Large Eddy Simulations: Where observations and modeling collides

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Cascade of Models

- General Circulation Models
- Regional Models
- Large-Eddy Simulations
- Direct Numerical Simulations

Cascade of Models

General Circulation Models

- Domain size: Entire Earth
- Horizontal Boundary conditions: None
- Horizontal grid spacing: 50km
- Total number of points: about $400 \times 400 \times 100$
- Simulation duration: Weeks - millennia
- Resolved: Hadley Circulation, fronts, ...
- Parameterized: Clouds, Boundary layers, Surface, Microphysics

Cascade of Models

Regional Models

- Domain size: Continental scale or smaller
- Studies of organization, deep systems,...
- Horizontal Boundary conditions: Nested/forced by GCM
- Horizontal grid spacing: $5\mathrm{km}$
- Total number of points: about $400 \times 400 \times 100$
- Simulation duration: Weeks
- Resolved: Deep clouds
- Parameterized: Shallow Clouds, Boundary layers, Surface, Microphysics

Cascade of Models

Large-Eddy Simulations

- Domain size: $1 - 100\mathrm{km}$
- Studies of boundary layer processes, idealized (and not so idealized) clouds
- Horizontal Boundary conditions: Periodic
- Horizontal grid spacing: $50\mathrm{m}$
- Total number of points: about $400 \times 400 \times 100$
- Simulation duration: Hours/Days
- Resolved: Shallow Clouds, Boundary layers
- Parameterized: Turbulence, Surface, Microphysics

Cascade of Models

Direct Numerical Simulations

- Domain size: $1\mathrm{m}$
- Studies of turbulence, possibly with interactions of other processes
- Horizontal Boundary conditions: Periodic
- Horizontal grid spacing: $1\mathrm{mm}$
- Total number of points: about $1000 \times 1000 \times 1000$
- Simulation duration: Minutes
- Resolved: Turbulence, surface (?)
- Parameterized: Microphysics

Cascade of Models
Other

Focus of LES is on Geophysical *Fluid Dynamics*
Many processes are still unresolved or beyond the scope of LES:

- Radiation - At best, 2D radiation is available
- Chemistry, aerosols and microphysics
- Near-Surface processes

History

- Dry LES: Smagorinsky (1963), Lilly(1967), Deardorff(1972)
- Cloudy LES: Sommeria(1976)
- ‘Big breakthrough LES’: Schmidt and Schumann (1989)
- ‘Huge breakthrough LES’: Earth Simulator Global LES (2001)

History I

Intercomparisons

- Dry CBL: Nieuwstadt et al. (1986, 1993) and Andren et al. (1994)
- Non-Precip Stratocumlus: Moeng et al. (1996)
- Radiative Smoke: Bretherton et al. (1999)
- Non-Precip Shallow Cu: Siebesma et al. (2003)
- Non-Precip Stratocumlus: Stevens et al. (2001)
- Diurnal Cycle Cu: Brown et al. (2001)
- Sheared and Stable BLs: Holtslag(2006), Beare(2006)
- Precip Stratocumlus: Ackerman et al. (2008)
- Precip Cumlus: van Zanten et al. (2011)
- Precip Stratocumlus: Ackerman et al. (2008)
- Radiative, transition runs: Sandu, de Roode, Blossey (2012)

When *not* to use LES

When your problem has ...

- ... nothing to do with turbulence
- ... exclusively to do with turbulence (use DNS!)
- ... is dominated by larger scales (e.g. frontal systems)

Or when you don't have sufficient computer power to do high resolution simulations. In which case, start doing theory.

What *can* be done with LES
Classical studies

- Clear convective boundary layers
- Shallow cumulus clouds
- Stratocumulus clouds

What *can* be done with LES

Modern studies

- Precipitation and microphysics
- Cloud and parcel tracking
- Deep convection
- Stable boundary layers
- Surface interaction
- Day-to-day runs like in Testbed situations

Model Philosophy

Why use stand-alone LES models at all?

