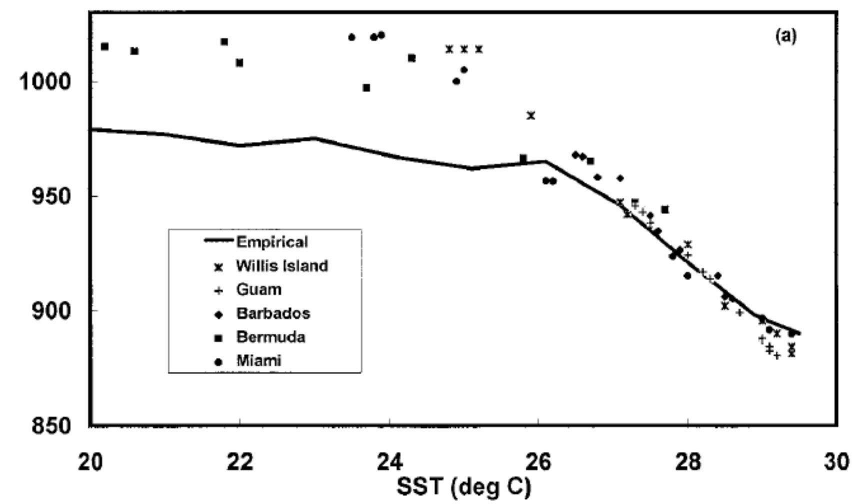
Intensity:

Max winds:



DeMaria and Kaplan (1994)

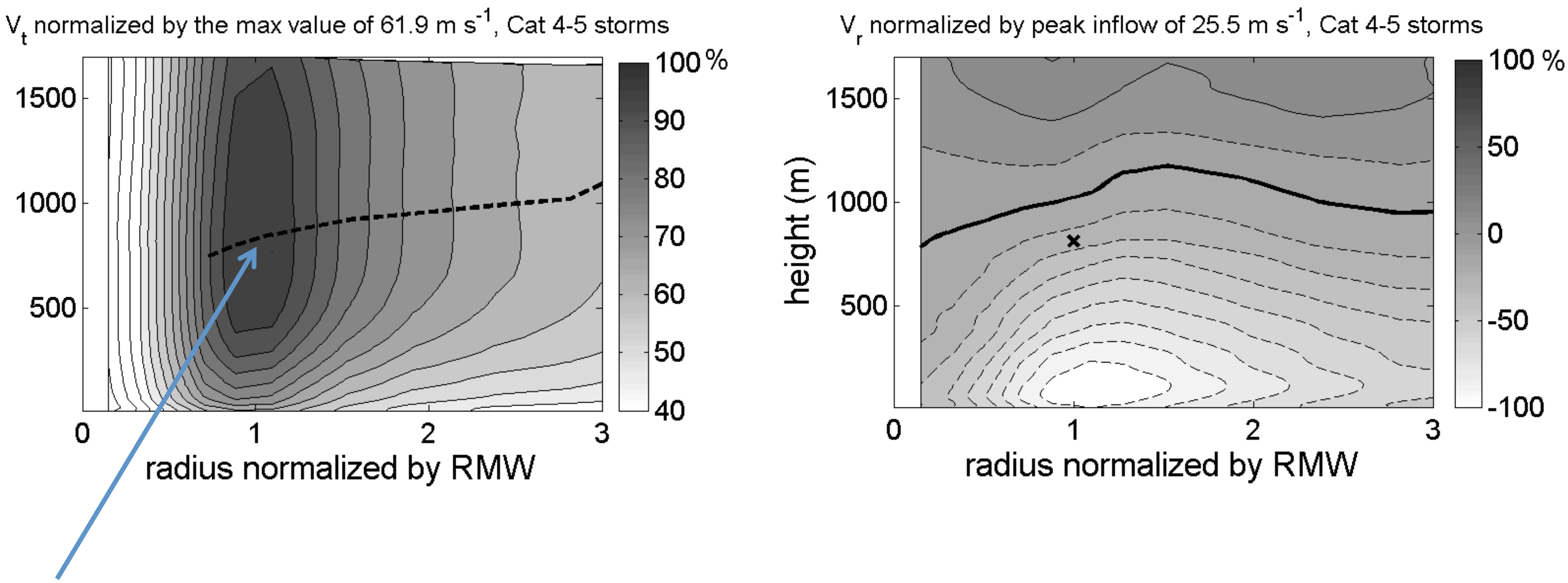
Min surface pressure:



Holland (1997)

Note: for above-surface V_{max}, 10-m sustained winds have been multiplied by 1.35

Structure:



Note: V_{max} located at 800-900 m MSL

Zhang et al (2011)

Other Metrics:

- Surface inflow angle: ≈ 23° (Powell et al 2009)

- Wind-pressure relationships: empirical equations from Knaff and Zehr (2007)

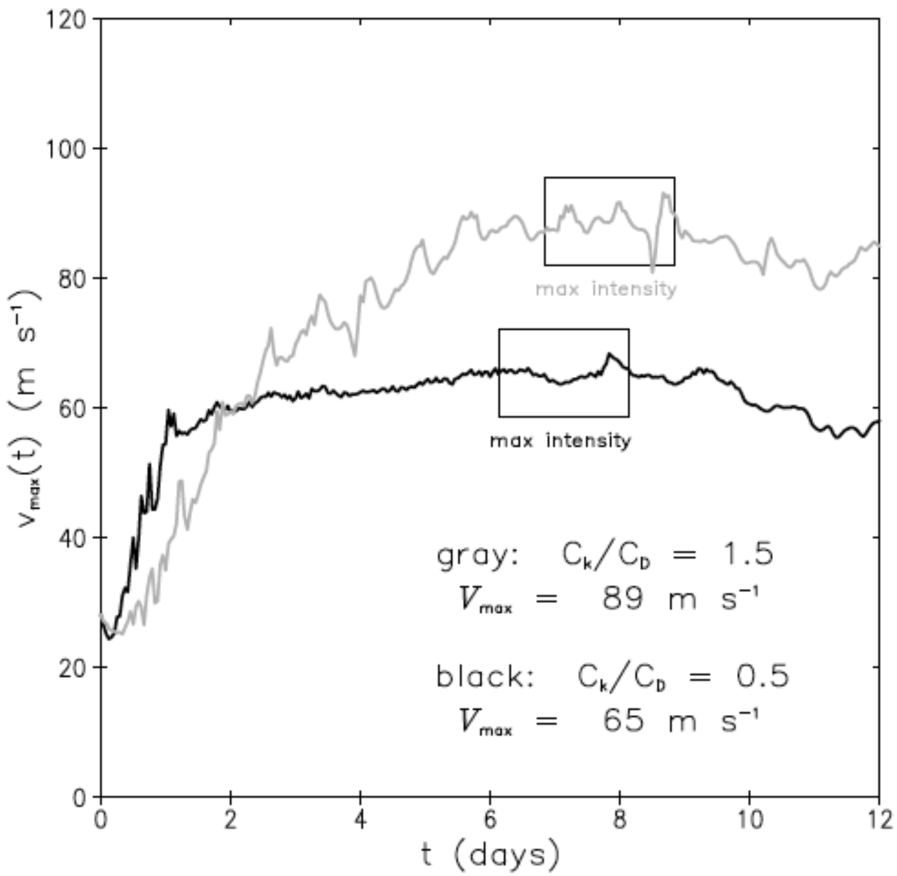
Model Setup

- CM1: Axisymmetric model with Δr = 1 km (some 3d results also)
- Δz varies (20 m to 250 m); 17 levels below 1 km (123 total levels)
  - First level for u,v is 10 m ASL
- 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

