The importance of small-scale turbulence on maximum hurricane intensity

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Presentation at Hurricane Science Workshop

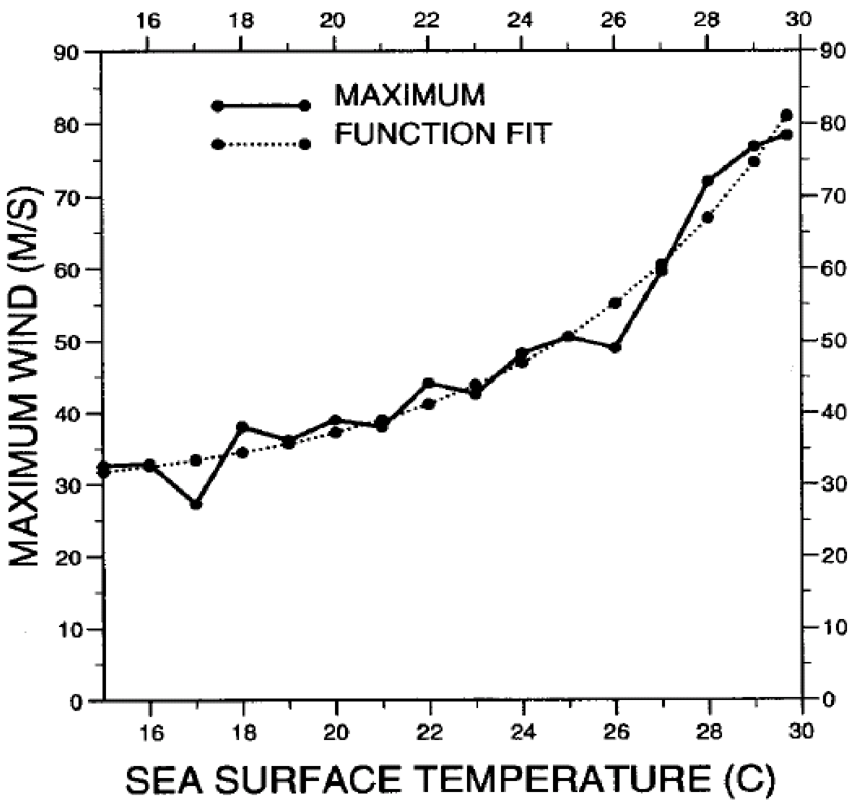
Boulder, Colorado

22 February 2010

Why study maximum intensity?

- Good observations:
  - especially in Atlantic (airplane reconnaissance)
- Theoretical limits:
  - provides a framework for understanding
- A simple test of numerical modeling systems:
  - (without the complications of real-data cases)

Method #1: Observational



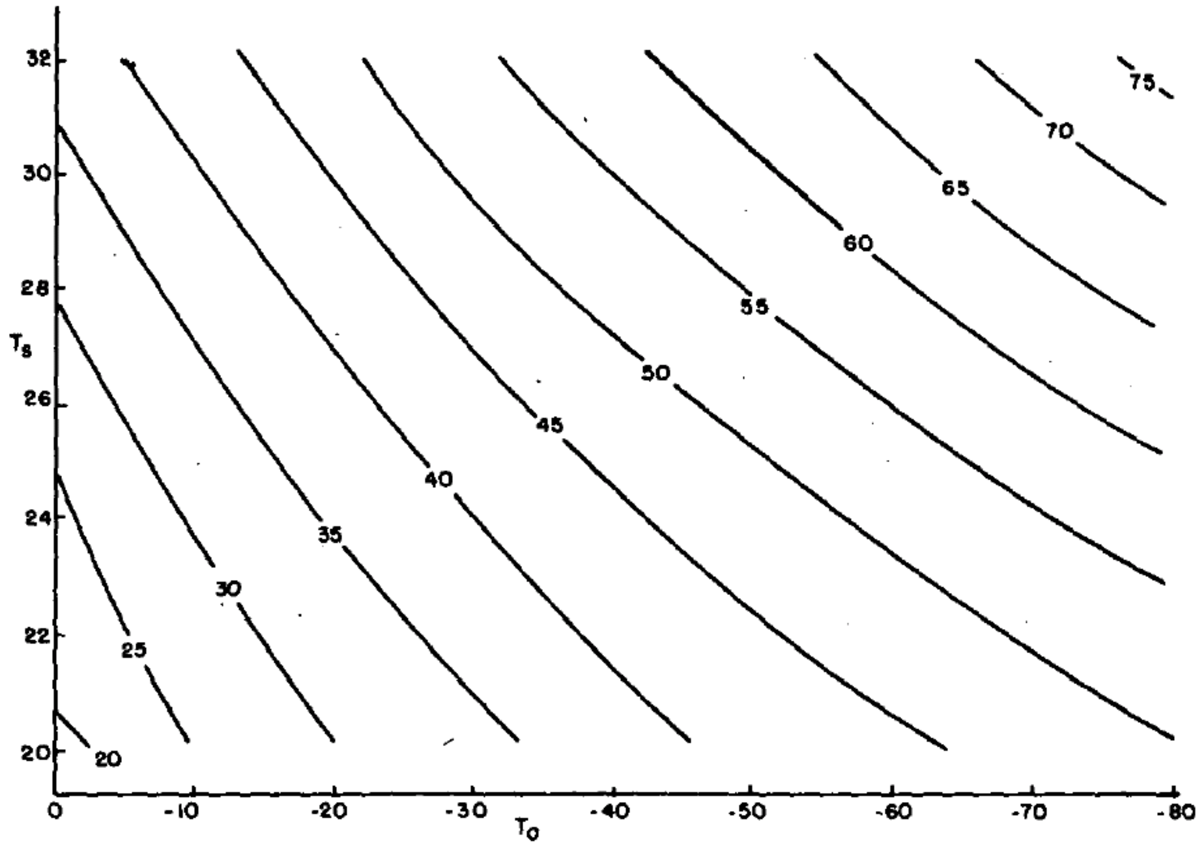
DeMaria and Kaplan (1994)

Advantages: very accurate

Disadvantages: not useful for some applications (climate change); limited physical insight

Method #2: Theoretical

sea-surface temperature



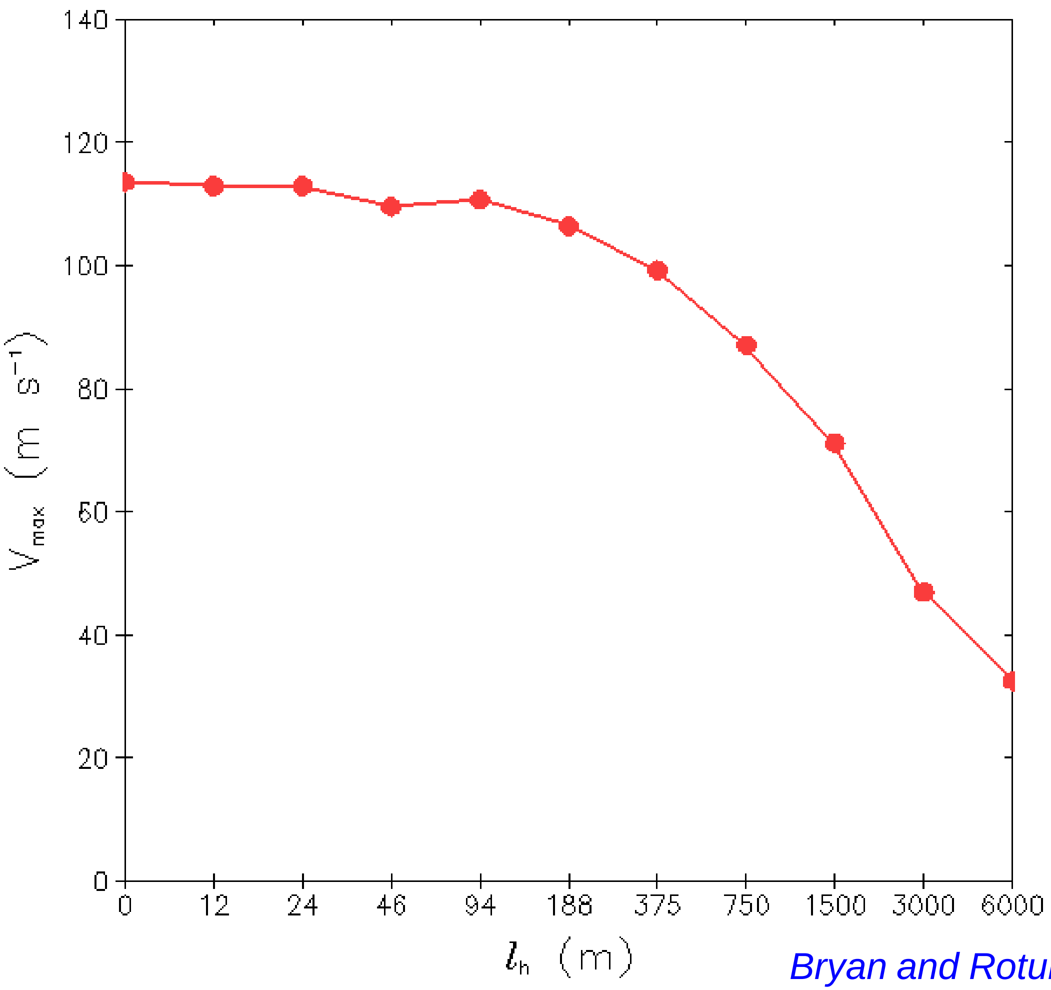
outflow temperature

Emanuel (1986)

