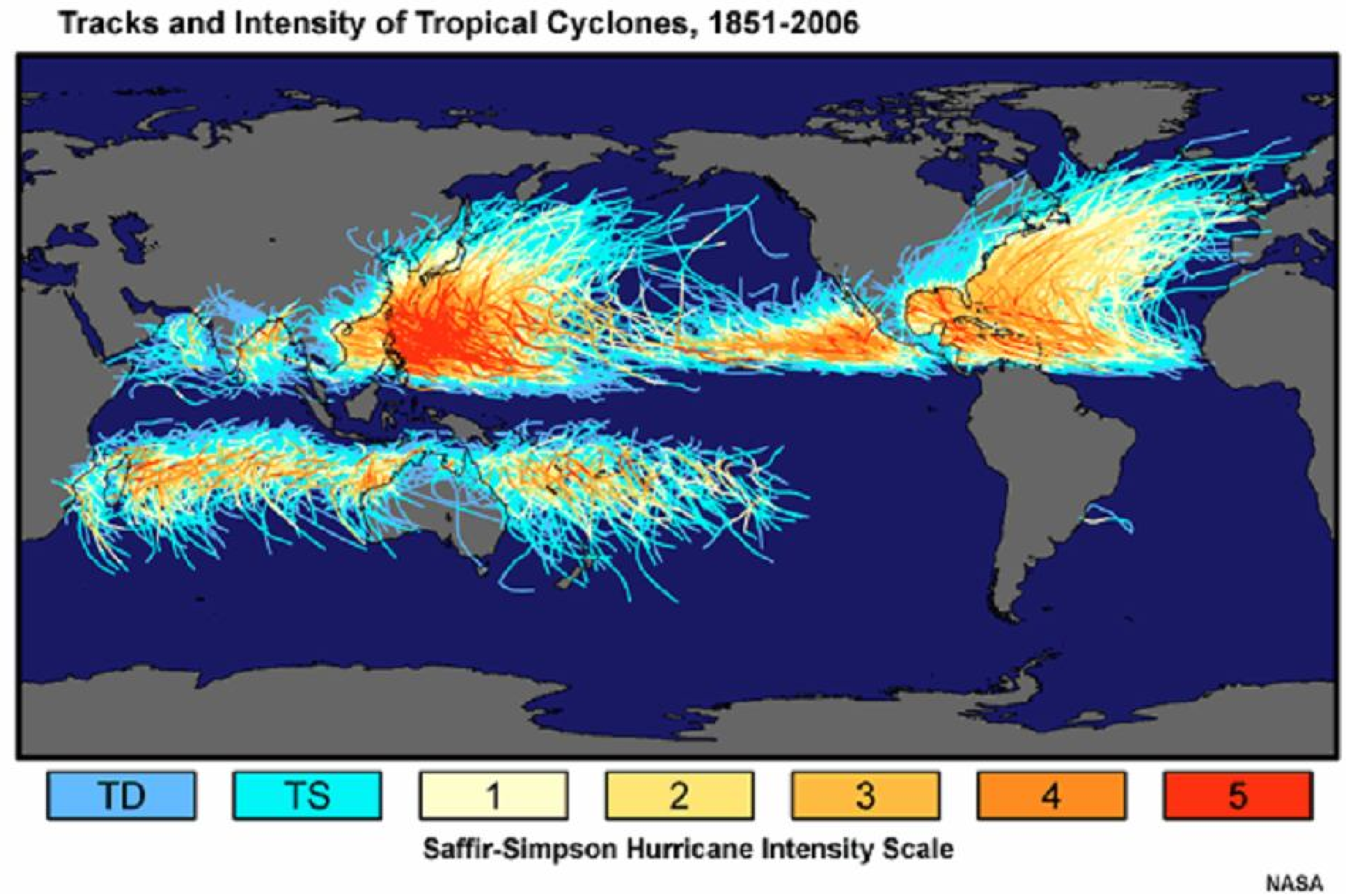
The maximum intensity of tropical cyclones in axisymmetric numerical model simulations

G. H. Bryan and R. Rotunno

Ivan Güttler
guettler@cirus.dhz.hr

Split, Croatia, 26. 5. 2009.

