Entrainment in Cumulus Clouds
What Resolution is Cloud-Resolving?

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with thanks to ECMWF, DWD

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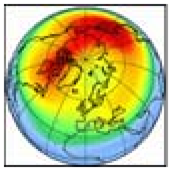
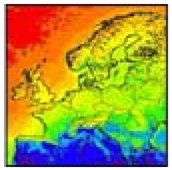
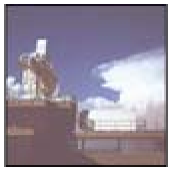



Motivation - Cloud-Resolving Models?

- NWP is moving to a horizontal resolution of 1-3 km.
- Why? To turn off the cumulus parameterisation.
- But, 1-3 km obviously doesn't resolve cumulus clouds.

So...

1. What resolution does resolve convection?
2. What is the scale of eddies that mix cloud and environmental air?
3. Is there a large-eddy regime for simulations of convection (bulk properties independent of subgrid closure)?

What result should simulations of convection give?

What mixing parameterisation do 1-3 km models need?

The Buoyant Thermal

Warm bubble in neutrally stratified atmosphere

For H >> D^o, initial bubble shape forgotten - self-similar

One parameter: total buoyancy, $Q = \int g \frac{T'}{T_o} dV$

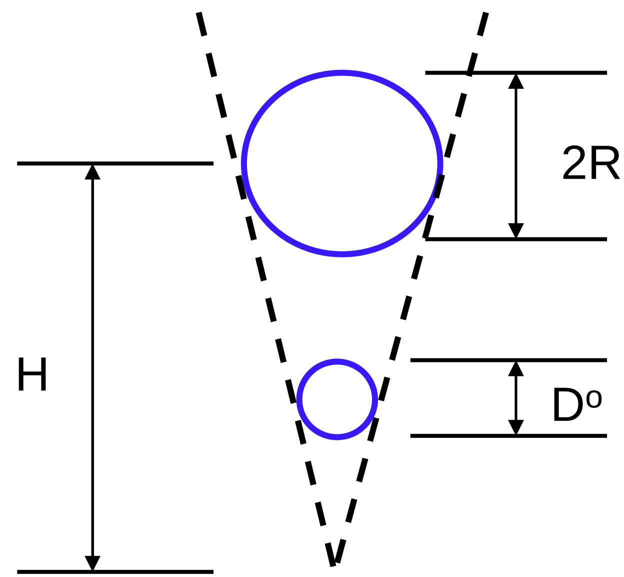
Solution:

- Radius $R = aQ^{1/4}t^{1/2}$
- Height $H = bQ^{1/4}t^{1/2}$
- Volume $V = cQ^{3/4}t^{3/2}$

(a, b, c constants)

Linear growth with height:

$R = (a/b)H \sim (0.1)H$



Required resolution: resolve bubble size, initially D^o

Thermal in a Stratified Environment

New length scale - height bubble can rise

$L_{buoy} = \Delta T^o / \Delta\Gamma$, where $\Delta\Gamma = dT/dz + g/c_p$

If $L_{buoy} >> D^o$, bubble still self-similar, and size increase (entrainment) still proportional to distance

This "entrainment hypothesis" is used in most cumulus parameterisations

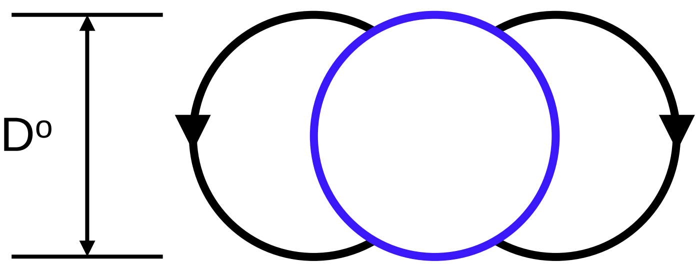
Required resolution is still D^o (e.g. Bryan et al. 2003)

But, for a cumulus cloud, Do ~ 1km and $\Delta T^o \sim 1$ K, $\Delta\Gamma \sim 3$ K/km, so $L_{buoy} \sim 333$m

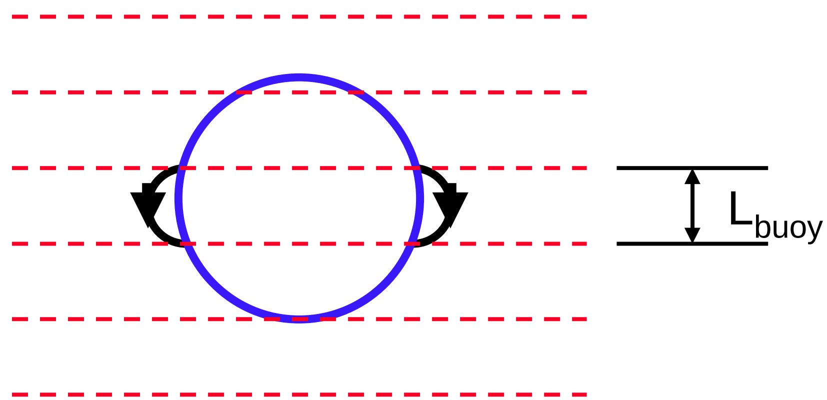
L_{buoy} is smaller than D^o!

A Moist Thermal (Stiller and Craig 2001)

- Warm saturated bubble in a moist adiabatic environment
- Height bubble can rise is unrestricted (in the absence of mixing) due to latent heat release
- Stratification limits scale of eddies that cross cloud boundary to L_{buoy}

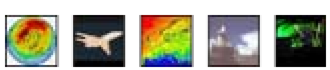


Dry thermal



Moist thermal

Required resolution: L_{buoy}



Do Simulations Converge for D^o or L_{buoy}?

Model:

- EULAG (Smolarkiewisz et al.)
- MP-DATA flux-corrected advection; no explicit diffusion
- Kessler microphysics (vapour, cloud water, rain)

Initial Conditions:

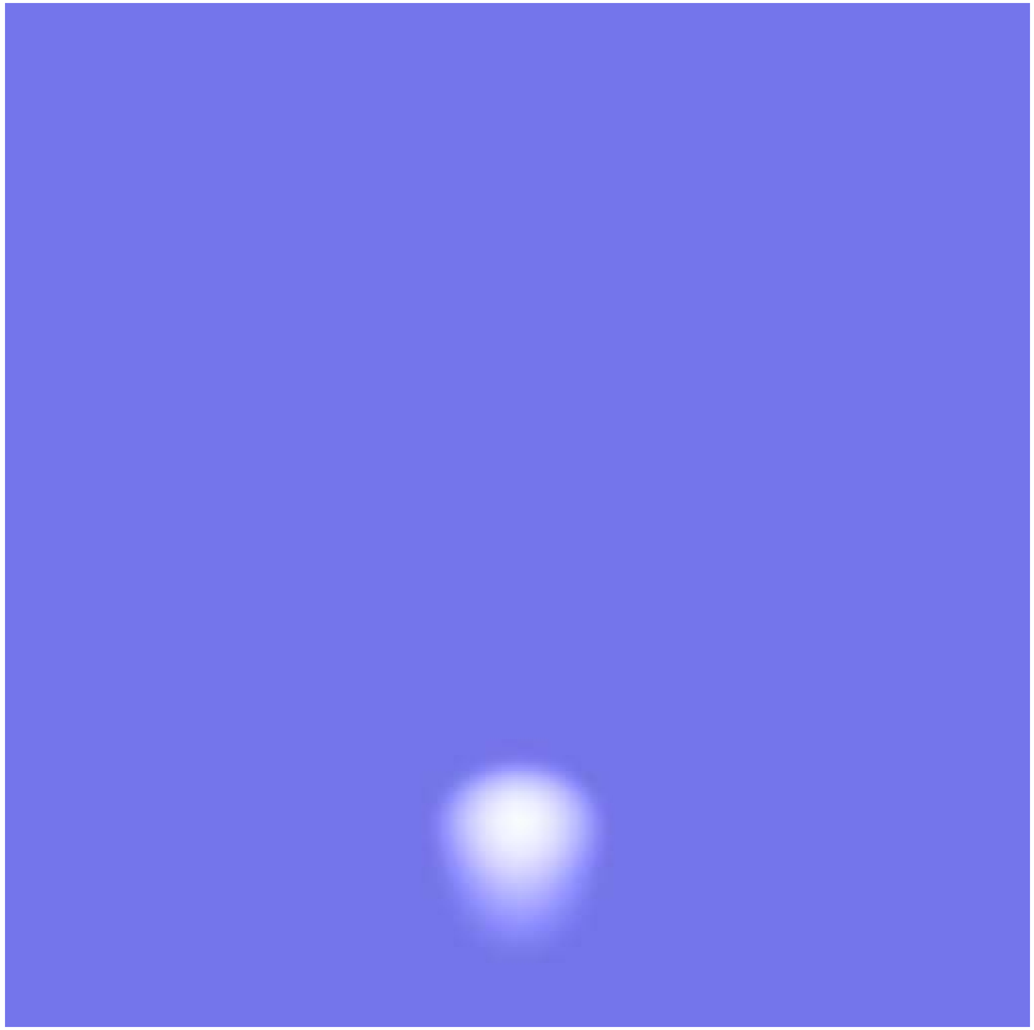
- Moist adiabatic environment, T_{sfc} = 288K
- Constant saturation deficit 0.3g/kg (RH decreasing with z from 97% to 5%)
- Initial spherical bubble, diameter D^o = 1000m, temperature excess ΔT^o=1K, RH=100%