    T_s = 29 °C is chosen so initial air-sea temperature difference is 2.2 °C (Cione et al 2000)
- Two microphysical schemes:
  - Rotunno and Emanuel (1987) liquid-only scheme
  - Morrison et al (2009) double-moment mixed-phase scheme
- Nominal setup: C_k = constant = 1.2x10^{-3}, C_d = constant
- Following results presented in terms of C_k/C_d

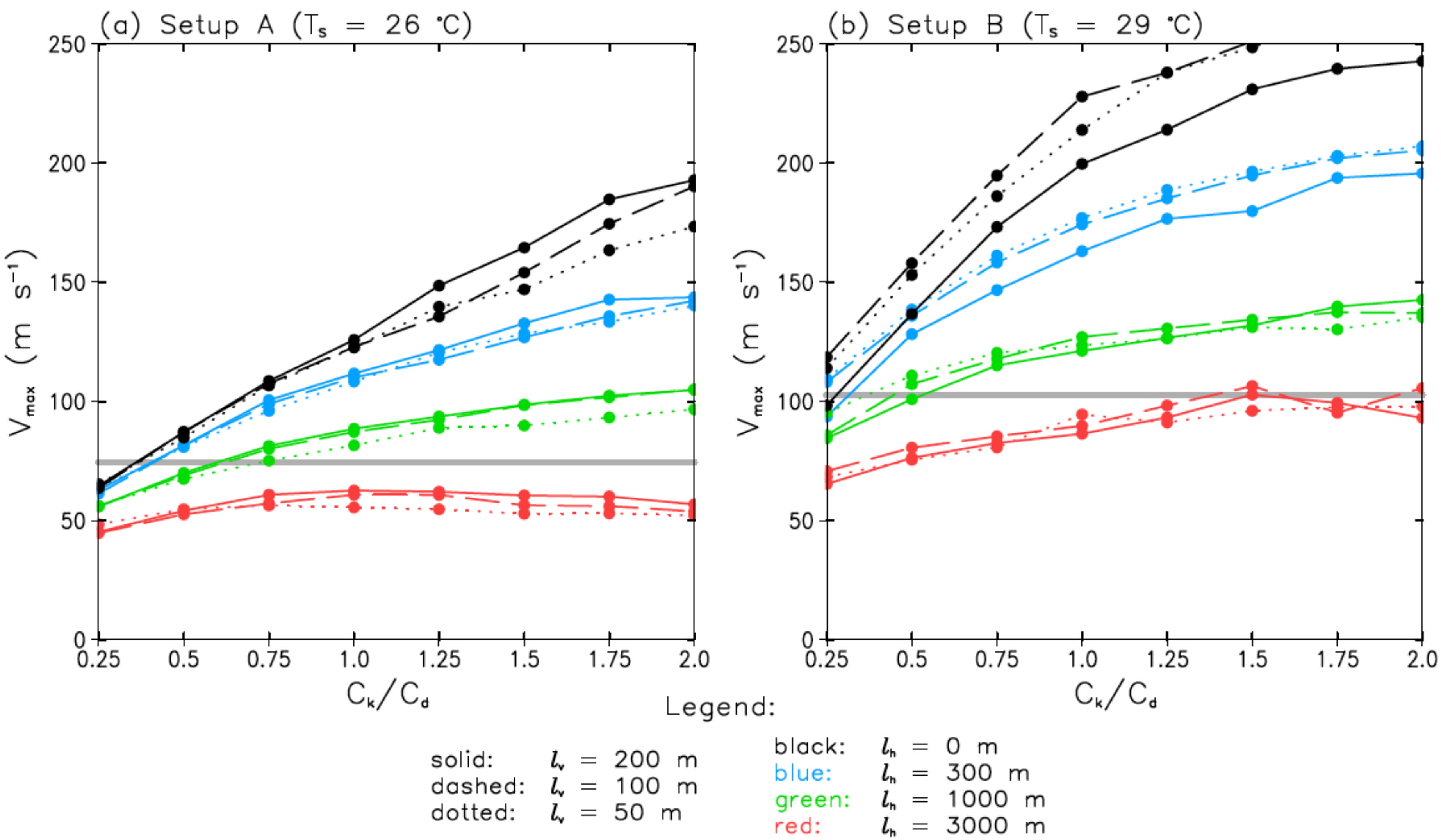
  (recall that obs/lab results are finding $C_k/C_d \approx 0.5$)
- See Bryan (2011, MWR, in press) for more details

Time of maximum intensity



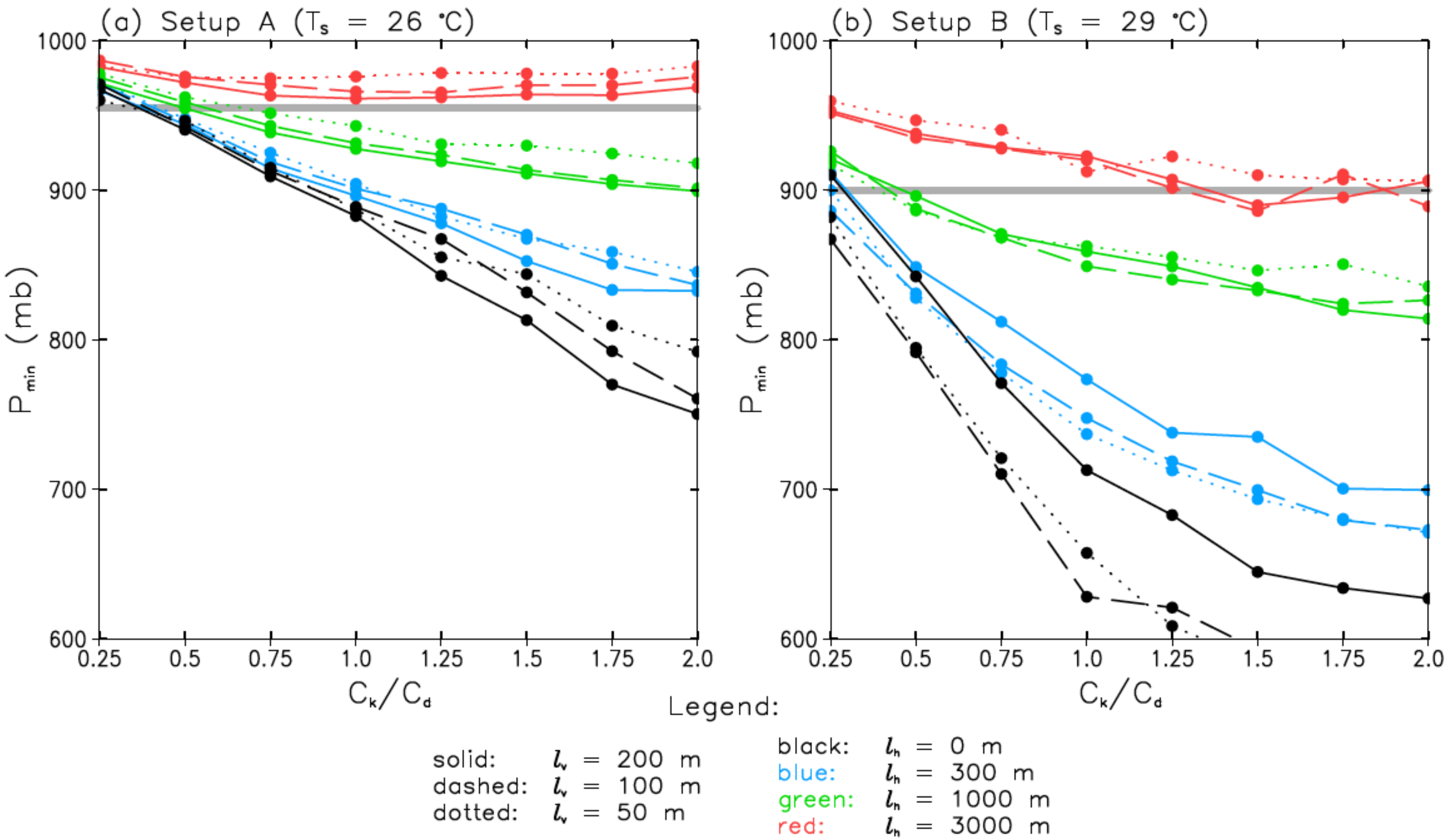
Maximum tangential windspeed (note: *above surface*)