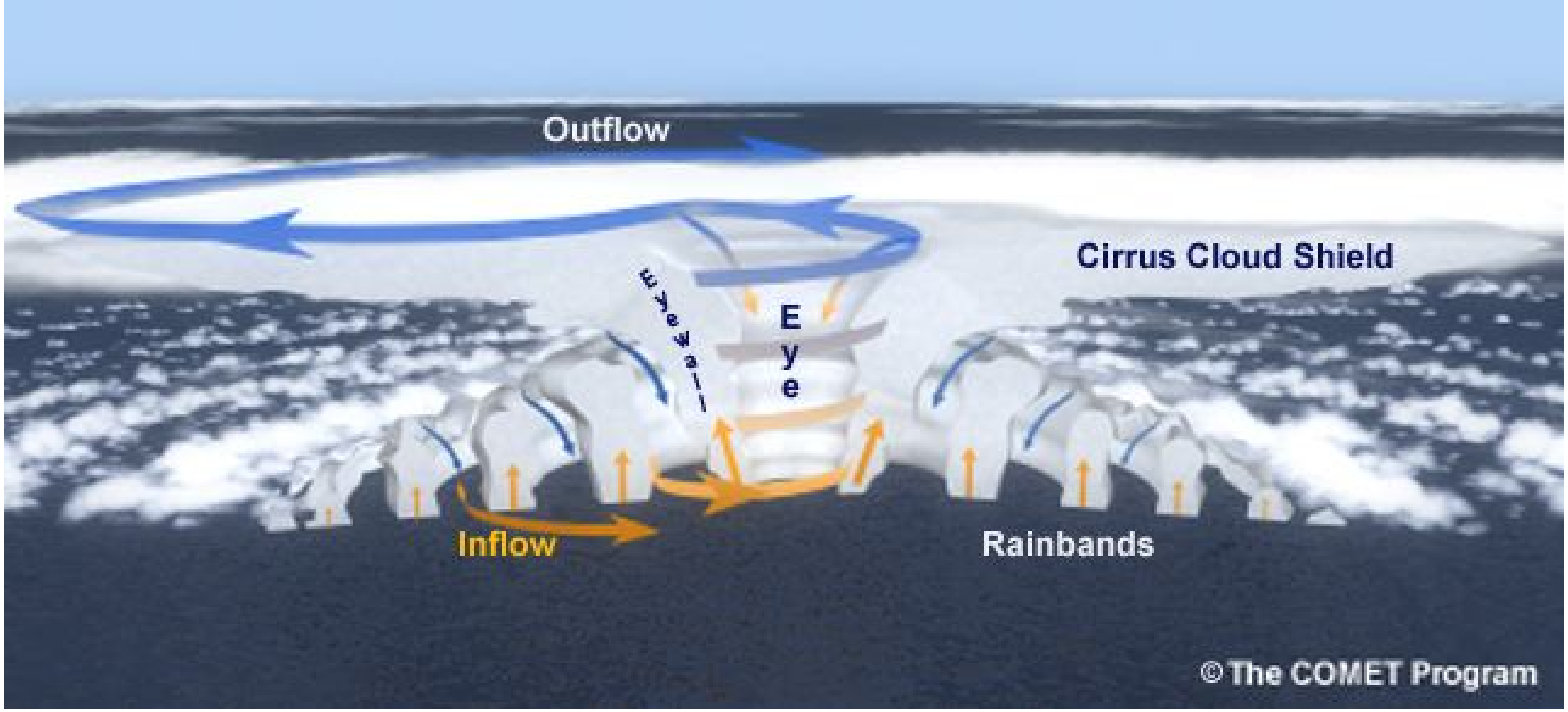
Introduction



Why are we interested in the maximum intensity of TCs?

1. real-time forecasting
2. hazard planning
3. consequences of climate change

Introduction



Approaches?

1. analytic approach
2. observational dataset
3. numerical models

Method

Sensitivity tests:

(1) grid spacing
(2) turbulence parameterization
(3) air-sea exchange coefficients
(4) microphysics parameterization
(5) governing equations
(6) ice microphysical processes
(7) water conservation
(8) domain size
(9) external lateral boundary conditions
(10) size and intensity of the initial vortex
(11) “precipitation mass sink” effect

Comparison with observations.

Model

1. nonhydrostatic
2. axisymmetric
3. compressible
4. improved mass and energy conservation → loss is less than 0.05%
5. inclusion of dissipative heating → increase in intensity by 20 %
6. time-dependent variables
    1. (u,v,w)
    2. π'
    3. θ
    4. q_v
    5. q_l

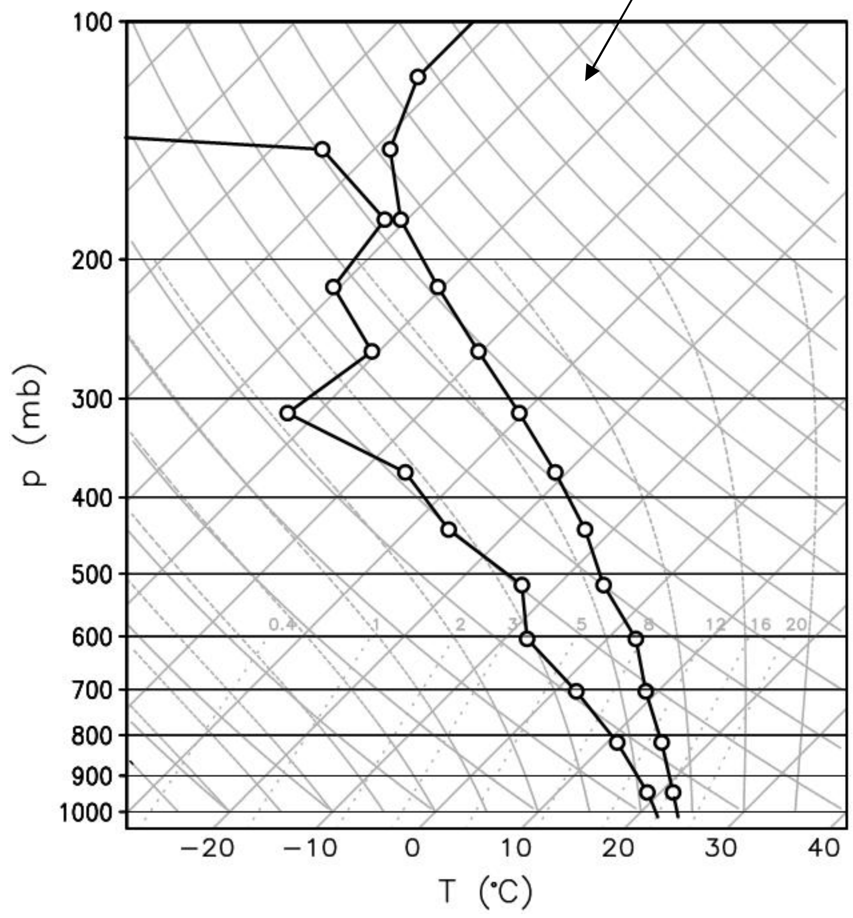
$$\nu_h S_h^2 + \nu_v S_v^2 - \nu_v N_m^2 = \epsilon$$

$$\epsilon_h = \nu_h^3/l_h^4 \qquad \epsilon_v = \nu_v^3/l_v^4$$

$$\nu_h = l_h^2 S_h \qquad \nu_v = l_v^2 \left(S_v^2 - N_m^2\right)^{1/2}$$

IB conditions

in RE87 “model neutral sounding”