Advantages: good physical insight; adaptable

Disadvantages: requires approximations (next talk)

Method #3: Numerical Simulations



Bryan and Rotunno (2009b)

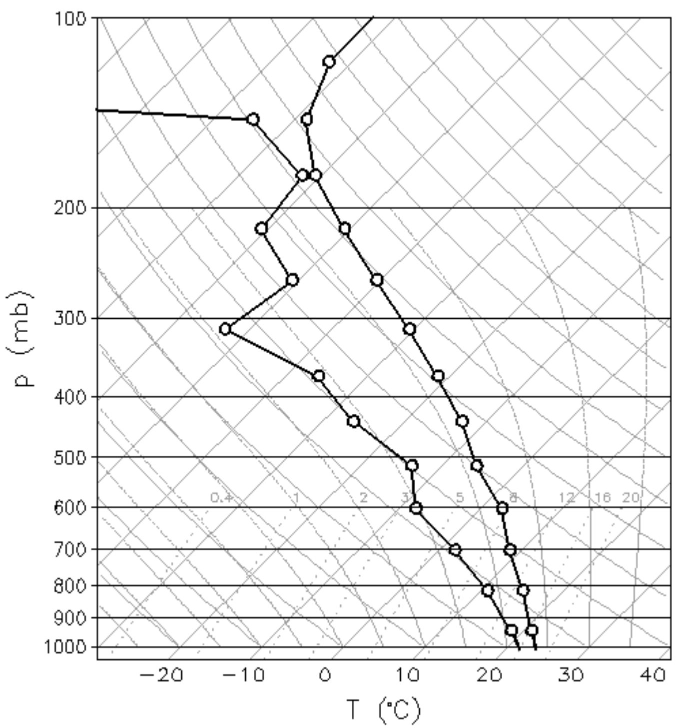
Advantages: it's easy!

Disadvantages: sensitivity to uncertain parameters (e.g., turbulence)

A numerical study of maximum hurricane intensity

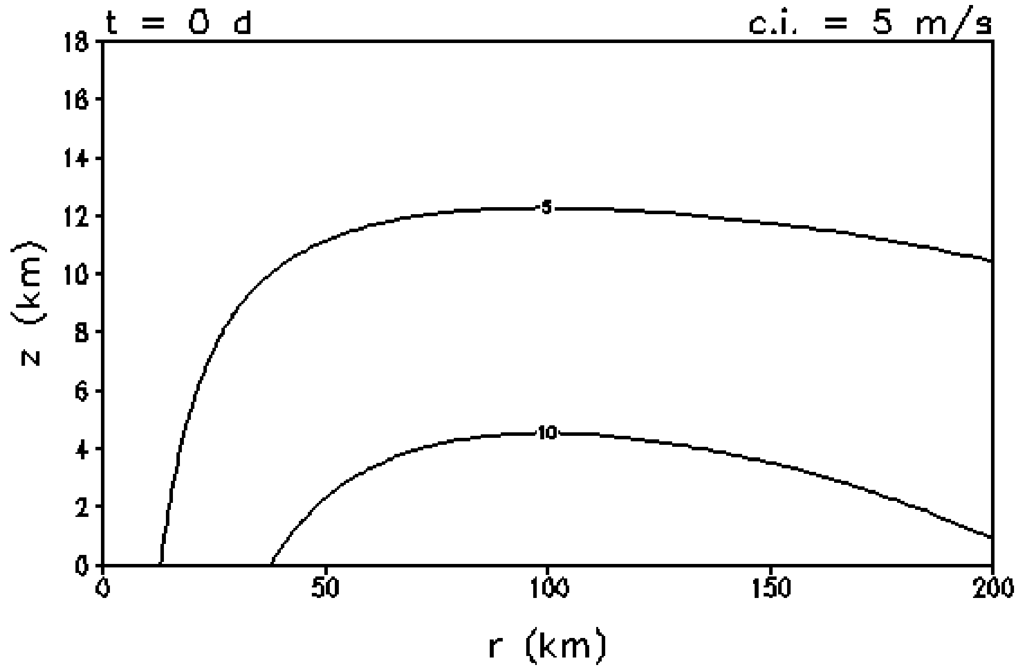
- Use a nonhydrostatic, cloud-resolving research model (CM1)
  - see Bryan and Rotunno (2009b, MWR)

- Setup:
  - Axisymmetric (r,z), then 3d
  - Constant SST (26.1 °C)
  - Δr = 1 km, Δz = 250 m
  - C_E / C_D = 1
  - Simple microphysics
  - Simple radiation



sounding from Rotunno and Emanuel (1987)

Initial conditions:

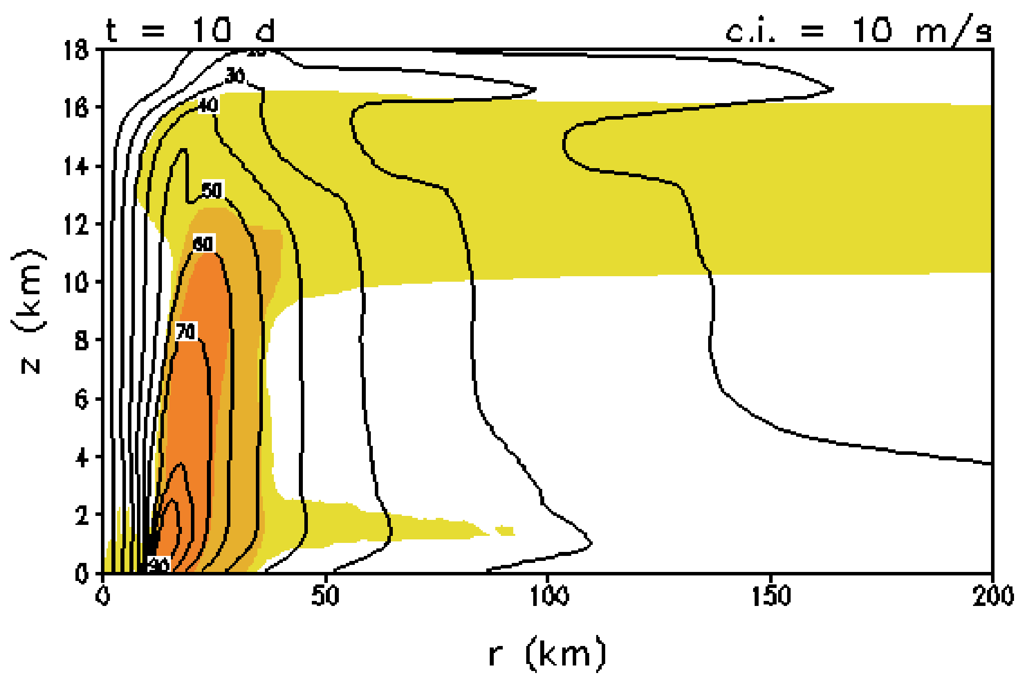


contours = v (m s^{-1})

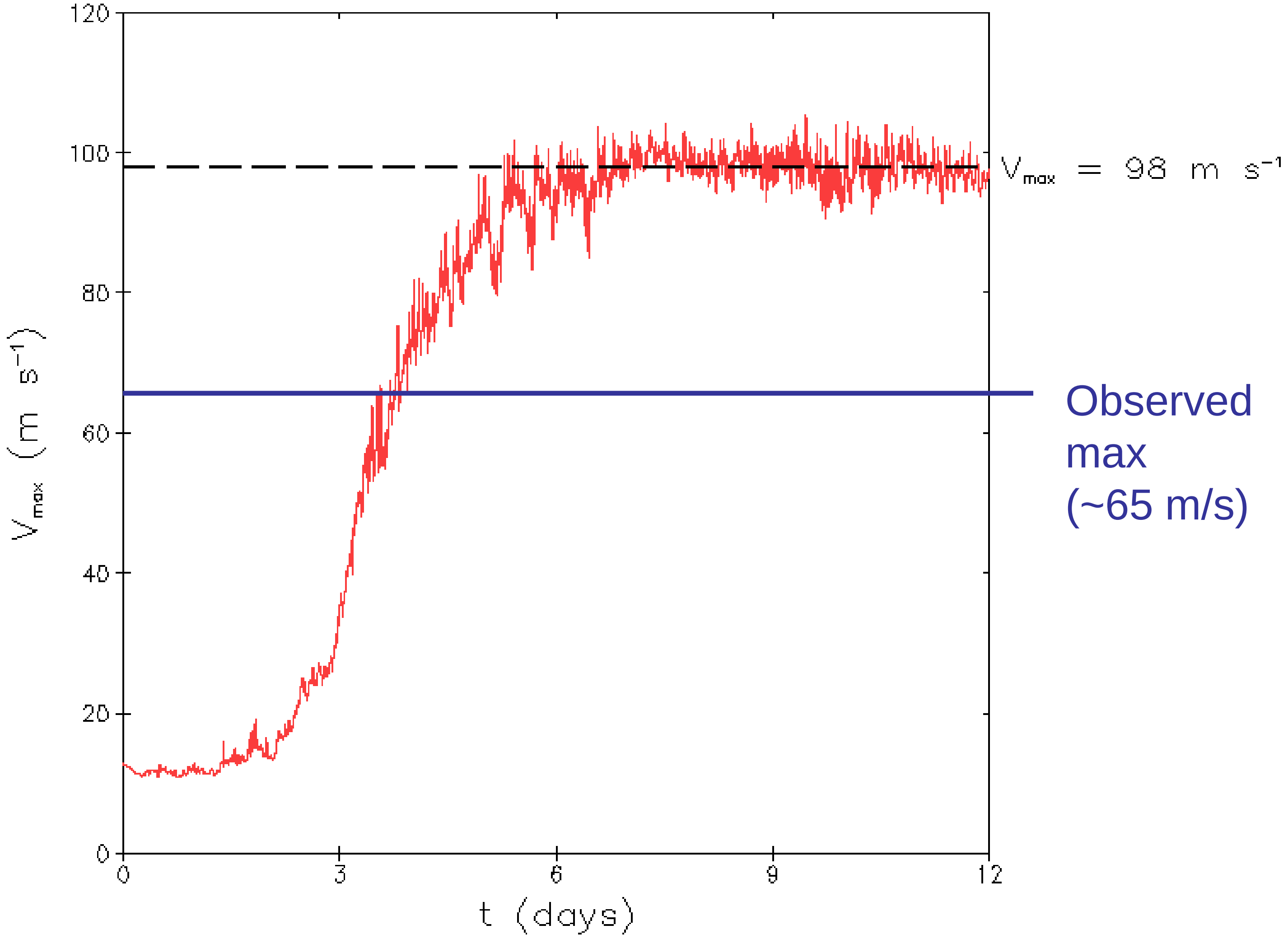
yellow = cloud

orange = rain

t = 10 days:



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



Settings in the model tested by Bryan and Rotunno (2009b) (in order from least important to most important):

- Resolution* (*as long as $\Delta r < 8$ km, $\Delta z < 500$ m)
- Numerics
- Initial vortex
- Governing equations
  - mass/energy conservation
- Microphysics
  - liquid / ice processes
  - fall velocity of condensate
- Surface exchange coefficients (C_E, C_D)
- Turbulence

Turbulence in an axisymmetric model:

- Must account for *all non-axisymmetric processes*

(boundary layer turbulence, roll vortices, eyewall mesovortices, vortex Rossby waves, etc)

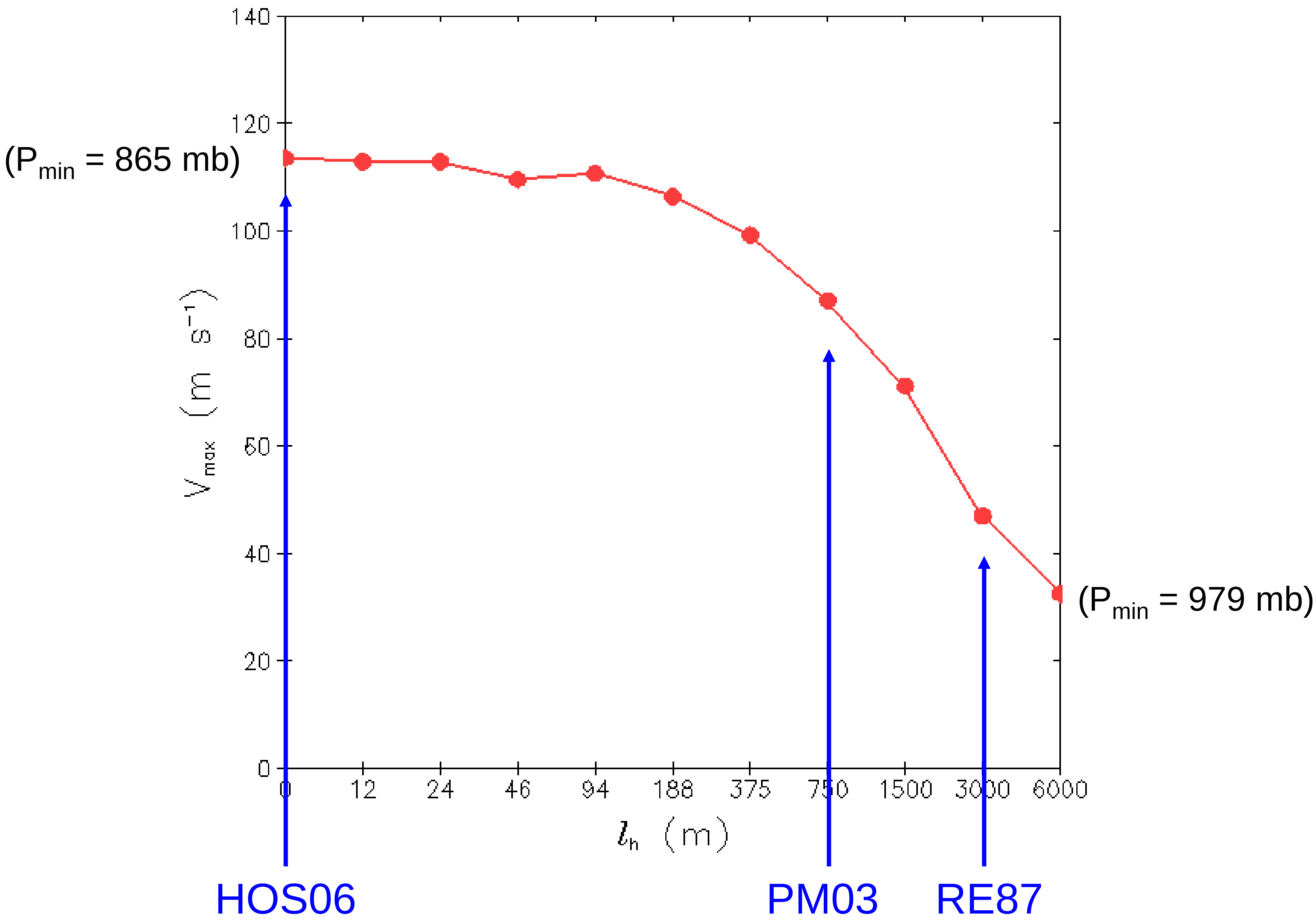
- Eddy viscosity in horizontal direction:□□

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

Where: l_h: a horizontal length scale (unknown)

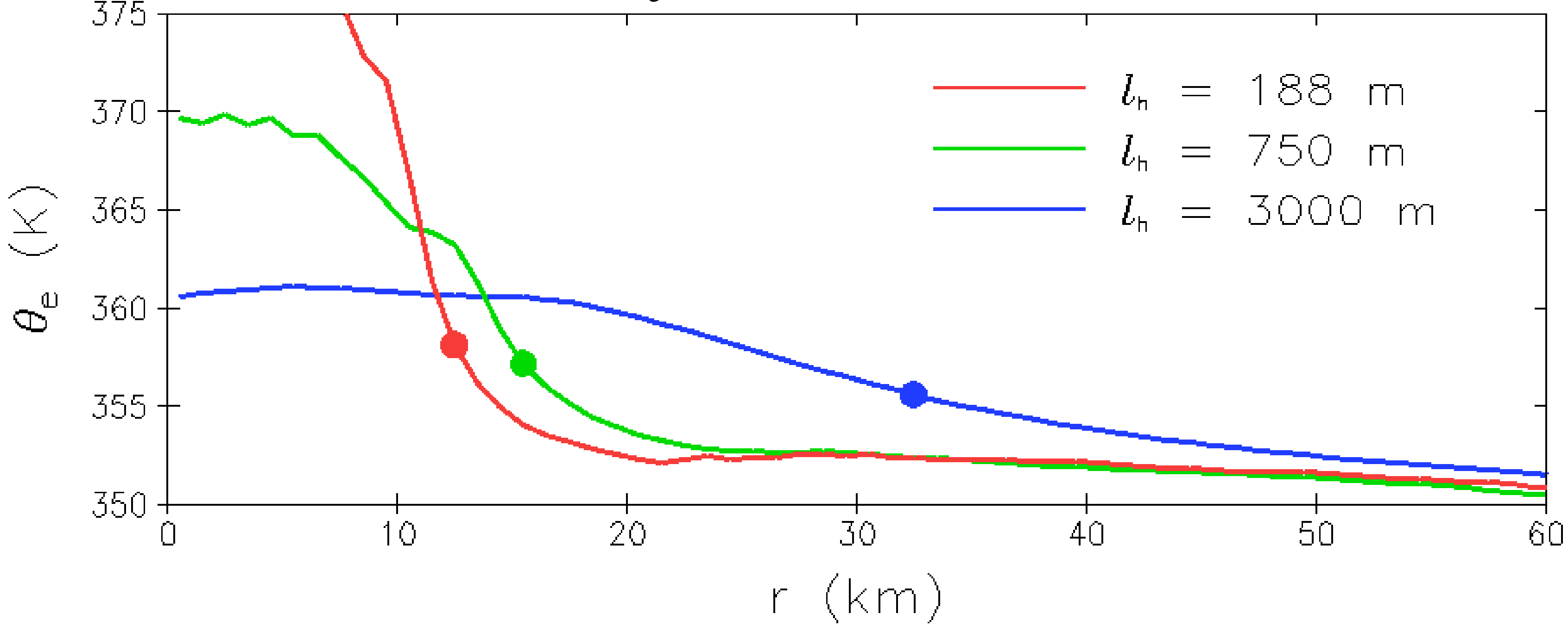
S_h: deformation (known from simulated flow)

sensitivity of V_{max} to horizontal turbulence:



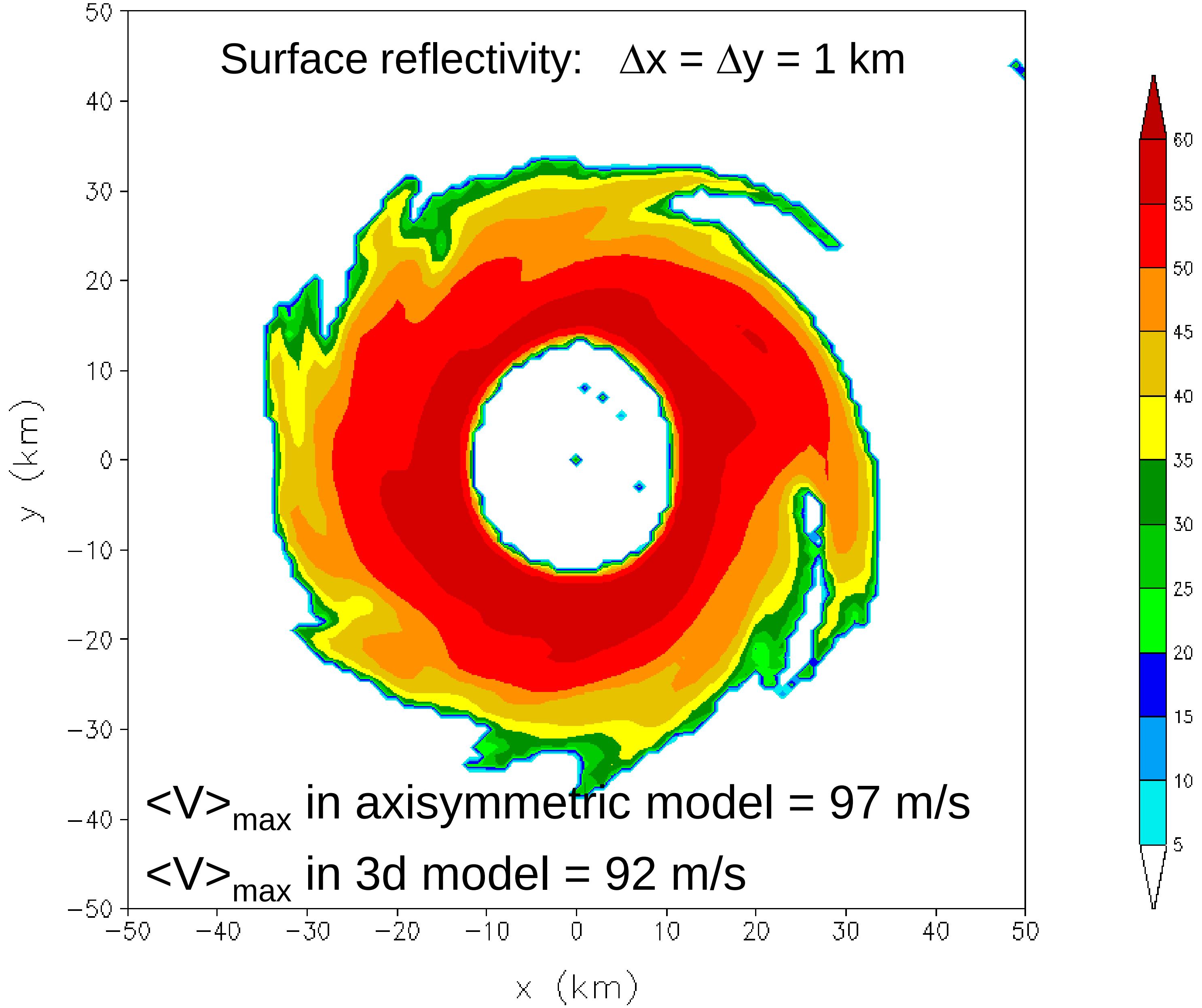
larger l_h $\rightarrow$ larger $\nu_h \rightarrow$ weaker radial gradients:

θ_e at $z = 1.1$ km

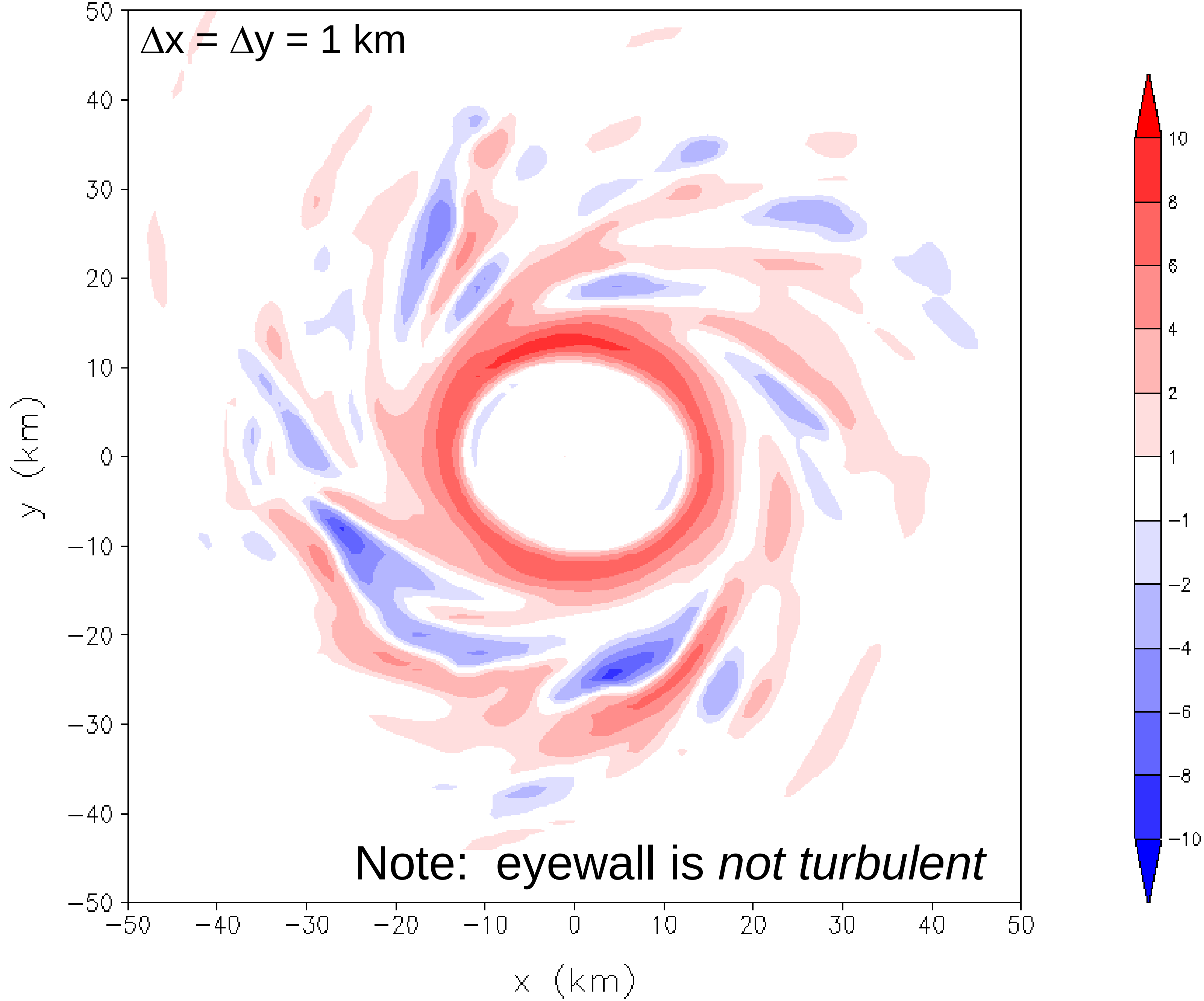


weaker radial gradients $\Leftrightarrow$ weaker cyclone

What happens in 3d simulations?