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

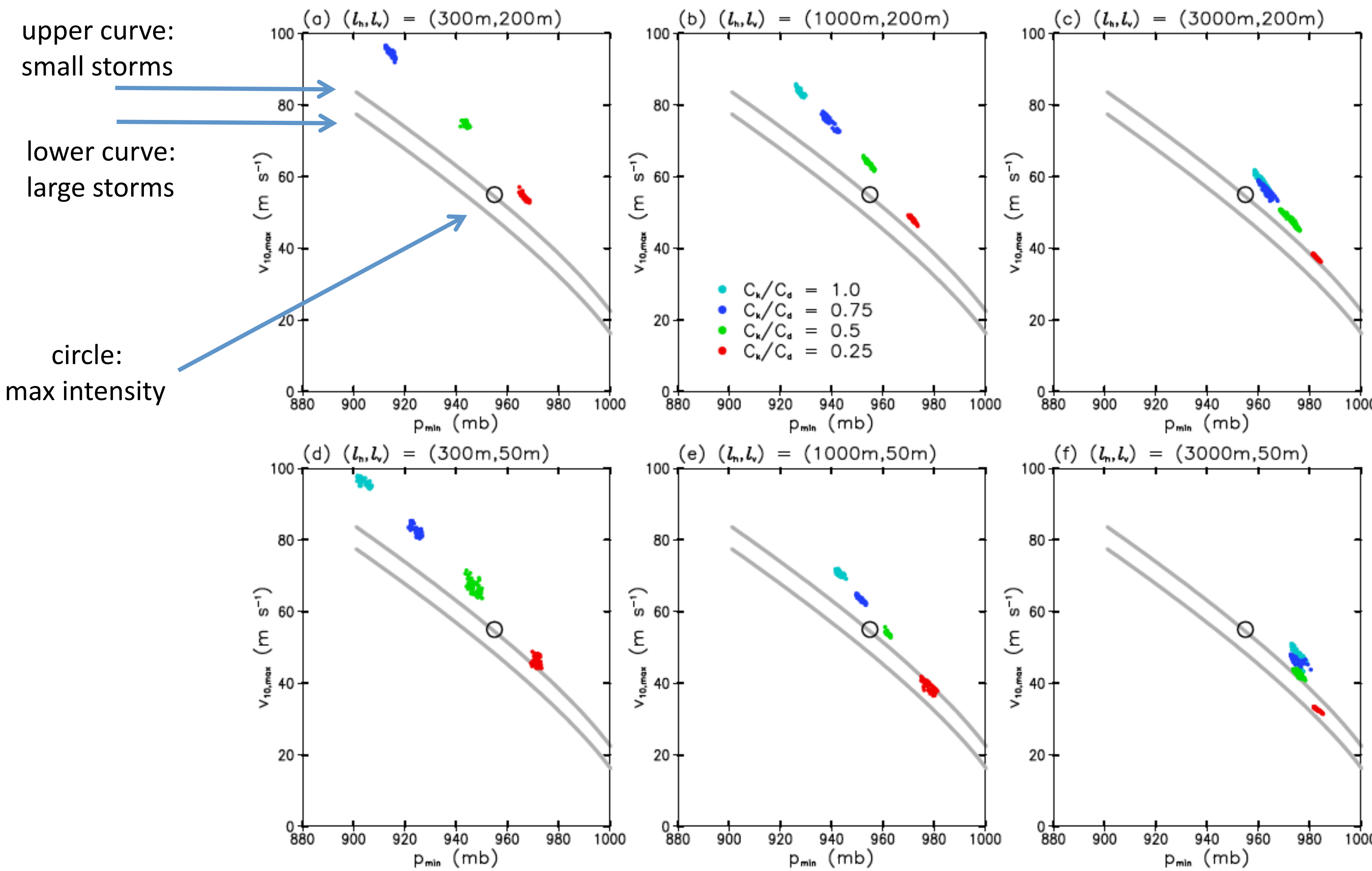


Minimum Surface Pressure

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



Wind-pressure relationship: Setup A (T_s = 26 °C)