SST = 26.13 °C

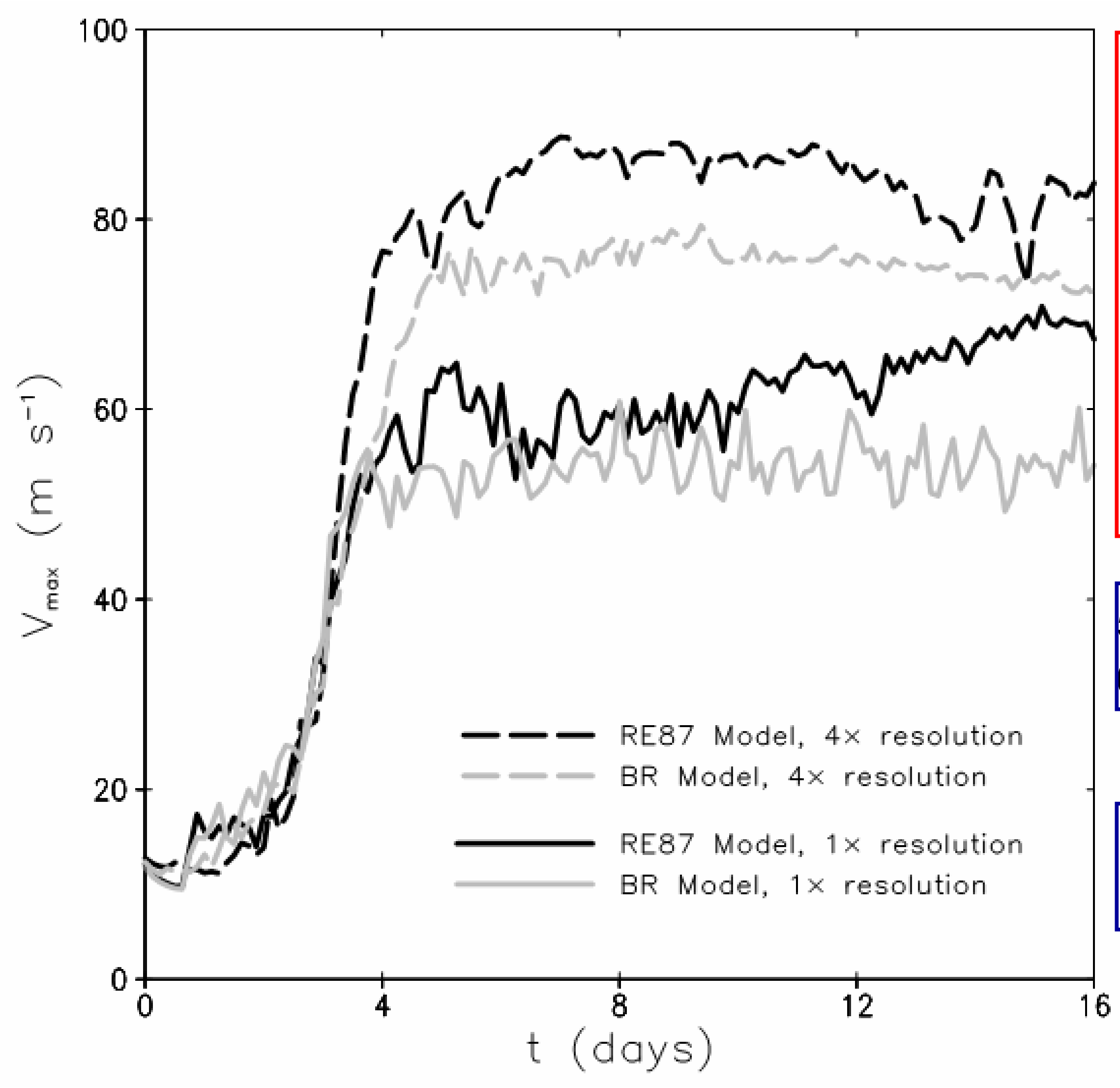
1500 km x 25 km

Δt = 7.5 s

Closed boundary condition with Newtonian damping

Intensity of initial vortex = 15 m/s

How to define maximum intensity?



(1) approx. steady state after approx. 6 days

(2) find maximum *v* in entire domain for each time step

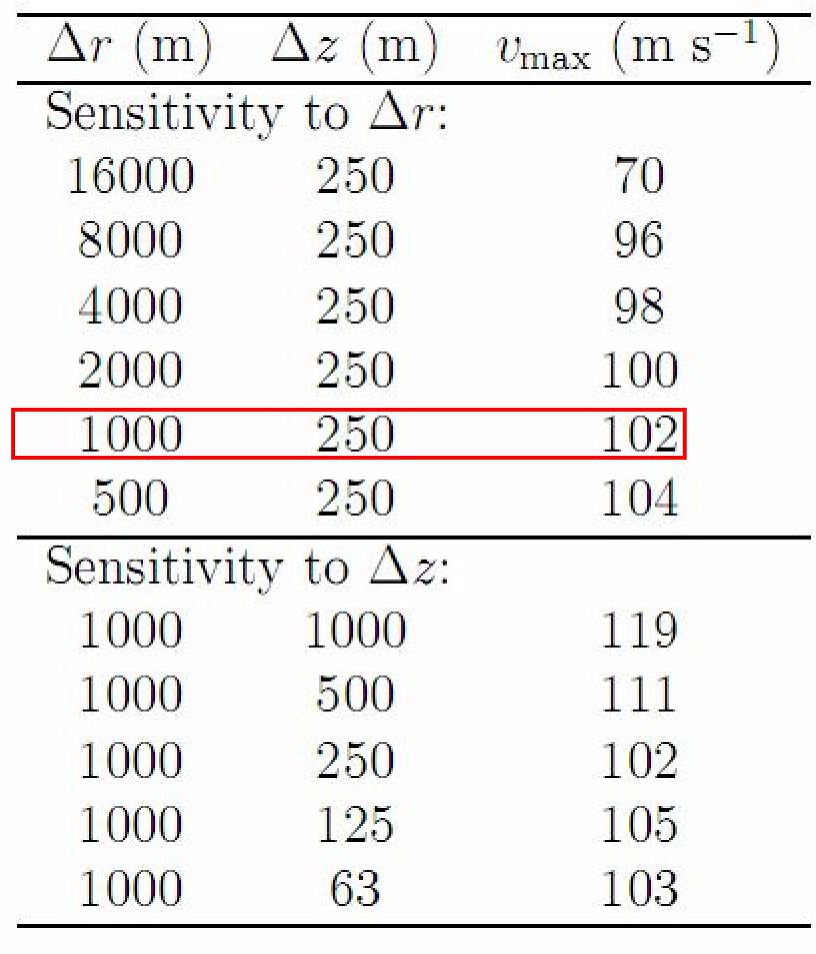
(3) make an average between t = 8 – 12 days

