The maximum intensity of hurricanes in axisymmetric numerical models

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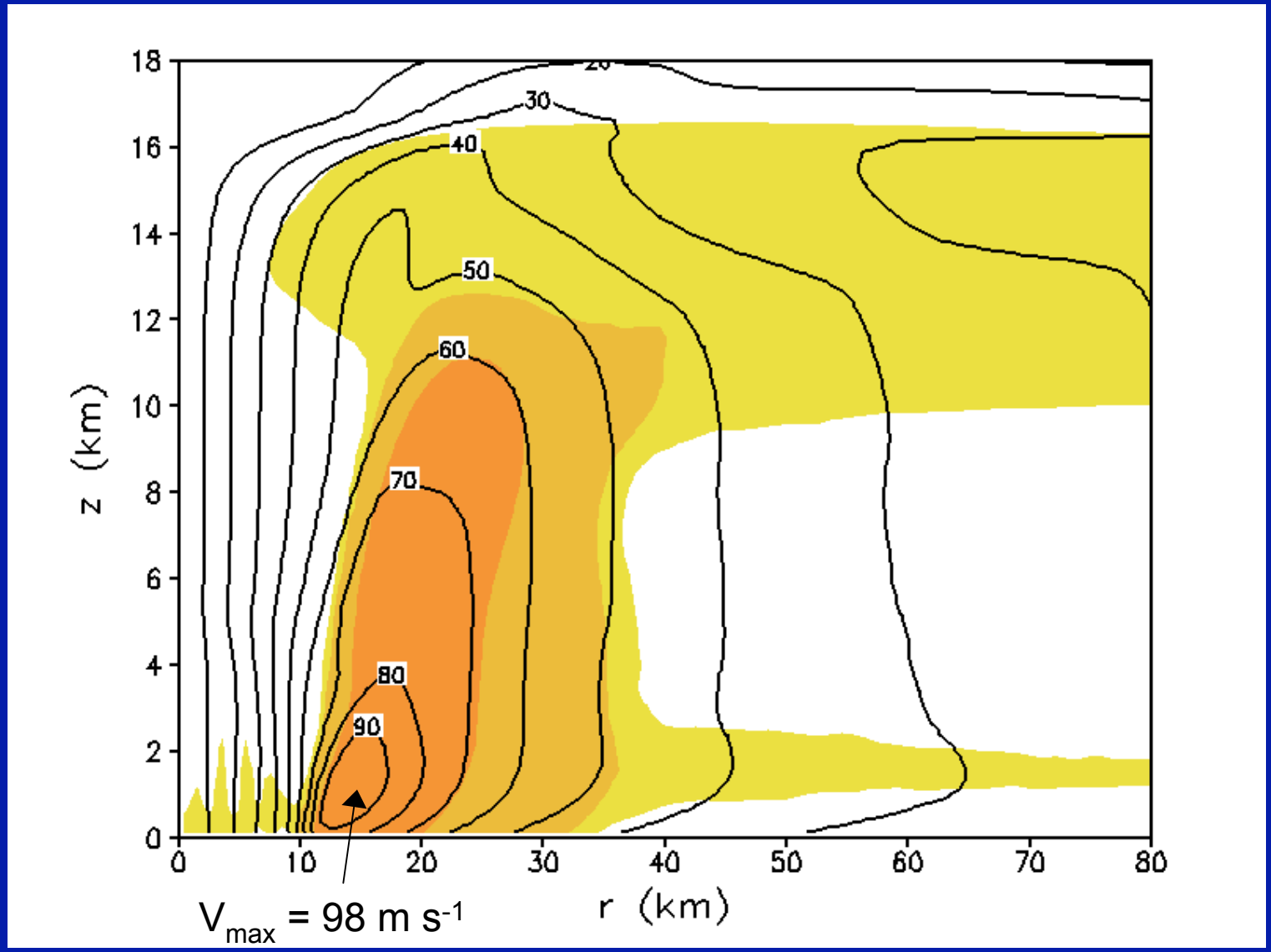
Output from an axisymmetric numerical model

yellow = cloud orange = rain contours = v (m s^{-1})



Methodology

- Same approach as Rotunno and Emanuel (1987) (hereafter RE87)
- A single specified environment
  - Same sounding as RE87
  - SST = 26 °C
- A mass- and energy-conserving model
  - Δr = 1 km, Δz = 250 m
  - see Bryan and Rotunno (2008b)

