Cumulus Entrainment in Convective Clouds and Storms

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BLUE WATERS
SUSTAINED PETASCALE COMPUTING

Entrainment

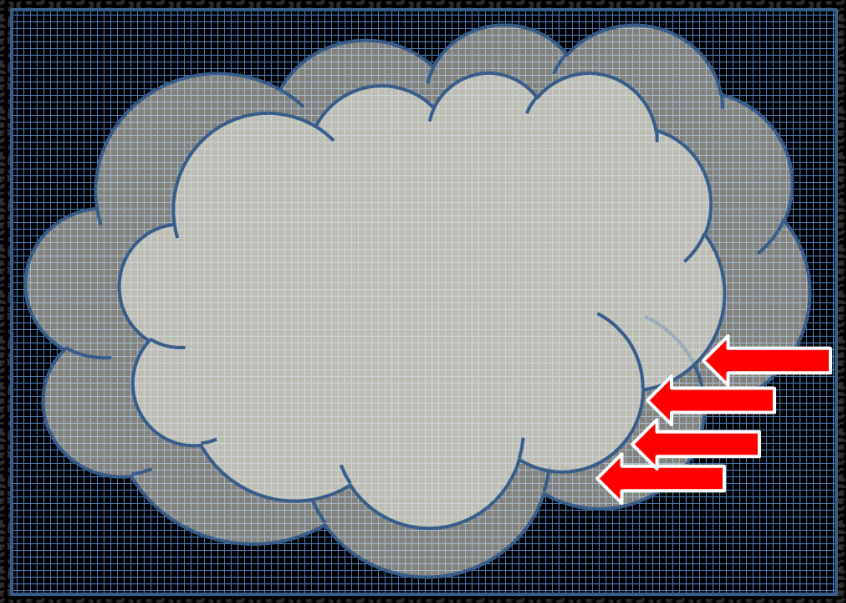
- Entrainment is the introduction of dry air from outside the cloud inward, by its own turbulent motions
  - the buoyancy of the cloud is reduced, limiting max cloud depth
  - the liquid water/ice in the cloud is reduced, limiting precipitation
- Improving forecasts of deeper (and hazardous) storms
- Good quantitative precipitation forecasts require accurate assessment of entrainment
- Entrainment rate is one of the most sensitive parameters in coarser NWPs and GCMs

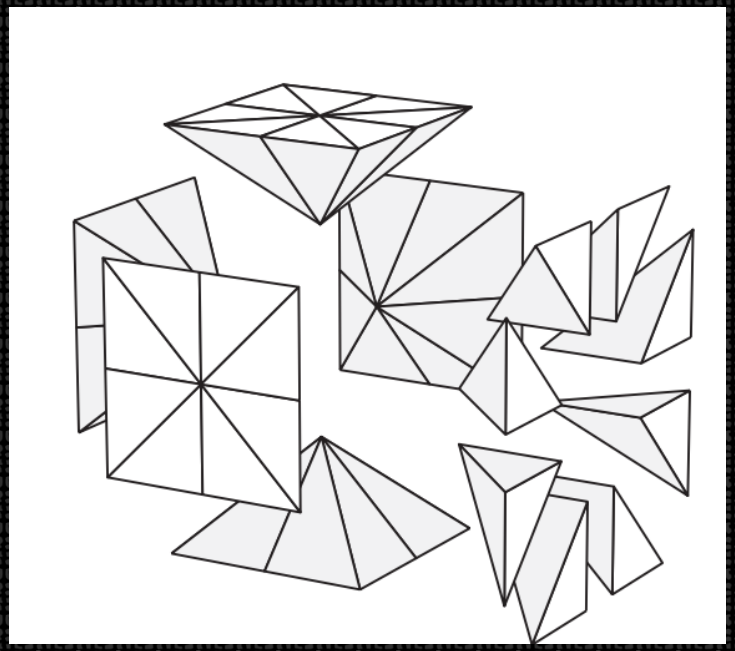
Calculating Entrainment

$$E - D = \rho \frac{dV}{dt} + \int_W \rho \boldsymbol{u} \cdot d\boldsymbol{W}$$