50 m/s
61.1 m/s

near surface

70 m/s for comparison

(1/5) Grid spacing



Δr (m)	Δz (m)	$v_{\max}$ (m s^{-1})
Sensitivity to Δr:		
16000	250	70
8000	250	96
4000	250	98
2000	250	100
1000	250	102
500	250	104
Sensitivity to Δz:		
1000	1000	119
1000	500	111
1000	250	102
1000	125	105
1000	63	103

l_h = 187.5 m
l_v = 50 m

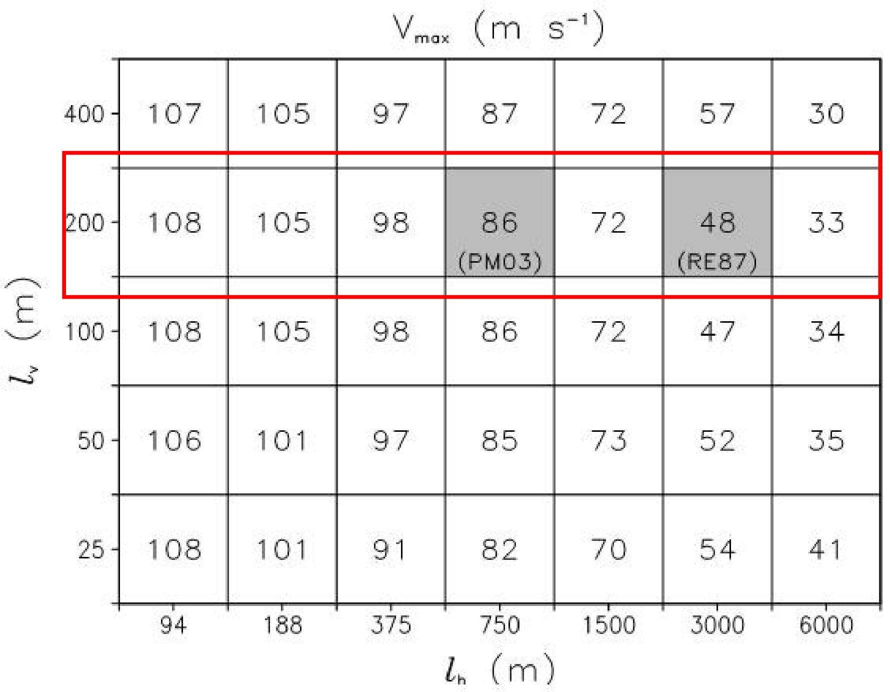
Lower Δr → higher $v_{\max}$

Lower Δz → lower $v_{\max}$

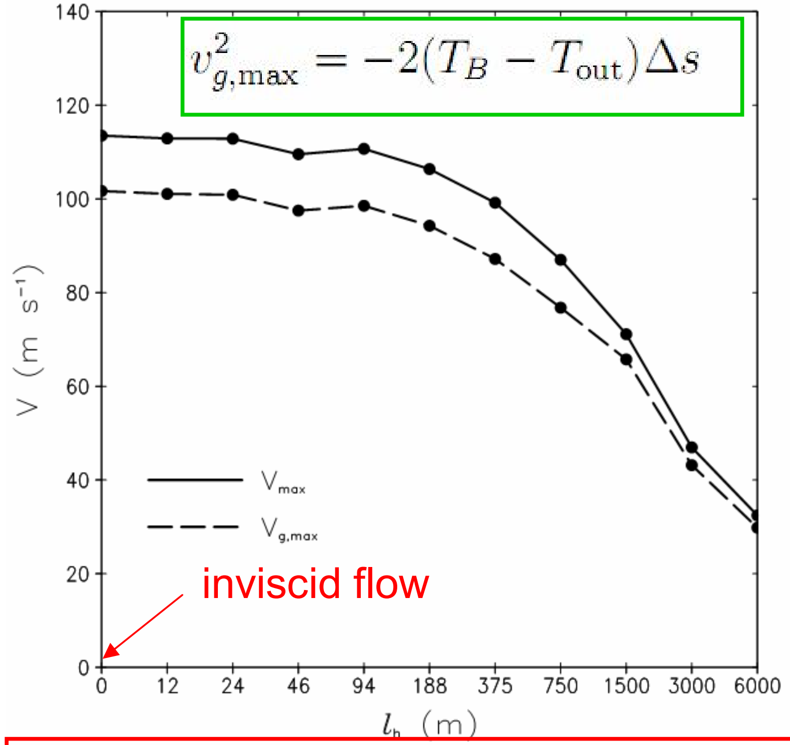
After additional tests:
Δr = 1 km if r < 64 km
Δr = 16 km for r = 1500 km

(2/5) Turbulence length scale

Configuration	Δr (km)	Δz (km)	Δt (s)	l_h (m)	l_v (m)
Default	1.0	0.25	7.5	(see text)	(see text)
1x (RE87)	15.0	1.25	20	3000	200
4x (PM03)	3.75	0.3125	5	750	200


V_{max} (m s^{-1})

l_v (m) \ l_h (m)	94	188	375	750	1500	3000	6000
400	107	105	97	87	72	57	30
200	108	105	98	86 (PM03)	72	48 (RE87)	33
100	108	105	98	86	72	47	34
50	106	101	97	85	73	52	35
25	108	101	91	82	70	54	41