Outline

1. Unresolved turbulence
2. Fall velocity of liquid water (V_t)
3. Comparison to E-MPI (the analytical maximum intensity derived by Emanuel)

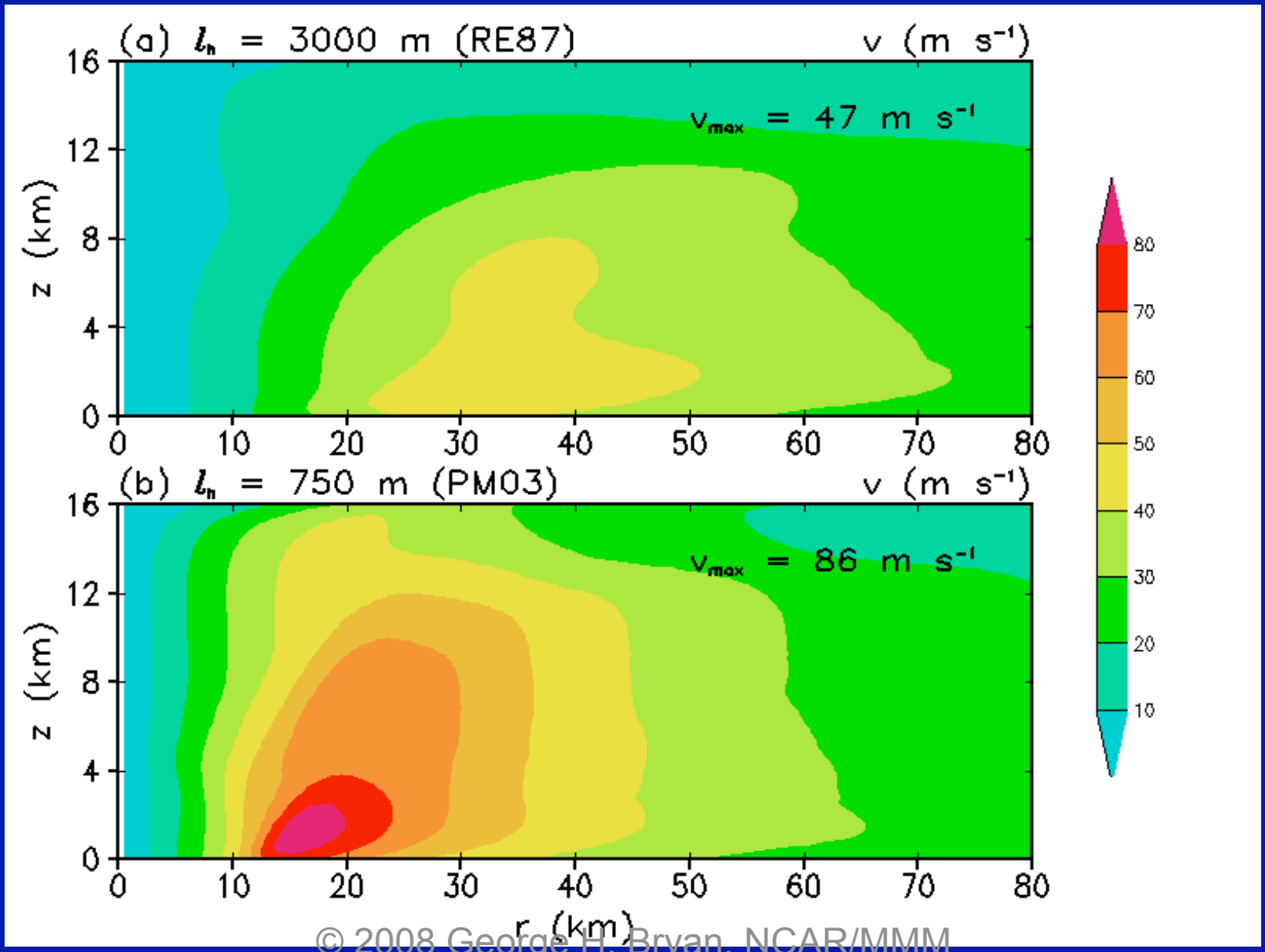
1) The turbulence parameterization

Turbulence intensity is proportional to:

