Smoke-cloud case revisited

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Laboratory simulations of radiatively induced entrainment in stratiform clouds

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$$w_e / w_i^* = 0.25 Ri_I^{-1}.$$

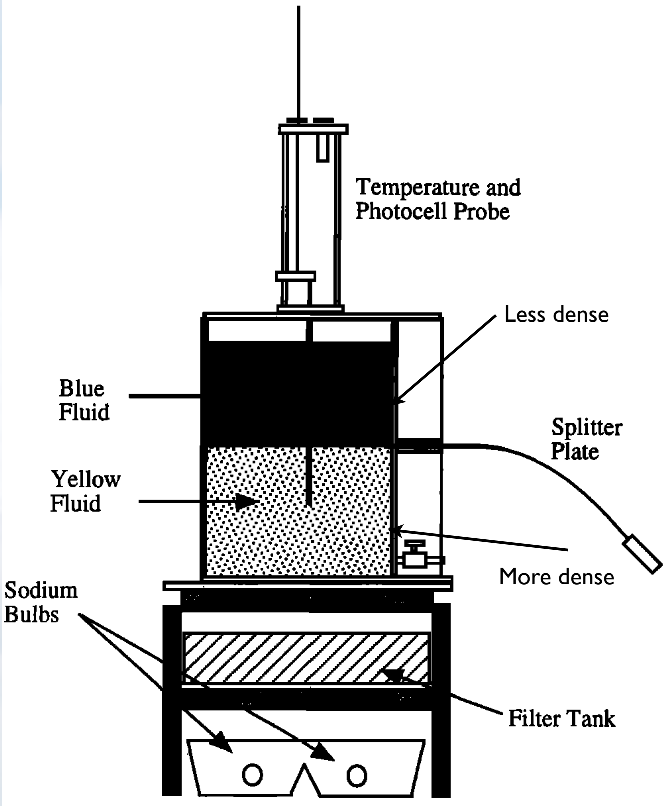
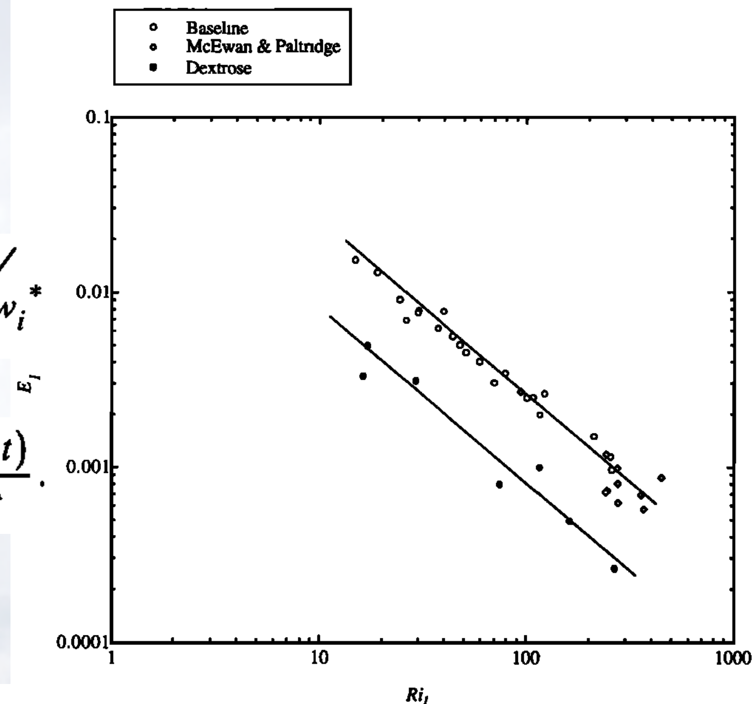


Figure 2. Experimental apparatus.



$$w_e / w_i^*$$

$$w_e \equiv \frac{dh(t)}{dt}.$$

$$w^* \propto (Qh)^{1/3}$$

$$Ri_i = \frac{g'h}{(w_i^*)^2},$$

Motivation: Can LES reproduce lab results (A=0.2-0.3)?