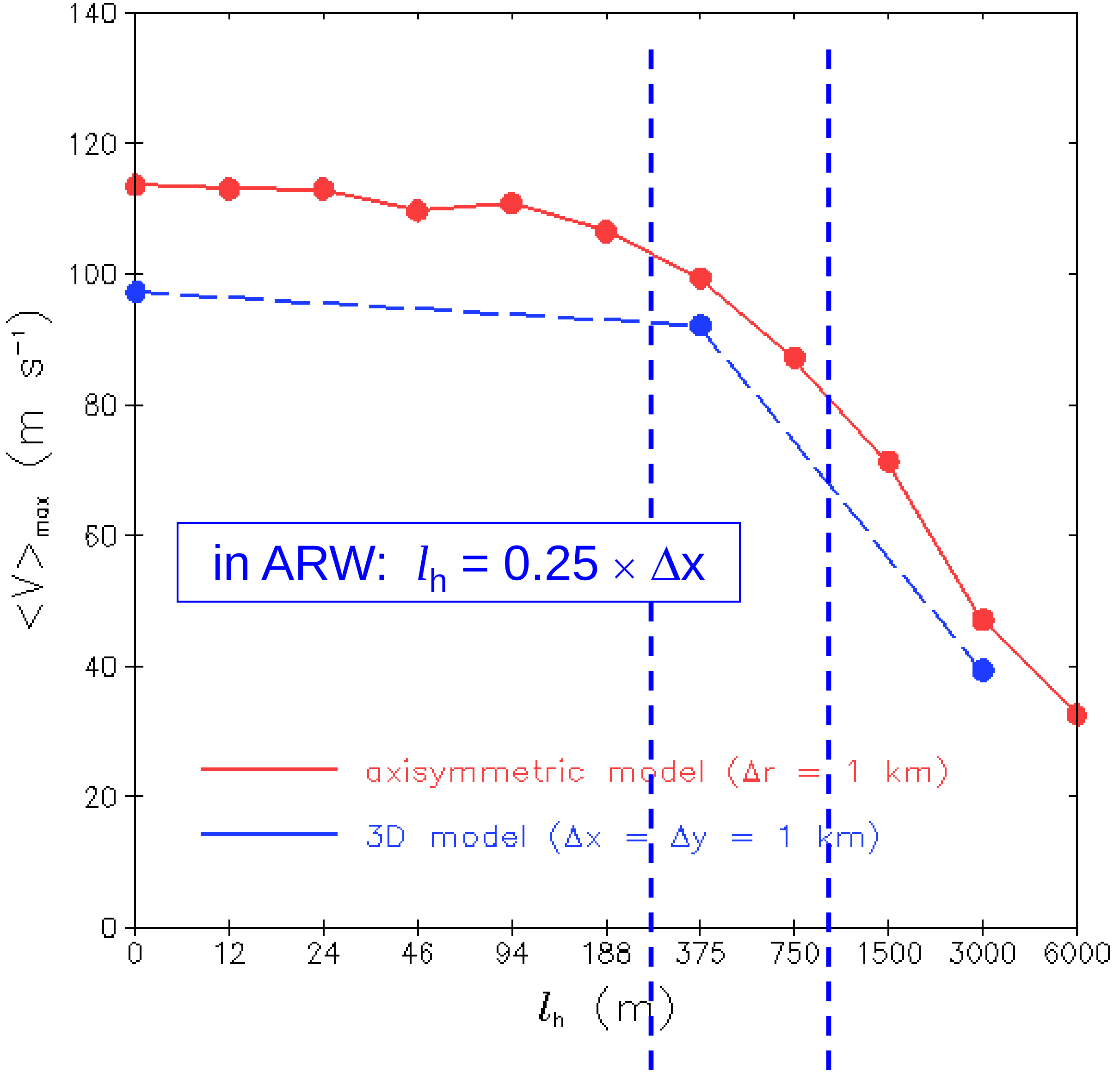


w (m/s) at z = 1 km



Δx = Δy = 1 km
Note: eyewall is *not turbulent*
y (km)
x (km)
50
40
30
20
10
0
−10
−20
−30
−40
−50
−50
−40
−30
−20
−10
0
10
20
30
40
50
10
8
6
4
2
1
−1
−2
−4
−6
−8
−10

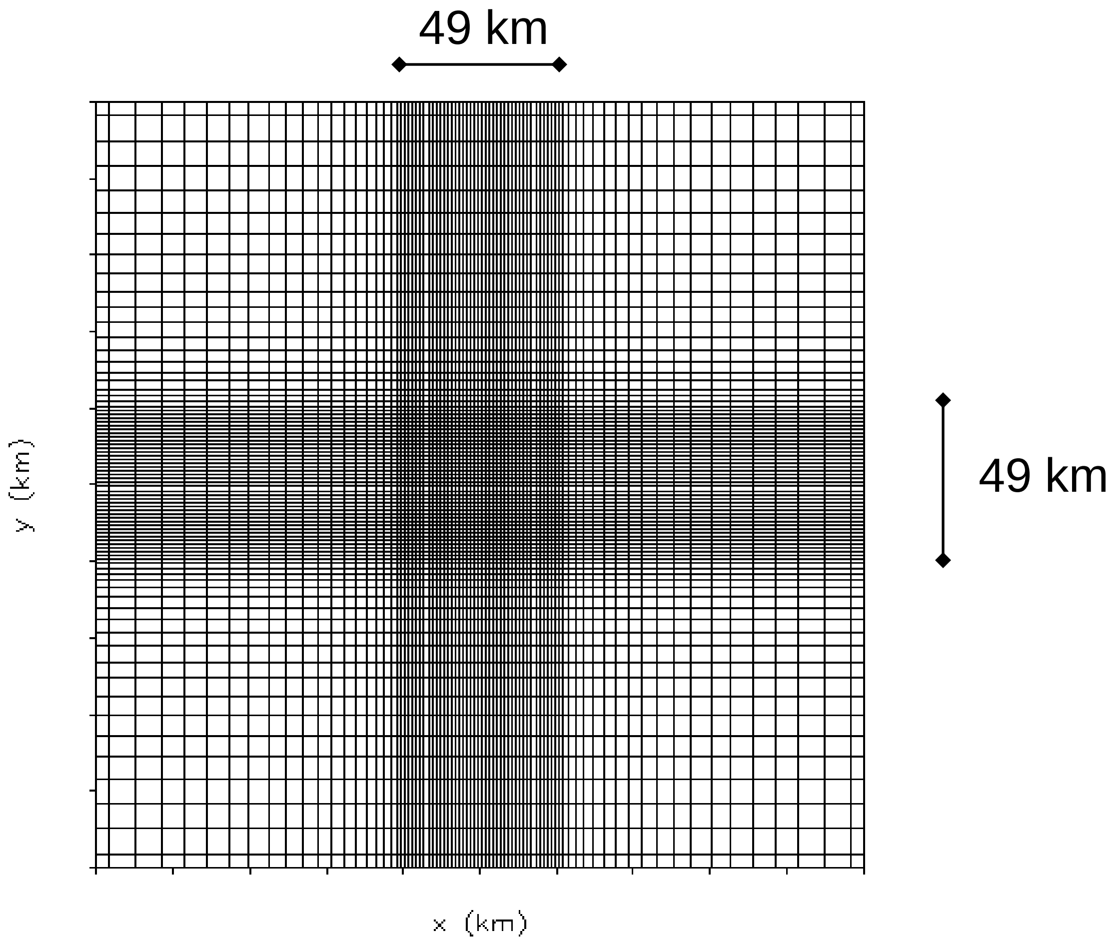
Max. azimuthally averaged V (m/s): 2d vs 3d



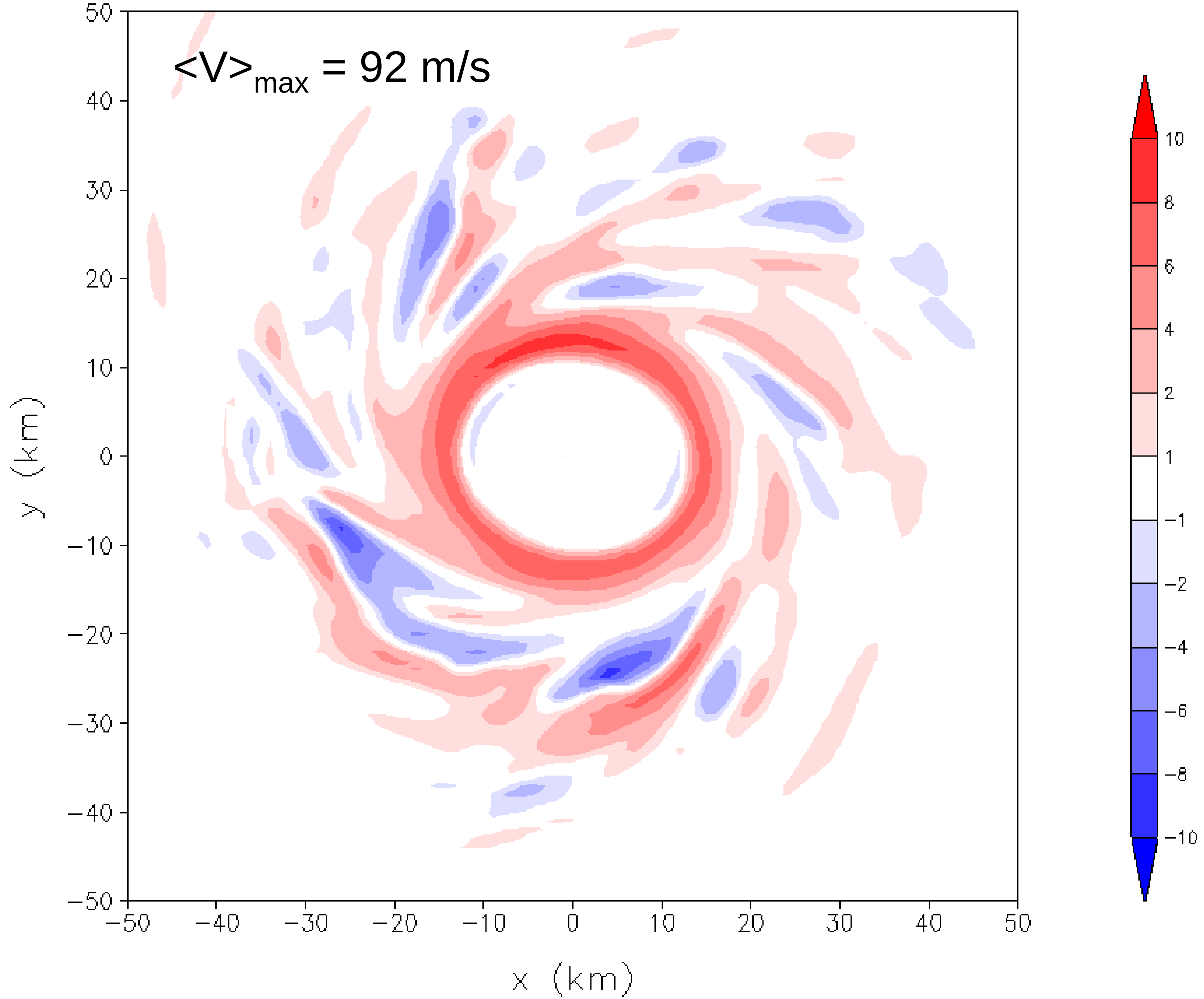
ARW (Δx = 1 km) ARW (Δx = 4 km)