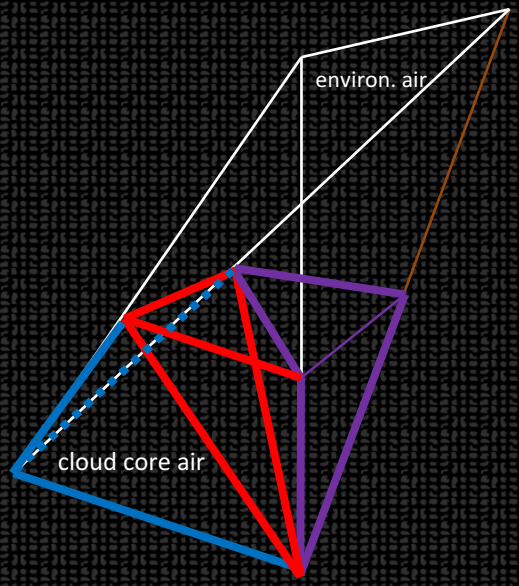
Rate of change in cloudy volume

Net mass flux into cloudy volume

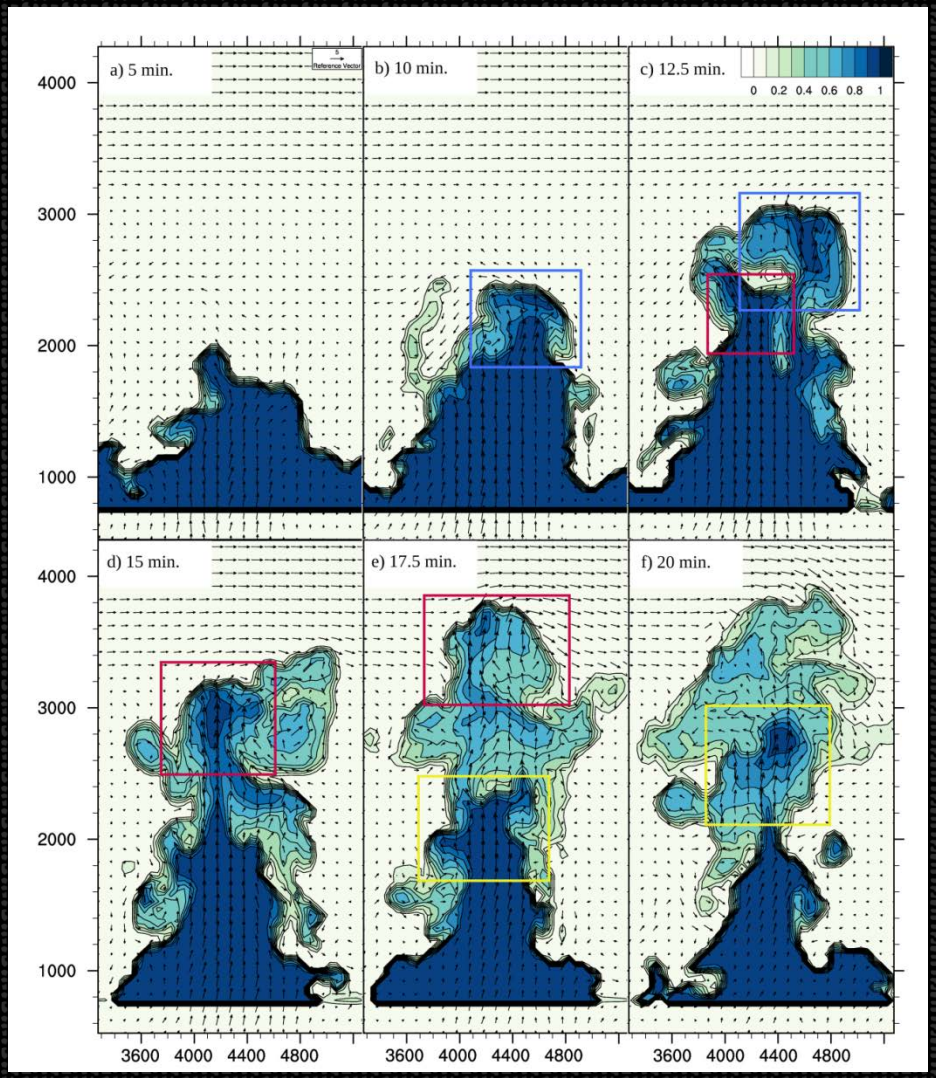




Dawe and Austin, 2011



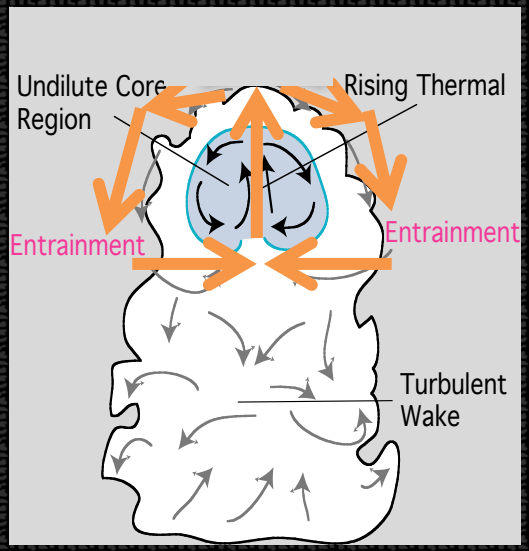
Entrainment Dependencies



Moser and Lasher-Trapp 2017

The passage of earlier thermals through a cloud may substantially moisten the local environment and mitigate entrainment in newer successive thermals.

The result may lead to longer cloud longevity and enhanced precipitation production.

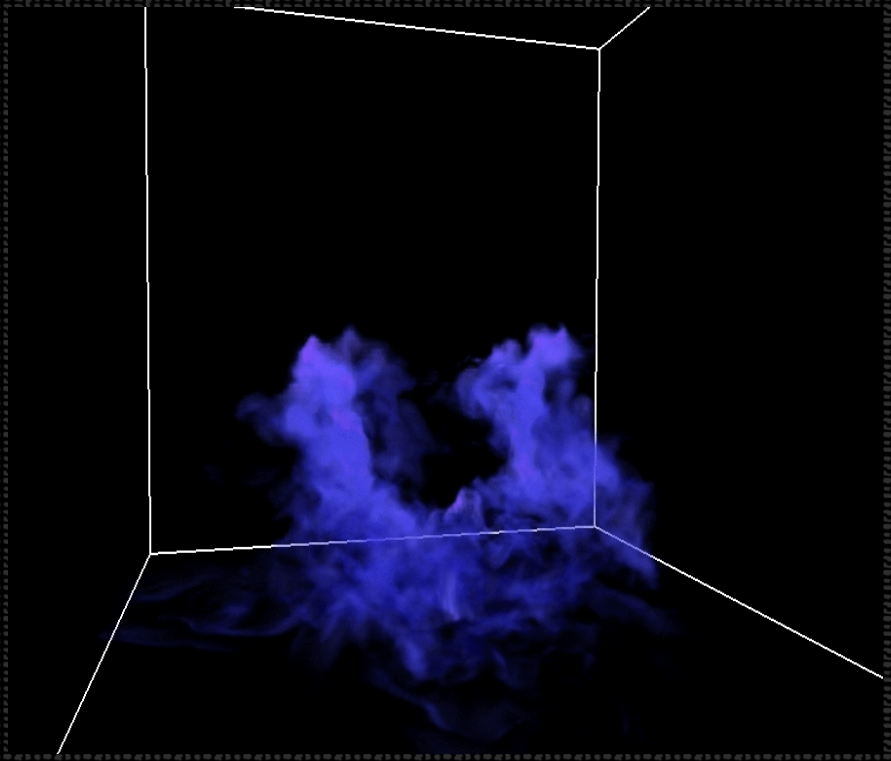


adapted from (Blyth, Cooper & Jensen 1988)

BW Benefits

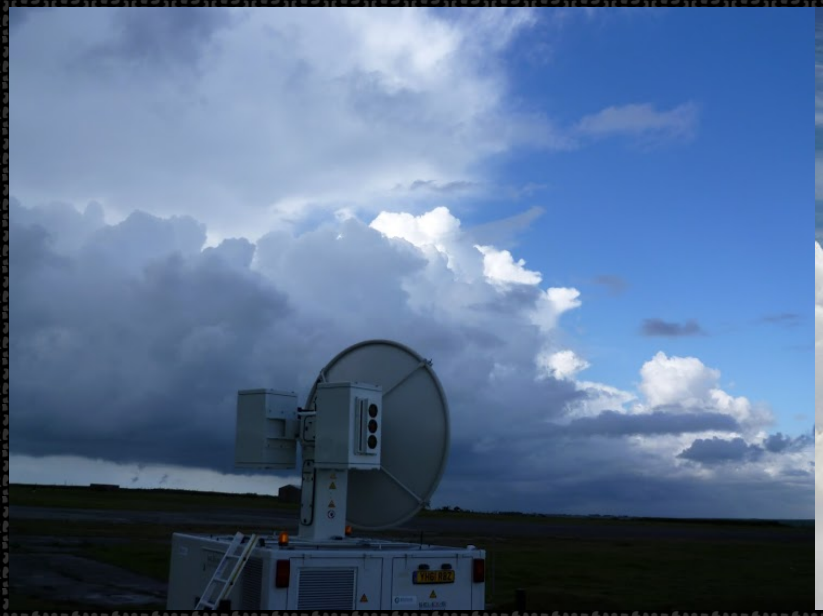
- Previous high resolution simulations of cumulus clouds were typically restricted to domains appropriate for one or two deep clouds (e.g. left)

