Realism of cloud structures in LES and its use for cloud and radiation parameterizations

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For details see: Siebesma and Jonker: Phys Rev Let. 85 p214 2000
Neggers et al: JAS 60 p1060 2003
De Roode et al: JAS 61 p403 2004
Climate Model Development strategy

- **Topics**: turbulence, clouds, convection, radiation

- **Methodology**:

  DALES

  Large Eddy Simulation Models + Observations

  \[ \text{Single Column Model version} \]

  \[ \text{3d RACMO-2} = \text{“limited area version of ECMWF-model”} \]

- Internationally embedded in: GEWEX Cloud System Systems (GCSS)
  (www.gewex.org/gcss.html)
### GCSS (WG1) bl-clouds Cases:

<table>
<thead>
<tr>
<th>Type</th>
<th>Case</th>
<th>Parameterization Issues addressed:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nocturnal Scu</td>
<td>FIRE (1987)</td>
<td>Top-entrainment</td>
</tr>
<tr>
<td>Shallow Cu (steady state)</td>
<td>BOMEX (1969)</td>
<td>Mass flux, cloud cover, lateral entrainment</td>
</tr>
<tr>
<td>Shallow Cu topped with Scu</td>
<td>ATEX (1971)</td>
<td>Mass flux, cloud cover, lateral and top entrainment</td>
</tr>
<tr>
<td>Shallow Cu (Diurnal Cycle)</td>
<td>ARM (June 21, 1997)</td>
<td>Mass flux, cloud cover, lateral entrainment</td>
</tr>
<tr>
<td>Scu (Diurnal Cycle)</td>
<td>FIRE (1987)</td>
<td>Top-entrainment, Radiation</td>
</tr>
<tr>
<td>Scu (precipitating)</td>
<td>DYCOMS (2001)</td>
<td>Top-entrainment, Radiation, Precipitation</td>
</tr>
</tbody>
</table>
LES widely used within GCSS to study turbulent transport in Cloud topped PBL

But............
3. Is this a Cloud??

How to answer this question?
Area-Perimeter analyses of cloud patterns

• Pioneered by Lovejoy (1981)
• Area-perimeter analyses using satellite and radar data
• Suggest a perimeter dimension $D_p = 4/3$ of projected clouds

Instead of
4. Similar analysis with LES clouds

- Measure Surface $A_s$ and linear size $l \equiv V^{1/3}$ of each cloud
- Plot in a log-log plot
  - $A_s \propto l^{D_s}$

- Assuming isotropy, observations would suggest $D_s = D_p + 1 = 7/3$
5. Result of one cloud field

\[ D_s = 2.34.. \]

\[ D = 2 \]
Repeat over 6000 clouds
7. Consequences

- Surface area can be written as a function of resolution $l$:

$$S(l) = S_L \left( \frac{l}{L} \right)^{2-D_s} \quad \text{with} \quad D_s \equiv \frac{7}{3}$$

- Euclidian area $S_L$ underestimates true cloud surface area $S(l=h)$ by a factor $\left( \frac{\eta}{L} \right)^{2-D_s} \approx 100$

- LES model resolution of $l=50m$ underestimates cloud surface area still by a factor 5!
8. Resolution dependence \( l_0 \) for transport over cloud boundary (1)

Transport = Contact area \( \times \) Flux

\[
T(l_0) = S(l_0) F(l_0) \quad \equiv \quad -S(l_0) K(l_0) \frac{\partial c}{\partial x}
\]

- turbulence
- diffusive flux

\( S(l_0) \)

\( K(l_0) \frac{\partial c}{\partial x} \)
8. Consequences for transport over cloud boundary (2)

\[ T(l_0) = S(l_0) F(l_0) \equiv -S(l_0) K(l_0) \frac{\Delta c}{l_0} \]

\[ S(l_0) = S_L \left( \frac{l_0}{L} \right)^{2-D_s} \quad K(l_0) = l_0 \delta u(l_0) \propto l_0 \delta u(L) \left( \frac{l_0}{L} \right)^{1/3} \]

(Richardson Law)

\[ T(l_0) = \Delta c \delta u(L) S(L) \left( \frac{l_0}{L} \right)^{7/3-D_s} \]