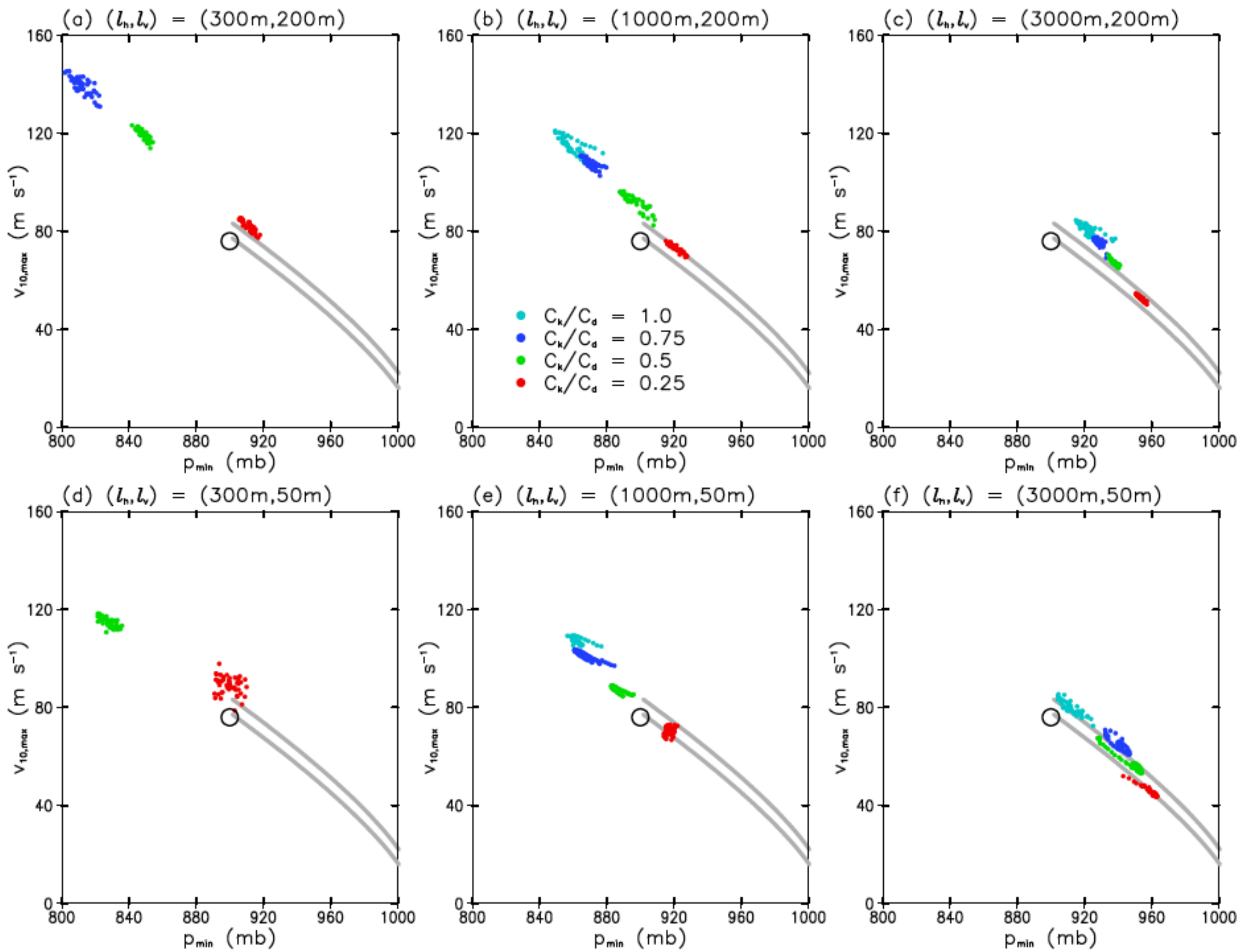


Wind-pressure relationship: Setup B (T_s = 29 °C)

upper curve:
small storms

lower curve:
large storms

circle:
max intensity



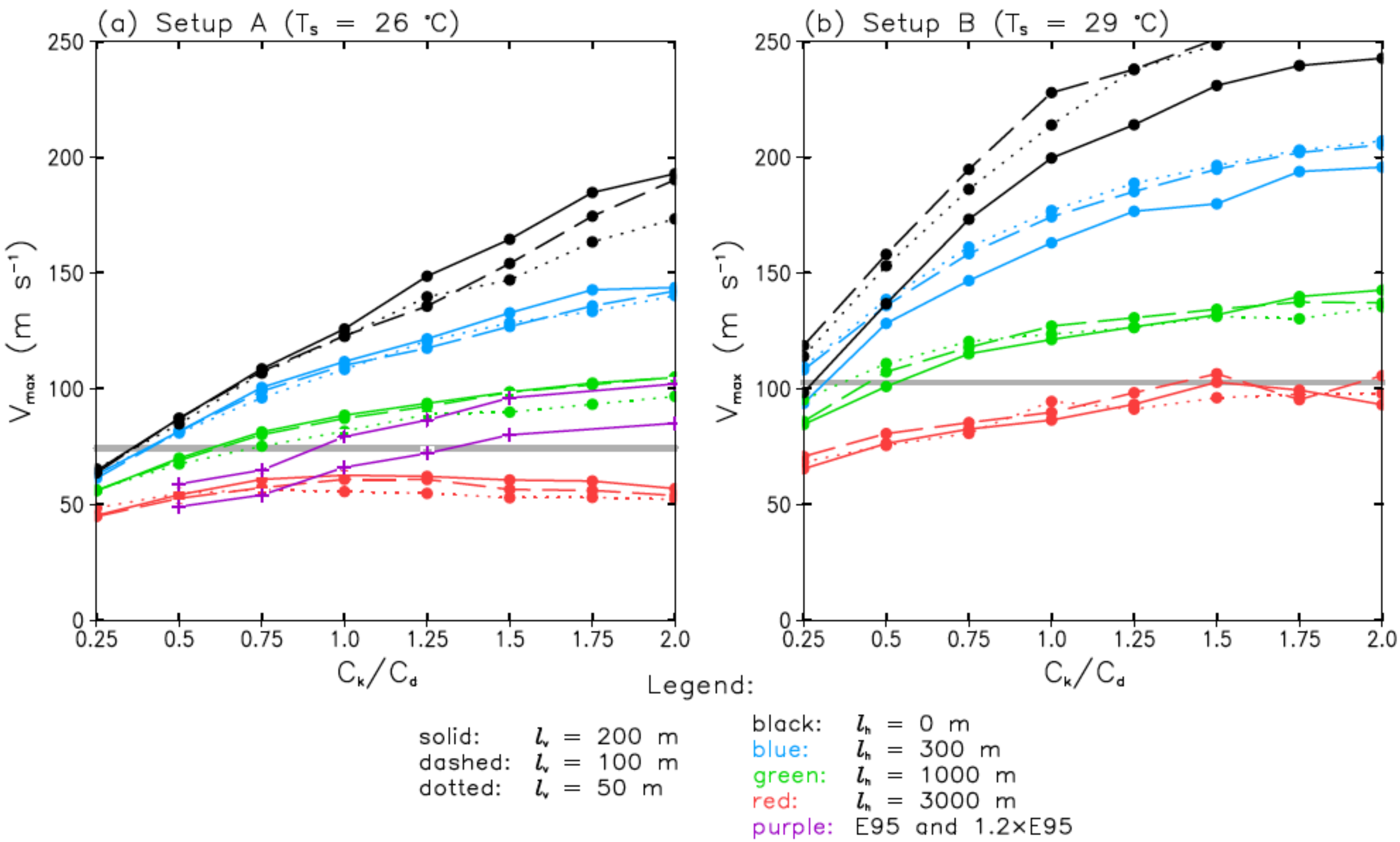
A similar study by Emanuel (1995)

- Concluded that C_k/C_d is most likely 1.2-1.5 in intense storms

- "In no event are the results from either [numerical] model consistent with values of C_k/C_d less than about three-fourths; otherwise, the wind speeds would be much weaker than observed."