A large-eddy simulation

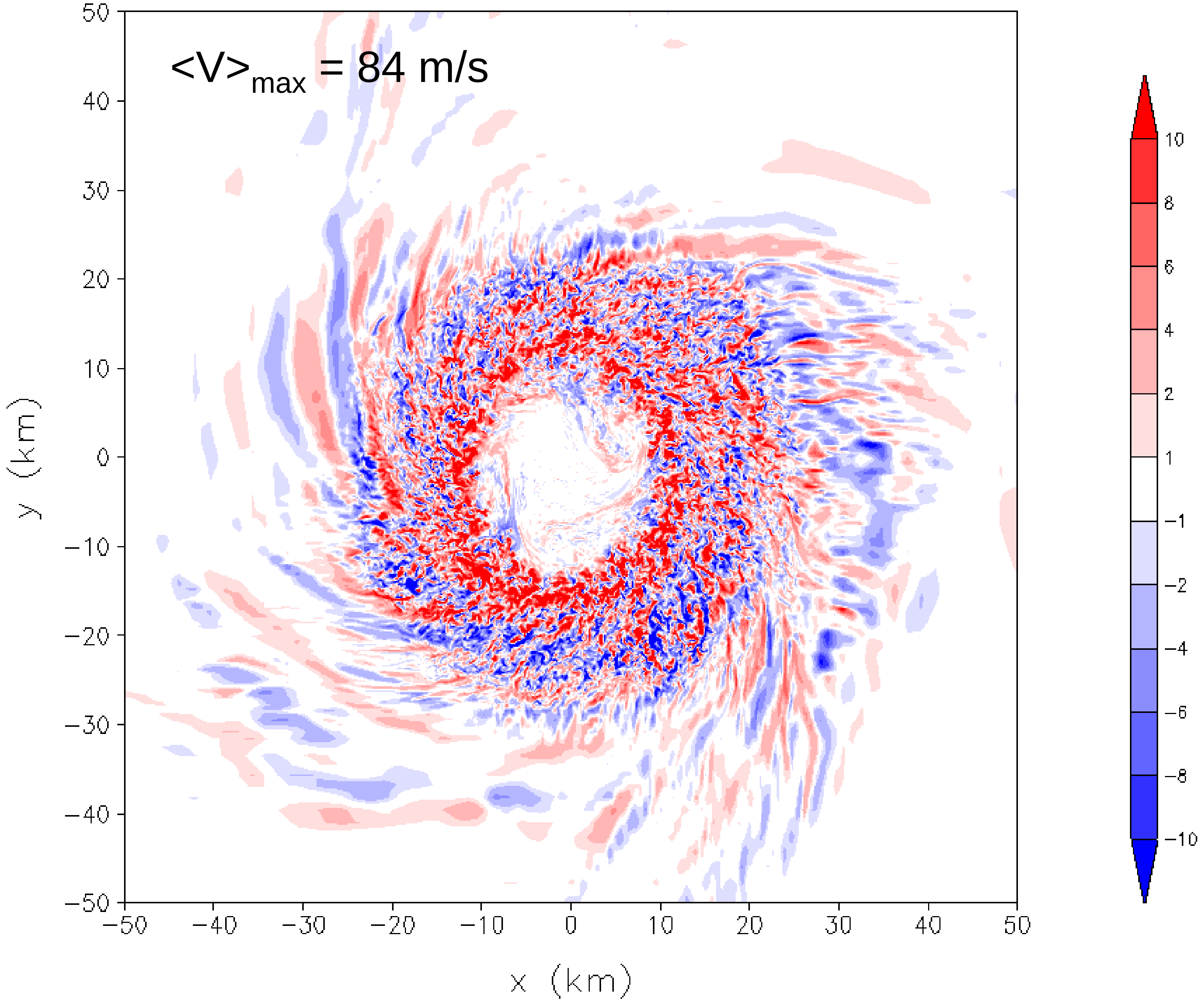
- Motivated by recent study by Rotunno et al. (2009, BAMS)
- In center: $\Delta x = \Delta y = \Delta z = 62.5$ m
- Initialized from 1-km simulation