- Research desires ad-hoc changes
- Big model structures (WRF, ECHAM, ICON...) tend to be cluttered, lots of unnecessary additions, hard to run and compile, unreadable,...
- Stand alone LES's are just small enough to understand (more or less)
- It is easy to code any forcing/output you want, and use it for 1 study
- Optimized for user/developer time, not CPU Time

(See: Heus et al , 2010, Geoscientific Model Descriptions)

- Spatially filter (smooth) the Navier Stokes Equations
- Ensure that the width of this spatial filter lies in the inertial subrange of the turbulent field
- Explicitly solve the most energetic scales
- Model the Sub Filter Scale (SFS) turbulence. The details of this SFS model should not matter.

We violate these principles on a daily basis. But still, over 90% of the energy in the bulk of the convective boundary layer is usually resolved.

Filtering

$$\bar{u} = \int G(r)u\mathrm{dr}$$

With G the filter (could be a (grid-)box, a gaussian, a spectral filter,....)

Navier Stokes Equations

$$\frac{\partial u_i}{\partial t} = \qquad -u_j\frac{\partial u_i}{\partial x_j} - c_p\Theta_0\frac{\partial \pi}{\partial x_i} \qquad +\nu\frac{\partial^2 u_i}{\partial x_j^2} + \mathcal{F}_i$$

Large-Eddy Equations

$$\frac{\partial \bar{u}_i}{\partial t} = -\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} - c_p \Theta_0 \frac{\partial \bar{\pi}}{\partial x_i} + \frac{1}{\rho_0} \frac{\partial (\rho_0 \tau_{ij})}{\partial x_j} + \mathcal{F}_i$$

$$\frac{\partial \bar{\phi}}{\partial t} = -\bar{u}_j \frac{\partial \bar{\phi}}{\partial x_j} + \frac{1}{\rho_0} \frac{\partial (\rho_0 \gamma_{\phi j})}{\partial x_j} + \mathcal{S}_\phi$$

Anelastic continuity

$$\frac{\partial (\rho_0 u_i)}{\partial x_i} = 0$$

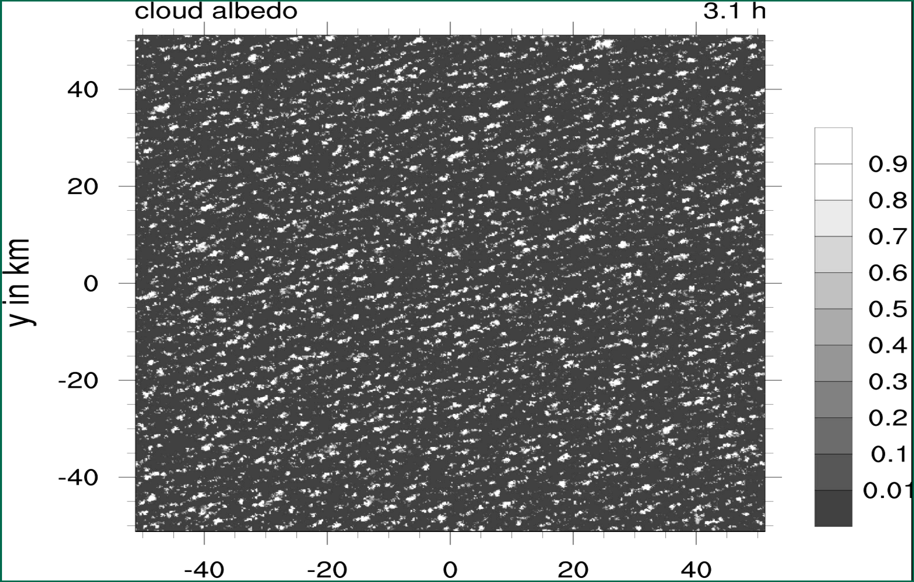
Ideal gas law equation of state

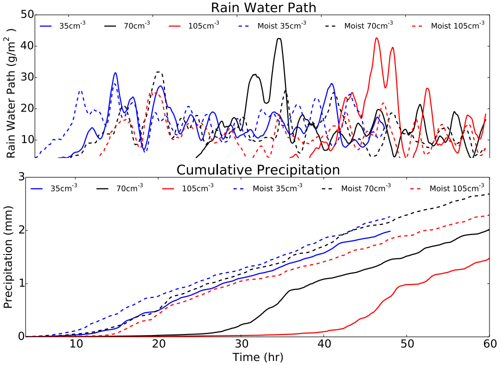
$$\theta_v = \theta \left(1 + (R_v/R_d - 1) q_t - (R_v/R_d) q_l\right).$$