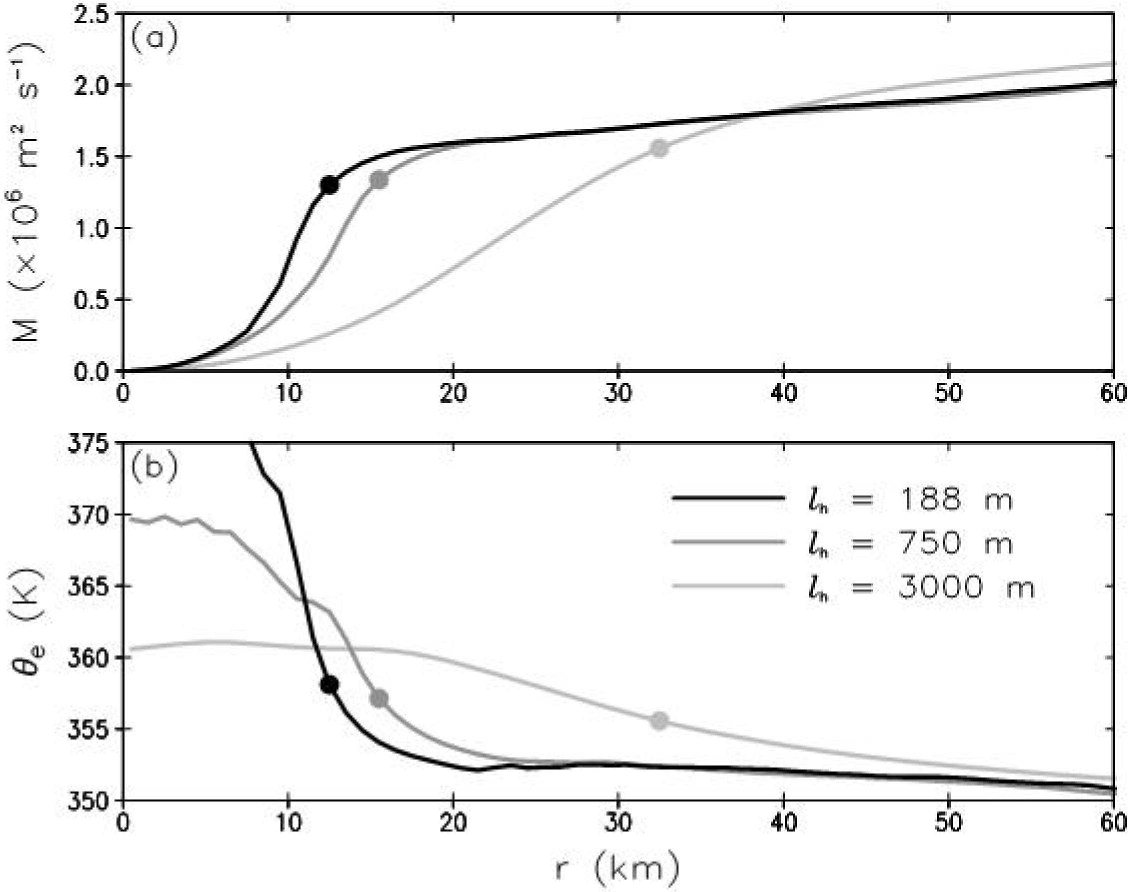

$$v^2_{g,\max} = -2(T_B - T_{\text{out}})\Delta s$$

inviscid flow

Additional tests:
(a) inviscid vs. truly inviscid model setup
(b) different l_h^s and l_h^m

(2/5) Turbulence length scale

$M \equiv rv + fr^2/2$ l_v = 200 m z = 1.1 km



l_h = 0 m
l_v = 200 m

Δr (m)	$v_{\max}$ (m s^{-1})	W (km)
16000	72	32.0
8000	97	16.0
4000	113	8.0
2000	110	8.0
1000	114	9.0
500	114	8.5
250	114	8.5

(2/5) Turbulence length scale

$v_{\max}$ = 48 m/s

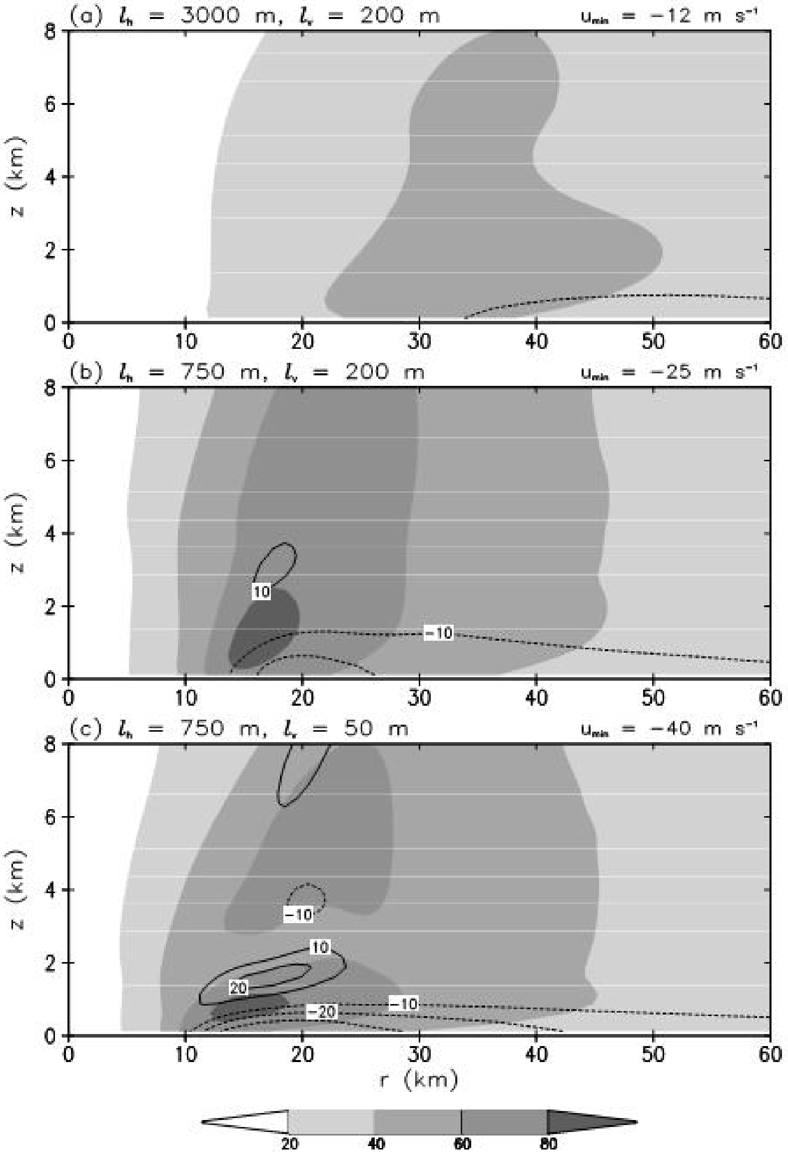
$u_{\max}$ = 12 m/s

$v_{\max}$ = 86 m/s

$u_{\max}$ = 25 m/s

$v_{\max}$ ≈ 86 m/s

$u_{\max}$ = 40 m/s



$v_{\max}$ =70 m/s
LeeJoice (2000)
Bell and Montgomery (2008)
Kepert (2006)