Key Length Scales

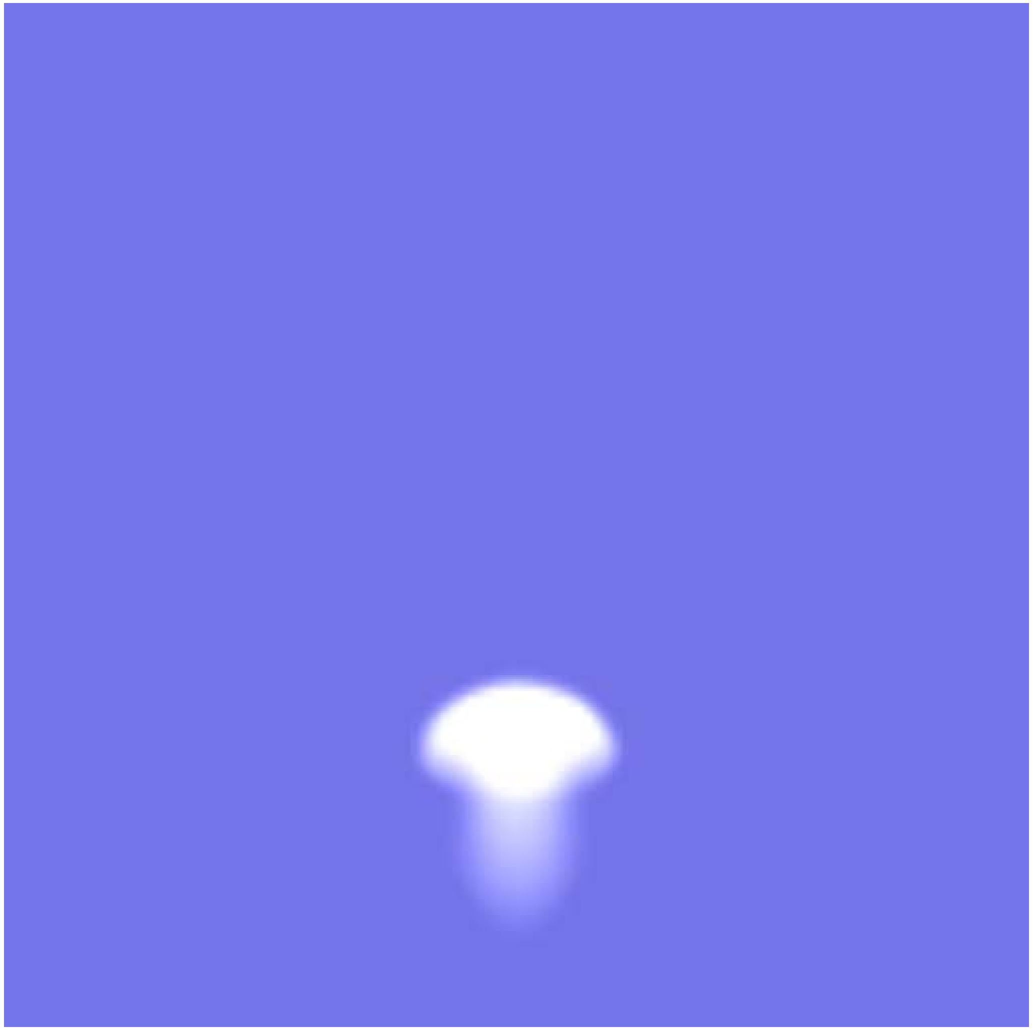
Resolution	Δ	70m
Buoyancy length	L_{buoy}	333m
Initial bubble size	D^o	1000m
Domain size	L	18000m (18x18x15 km)

To demonstrate LES, need at least one decade of inertial subrange, i.e. $\Delta \sim 5$ m - more than 3000^3 gridpoints.