Closure

- $\tau_{ij} \equiv \overline{u_i u_j} - \bar{u}_i \bar{u}_j$ is the Sub Filter Scale flux and needs to be modeled
- Can be done by
  - Smagorinsky diagnostic closure
  - Deardorff prognostic TKE
  - Higher order closures
  - Nothing at all (Numerical diffusion)
- All models start off with models for homogeneous isotropic turbulence
- Empirical modifications are nearly always done to match stable turbulence and condensation gradients.

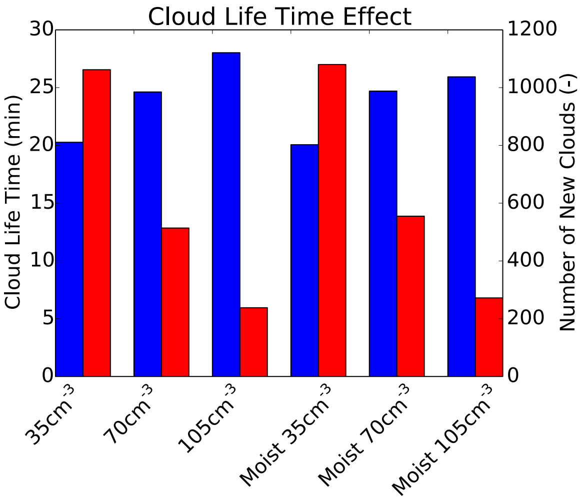
Aerosol Indirect Effects





- Strong fluctuations
- All cases go through three phases: Random, transition, organized
- An increased CDNC can delay the onset of organization by almost 2 days
- All organized states show similar precipitation rates

Cloud Life Time Effect



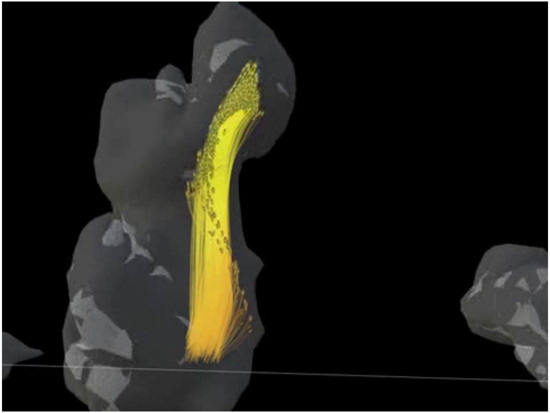
Back to Observations

- In our LES simulations, we see the thermodynamics dominating the aerosol effects (for the cloud radiative forcing)
- Transients effects possible
- Do we believe this as gospel? No. It is only a model
- Using this knowledge, a careful experiment across the Atlantic (with or without Saharan dust) could shed more light on these hypotheses

See: Seifert et al (submitted)

Where does in-cloud air come from?

Using Lagrangian Particle Tracking, we can determine what in-cloud air comes from what place



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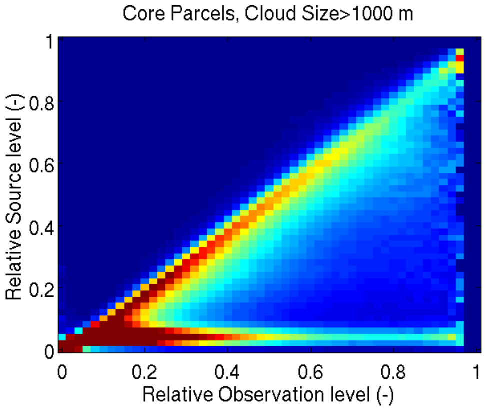
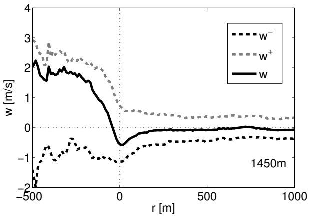


All entrainment comes from the sides, and dilution is strong

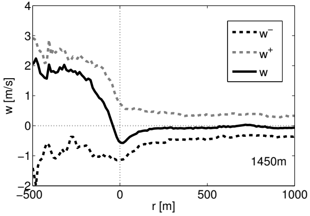
What Happens During this Lateral Mixing?