TABLE 3. 2–3 HOUR AVERAGES OF SELECTED MODEL PARAMETERS (MKS UNITS) DESCRIBED IN TEXT

CODE	$w_e * 10^3$ (mm s^{-1})	$\sqrt{\mathrm{TKE}_{\mathrm{blav}}}$ (m s^{-1})	w_* (m s^{-1})	A	F_{above} (W m^{-2})
UKMO-M	2.20	0.743	0.948	0.47	0
CSU	2.90	0.698	0.908	0.70	0
WVU	2.89	0.686	0.890	0.74	0
ARAP	2.58	0.687	0.917	0.60	0
NCAR	2.85	0.744	0.885	0.76	6
UKMO-M	3.16	0.632	0.825	1.01	0
MPI	3.80	0.618	0.801	1.33	0
CSU	3.39	0.633	0.772	1.32	0
UOK	3.19	0.647	0.797	1.12	0
IMAU	3.66	0.577	0.749	1.55	0
UW	2.57	0.594	0.889	0.64	12
SB	3.11	0.561	0.864	0.86	0
WVU	4.64	0.560	0.714	2.27	0
ARAP	3.42	0.563	0.771	1.32	0
UKMO-N	2.05	0.697	0.956	0.43	3
NCAR	3.62	0.679	0.839	1.13	4
MNH	4.25	0.572	0.789	1.58	1
CU	3.25	0.696	0.838	1.01	6
CU-NL	3.45	0.688	0.852	1.02	6
UKMO-M	4.81	0.884	0.639	3.29	0
CSU	5.58	0.821	0.529	6.75	0
UW	4.65	0.863	0.764	1.82	8
AERO	6.07	0.457	0.557	6.31	0
AERO-HI	4.81	0.531	0.700	2.54	0
MNH	4.59	0.470	0.722	2.22	0

Blank lines separate groups of runs, in the order 3-DH, 3-DM, 3-DN, 2-D and 1-D.

$$\boxed{\frac{w_e}{w_*} = \frac{A}{R_i}}$$

Smoke-cloud Case Setup

LES Model: SAM 6.7.5

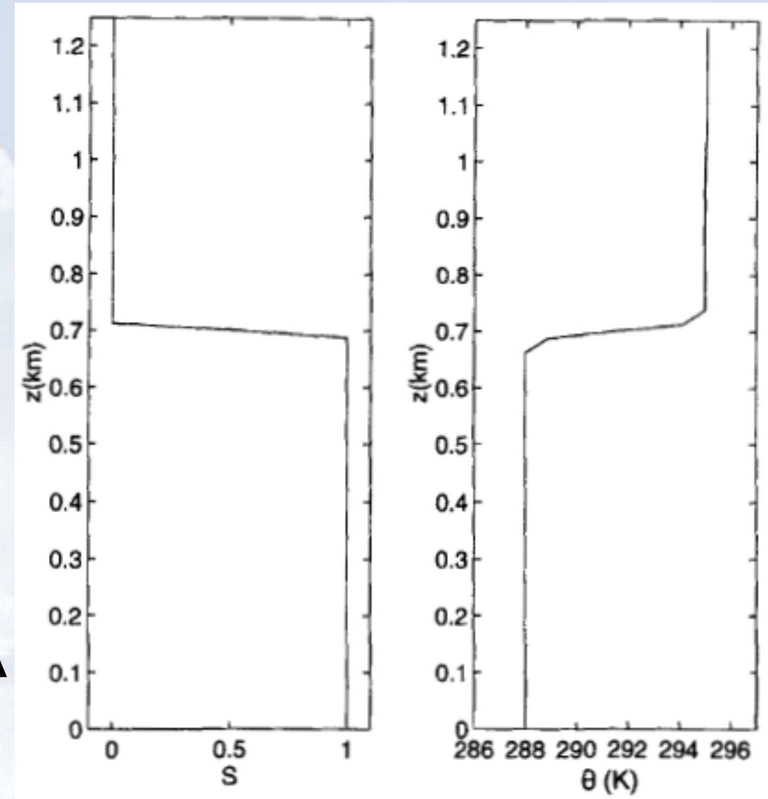
Domains/Grids:

Δx=10 m, Δz=5m, Δt = 1s, 512x512x300
Δx=5 m,   Δz=2-5m, Δt=0.5s, 1024x1024x300
Δx=5 m,   Δz=1-5m, Δt=0.5s, 1024x1024x400

Smoke concentrations: 0.5, 1.0, 2.0, 3.0

Δ

Δ



From Stevens and Bretherton (1999)

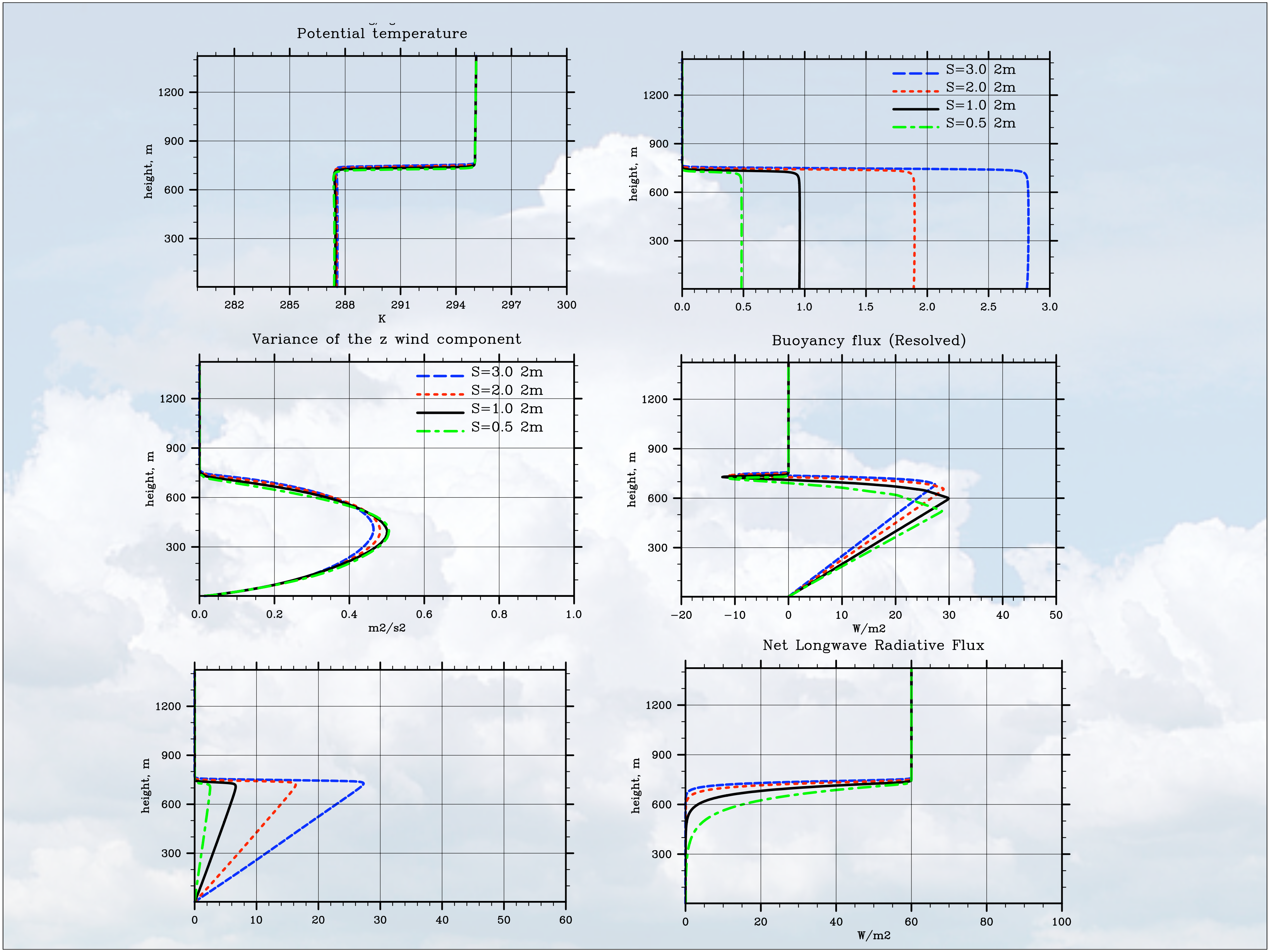
Radiation Forcing:

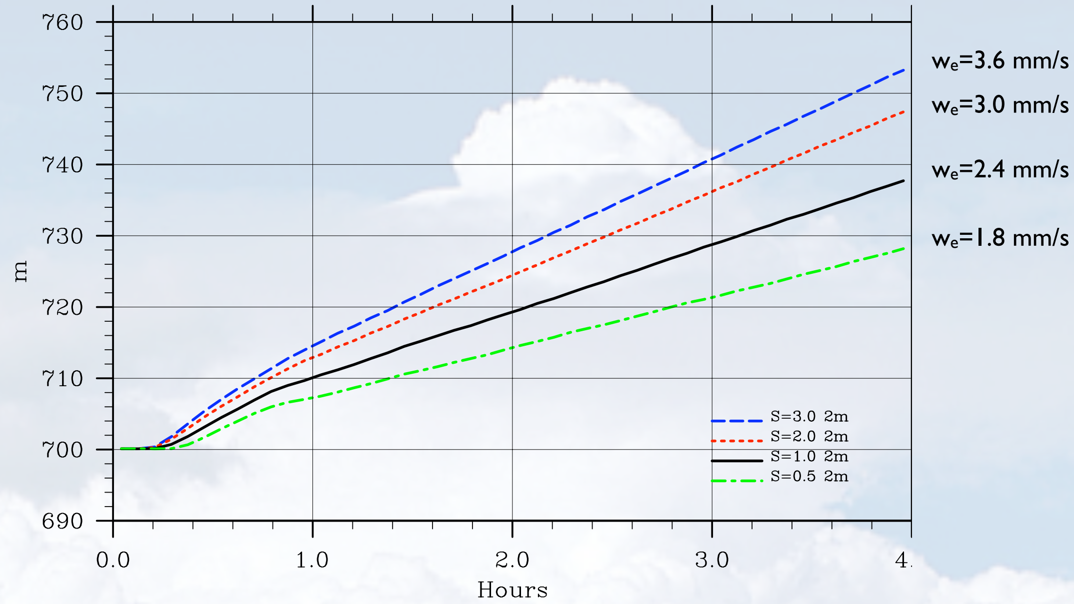
$$F(z) = F_0 \exp(-\tau_s(z))$$

$$\tau_s(z) = K_a \int_z^H \rho_0 S(z)\,dz$$

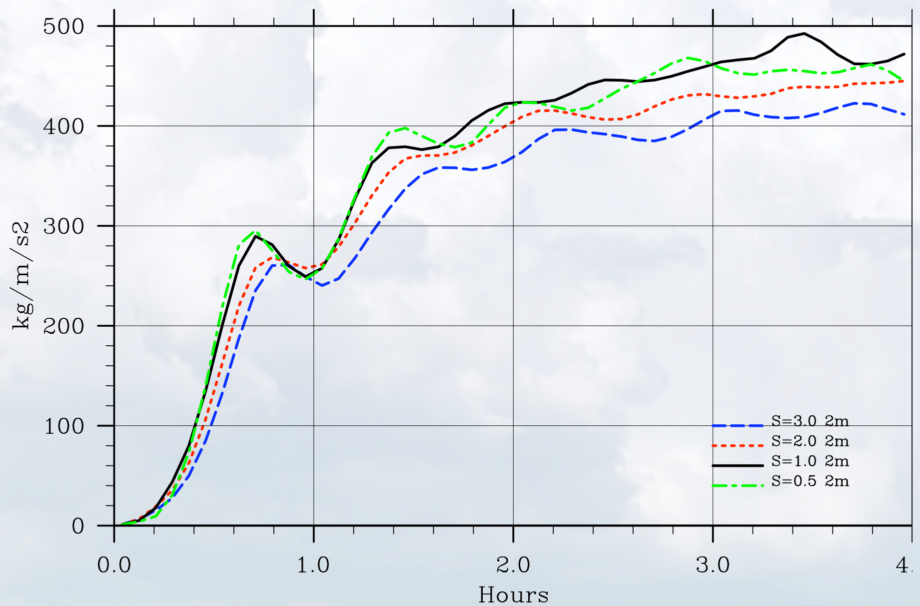
$$K_a = 0.02 m^2 kg^{-1}$$

Computer: BlueGene/L ‘New York Blue’
at Stony Brook University/Brookhaven NL

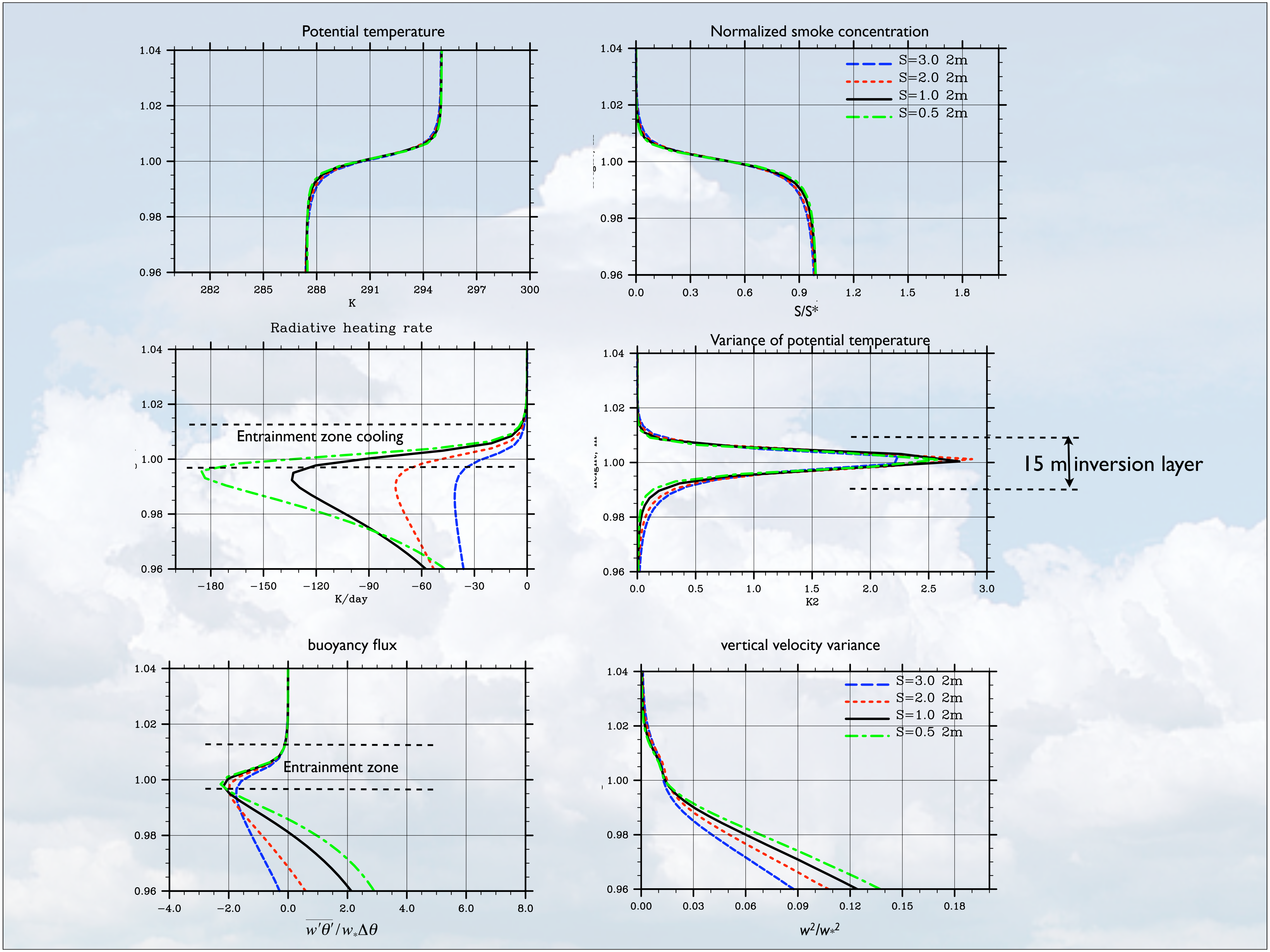

Potential temperature
height, m
K
282
285
288
291
294
297
300
300
600
900
1200
S=3.0 2m
S=2.0 2m
S=1.0 2m
S=0.5 2m
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Variance of the z wind component
m2/s2
0.2
0.4
0.6
0.8
Buoyancy flux (Resolved)
W/m2
−20
−10
0
10
20
30
40
50
60
Net Longwave Radiative Flux
80
100