- Vast scale of BW allows for a more realistic simulation of organized convection involving a population of clouds (e.g. right)



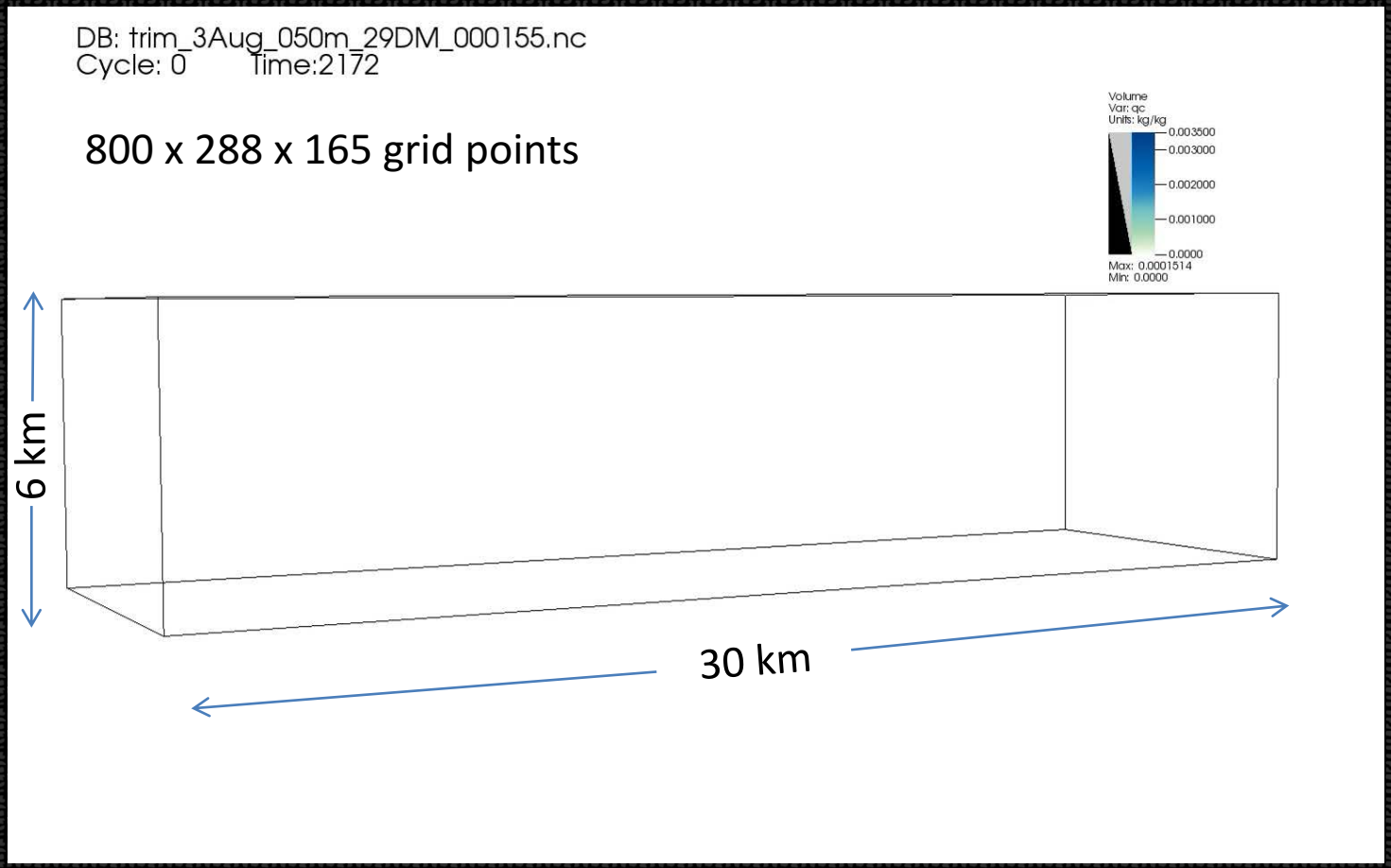
Influences of Neighboring Clouds

- Clouds are rarely found to develop in complete isolation
- Can neighboring clouds mutually change the rate of entrainment or change the moisture characteristics of the entrained air?
- Are there significant changes in a cloud's microphysics or dynamics?