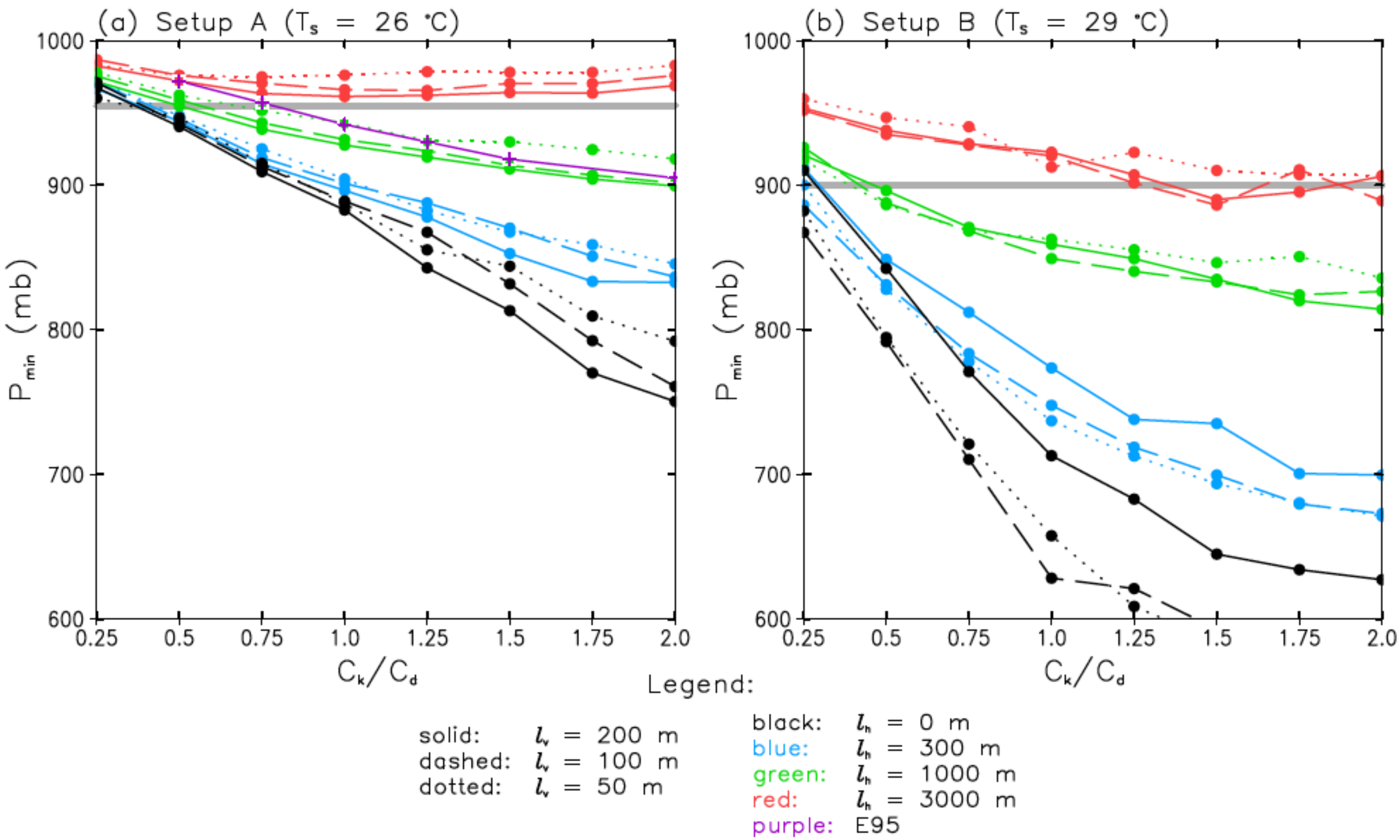
Maximum tangential windspeed (note: *above surface*)