Evolution of Cloud - 04 min



Evolution of Cloud - 08 min



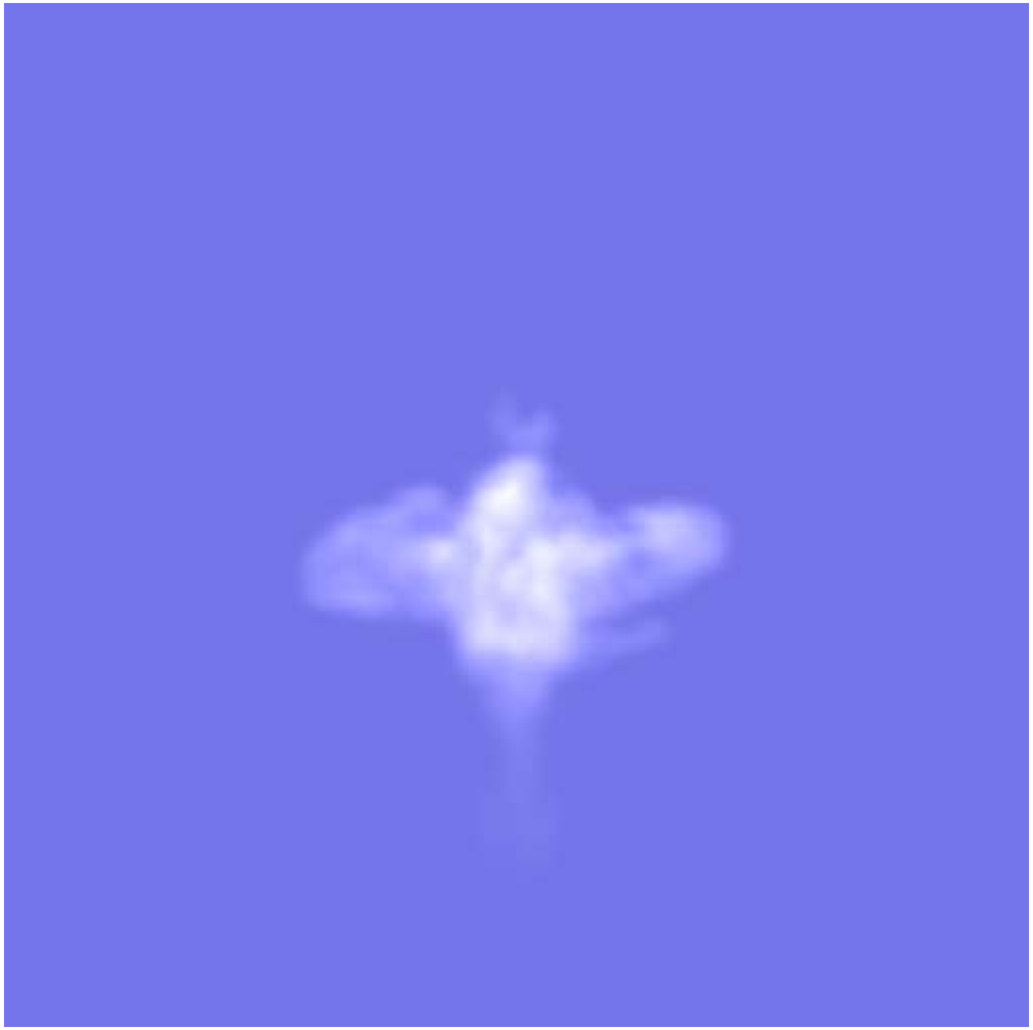
Evolution of Cloud - 12 min

Evolution of Cloud - 16 min

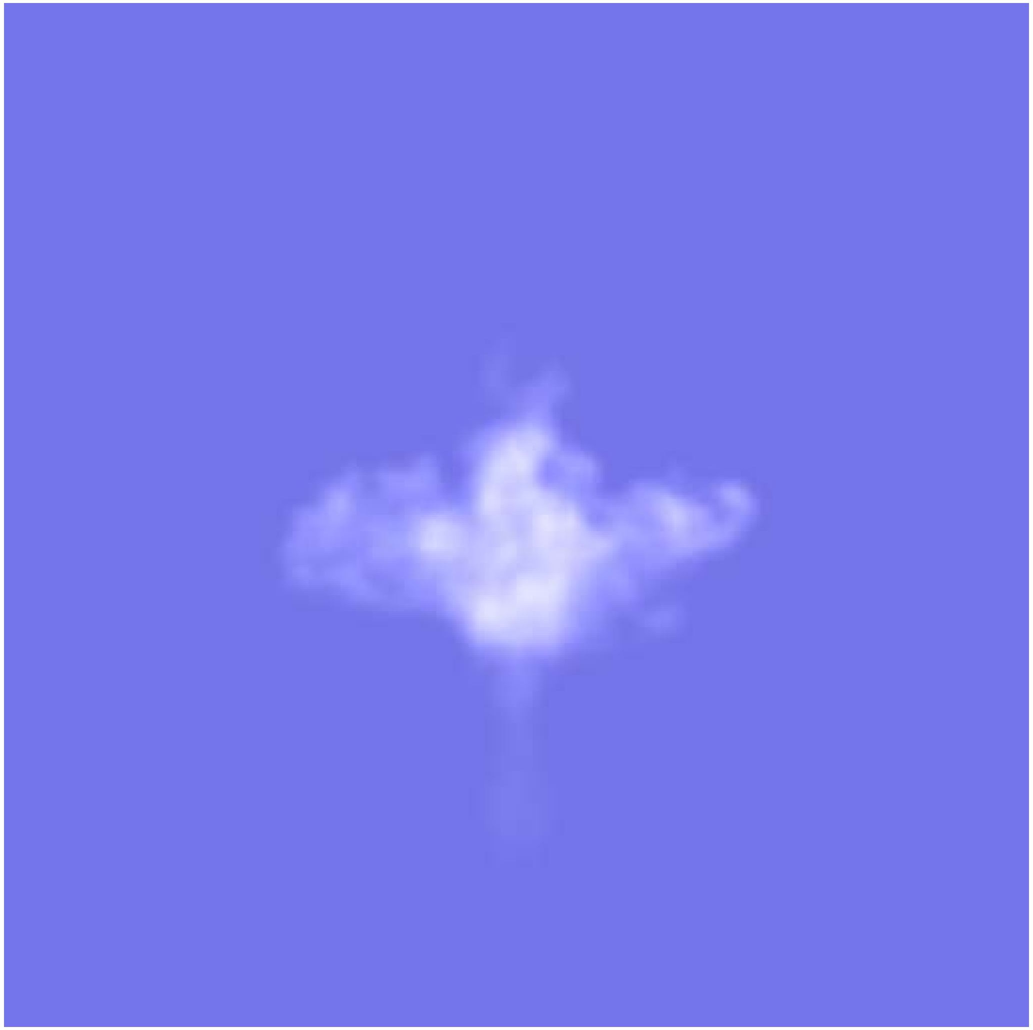
Evolution of Cloud - 20 min

Evolution of Cloud - 24 min

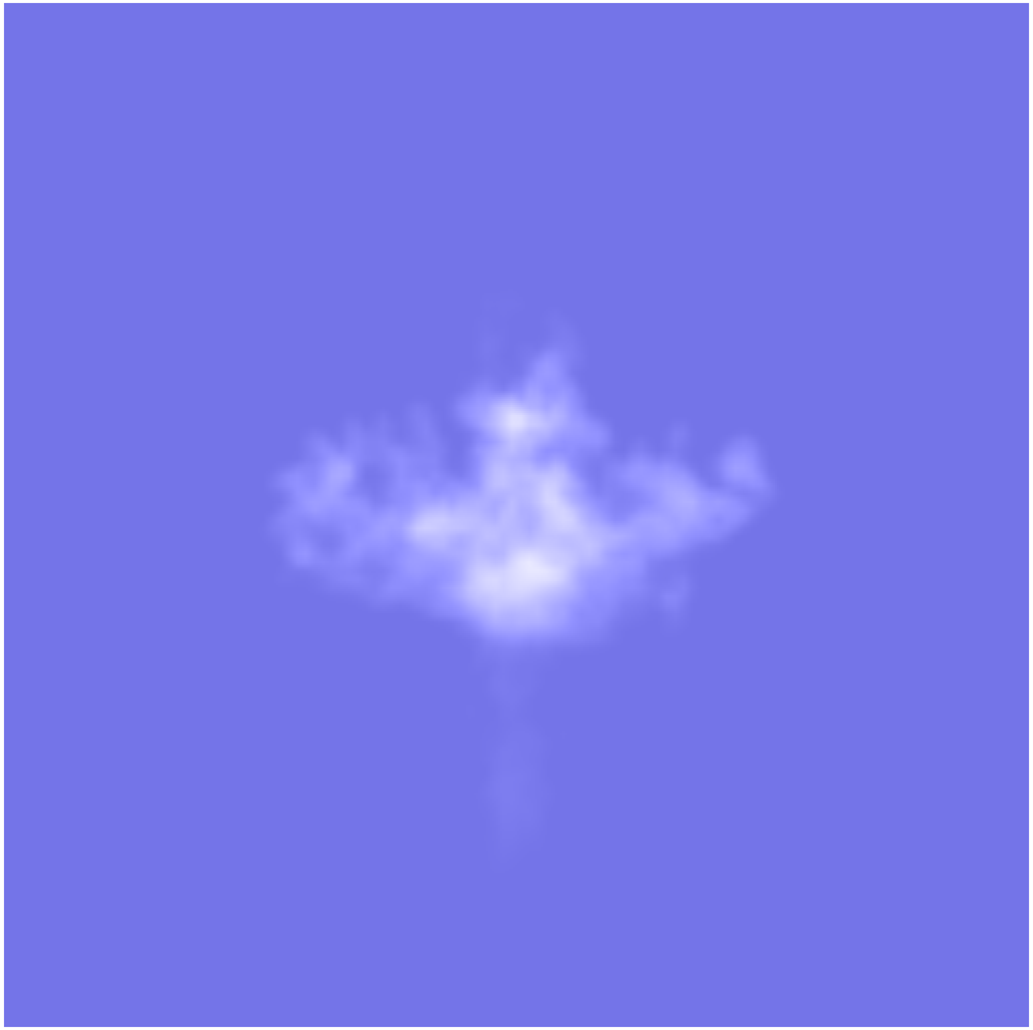
Evolution of Cloud - 28 min