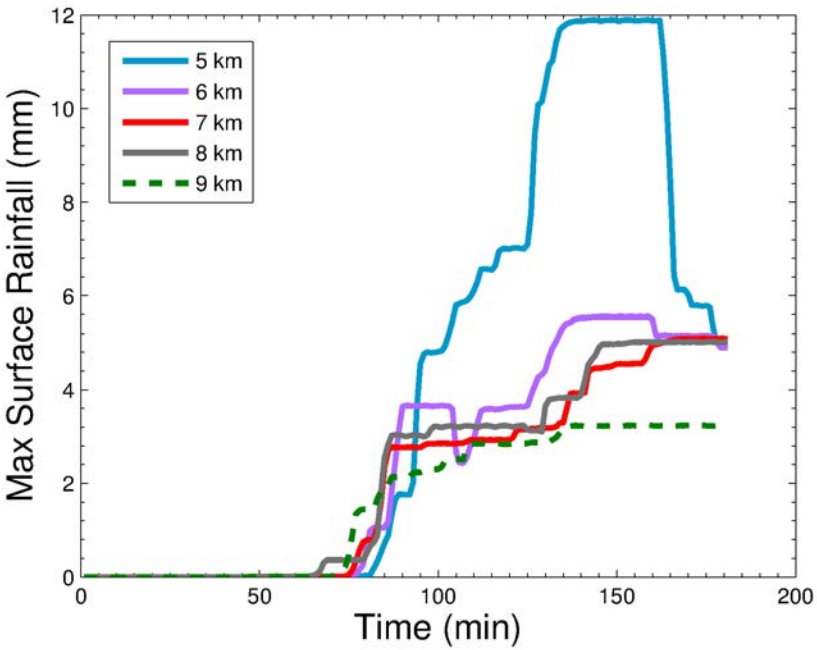


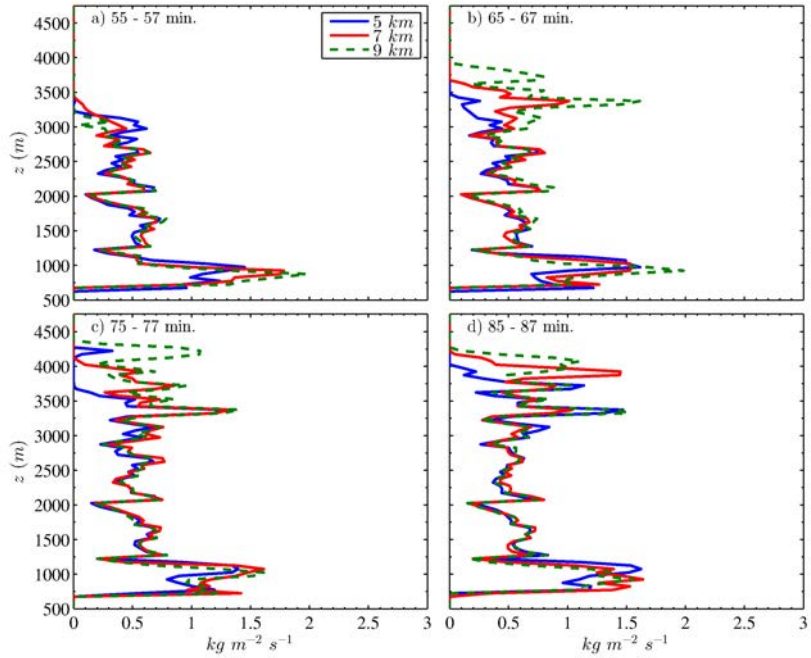
George Bryan's CM1 Model

- Coarse-grained parallelization, pure MPI
- Designed to scale to tens of thousands of processors
- Solver details:
  - RK3 time integration, $5^{th}/6^{th}$ order advection
  - NSSL or Morrison double-moment microphysics
  - Energy conserving form of equations
- Offline entrainment calculations require frequent data output to track the edges of the defined cloud core (≈3 s)



- Simulate organized convection i.e. clouds developing over convergence line
- Initial distance between clouds can be controlled by using surface heat fluxes (e.g. 5 km in above simulation and up to 9 km in other simulations)
- Each cloud composed of multiple thermals of different sizes and trajectories as they rise from the heat surface, leading to convective variability