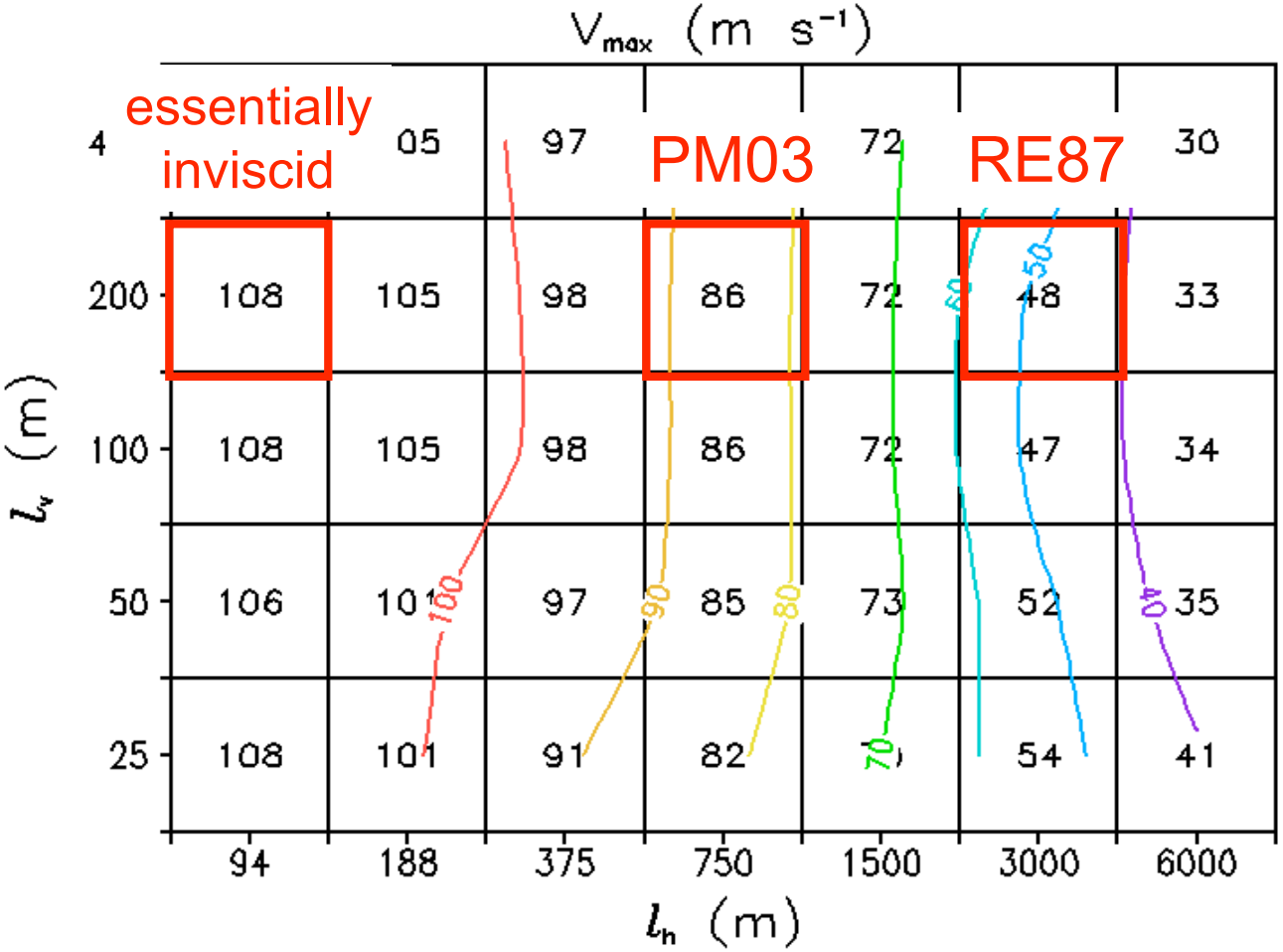
- a specified horizontal length scale (l_h)
- a specified vertical length scale (l_v)

NOTE: There is no theoretical guidance for how to set l_h and l_v in axisymmetric numerical models!