w (m/s) at z = 1 km: Δx = 1000 m

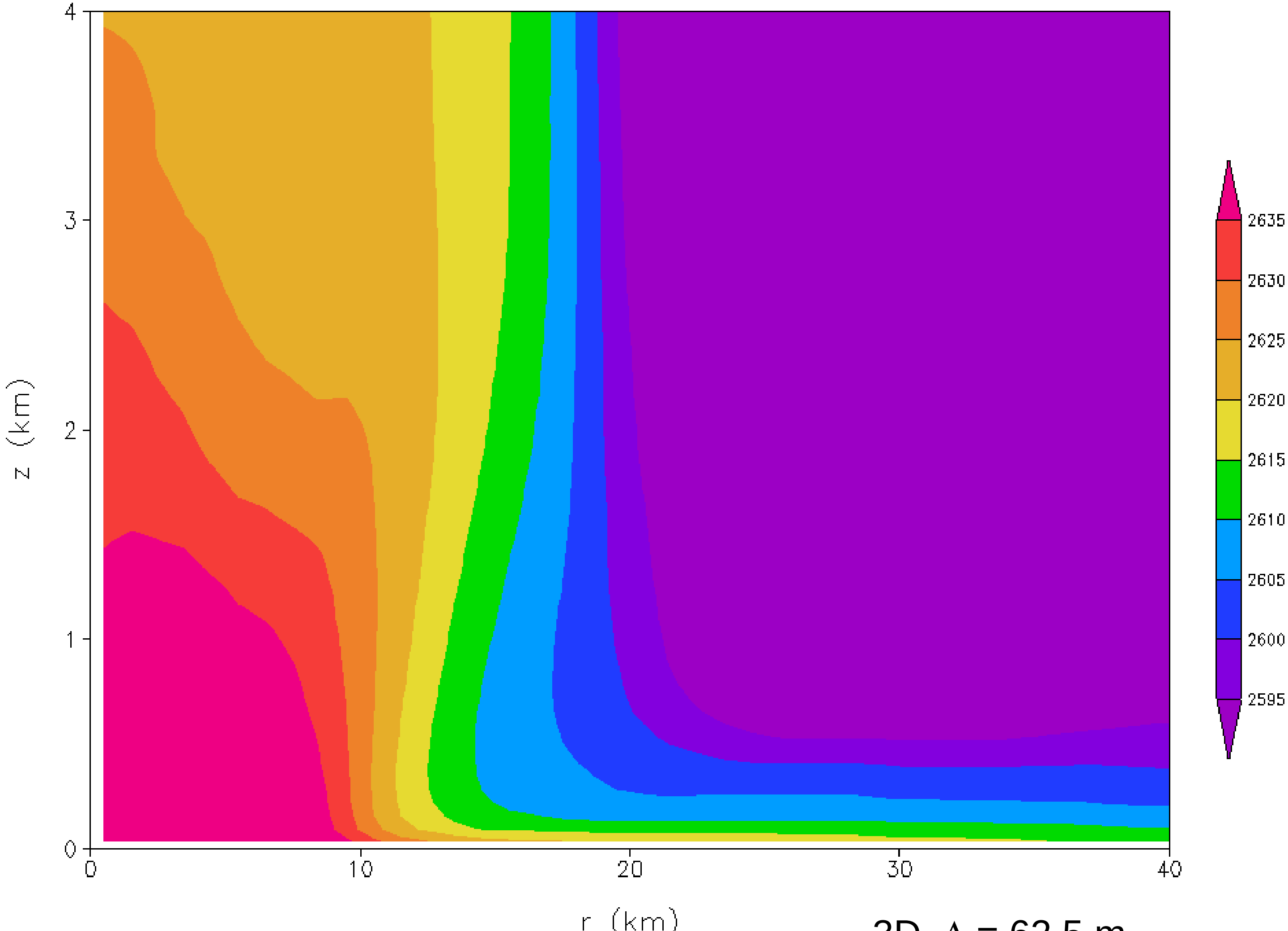


w (m/s) at z = 1 km: Δx = 62.5 m



Let $\alpha(r,\phi,z) = \langle\alpha\rangle(r,z) + \alpha'(r,\phi,z)$

shaded: $\langle s \rangle$

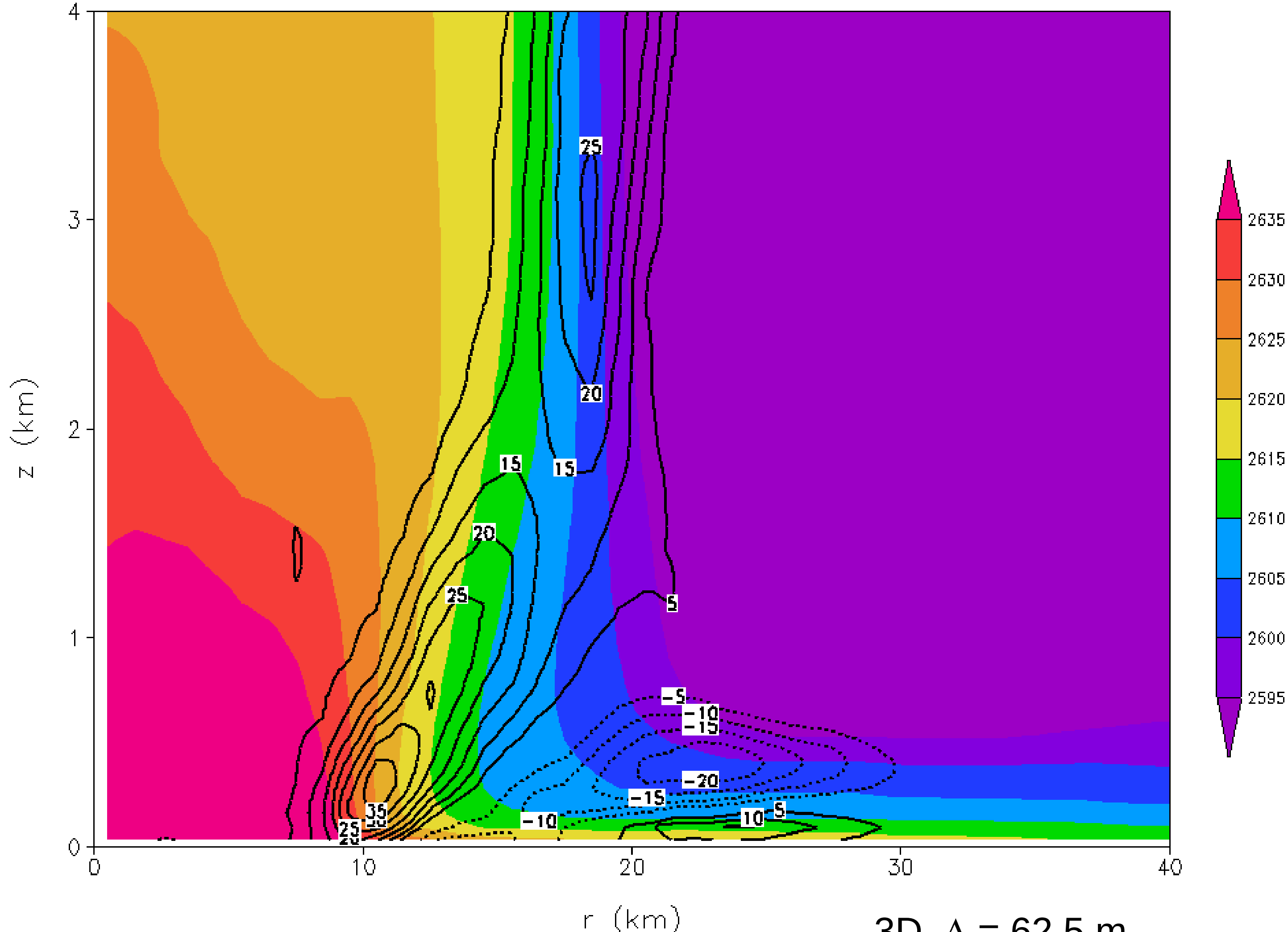


3D, Δ = 62.5 m

Let $\alpha(r,\phi,z) = <\alpha>(r,z) + \alpha'(r,\phi,z)$

shaded: $<s>$

contours: $<u's'>$ (turbulent flux of s in radial direction)

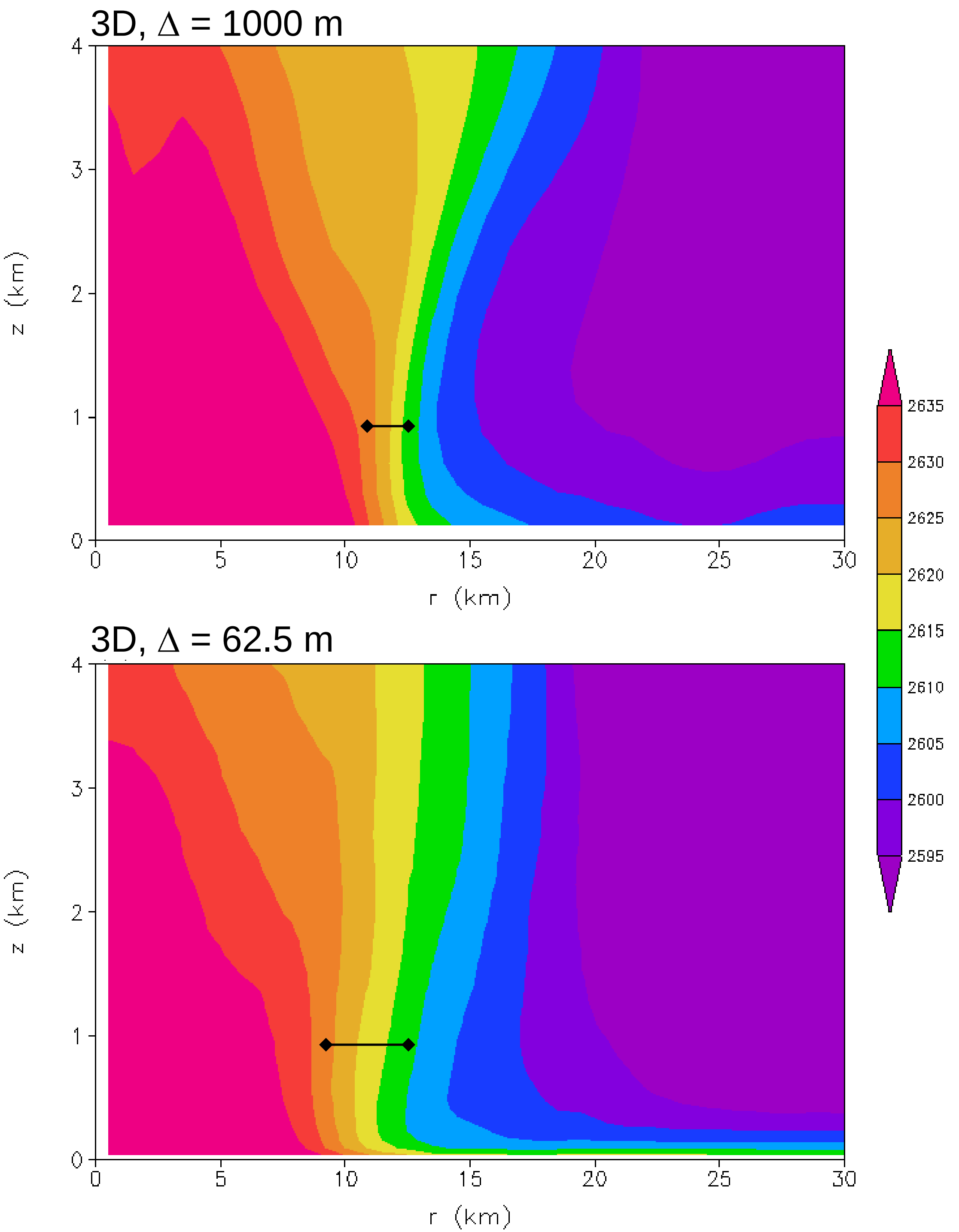


3D, Δ = 62.5 m

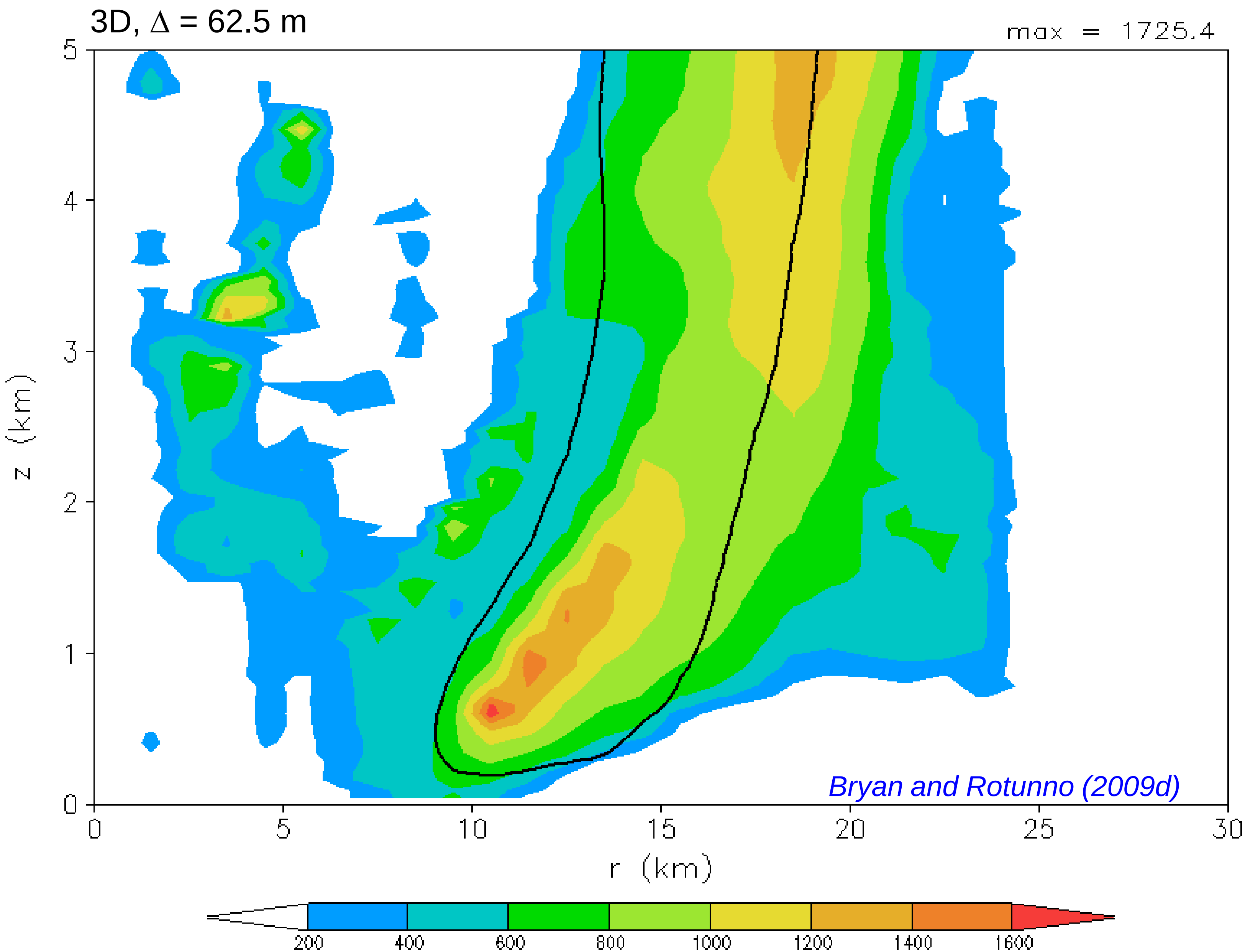
moist entropy, <*s*>:

$$\frac{\partial \langle s \rangle}{\partial r} = -8.8 \times 10^{-3} \text{ m s}^{-2} \text{ K}^{-1}$$

$$\frac{\partial \langle s \rangle}{\partial r} = -4.3 \times 10^{-3} \text{ m s}^{-2} \text{ K}^{-1}$$