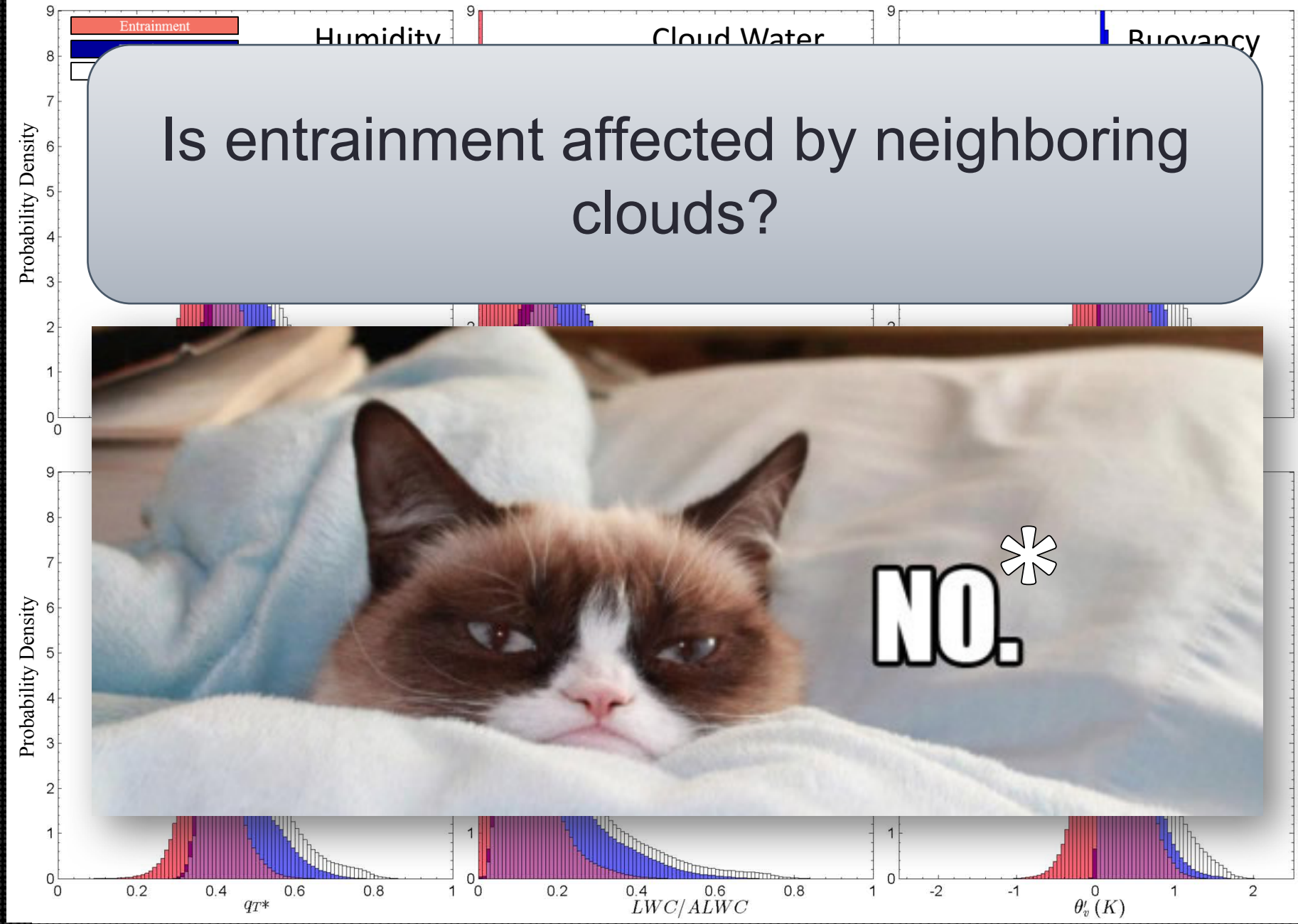


Max surface rainfall over any grid point

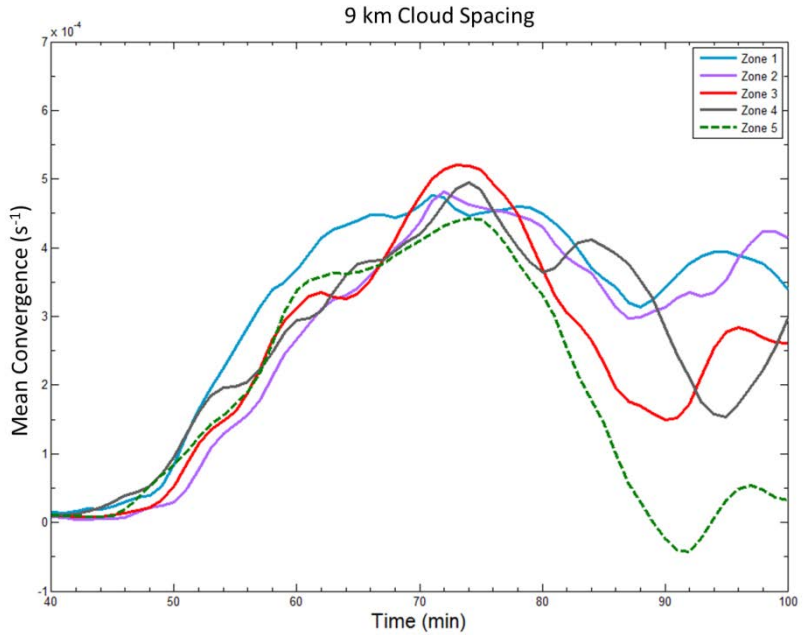
Entrained mass flux per surface area

- General increase in maximum rainfall as clouds develop closer to each other, although not initially
- Averaged rates of entrainment (and detrainment) only vary by tiny differences except near cloud top due to varying cloud top arrival times

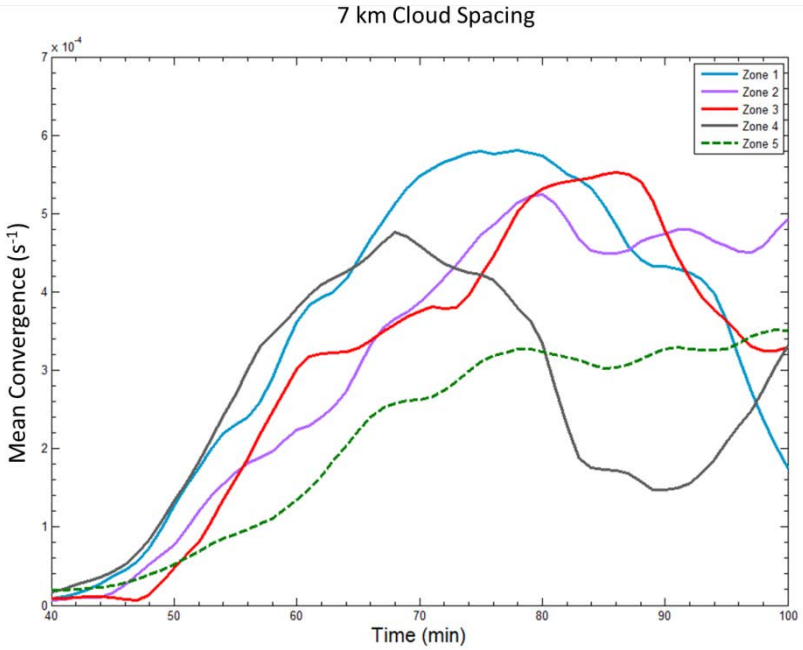
Top: 5 km Spacing / Bottom: 9 km Spacing

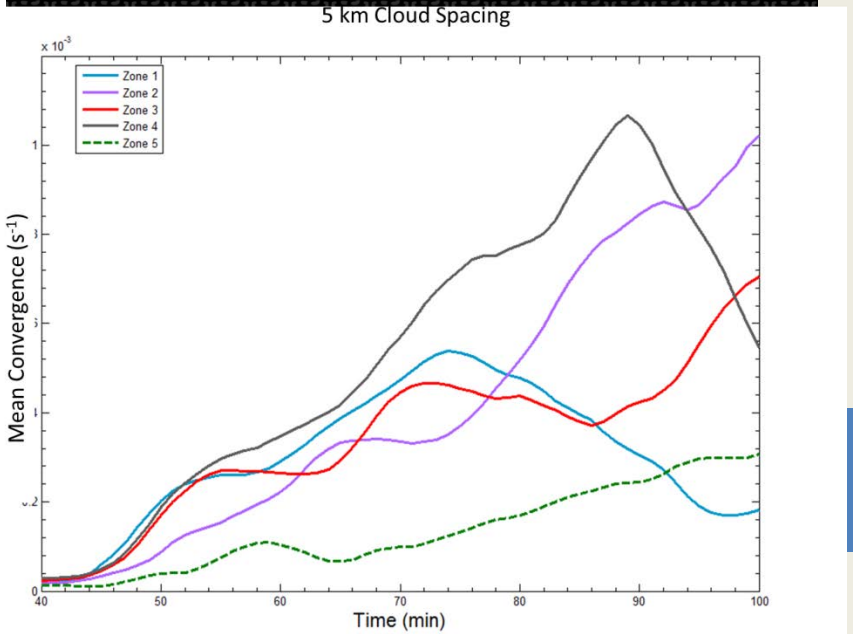


Is entrainment affected by neighboring clouds?



- More isolated clouds compete less for the sub-cloud inflow, allowing them to precipitate earlier.
- As clouds are brought closer together, some clouds interfered with the inflow of others
- Larger convective variability due to competition for sub-cloud inflow is ultimately more important than entrainment for rainfall

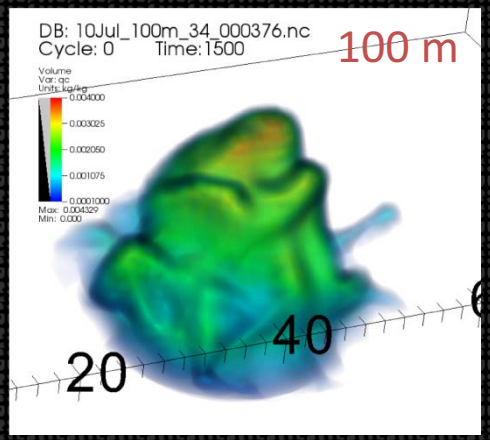




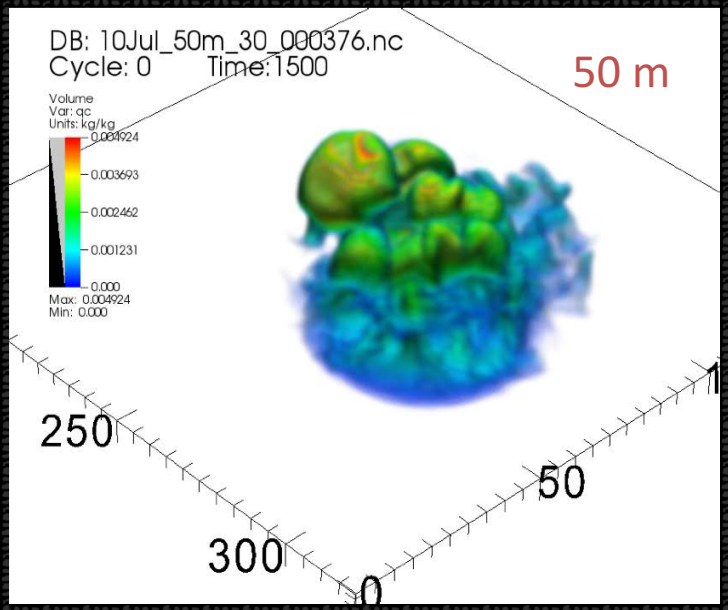
Big whorls have little whorls,
Which feed on their velocity;
And little whorls have lesser whorls,
And so on to viscosity.