(2/5) Turbulence length scale - summary

If $l_h \rightarrow 0$ m **then** maximum intensity **but** unnatural

If $l_h \approx 3000$ m **then** there is no setup that produces intensity greater than 70 m/s

Gradient of moist entropy in the eyewall $\boxed{\boxed{-1.7 \times 10^{-3}\ \mathrm{m\ s^{-2}\ K^{-1}}}}$

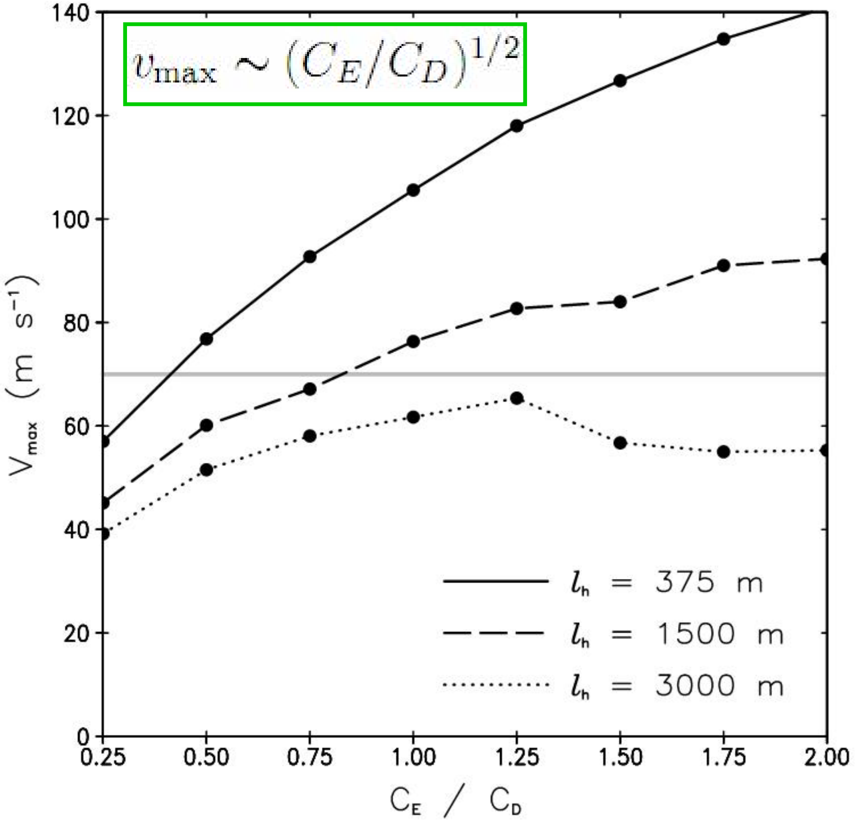
After the comparison with observations $\boxed{l_h \approx 1500\ \mathrm{m}}$ and $\boxed{l_v \approx 100\ \mathrm{m}}$ seems appropriate.