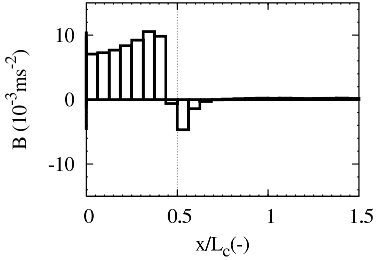
- A thin ring around the clouds of negatively buoyant air
- Compensates 20% of the cloud core mass flux
- Modifies entrainment, microphysics, dispersion,...



What Happens During this Lateral Mixing?

- A thin ring around the clouds of negatively buoyant air
- Compensates 20% of the cloud core mass flux
- Modifies entrainment, microphysics, dispersion,...
- Works through lateral entrainment and evaporative cooling

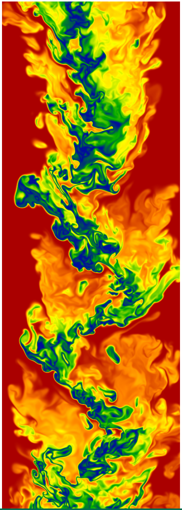




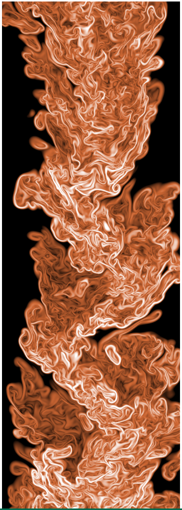
Direct Numerical Simulations of the Subsiding Shell

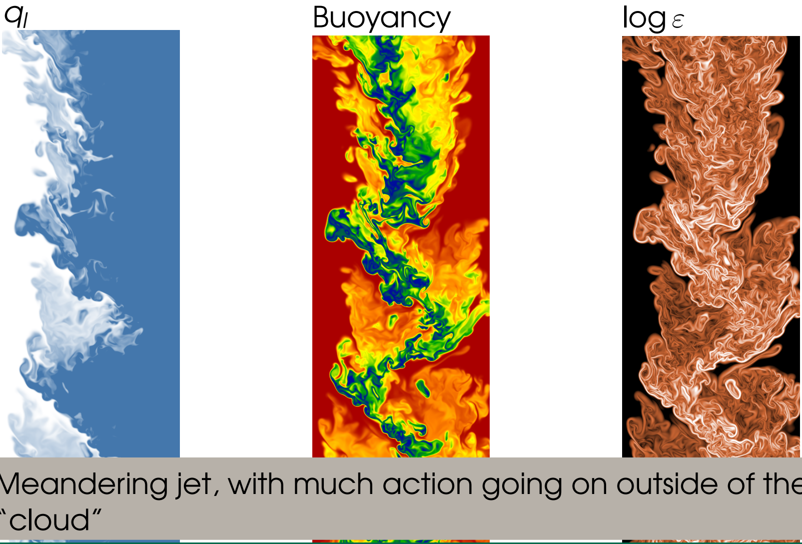
q_l

Buoyancy



$\log \varepsilon$





Meandering jet, with much action going on outside of the "cloud"