-- Lewis Richardson

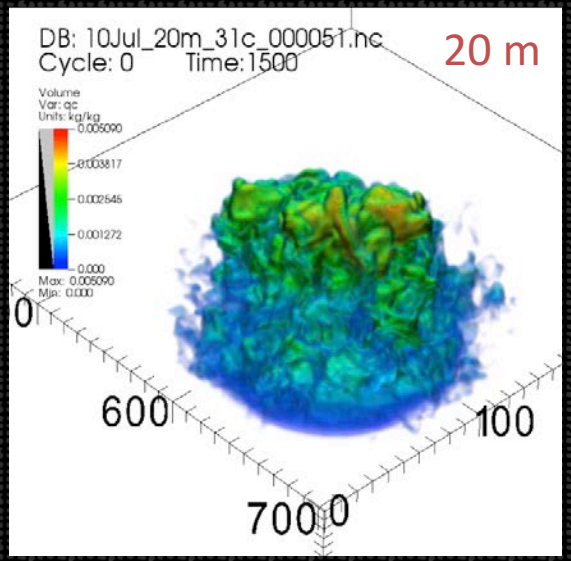
What is the minimum size of a ‘whorl’ that may contribute to cloud dilution?



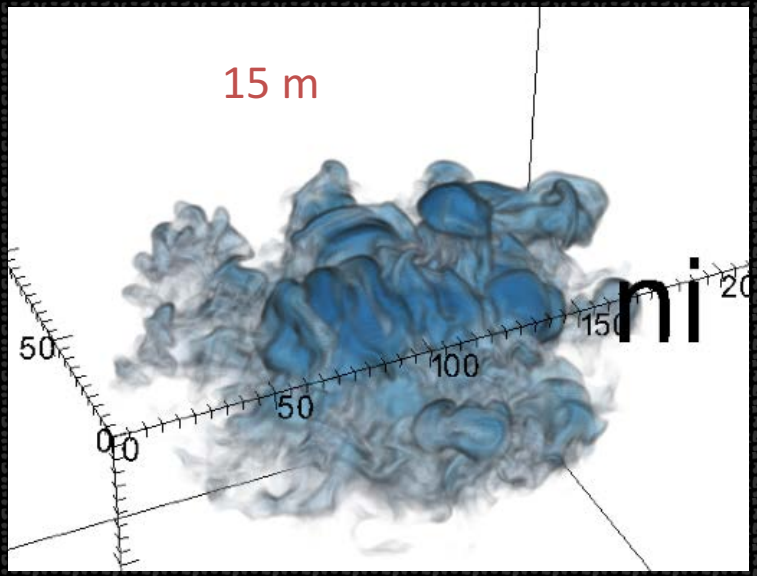
Resolving ~ 400-600 m eddies



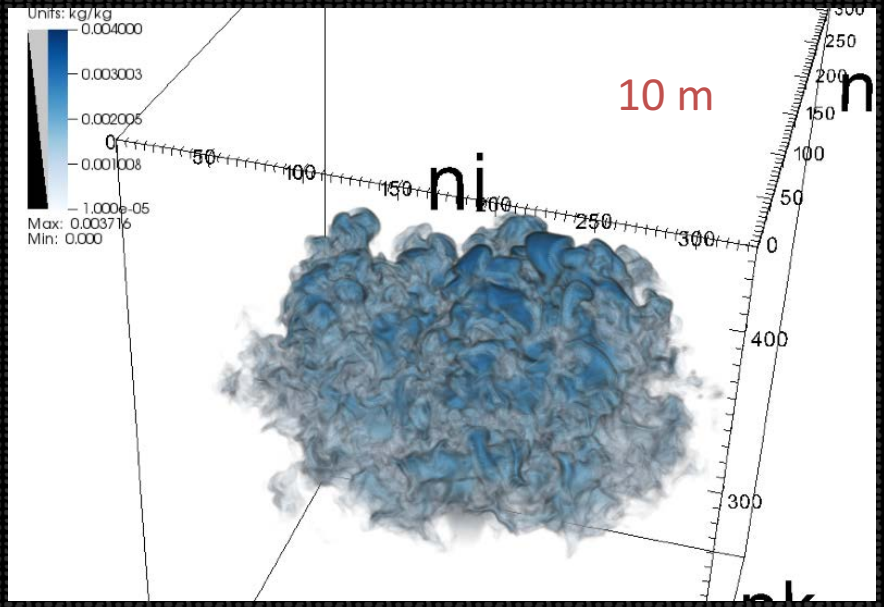
Resolving ~ 200-300 m eddies



Resolving ~ 80-100 m eddies