(3/5) Ratio of surface exchange coefficients

Simulations and theory → maximum intensity very sensitive to C_E/C_D

Observations → $0.5 < C_E/C_D < 1.5$

→ $C_E = 1.2 \times 10^{-3}$



$$v_{\max} \sim (C_E/C_D)^{1/2}$$

$$v_{\max} \sim (C_E/C_D)^{0.44}$$

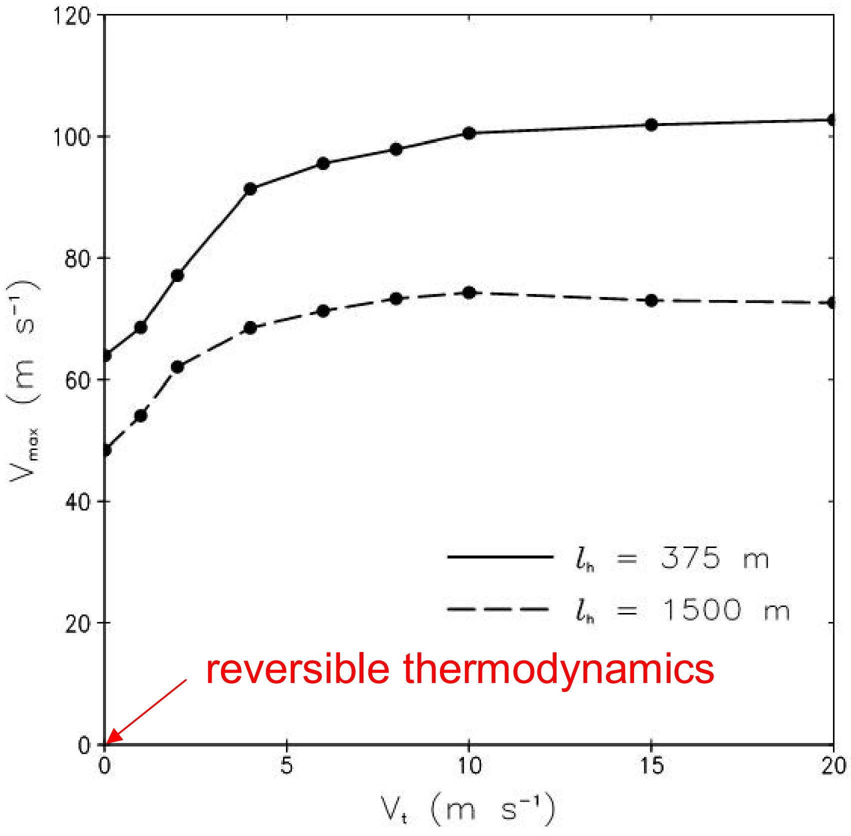
$$v_{\max} \sim (C_E/C_D)^{0.53}$$

$$v_{\max} \sim (C_E/C_D)^{0.34}$$

$$v_{\max} \sim (C_E/C_D)^{0.31}$$

(4/5) Liquid water fall velocity

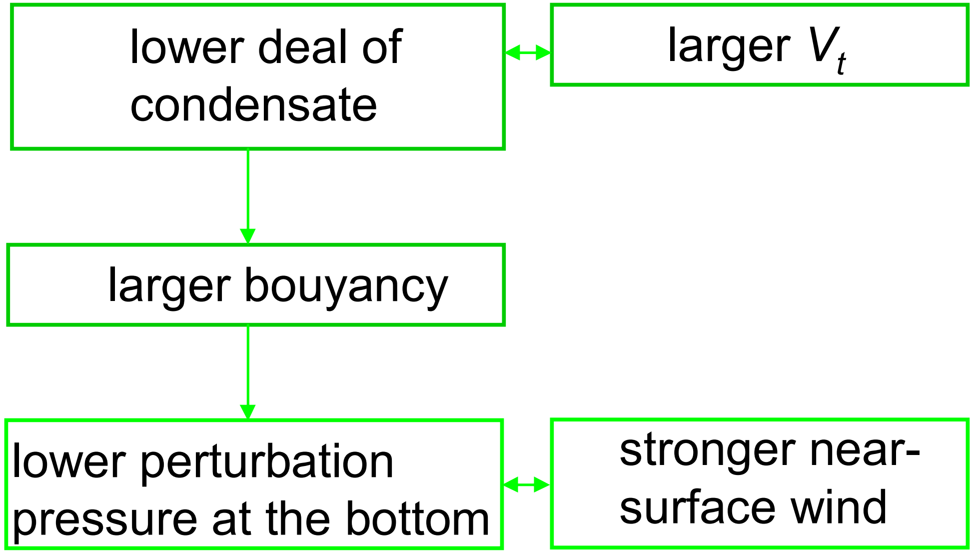
If $q_l > 1$ g/kg **then** liquid falls with V_t



reversible thermodynamics

Additional tests:

(a) $V_t \sim q_l$
(b) ice processes
(c) pseudoadiabatic process



lower deal of condensate

larger V_t

larger bouyancy

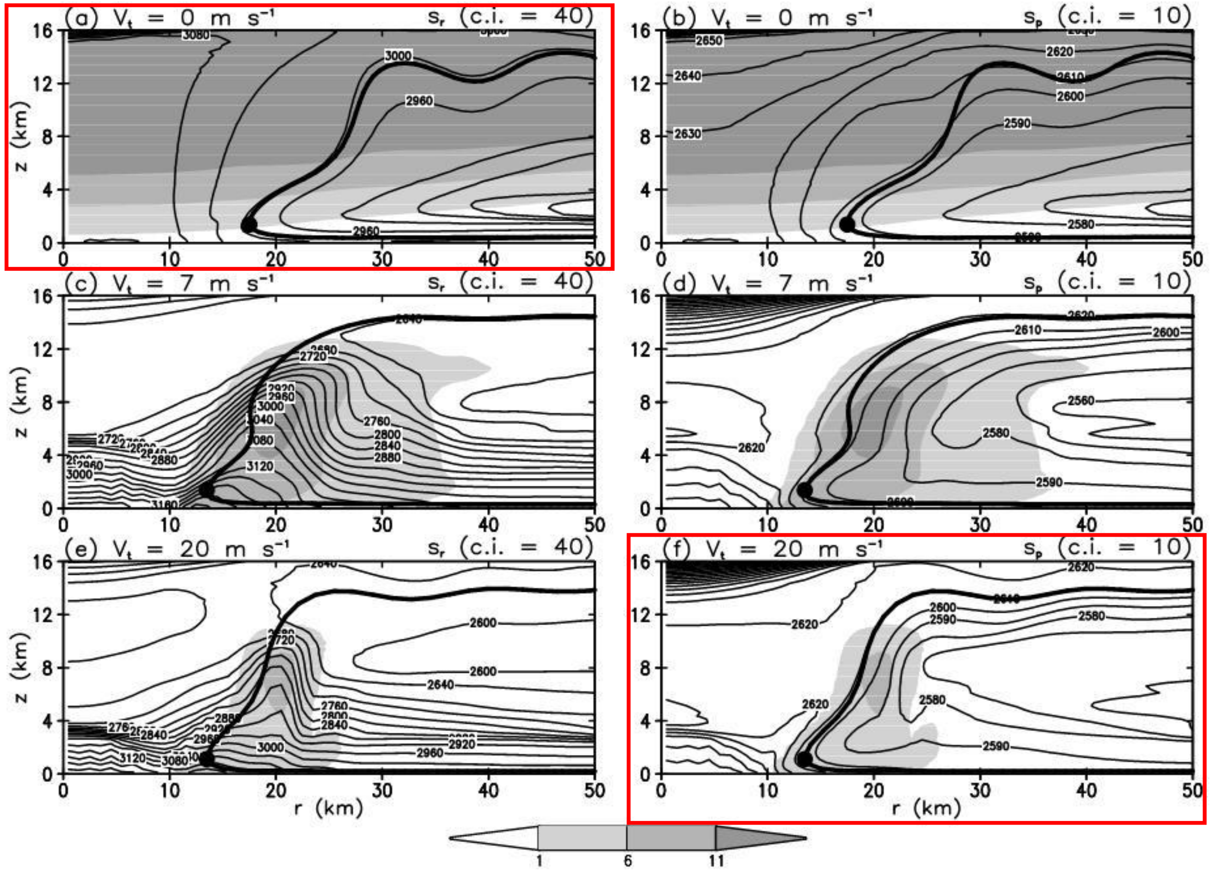
lower perturbation pressure at the bottom