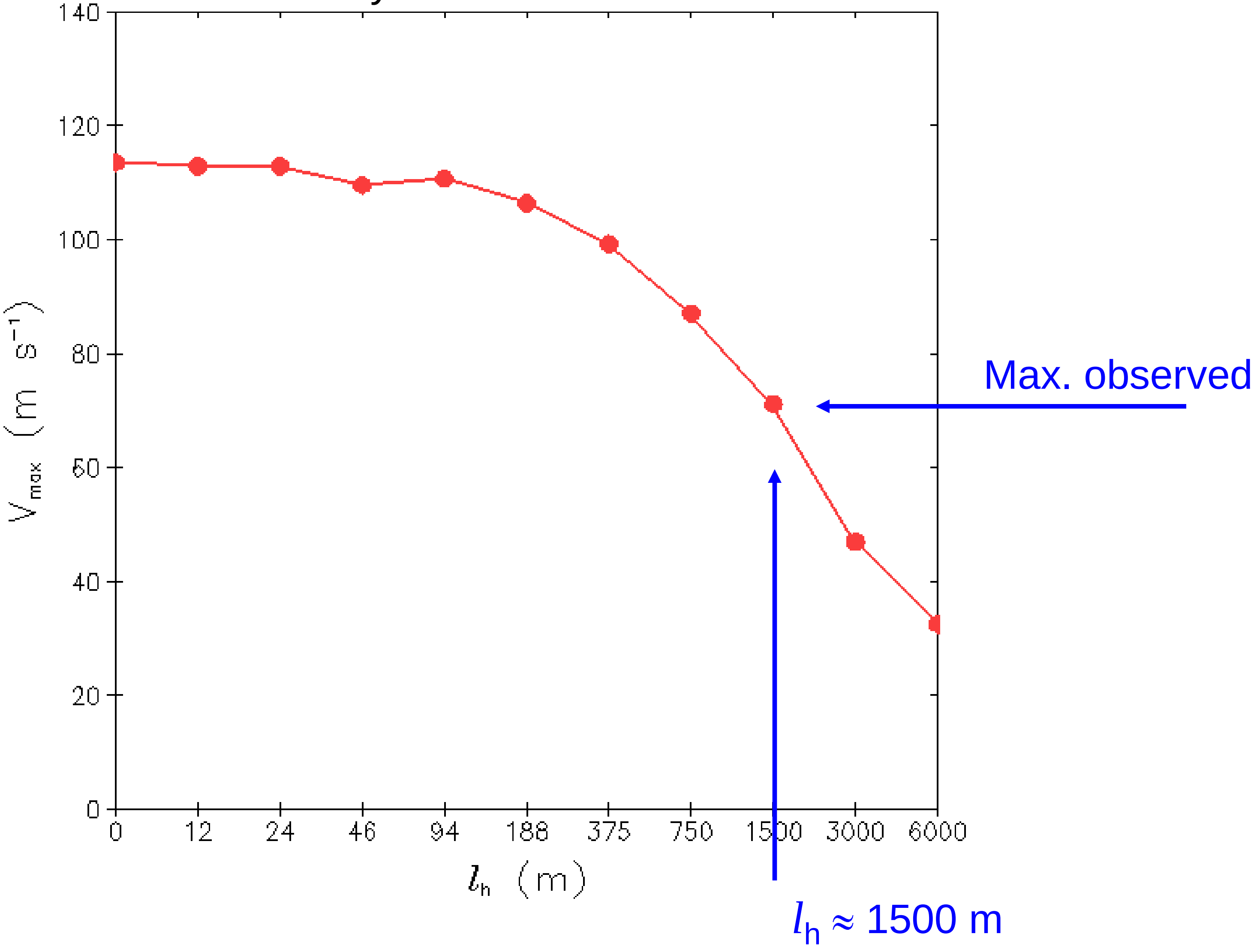


diagnosed turbulence length scale (l_h)

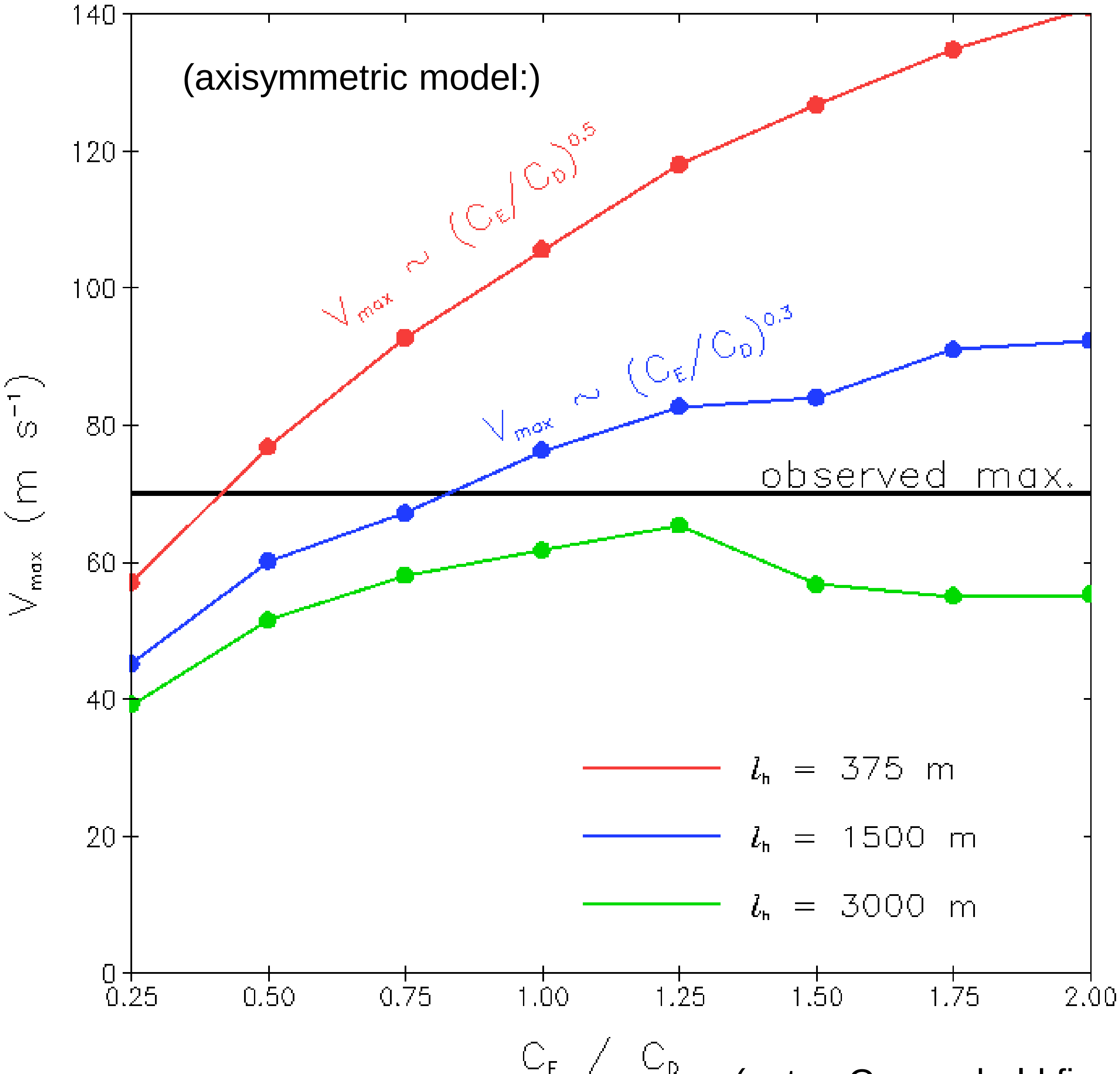


sensitivity of V_{max} to horizontal turbulence:

axisymmetric model:



sensitivity of V_{max} to surface exchange coefficients:



(note: C_E was held fixed at 1.2×10^{-3})

Summary

- Turbulence in the eyewall of hurricanes *reduces* hurricane intensity

- Very high resolution (Δx < 100 m) and a 3d numerical model are required to simulate directly turbulent processes (see also Rotunno et al., BAMS, December 2009)

… otherwise, turbulent processes must be *parameterized* (even with $\Delta \approx$ 1 km, and even with 3d simulations)

… we think $l_h \approx 1000$ m

articles and code: http://www.mmm.ucar.edu/people/bryan/