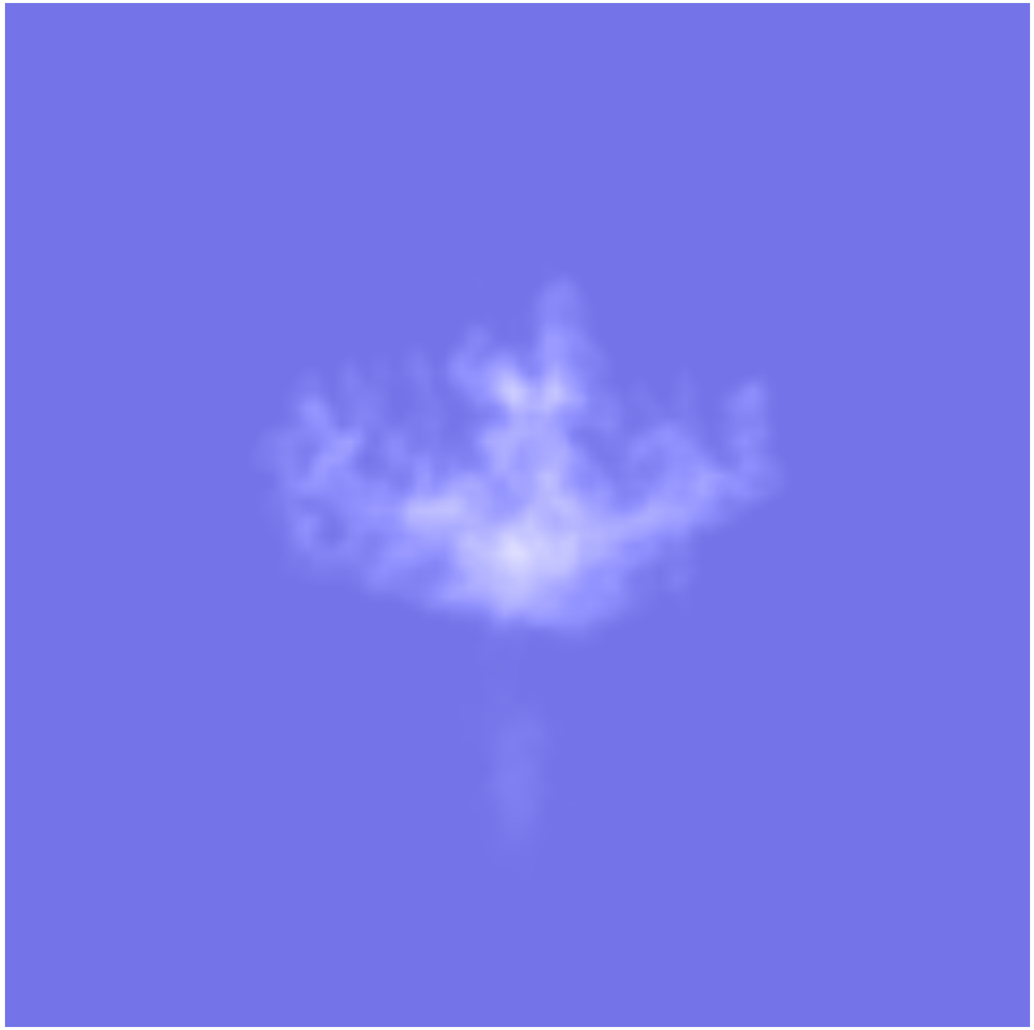
Evolution of Cloud - 32 min



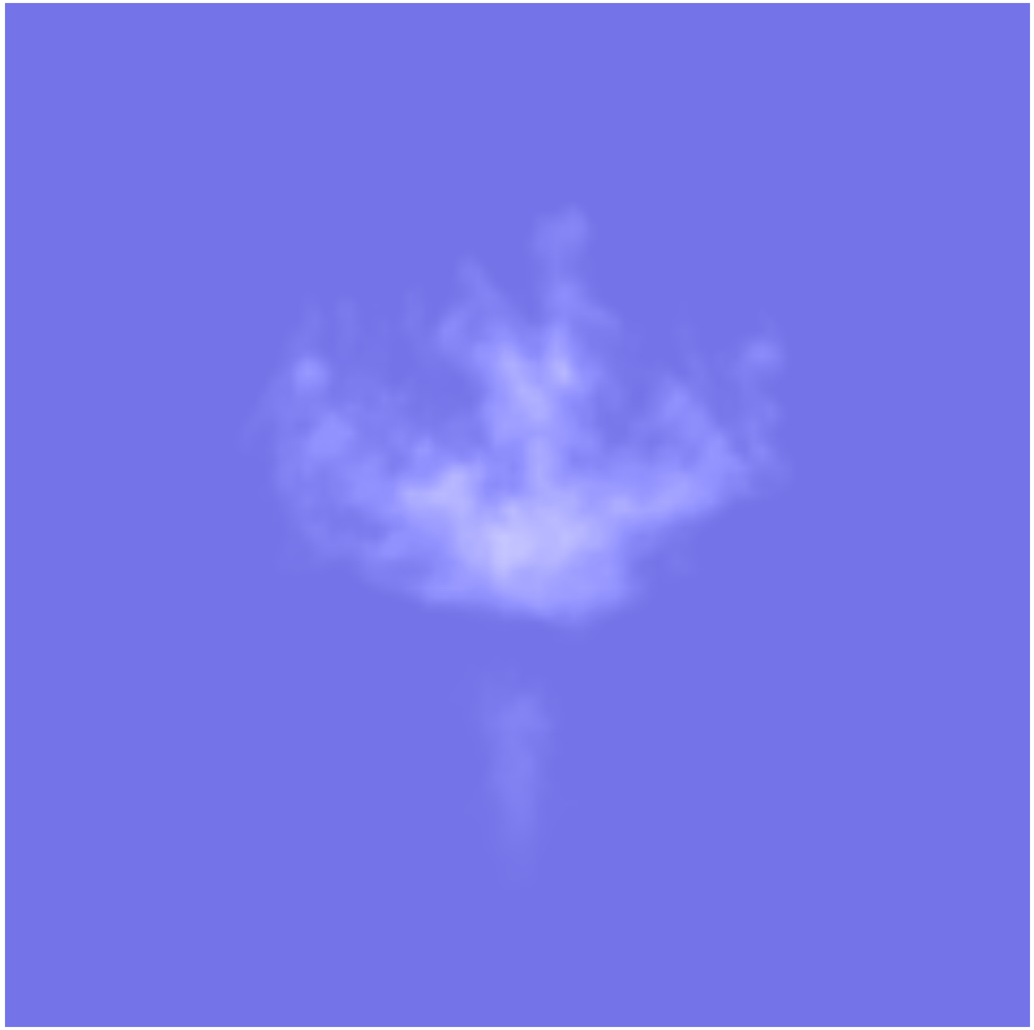
Evolution of Cloud - 36 min

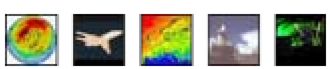


Evolution of Cloud - 40 min

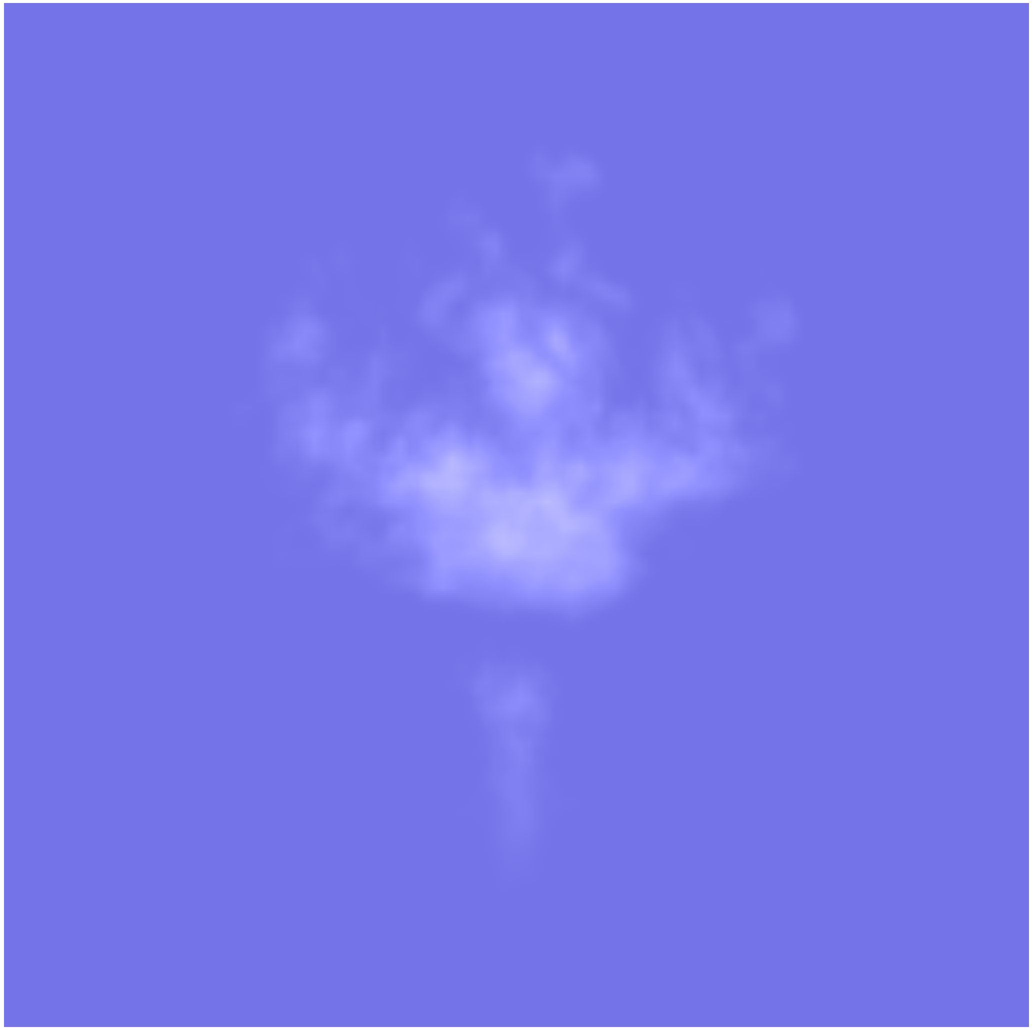


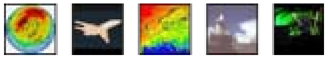
Evolution of Cloud - 44 min



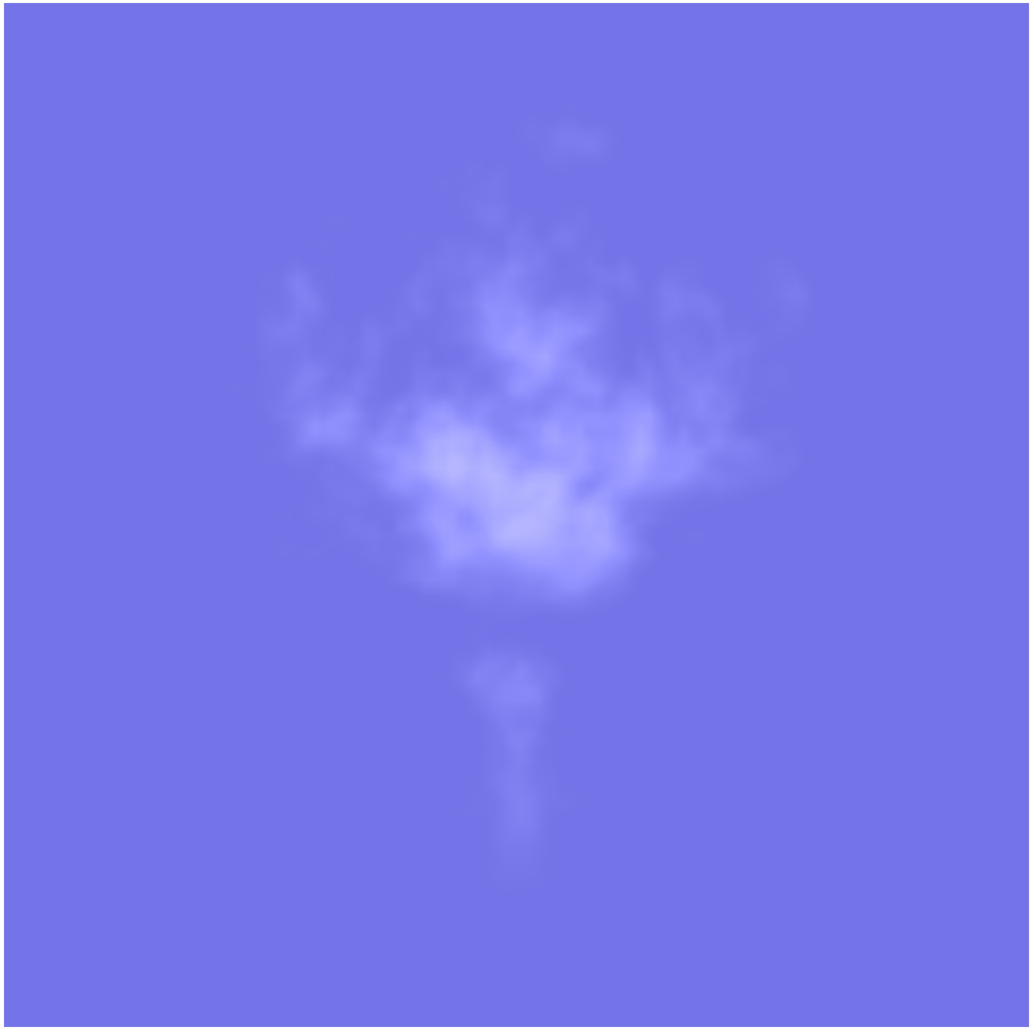