Scaling Laws

w scaling

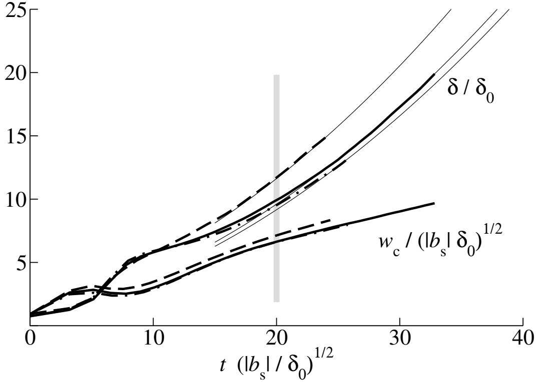
$$w_c = \sqrt{2(c_1/c_2)b_s\delta}$$

δ scaling

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \sqrt{2c_1c_2b_s\delta}$$

$$\delta(t) = (c_1c_2b_s/2)(t-t_1)^2 + \sqrt{2c_1c_2b_s\delta_1}(t-t_1) + \delta_1$$

Scaling in time



The thin lines denote the quadratic scaling... it fits.

Comparison with observations

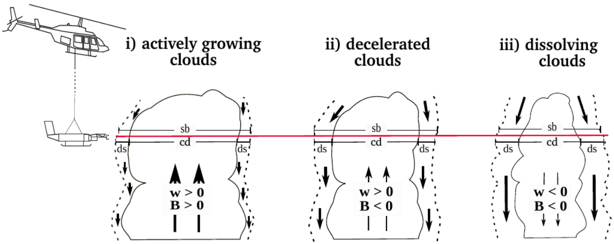
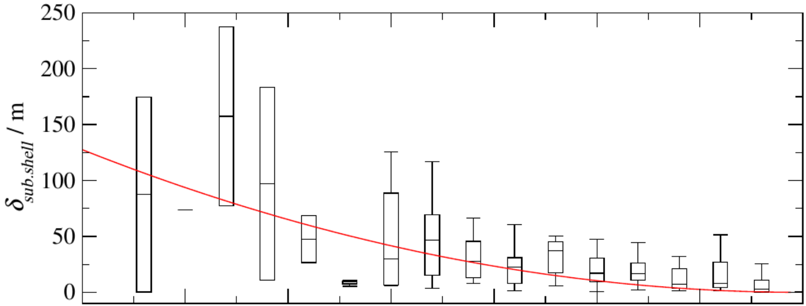


FIG. 6. Schematic picture of the evolution of a cumulus cloud from actively growing to dissolving, where the growth of the subsiding shell at the expense of the cloud is illustrated. Here, *ds* marks the distance from beginning of the subsiding shell to the entrance of the cloud core region and *sb* marks the thickness of the whole system.

Comparison with observations



Conclusions - Cloudy Turbulence

- Lateral mixing trumps vertical mixing
- But the subsiding shell takes care of much of the transport
- DNS modeling of the shell compares well with detailed observations
- Ping Pong between LES, observations, DNS, observations, theory and parameterization to get everything right (with many co-authors!)

Testbed

(See: Neggers et al (BAMS,2012) for the testbed, Corbietta et al (submitted for the overlap))

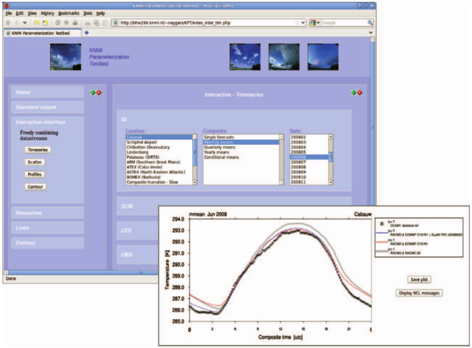
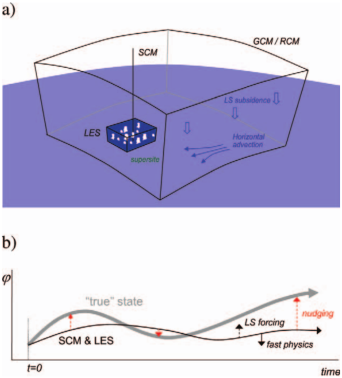
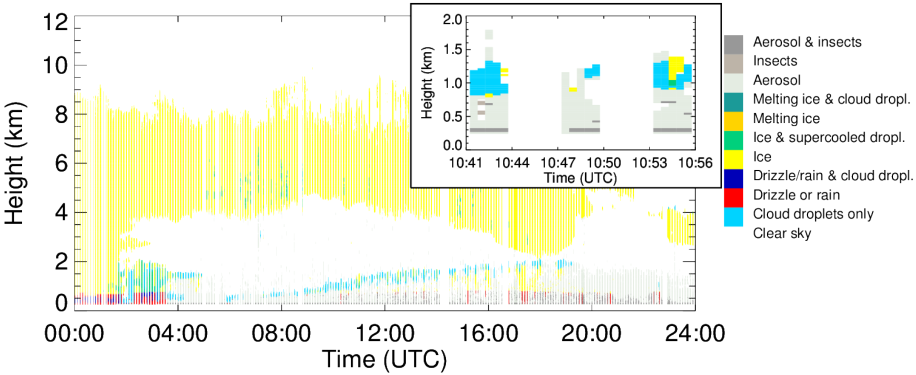