Sensitivity to l_h: v (m s^{-1})



Sensitivity to turbulence length scales



Unnatural structures as l_v changes:

For largest l_v: PBL depths > 2 km

For smallest l_v: $|u| > 40$ m s^{-1}

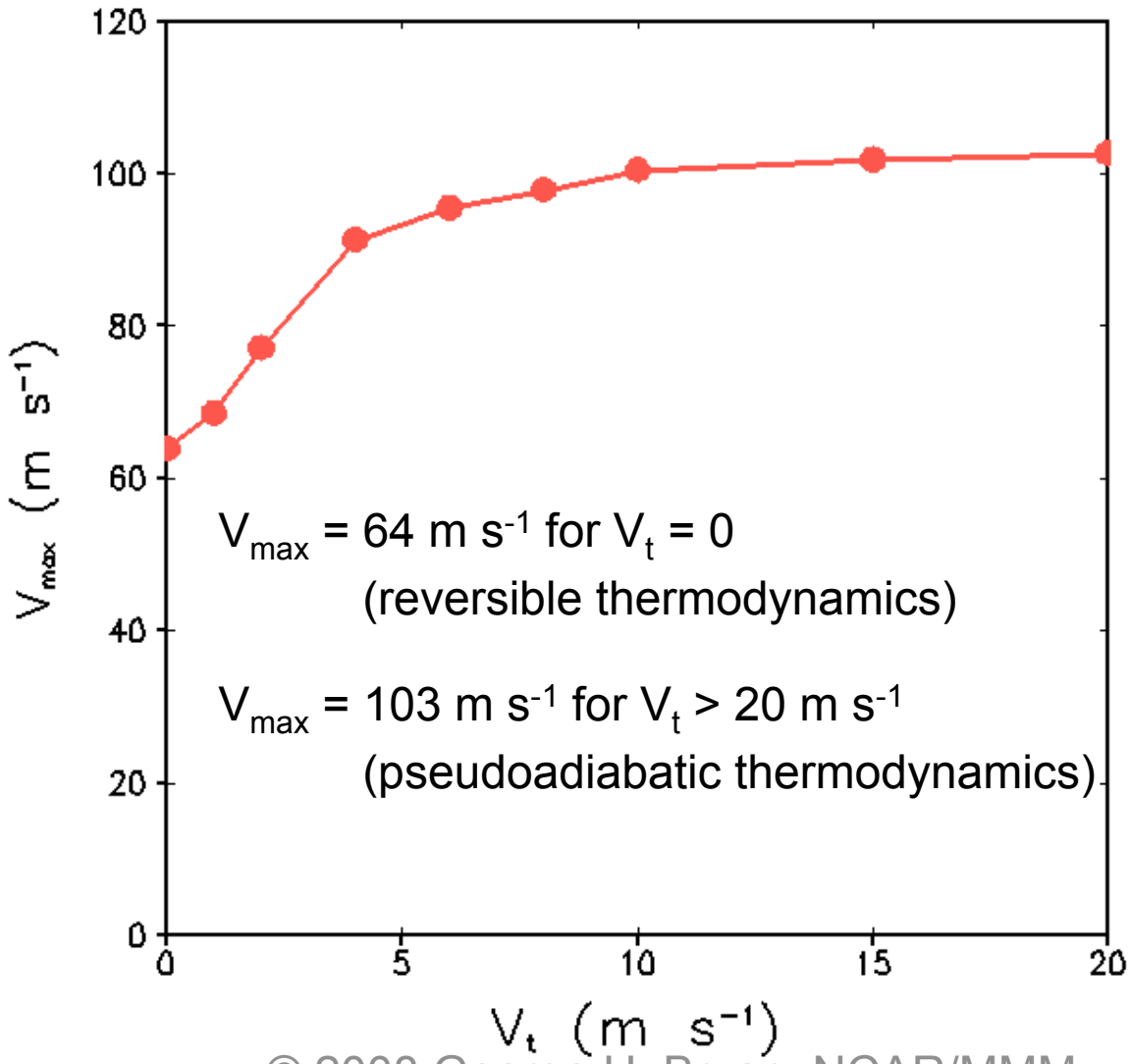
Sensitivity to l_h:

Strong frontogenesis in eyewall

Turbulence limits frontal collapse

2) Sensitivity to terminal fall velocity of liquid (V_t)

(RE87 default: V_t = 7 m s^{-1})