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



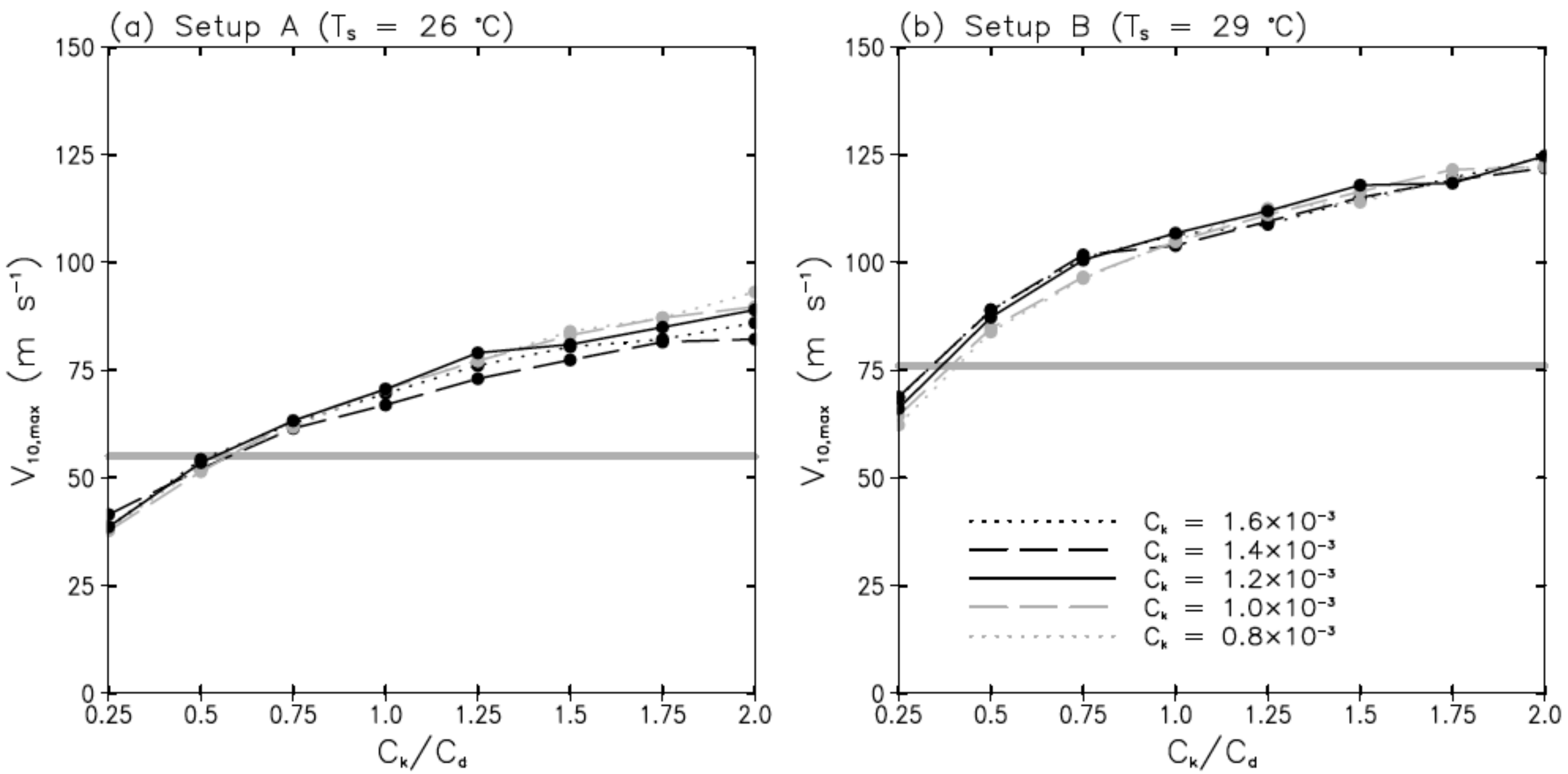
Minimum Surface Pressure

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



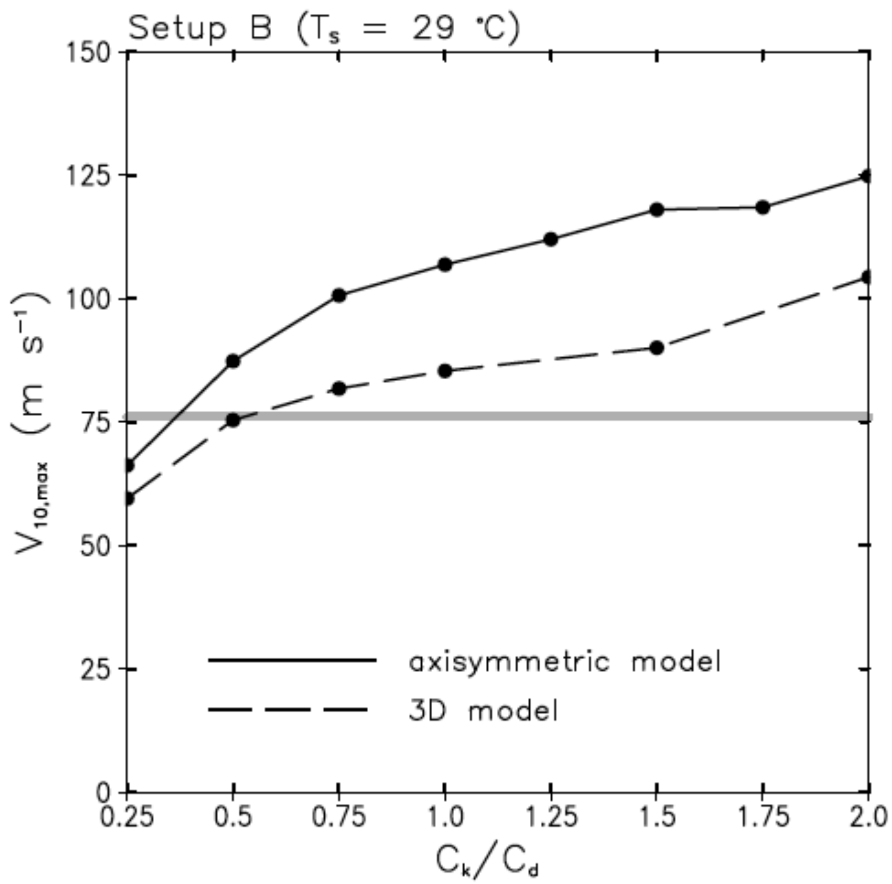
Results using different C_k

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



Comparison of axisymmetric model and 3D model

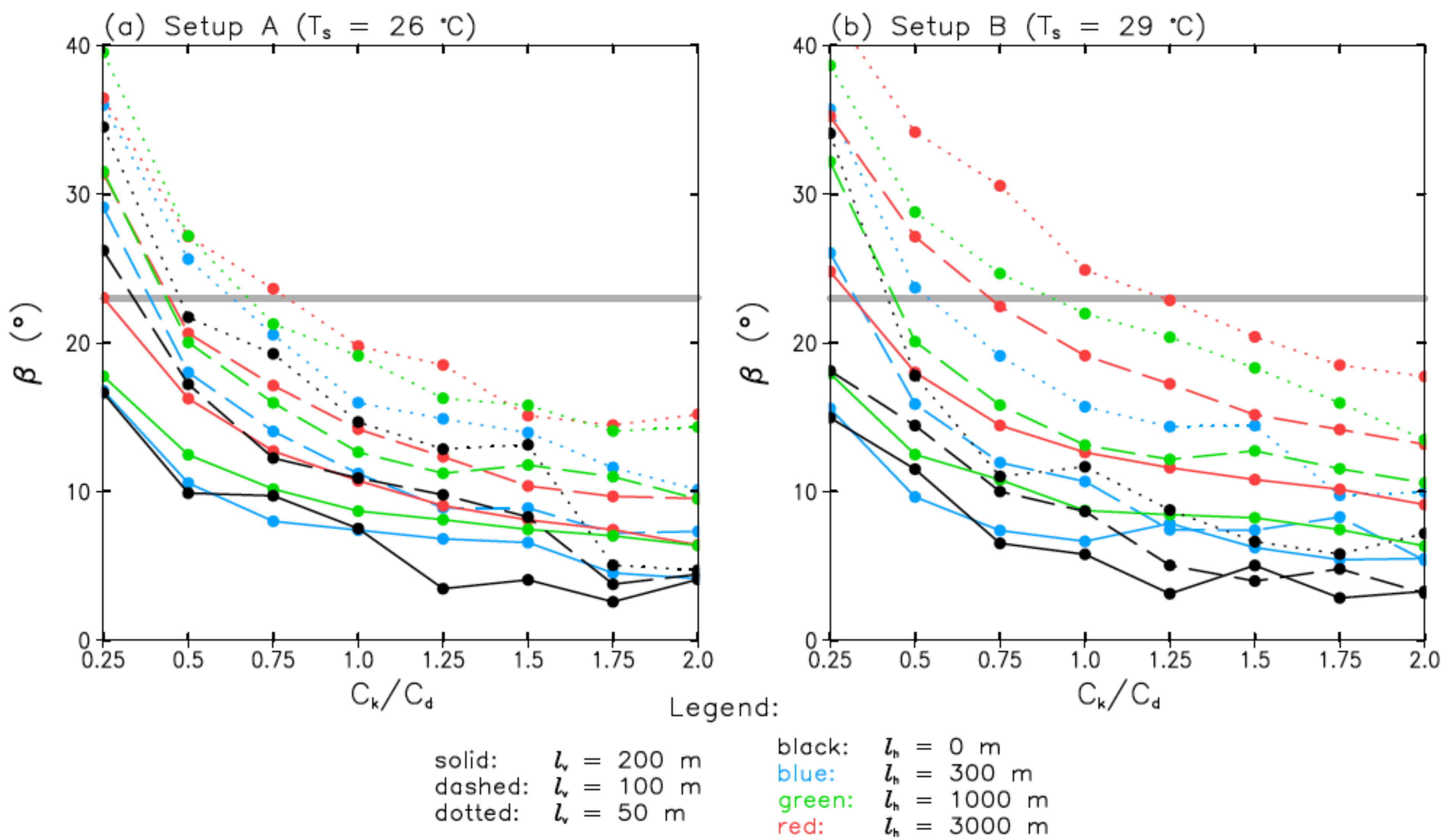
(here, showing only simulations with l_h = 1000m and l_v = 50m)



(azimuthally averaged)