stronger near-surface wind

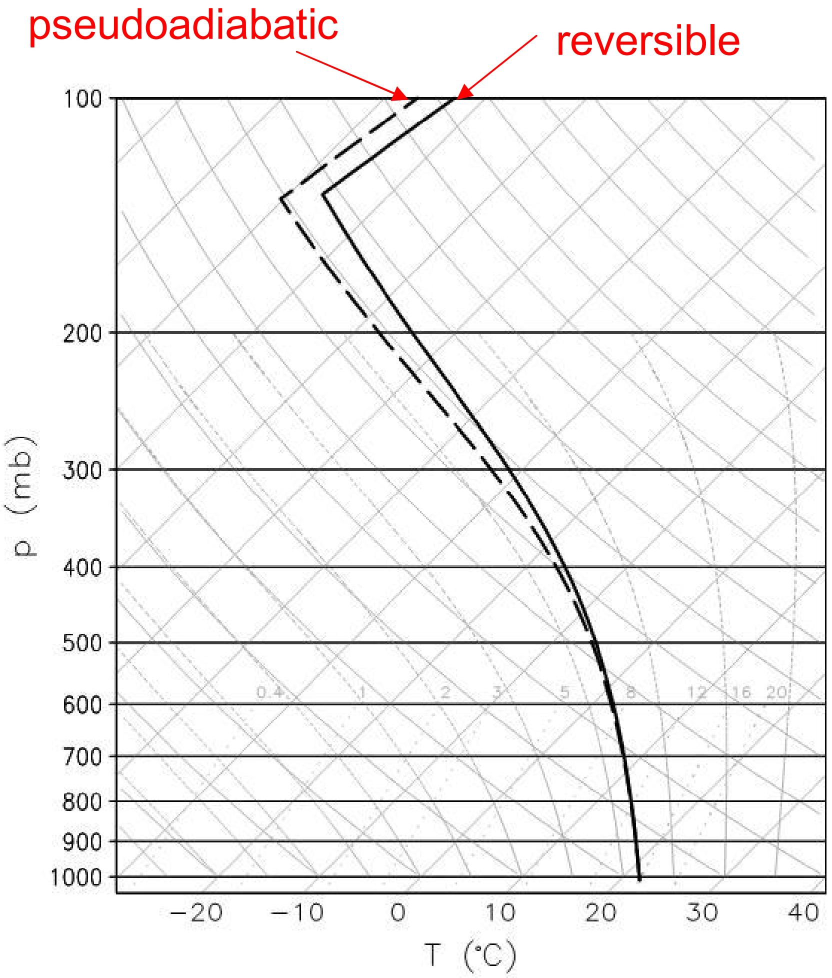
(4/5) Liquid water fall velocity

$$V_t = 0 \qquad s_r = (c_p + c_l r_t)\ln T - R_d \ln p_d + \frac{L_v q_v}{T} - R_v q_v \ln(\mathcal{H})$$

$$V_t \to \infty \qquad s_p = c_p \ln T - R_d \ln p_d + \frac{L_0 q_v}{T} - R_v q_v \ln(\mathcal{H})$$



(4/5) Liquid water fall velocity


pseudoadiabatic

reversible

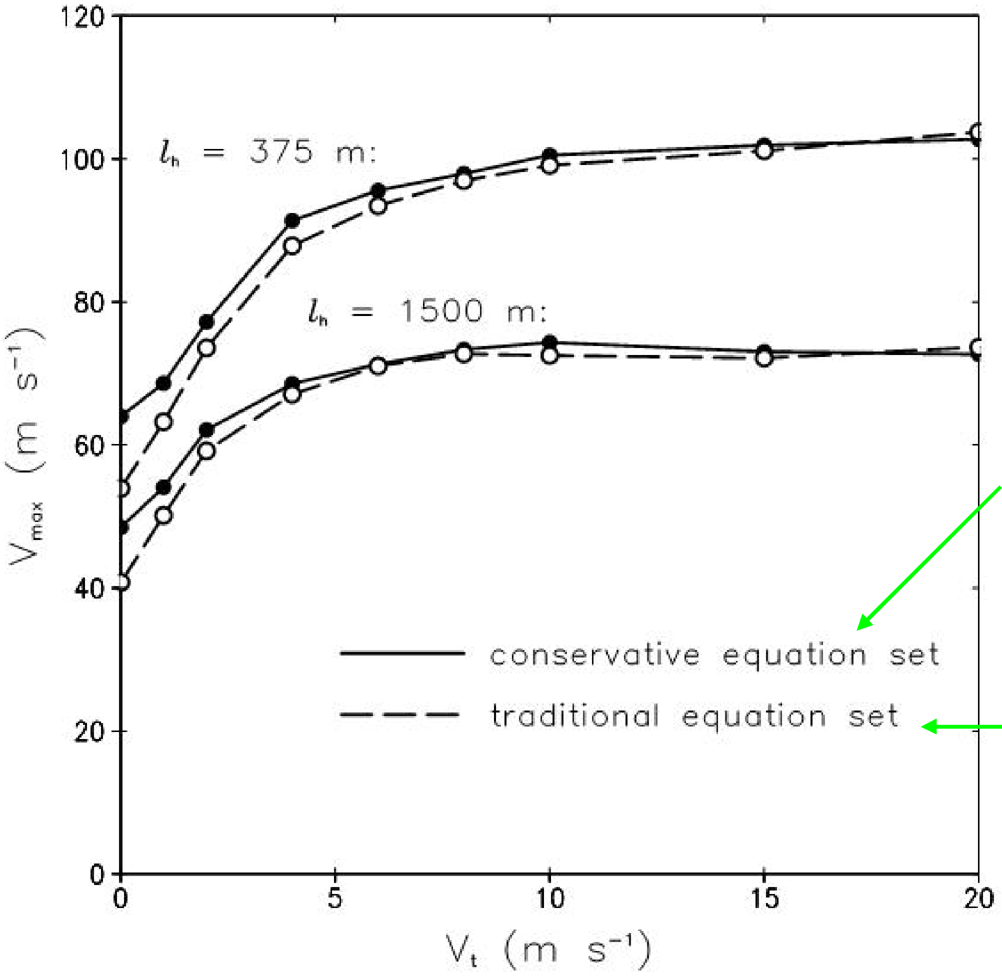
CAPE = 0

θ_e same as before

$l_h = 375$ m

Setup: sounding/thermodynamics	$v_{\max}$ (m s^{-1})
control / reversible	64
control / pseudoadiabatic	103
reversible / reversible	40
pseudoadiabatic / pseudoadiabatic	104

(5/5) Equation set



internal energy for moist flow conserved

pseudoadiabatic assumption

Summary

Maximum intensity occurs when:

(1) Δr = 1 km or less and Δz= 250 m or less

(2) inviscid flow in the radial direction → unnatural structures

(3) pseudoadiabatic thermodynamics (V_t ~ 10 m/s and greater) → not applicable

(4) conservative set of equations

- Greatest sensitivity to the specification of turbulence intensity.
- $l_h \approx 1500$ m and $l_v \approx 100$ m are reasonable settings.
- Less sensitivity to C_E/C_D than theory predicts for greater intensity of turbulence.

Thank you for your attention!