Evolution of Cloud - 48 min

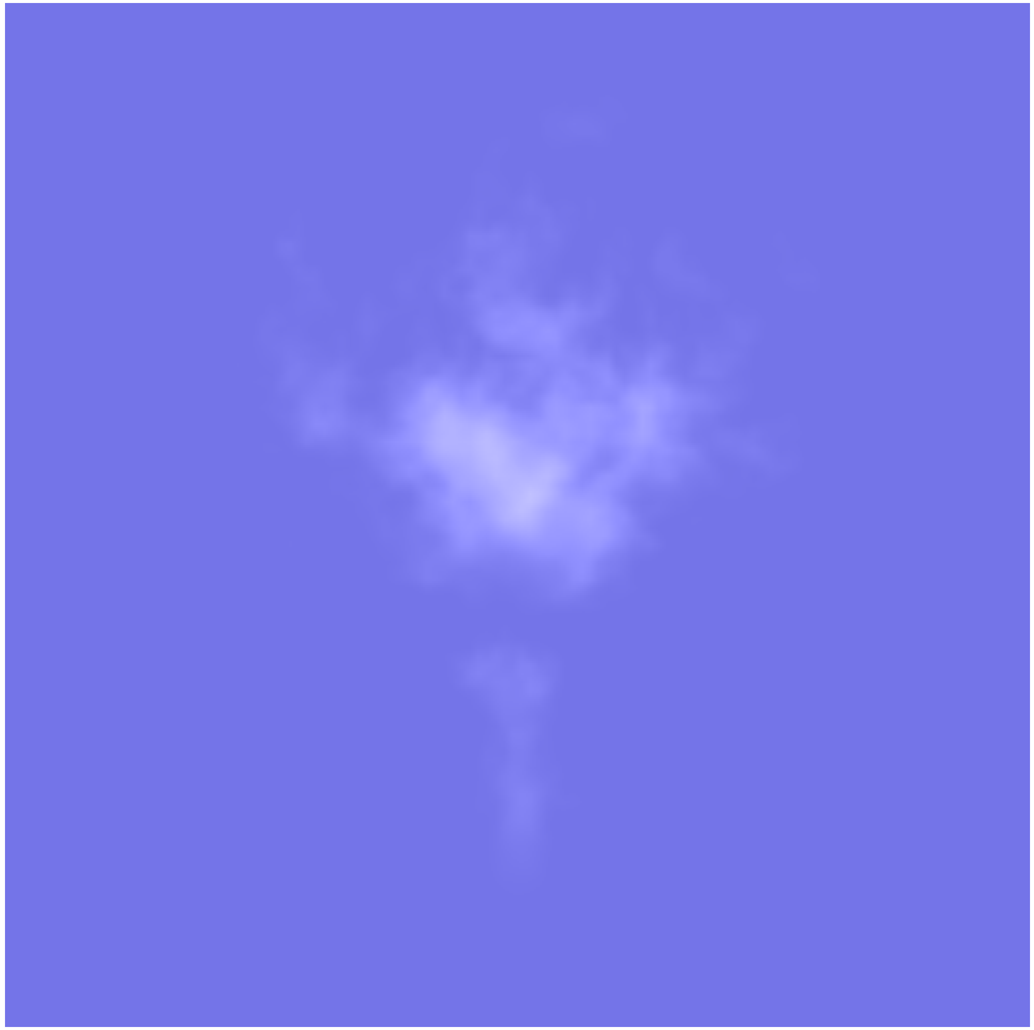




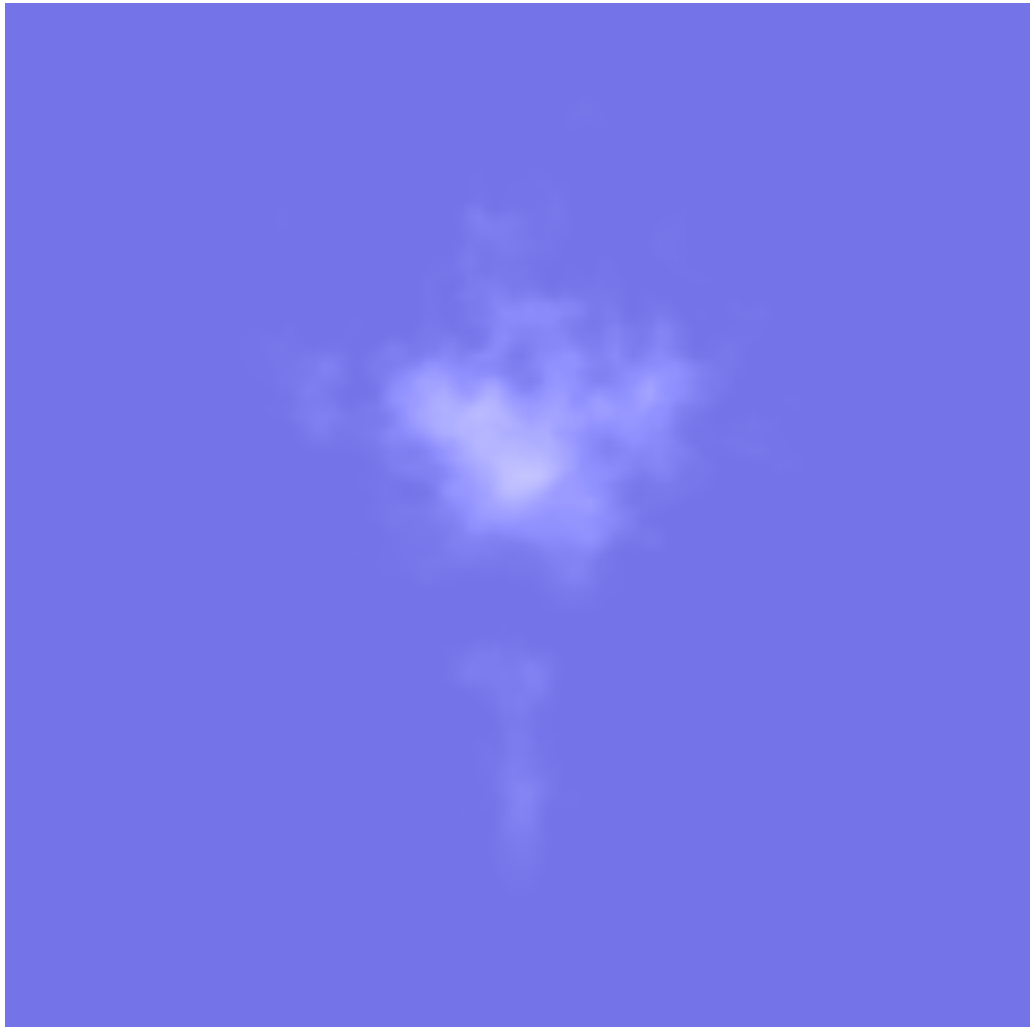
Evolution of Cloud - 52 min



Evolution of Cloud - 56 min



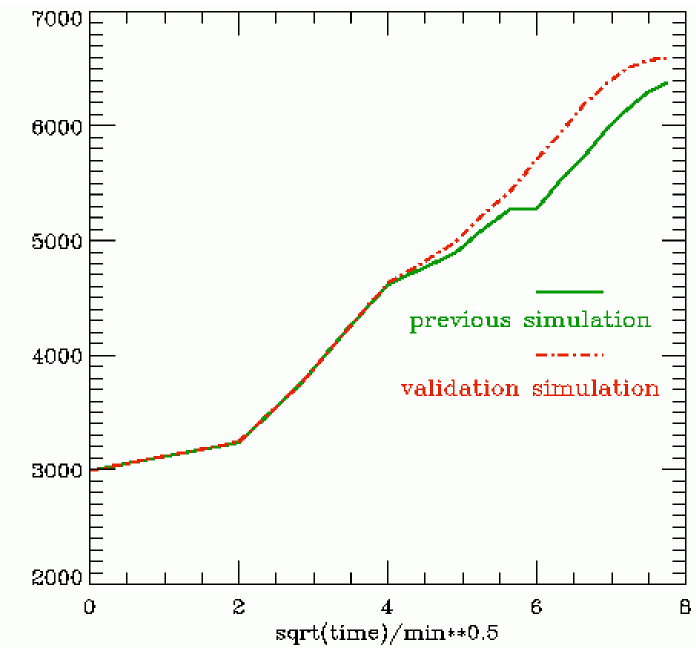
Evolution of Cloud - 60 min



Time Evolution of Bubble

(two runs, started from slightly perturbed initial conditions)