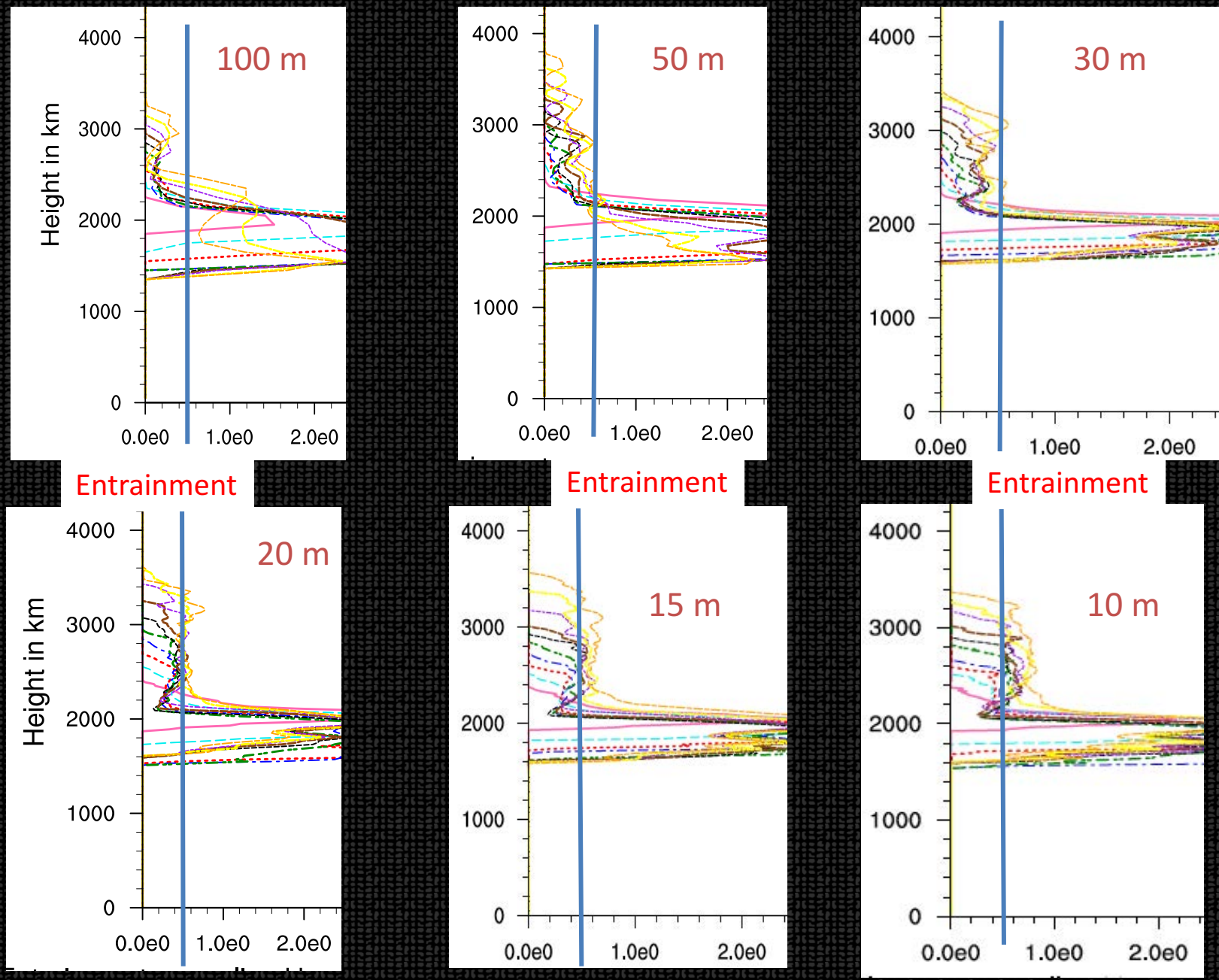


Resolving ~ 60-75 m eddies

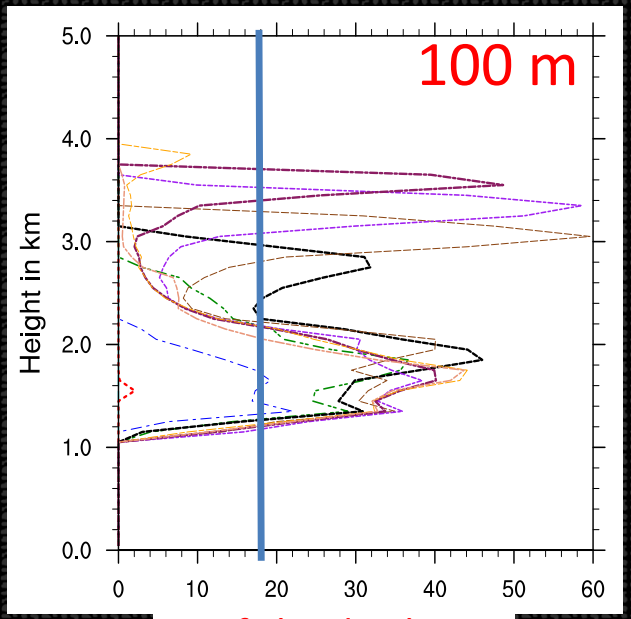


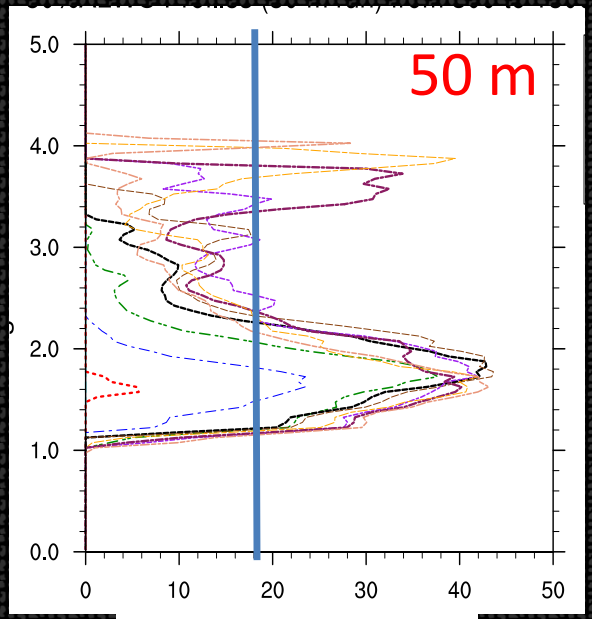
Resolving ~ 40-50 m eddies

Time Series of Entrainment Profiles– not quite converged



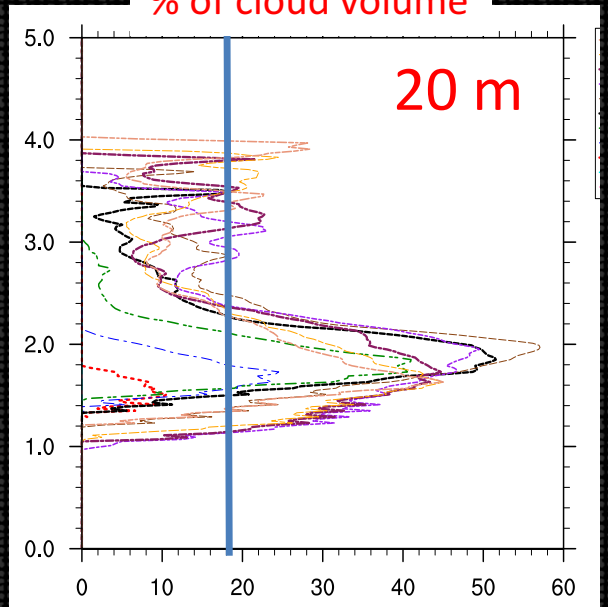
% of cloud volume exceeding 80% ALWC: converging more quickly