θ_e (formulated appropriately) and trajectory

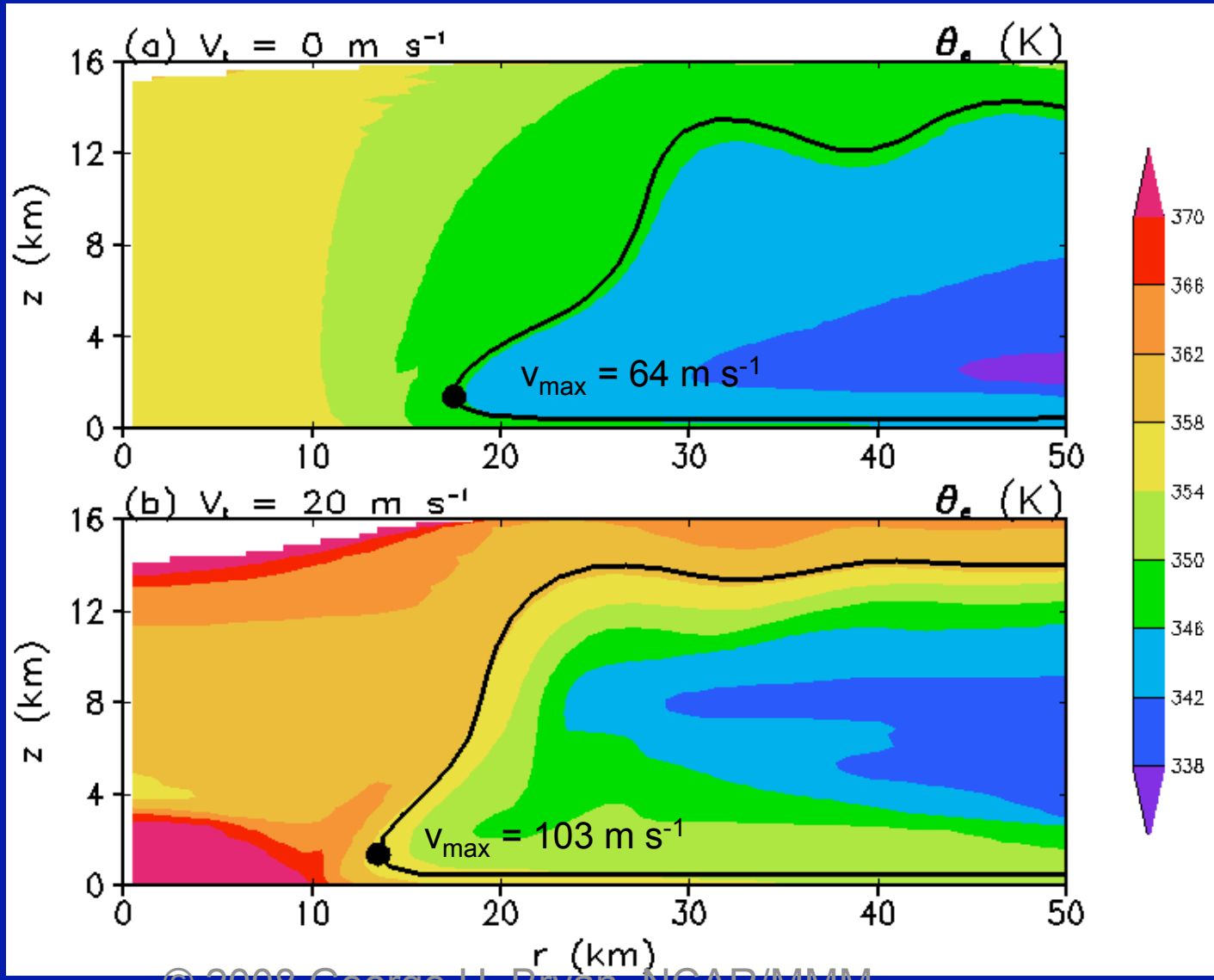
shaded: θ_e black dot: location of v_{max} black line: trajectory

reversible configuration:

θ_e^r is shaded

essentially pseudoadiabatic configuration:

θ_e^p is shaded

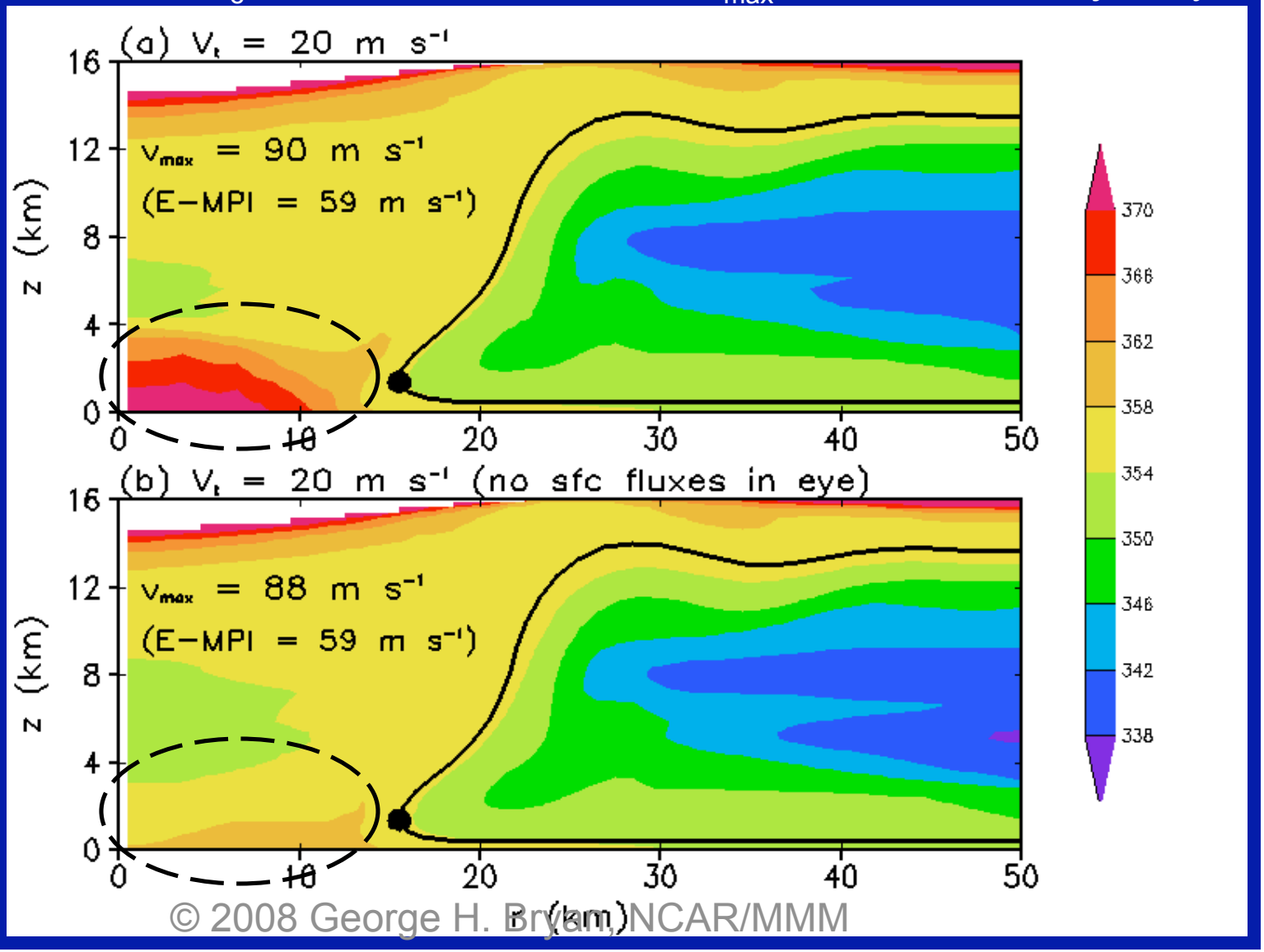


Evaluation of the “high entropy reservoir”