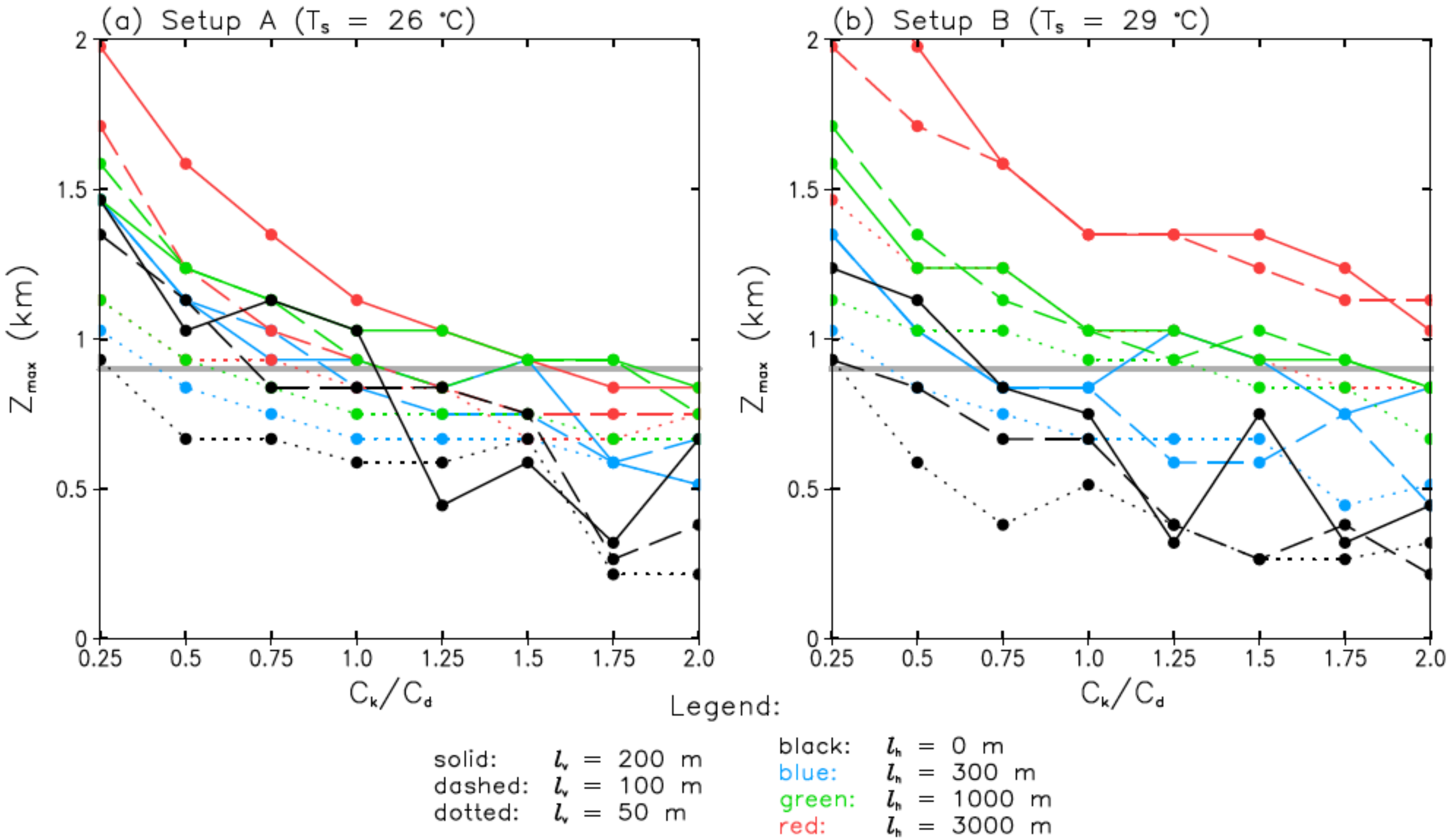
Surface (10-m) inflow angle

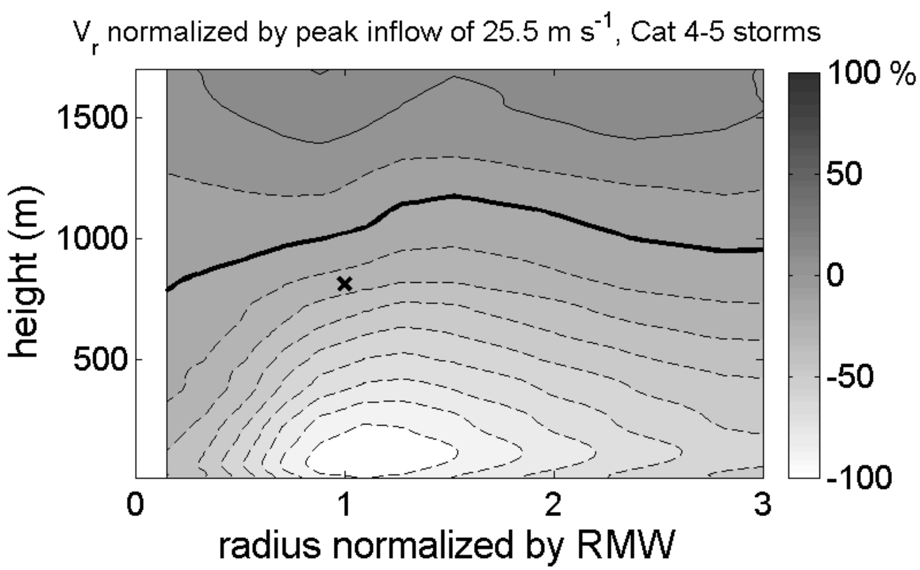
---> Horizontal gray line: average value from dropsonde observations (Powell et al 2009)



Height of V_{max}

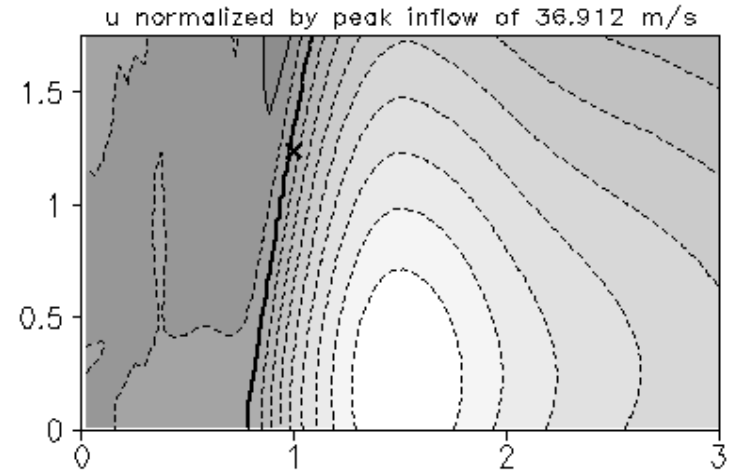
---> Horizontal gray line: value from composite analysis of dropsonde data (Zhang et al 2011)



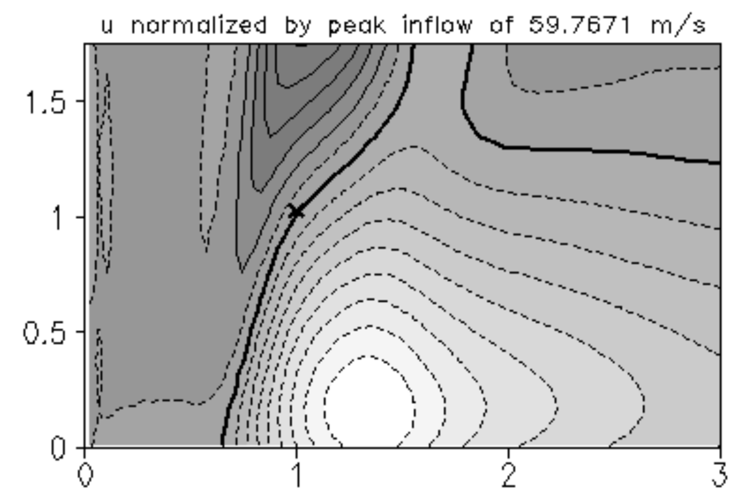


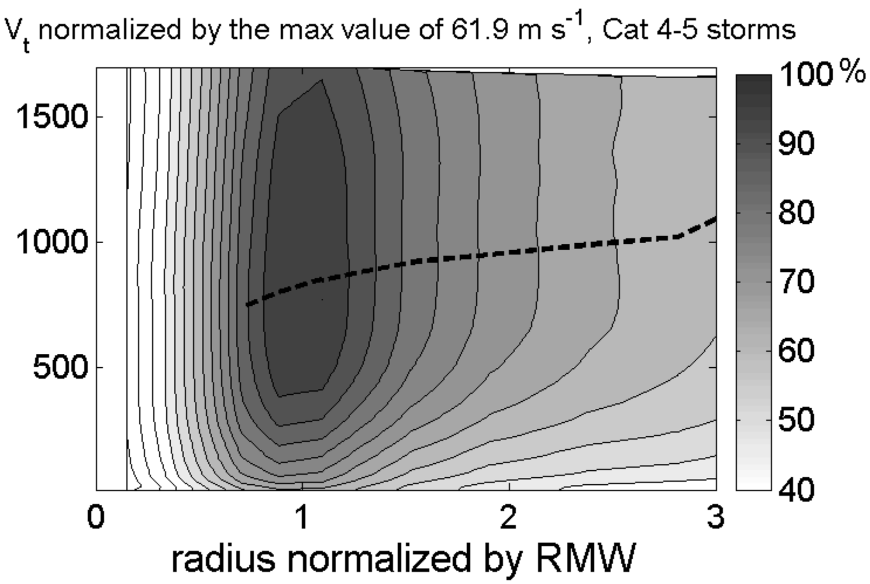
Zhang et al (2011)