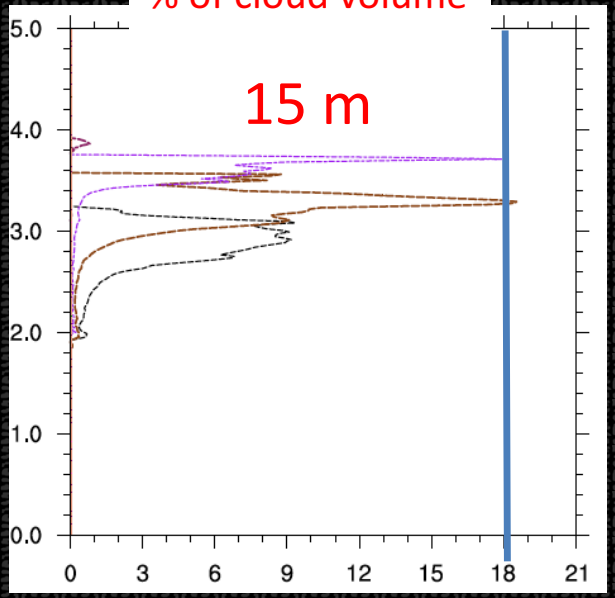


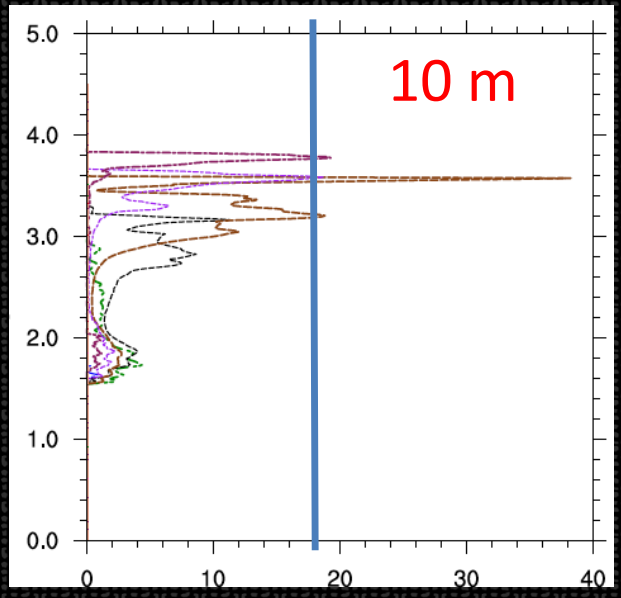


% of cloud volume

% of cloud volume







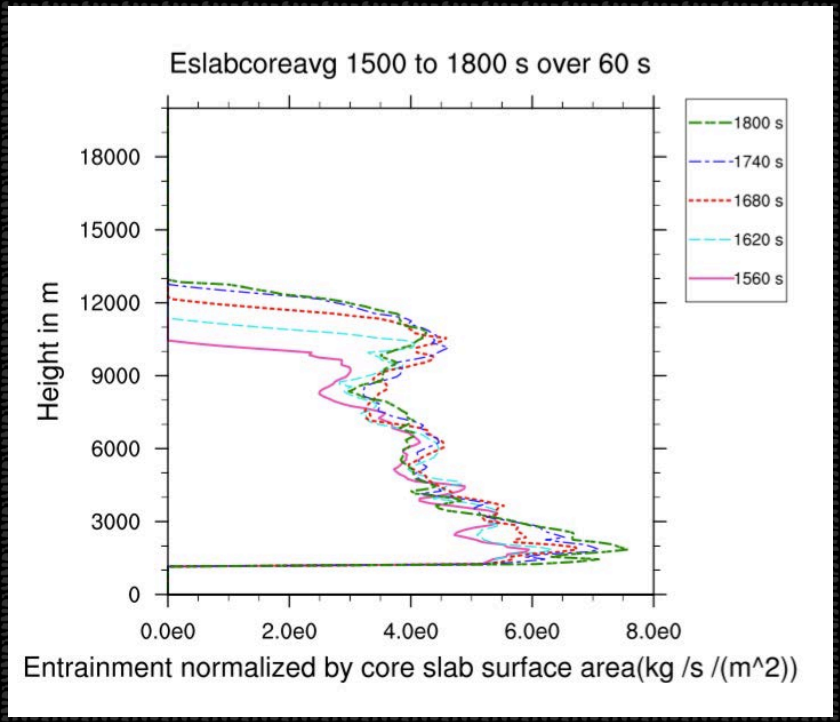
There is a lower limit on eddy sizes that are effective in diluting the cloud core.

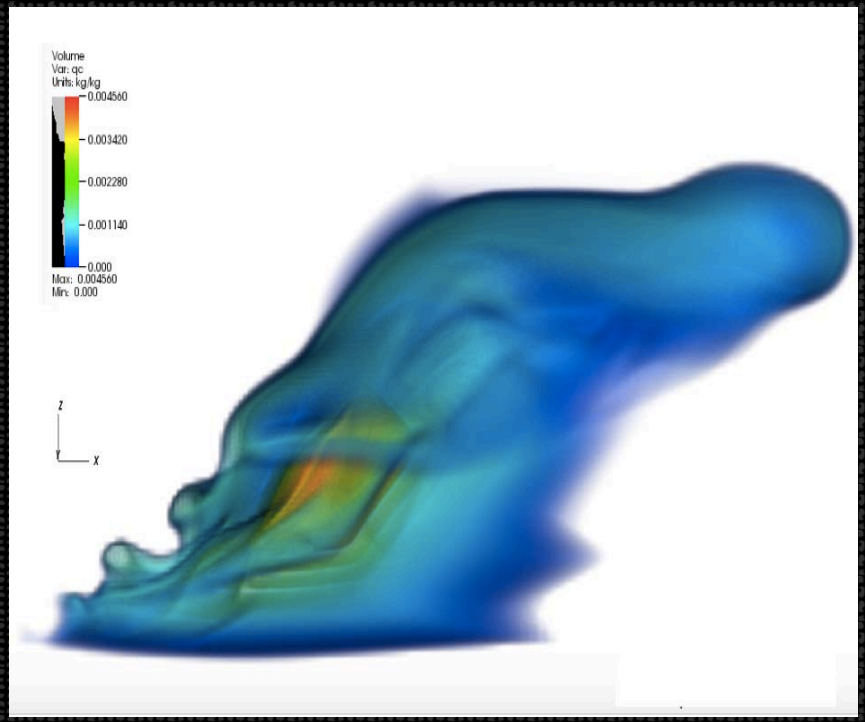
As resolution increases and we resolve smaller turbulent eddies, at some point the cloud dilution won't change.

For this cloud, it appears to occur ~ 15 m resolution, implying eddies < 60 m or so are not important for entrainment. → universality?

Future Work

- Determine eddy-updraft scale relationship across different scales, i.e. minimum effective size for eddies in a supercell?
- Introduce parallel NETCDF or HDF5 into CM1 to relieve scaling issues
- Integrate parallelized entrainment calculations into CM1 (currently prototyped in a separate model)





Acknowledgements

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