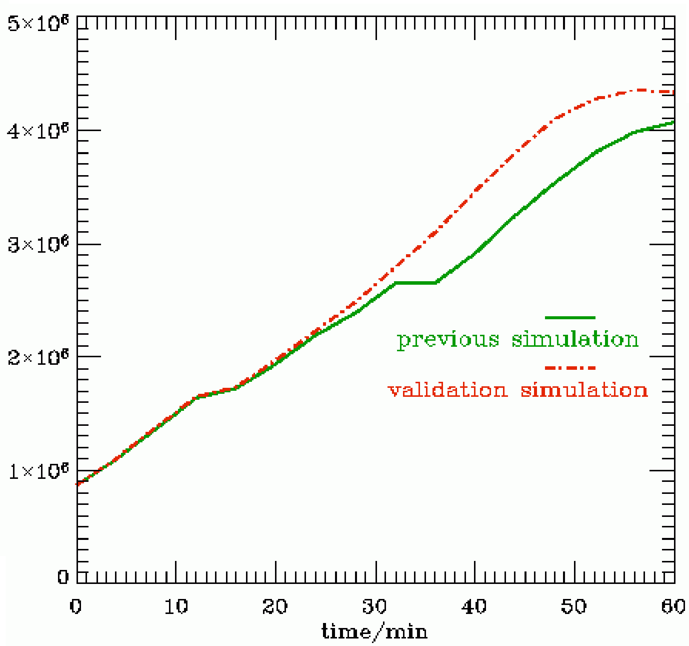
Height (m)



Time$^{1/2}$ (min$^{1/2}$)

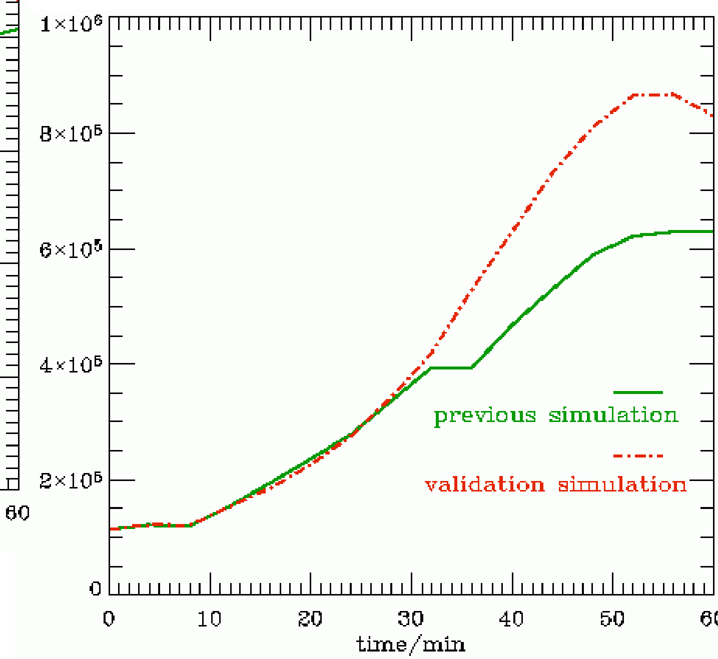
(for dry thermal these plots should be linear)

Volume$^{2/3}$ (m^2)

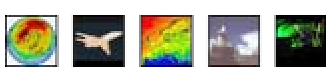


Time (min)

Radius^2 (m^2)



Time (min)



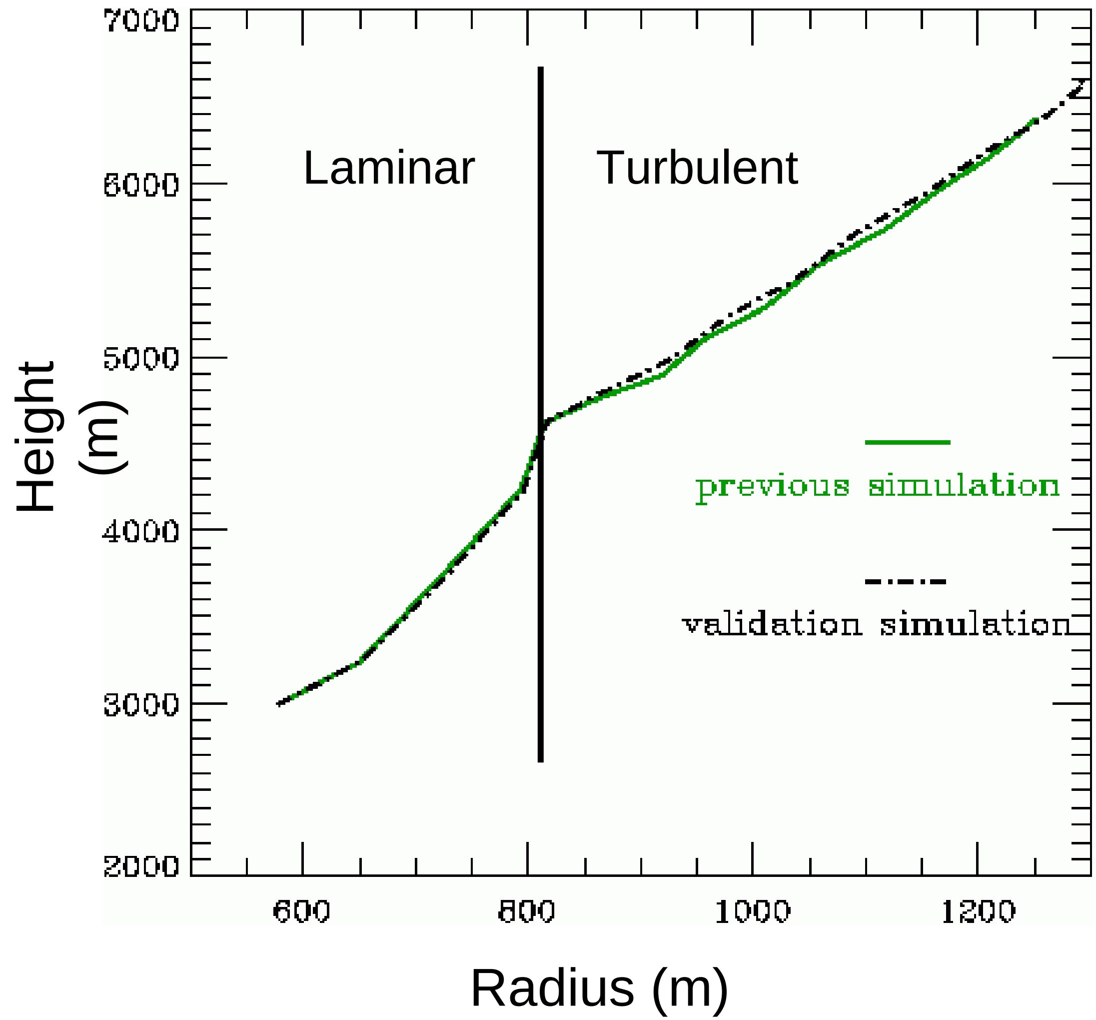
A More Robust Convergence Measure

Two-stage evolution:

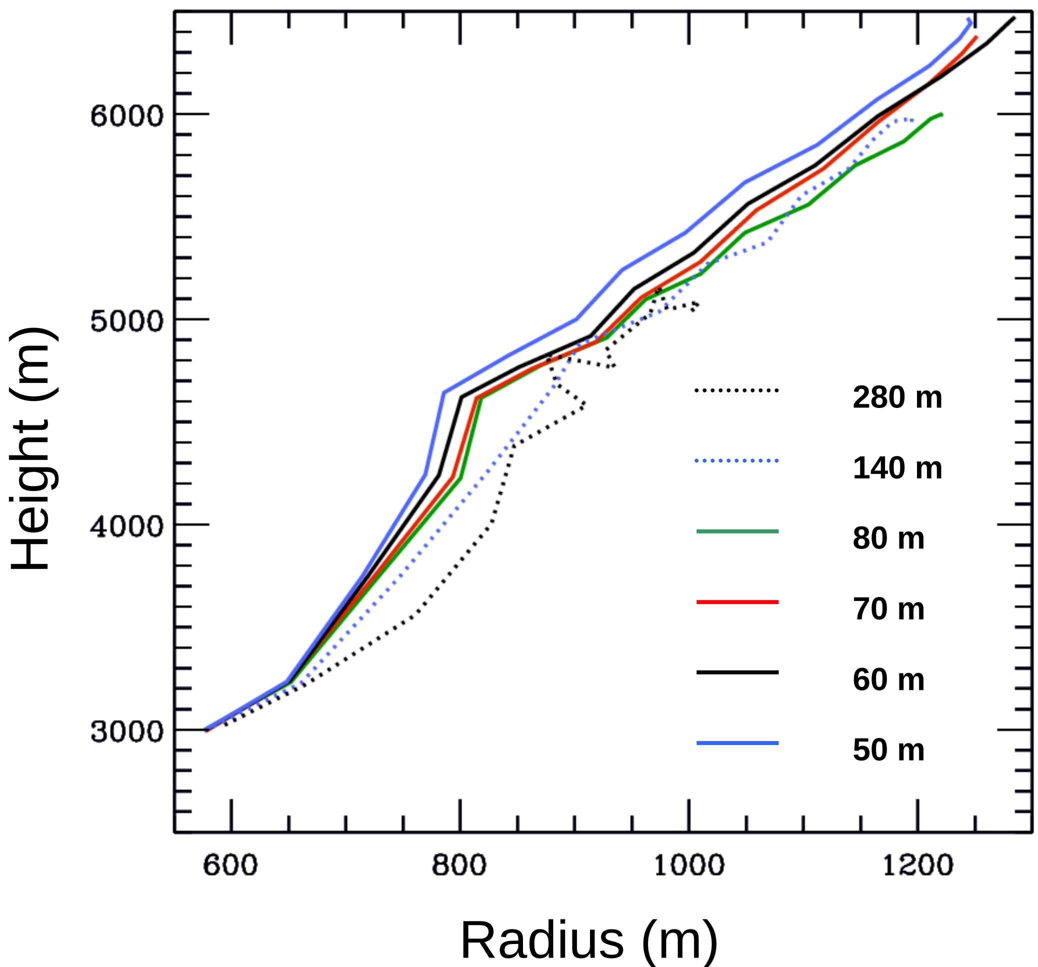
- Laminar phase
- Turbulent phase

Height proportional to radius in turbulent phase

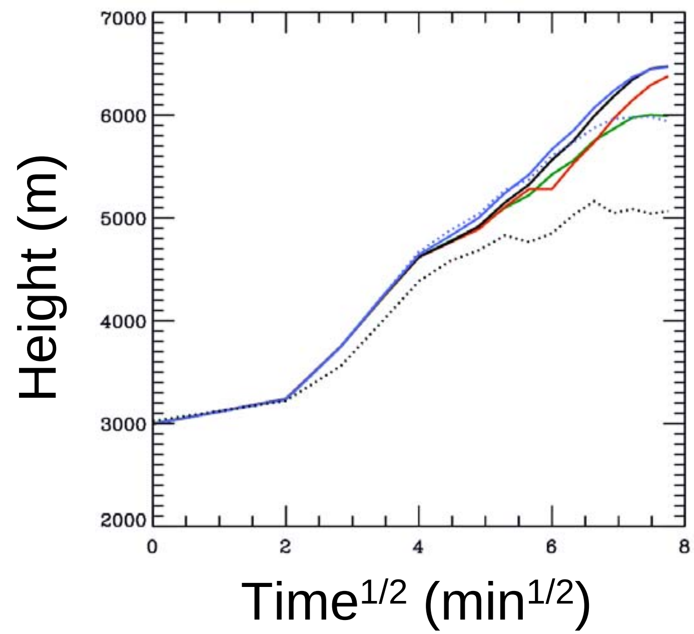
(variability in time series due to variations in speed of evolution)



ΔTº = 1.0K - Convergence?



Radius-height scaling established for: Δ = 70m



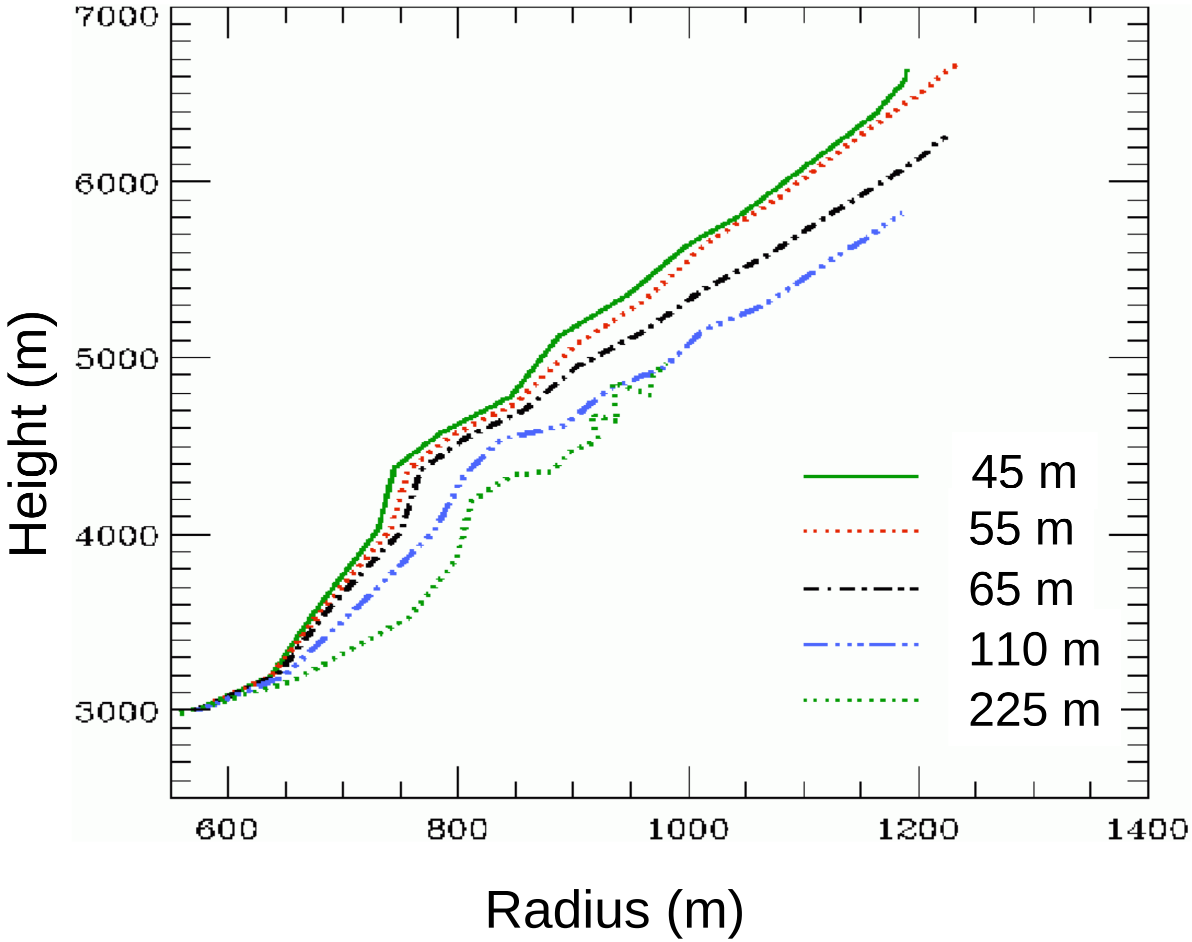
Sensitivity Tests

ΔT^o(K)	L_{buoy}(m)	L_{eff} (m)	Resolution Δ (m)
0.8	266	1.88	225 110 | 65 | 55 45
1.0	333	1.5	280 140 80 || 70 60 50
1.8	600	0.8	250 135 |120 85 |

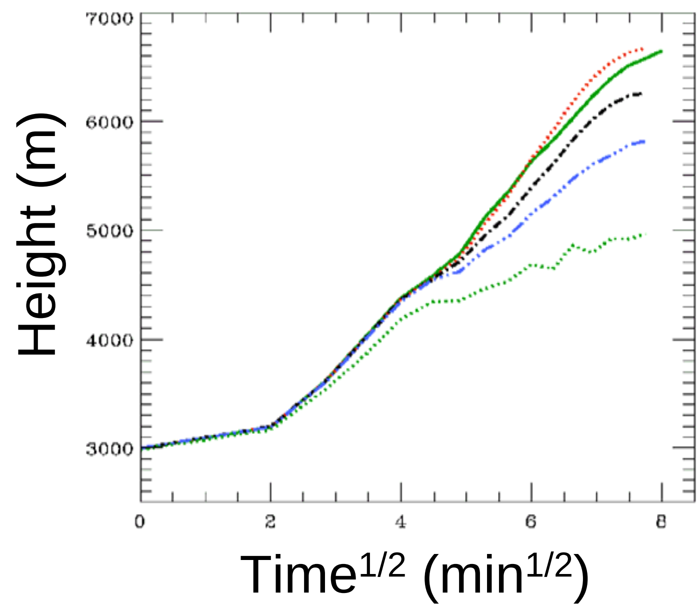
- If need to resolve bubble scale D^o, expect convergence at Δ=70m for all ΔT^o (blue lines)

- If need to resolve L_{buoy}, expect convergence where L_{buoy}/Δ ~ 333m/70m ~ 5 (black lines)