shaded: θ_e black dot: location of v_{max} black line: trajectory

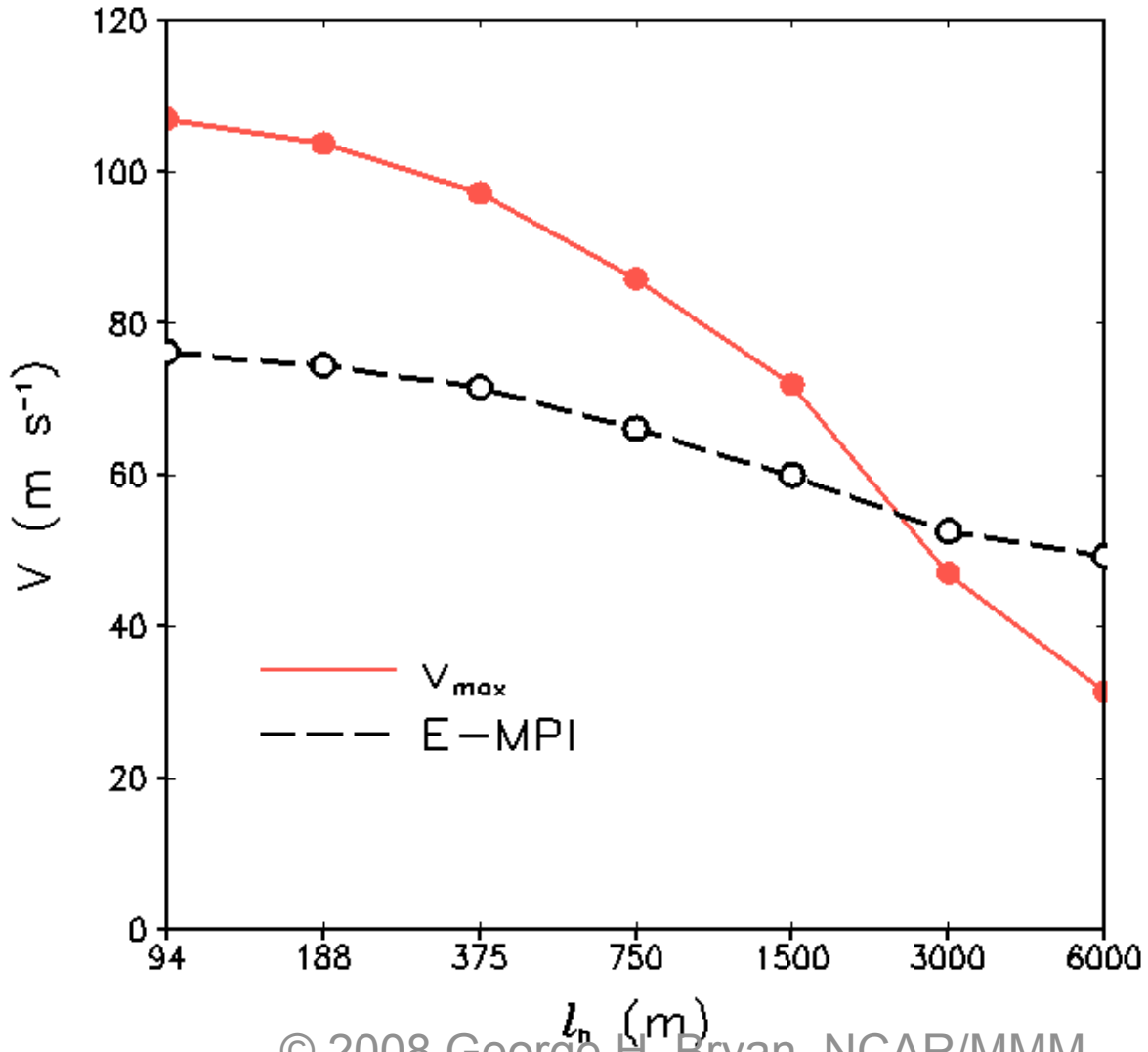
default configuration:

no surface fluxes in eye:



3) V_{max} compared to E-MPI

(using same method as PM03)



Components of E-MPI

- Moist slantwise neutrality
  - ?
- PBL Model
  - ?
- Gradient-wind and hydrostatic balance
  - ?

Components of E-MPI

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  - $\rightarrow$ does not explain discrepancy
  - $\rightarrow$ M and s are conserved along streamlines
- PBL Model
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Components of E-MPI

- Moist slantwise neutrality
  - → does not explain discrepancy
  - → M and s are conserved along streamlines
- PBL Model
  - → does not explain discrepancy
  - → $ds/dM \approx -\tau_s/\tau_m$
- Gradient-wind and hydrostatic balance
  - → This *is* the primary source of the discrepancy
  - → The problem seems to be: how to estimate the impact of this assumption

MPI+

- The approach was established by D. Lilly in the 1970s (manuscript unpublished)
  - Integrate conservation equations over a control volume enclosing eyewall
- Summarized recently by Emanuel (2004)
  - see also Bister and Emanuel (1998)
- Allowing for unbalanced flow, we find:

$$V_{\max}^2 = (T_b - T_0)\, M_b \frac{ds}{dM} + \frac{M_b \eta_b}{\rho_b r_b} \frac{d\psi}{dM}$$