FIG. 1. A snapshot of the KPT interface, including the main selection menu (background) and an example plot (foreground) that evaluates monthly-mean model data (solid lines) against Cabauw measurements (asterisks).

Testbed


a)
GCM / RCM
SCM
LES
supersite
LS subsidence
Horizontal advection
b)
φ
"true" state
SCM & LES
LS forcing
nudging
fast physics
t=0
time

Cloud Overlap



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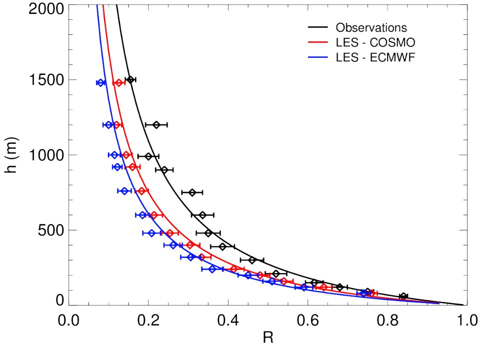

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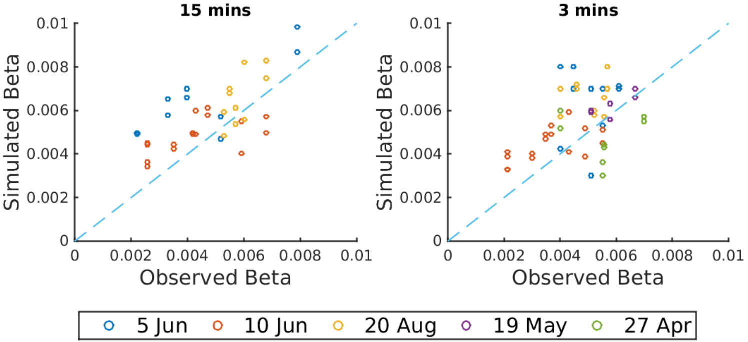

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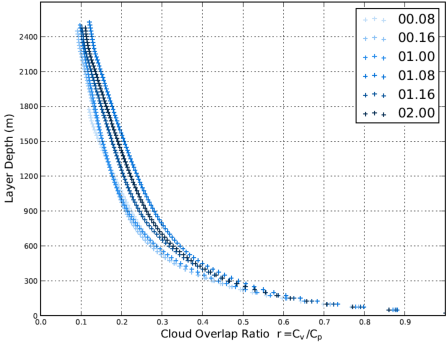

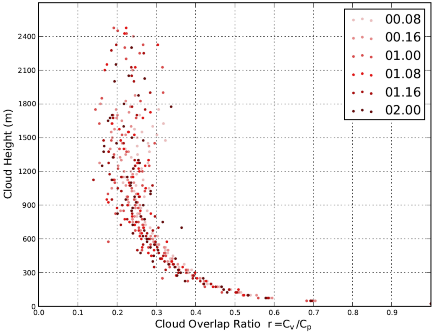

Conclusions

- LES is a powerful tool, but much more so in combination with (other) observations
- Use it whenever you can, but make sure that it is applicable to your situation
- Just like with remote sensing, peek into the black box before you go