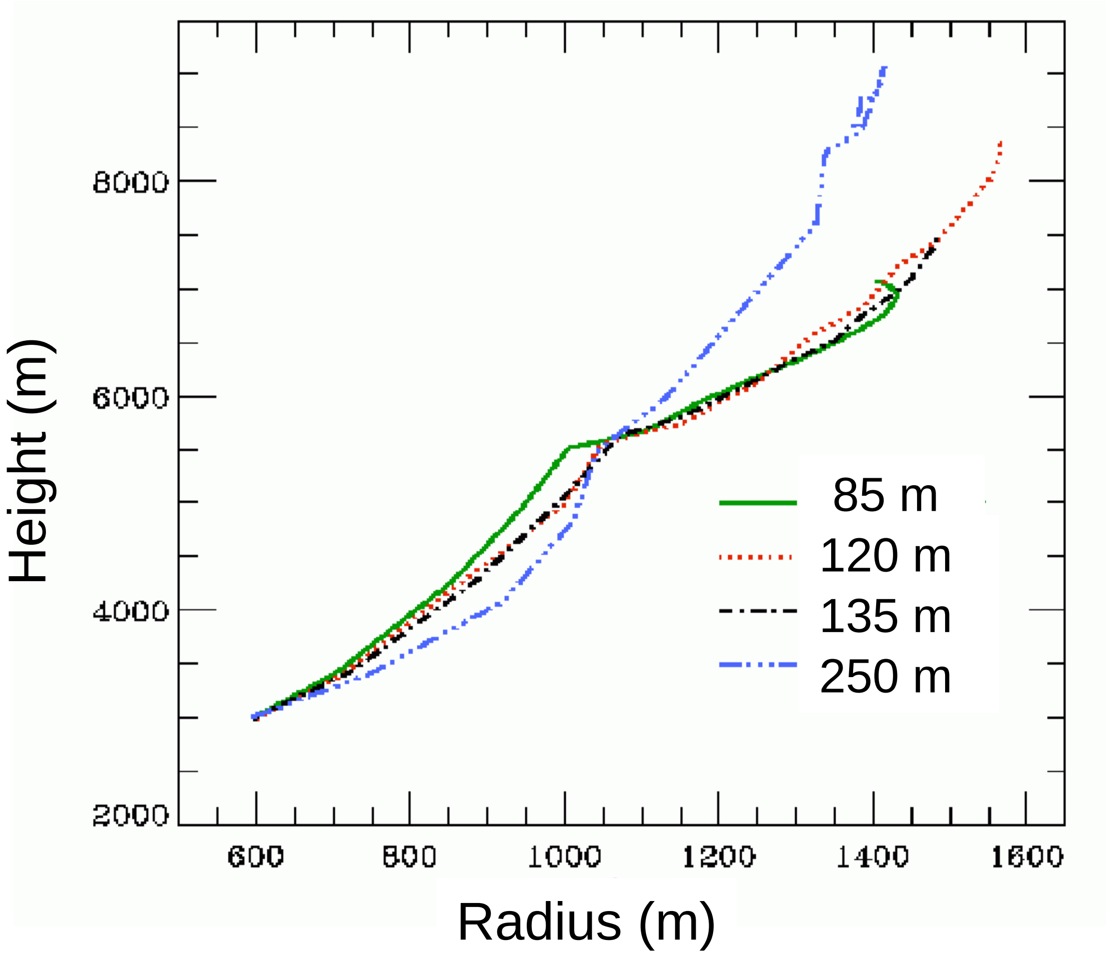
ΔTº = 0.8K - Convergence?



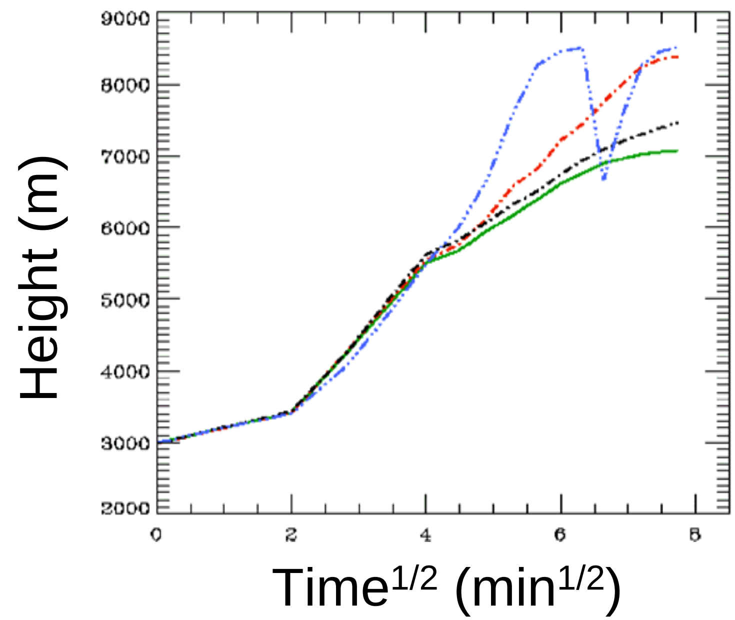
Radius-height scaling established for: Δ = 55m



ΔTº = 1.8K - Convergence?



Radius-height scaling established for: Δ = 135m

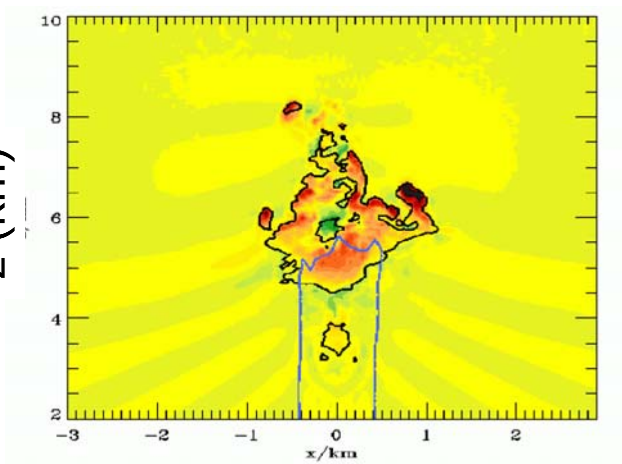


When L_{buoy} ~ D^o

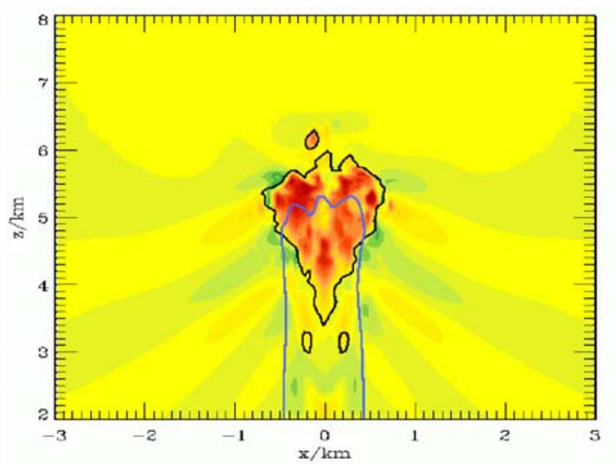
- For ΔT^o = 1.8K, L_{buoy} ~ 600 m is similar to D^o ~ 1000m
- Entrainment eddies are close to the size of the bubble
- Bubble shows more coherent vortex ring structure, as for dry thermal

Expected length scale for convergence remains L_{buoy} ~ D^o

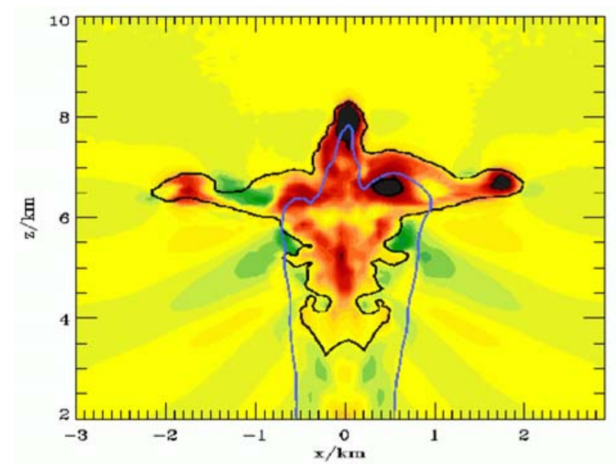
ΔT^o = 0.8K



ΔT^o = 1.0K



ΔT^o = 1.8K



z (km)

x (km)

Vertical velocity

-7.0 –5.5 –4.0 –2.5 –1.0 0.50 2.0 3.5 5.0 6.5

Sensitivity Tests

<table>
<tr><th>ΔT^o (K)</th><th>L_{buoy} (m)</th><th>H/R</th><th>Resolution Δ (m)</th></tr>
<tr><td>0.8</td><td>266</td><td>0.21</td><td>225 110 | 65 | 55 45</td></tr>
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<tr><td></td><td></td><td></td><td>(bad) (good)</td></tr>
</table>

- If need to resolve bubble scale D^o, expect convergence at Δ = 70m for all ΔT^o (blue lines)

- If need to resolve L_{buoy}, expect convergence where L_{buoy}/Δ ~ 333m/70m ~ 5 (black lines)

Conclusion

L_{buoy} is relevant length scale for convergence
(to the extent that we have seen convergence)

Unanswered questions

1. Is there an LES regime? - need very high resolution, e.g. adaptive grids (METSTROEM)
2. How coarse can the resolution for NWP be?
   - Subgrid mixing model including L_{buoy}
   - Hydrostatic re-scaling (Kuang and Bretherton 2004)

Application: Turbulence around convective clouds