l_h = 1000 m, l_v = 200 m



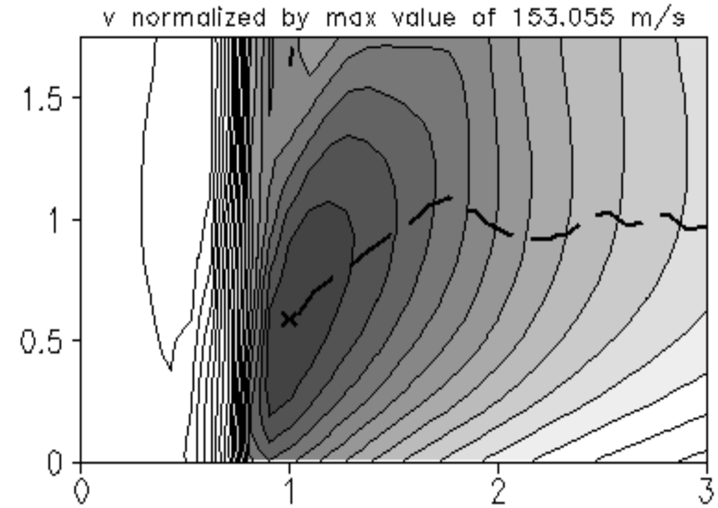
l_h = 1000 m, l_v = 50 m



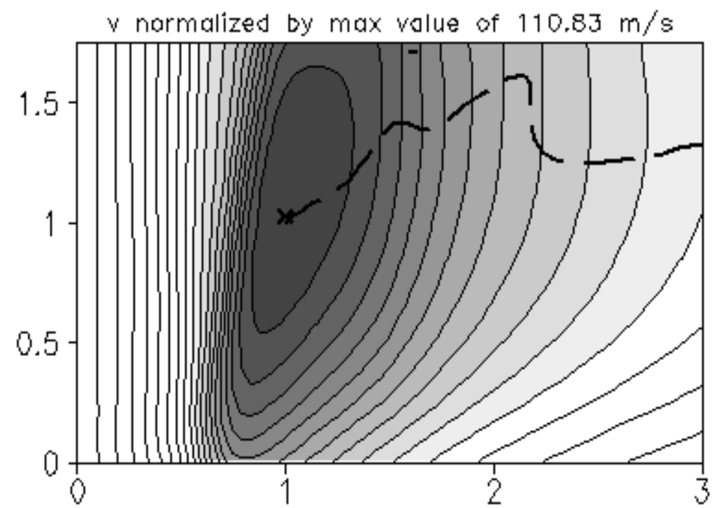


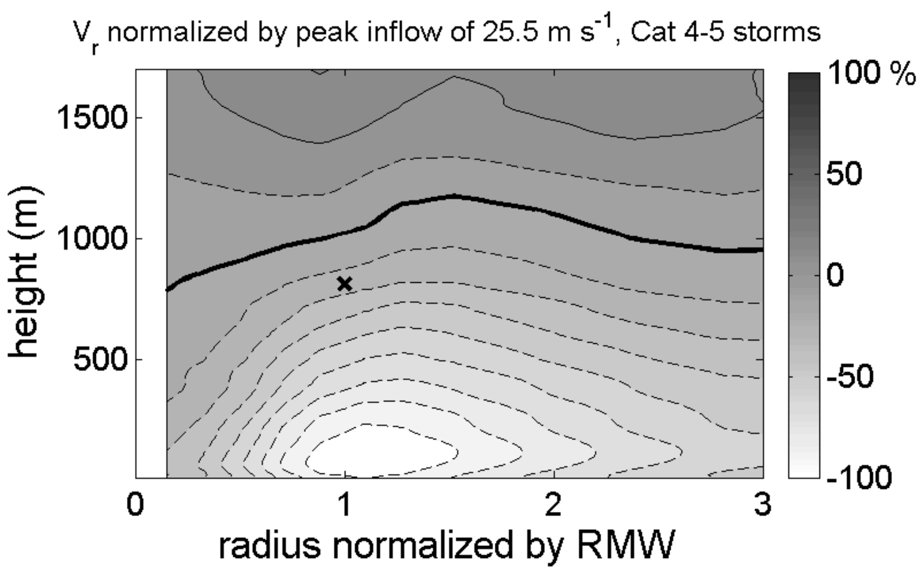
Zhang et al (2011)

$l_h = 0,\ l_v = 50$ m



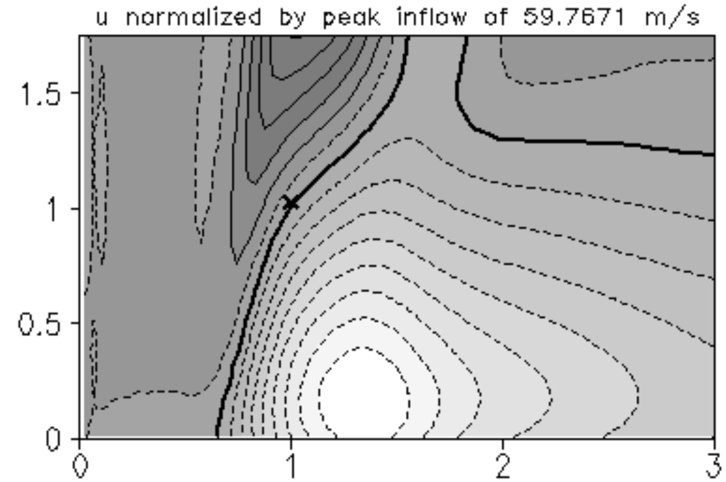
$l_h = 1000$ m, $l_v = 50$ m



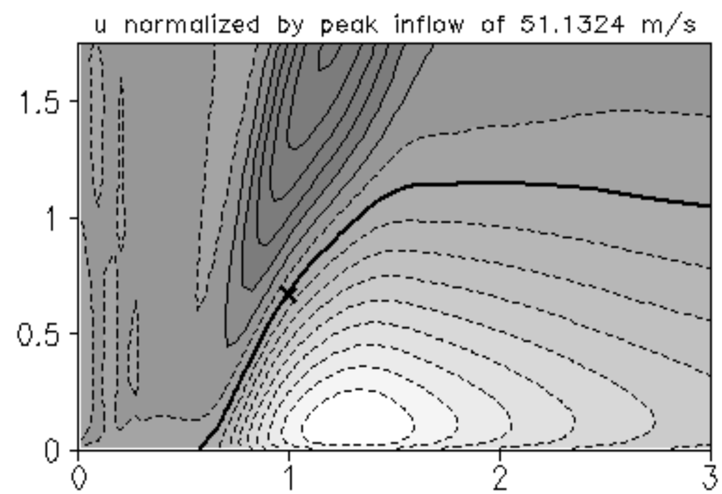


Zhang et al (2011)

l_h = 1000 m, l_v = const. = 50 m



l_h = 1000 m, l_v variable; l_∞ = 50 m



- Summary: Settings for Category 4-5 storms:
  - $l_h \approx 1000$ m (although, axisymmetric models need larger l_h)
  - $l_v \approx 50$ m (variable $l_v(z)$ produces better structure than constant l_v)
  - $C_k/C_d \approx 0.5$

- Other aspects of simulations not show:
  - Air-sea temperature difference varies with V_{max} (settings above give 2.5-3.5 °C)
  - Storm size: RMW varies with l_h
    Radius of gale-force winds varies with C_k/C_d
  - Dynamics/theory: gradient-wind imbalance (overshoot) increases as C_k/C_d decreases (E86 theory works ok as long as $C_k/C_d > 1.5$)