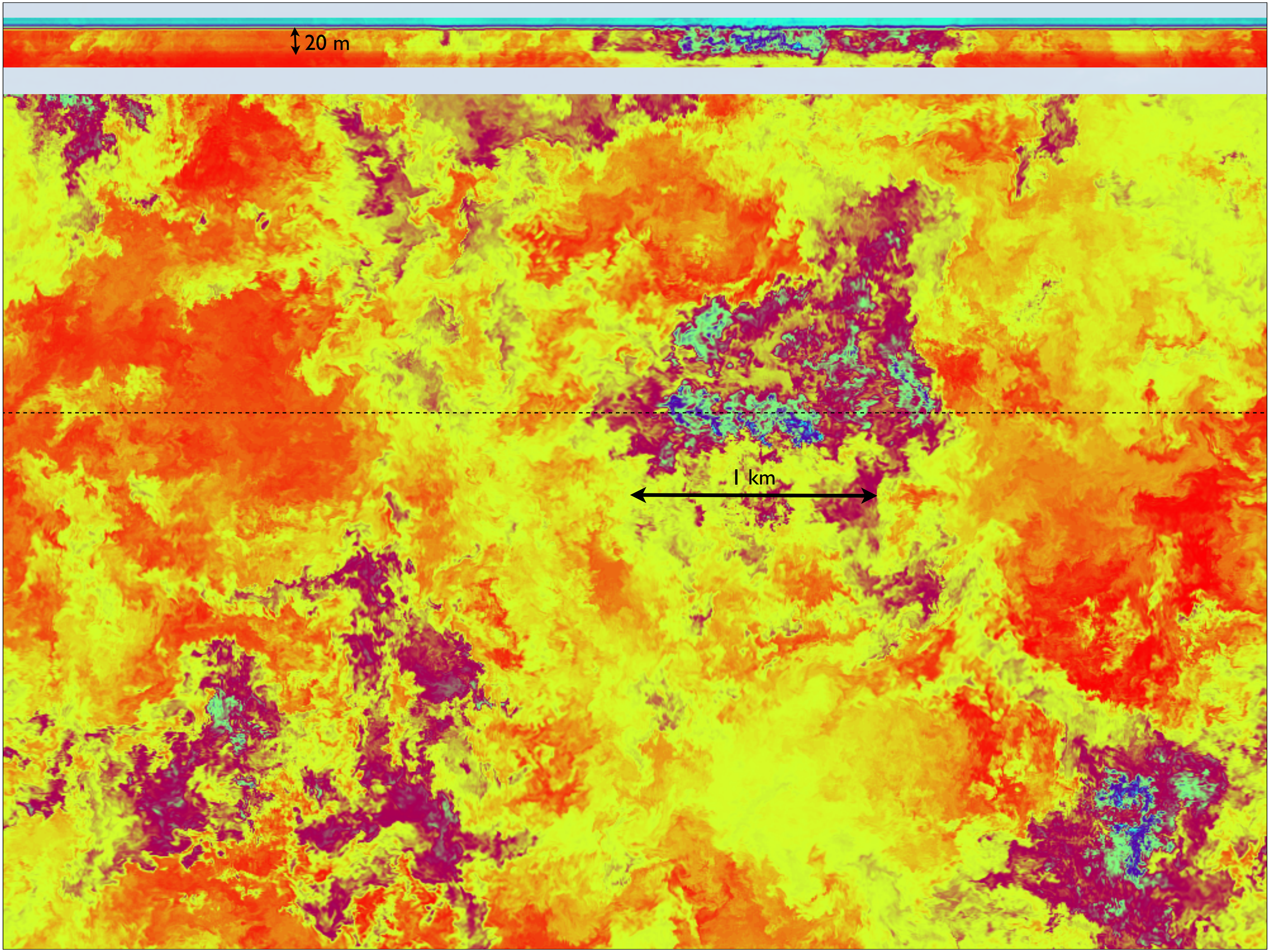


760
750
740
730
720
710
700
690
m
0.0
1.0
2.0
3.0
Hours
w_e=3.6 mm/s
w_e=3.0 mm/s
w_e=2.4 mm/s
w_e=1.8 mm/s
S=3.0 2m
S=2.0 2m
S=1.0 2m
S=0.5 2m



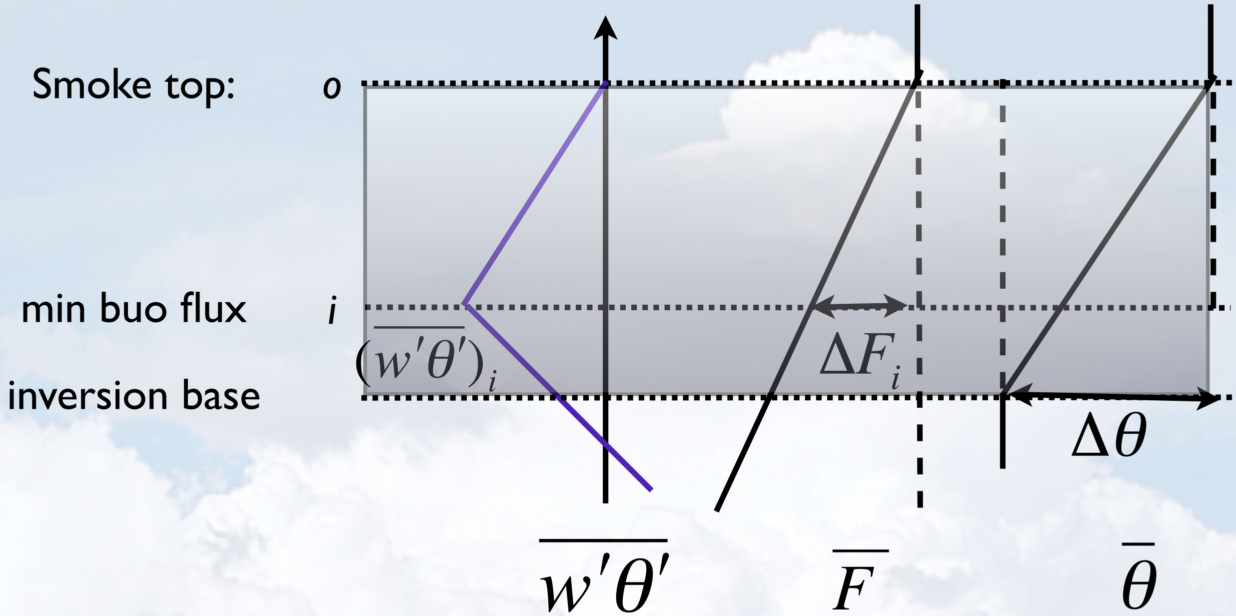
500
400
300
200
100
0
kg/m/s2
0.0
1.0
2.0
3.0
Hours
S=3.0 2m
S=2.0 2m
S=1.0 2m
S=0.5 2m


Potential temperature
K
Normalized smoke concentration
S=3.0 2m
S=2.0 2m
S=1.0 2m
S=0.5 2m
S/S*
Radiative heating rate
Entrainment zone cooling
K/day
Variance of potential temperature
K2
15 m inversion layer
buoyancy flux
Entrainment zone
$\overline{w'\theta'}/w_*\Delta\theta$
vertical velocity variance
S=3.0 2m
S=2.0 2m
S=1.0 2m
S=0.5 2m
w^2/w_*^2


20 m
1 km

Effect of radiation on entrainment efficiency.