E-MPI

contribution from unbalanced flow

MPI$^+$

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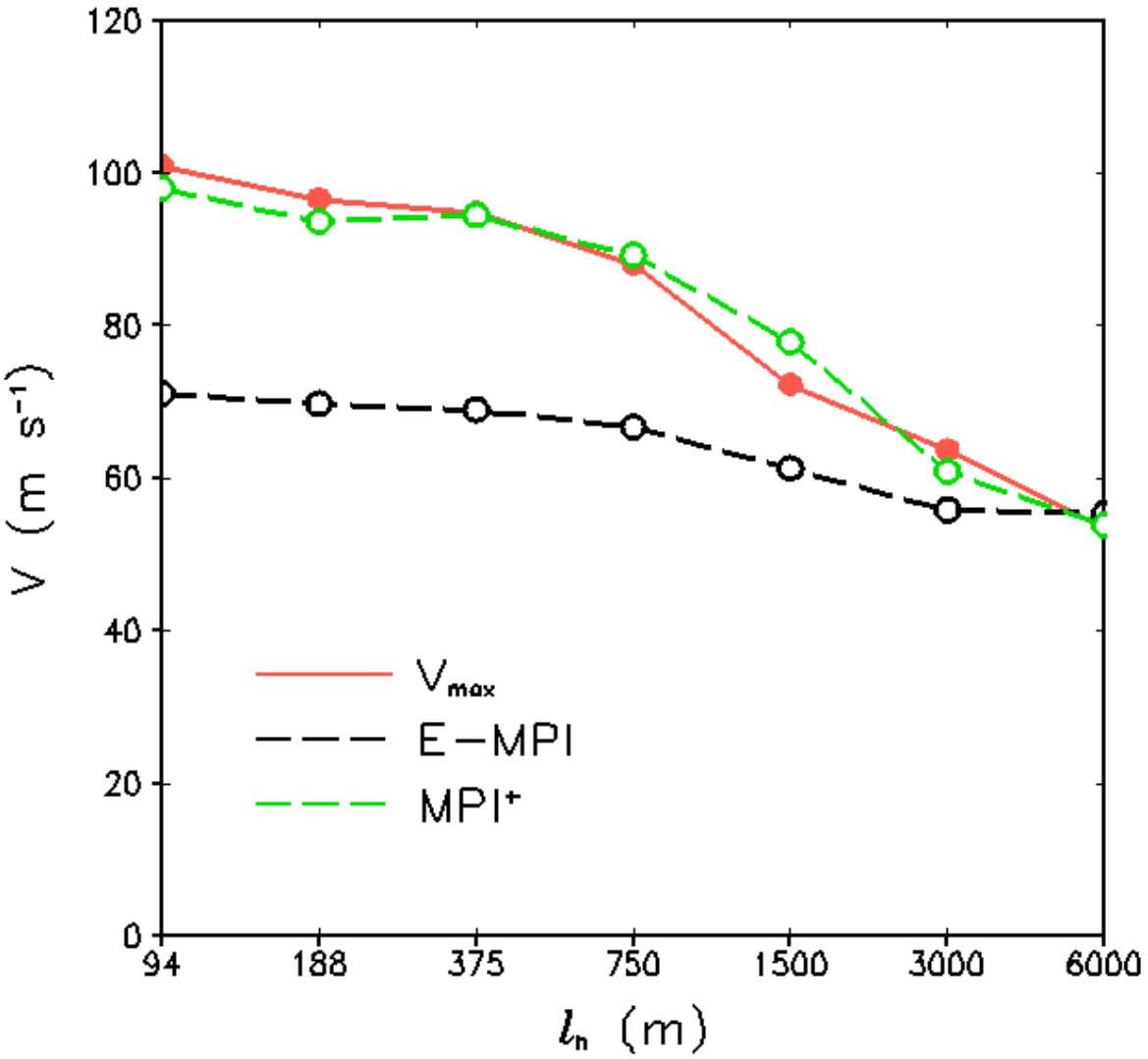
  - Integrate conservation equations over a control volume enclosing eyewall
- Summarized recently by Emanuel (2004)
  - see also Bister and Emanuel (1998)
- Allowing for unbalanced flow, we find:

$$V_{\max}^2 = -\left(T_b - T_0\right) M_b \frac{ds}{dM} - \frac{M_b \eta_b}{\rho_b r_b} \frac{d\psi}{dM}$$

…. rearrange ….

$$\text{MPI}^+ = \left(\text{E-MPI}^2 + r_m \eta_b w_b \right)^{1/2}$$

Evaluation of MPI$^+$



Conclusions

- Maximum intensity occurs for:
  - inviscid flow (in radial direction)
  - pseudoadiabatic thermodynamics ($V_t \rightarrow \infty$)
- Explanation for E-MPI < v_{max} :
  - slantwise neutrality is not the source of the discrepancy
  - PBL closure is not the source of the discrepancy
  - gradient-wind and hydrostatic balance assumption *is* the source of the discrepancy
- MPI$^+$
  - A term associated with unbalanced flow explains the ~10-40% weak bias of E-MPI

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