No resolution dependancy for Ds=7/3!! Coincidence??
Conclusions

• LES models simulate the correct cloud geometry
• Cloud surface dimension $D_s = 7/3$
• Transport over cloud boundaries are scale independent within LES
• Repeating scaling arguments for $l_0 = h$ can be used as a heuristic proof for $D_s = 7/3$ (Use Reynolds number similarity (Sreenivasan et al, Proc Soc. London (1989))
Cloud size distributions

• Many observational studies:
  • Exponential (Plank 1969, Wielicki and Welch 1986)
  • Log-normal (Lopez 1977)
  • Power law (Cahalan and Joseph 1989, Benner and Curry 1998)
Cloud size distributions (2)

- Repeat with LES. Advantages
  - Controlled conditions
  - Statistics can be made arbitrary accurate
  - Link with dynamics can be established

Specific Questions:
- What is the functional form of the pdf?
- What is the dominating size for the cloud cover?
- Which clouds dominate the vertical transport?
Definitions:

Projection area of cloud $n$: $A^p_n$

Size: $l_n = \sqrt{A^p_n}$

Total number of clouds: $N \equiv \int_0^\infty N(l) dl$

Cloud fraction: $a \equiv \int_0^\infty \alpha(l) dl$

Related through: $\alpha(l) \equiv \frac{l^2 N(l)}{L_x L_y}$
Cloud Size Density

- Power law with $b=-1.7$
  \[ N(l) \propto l^b \]
- Scale break in all cases
- Scale break size $l_d$ case dependant ($700m$-$1250m$)

Typical Domain: 128x128x128
Number of clouds sampled: 35000
Cloud size density (2)

- Universal pdf when rescaled with scale-break size $l_d$
Cloud Fraction density

\[ \alpha(l) = N(l)l^2 \propto l^{b+2} \]

With \( b = -1.7 \) (until scale break size)

- \( b < -2 \) smallest clouds dominate cloud cover
- \( b > -2 \) largest clouds dominate cloud cover

Due to scale break there is an intermediate dominating size
Conclusions

• Cloud size distribution: \( N(l) \propto l^b \) with \( b = -1.7 \)
• Non-universal scale break size beyond which the number density falls off stronger. (Only free parameter left)
• No resolution dependency has been found (see paper)
• Intermediated cloud size has been found which dominates the cloud fraction.

Open Questions:

• What is the physics behind the power law of the cloud density distribution?
• What is causing the scale break?
How to use this cloud variability to build cloud and radiation parameterizations?

Statistical cloud schemes
Statistical Cloud Schemes (2):

Convenient to introduce:

“The distance to the saturation curve”

\[ s \equiv q_t - q_s(p, T) \]

Normalise \( s \) by its variance:

\[ Q \equiv \bar{t} \equiv \frac{q_t - q_s}{\sigma_s} \]

Sommeria and Deardorf (JAS, 1976)
Verification (with LES)

Cloud cover

\[ Q \equiv \bar{t} \equiv \frac{\bar{q}_t - \bar{q}_s}{\sigma_s} \]

Bechtold and Cuijpers JAS 1995

Bechtold and Siebesma JAS 1999
Verification (with Observations)

Wood, Field and Cotton 2002 Atm. Research
Remarks:

1. Gaussian PDF “good enough” to estimate liquid water and cloud cover.

2. Correct limit: if $dx \to 0$ then $\sigma_s \to 0$ and the scheme converges to the all-or-nothing limit

3. Parameterization problem reduced to finding the subgrid variability, i.e. finding $\sigma_s$. 
Convection and turbulence parameterization give estimate of $\sigma_s$

- Cloud scheme: $a_c = f\left(\frac{\bar{q}_t - \bar{q}_s}{\sigma_s}\right)$
- Radiation scheme: $R(\bar{q}_t, \sigma_s)$
- McICA by employing the variance

- Subgrid variability (at least the 2nd moment) for the thermodynamic variables needs to be taken into account in any GCM for parameterizations of convection, clouds and radiation in a consistent way.

- At present this has not be accomplished in any GCM.
How does the variability change with resolution?

\[
\sigma_s \approx ?
\]

\[
\sigma_s \approx ?
\]

\[
\sigma_s \approx 0
\]

All or nothing

Calculate in LES: \( \langle \sigma_q(l) \rangle \)
No growth of $\langle \sigma_q(l) \rangle$
For size $l > 5$ km
How about Stratocumulus?

Observations give:

Standard deviation of $s (= q_t - q_s)$ scales as $s \sim L^{1/3}$

from 100m up to 100km, consistent with a 5/3 spectrum over this range.