Deardorff (1981), Moeng (1999), Lock and McVean (1999), ...



$$\left(\frac{\partial z_i}{\partial t} - w_s\right)\left(\overline{\theta}_o - \overline{\theta}_i\right) = -(\overline{w'\theta'})_i + \frac{\Delta F_i}{\rho c_p}$$

$w_s = 0$ No subsidence $\overline{\theta}_o - \overline{\theta}_i = \eta\Delta\theta$ $0 \le \eta \le 1$

$\eta \approx 0.7 - 0.8$

$$\boxed{w_e \eta \Delta\overline{\theta} = -(\overline{w'\theta'})_i + \frac{\Delta F_i}{\rho c_p}}$$

$$w_e \equiv \frac{\partial z_i}{\partial t}$$

$$w_e \eta \Delta\bar{\theta} = -(\overline{w'\theta'})_i + \frac{\Delta F_i}{\rho c_p}$$

$$-(\overline{w'\theta'})_i = A' \frac{2.5}{z_i} \int_o^{z_i} \overline{w'\theta'} dz$$ (Closure)

$$w_* = \left(2.5\beta \int_o^{z_i} \overline{w'\theta'} dz \right)^{1/3}$$ Deardorff (1980)

$$R_i = \frac{\beta z_i \Delta\theta}{w_*^2}$$

$$\boxed{\frac{w_e}{w_*} = \frac{A}{R_i}}$$

$$\boxed{A = A' \frac{1}{\eta} \left(1 + \frac{R_i \Delta F_i}{\rho c_p w_* \Delta\theta} \right)}$$

$$\boxed{A = A' \frac{1}{\eta} \left(1 + \frac{\Delta F_i}{F_0} \right)}$$

$$\frac{R_i \Delta F_i}{\rho c_p w_* \Delta\theta} = \frac{\Delta F_i}{\rho c_p w_* \Delta\theta} \times \frac{\beta z_i \Delta\theta}{w_*^2} = \frac{\tau_c}{\tau_{rad}} = \frac{\Delta F_i}{F_i w_*^3} \times \frac{\beta F_i z_i}{\rho c_p} = \frac{\Delta F_i}{F_i w_*^3} w_*^3 = \frac{\Delta F_i}{F_0}$$

$$\tau_{rad} = \frac{1}{\rho c_p} \frac{\Delta F_i}{\Delta z_u} \Big/ \Delta\theta$$

inversion radiation heating time scale

$$\Delta z_u = \frac{w_*^2}{\beta \Delta\theta}$$

inversion scale

$$\tau_c = z_i / w_*$$

convective overturning time-scale

Case	Hor. Res m	Vert. Res inversion m	Time Step s	S	W_e mm/s	W_* m/s	Ri	A	A’	ΔF_i W/m2	η
HiRes1.0	5	1	0.5	1.0	2.0	0.96	202	0.42	0.32	4.4	0.84
MidRes0.5	5	2	0.5	0.5	1.8	0.93	218	0.43	0.33	3.1	0.78
MidRes1.0	5	2	0.5	1.0	2.5	0.94	213	0.57	0.36	5.5	0.77
MidRes2.0	5	2	0.5	2.0	3.0	0.93	217	0.70	0.45	7.0	0.72
MidRes3.0	5	2	0.5	3.0	3.6	0.91	226	0.89	0.53	10.9	0.84
LowRes1.0	10	5	1.0	1.0	3.0	0.91	226	0.74	0.47	6.8	0.76

- **No conversion of 2 m and 1 m vertical resolution results**

Conclusions

- Strong sensitivity of the entrainment velocity and entrainment efficiency parameter to the entrainment zone radiative cooling shown by earlier studies with coarser grids is confirmed;

- Different entrainment rates for 4 different smoke concentrations occur at similar characteristics of turbulence in the entrainment zone which suggests that most of variation in the entrainment rates among the cases is due to different radiative cooling above the level of minimum buoyancy;

- High-resolution simulations of the smoke-cloud GCSS case up to 1 m vertical resolution and 5 m horizontal show no convergence of the entrainment velocity;