Mesoscale Organisation!!

How about LES??

Wood, Field and Cotton 2002 Atm. Research
Davies, Marshak and Cahalan JAS 53 1996
Large-Eddy Simulations

• Parallelized version
• Large horizontal domain 25.6 x 25.6 km$^2$
• Number of grid points 256 x 256 x 80
• $\Delta x = \Delta y = 100$ m, $\Delta z < 20$ m
• Cyclic boundary conditions
• Simulation time 10 hours

Nocturnal stratocumulus cloud layer, initialization based on observations (FIRE I)
LES does show mesoscale growth
Same analysis as Wood et. al

\[
\frac{\sigma_s^2(l)}{\sigma_s^2(l_0)} \text{ vs } l \quad (\propto l^{2/3}?)
\]

- Variance grows with scale and time
- But …. Not with the expected scaling!!
Conclusions

• LES does produce realistic cloud structures
• GCSS provides a large data set of 3d cloud scenes that can be used for radiative transfer studies
• GCM’s are still in a poor state concerning cloud inhomogeneity effects
• Simultaneous measurements of cloud structures and radiation measurements offers a strong constraint for cloud-radiation effects that will reduce the infamous “tuning-freedom”
• ATEX: Marine Cumulus Topped With Scu

Courtesy: Dave Stevens; Lawrence Livermore National Laboratory
EUROCS  Model Evaluation:

Hadley Circulation in the Pacific:
- Well defined large scale circulation
- Monthly mean deviations from climatology relatively small
- All studied cloud types within EUROCS are present in well geographically separated way.
- Future Changes in Climate for Europe are connected with changes in the Hadley Circulation (see Dutch Challenge Project)

Use JJA 1998 as an example:
- Most data directly available
- Not too strong El Nino

required output: vertical profiles single level parameters

(Siebesma and coauthors: QJRMS November 2004.)

www.knmi.nl/samenw/eurocs
Liquid water Path

ECMWF, RACMO: too high
MetO: too low
Too high
Too low
Surface downward shortwave Radiation

- Consistent: Mirror Image of TOA SW.
Liquid water Path

ECMWF, RACMO: too high

MetO: too low

Too high

Too low
Scatter plot: LWP versus Transmissivity.

\[ T = \frac{\langle F_{rad,sw,down,srf} \rangle}{\langle F_{rad,sw,down,toa} \rangle} \]

With:

\[ \langle . . \rangle = \text{monthly time averages over [9hr,15hr] local time} \]

- Clouds in MetO and ECHAM are too reflective.
- Differences in radiation schemes! Tuning?!
LES run of diurnal cycle of cumulus:
ARM site Oklahoma June 21 1997
Intercomparison results for 1D-model versions of GCM’s

(for details see http://www.knmi.nl/samenw/eurocs)
Environmental profile

Saturation curve

Zero-buoyancy line
Not a complete demonstration of the fact that clouds are fractal! Nature could play the following trick on us:

\[ A = 2\pi r h \]
\[ V = \pi r^2 h \]

Remember: \( l \equiv V^{1/3} \)

\[ h \propto r^\alpha \]

\[ A \propto l^{\frac{3(1+\alpha)}{2+\alpha}} \]

with \( \alpha = \frac{5}{2} \)
6. Direct measurement of correlation dimension

\[ C(l) = \sum_{i,j} \theta(l - |\vec{x}_i - \vec{x}_j|) \propto \ell^{D_s} \]
Large Eddy Simulation (LES) Modelling

- High Resolution Non-hydrostatic Model: ~50m
- Large eddies explicitly resolved by NS-equations
- inertial range partially resolved
- Therefore: subgrid eddies can be realistically parametrised by using Kolmogorov theory

\[
\ln(Energy) = \ln(wave\ number) - \frac{1}{l_{d}^{-1}} \approx 1\ mm^{-1}
\]

\[
\ln(Energy) = \ln(wave\ number) - \frac{1}{l_{0}^{-1}} \sim 1\ km^{-1}
\]

Inertial Range
Resolution LES
Dissipation Range

\[
l_{d}^{-1} \approx 1\ mm^{-1}
\]

\[
l_{0}^{-1} \sim 1\ km^{-1}
\]
CLOUDS in GCM’s: What are the problems?

- Many of the observed clouds and especially the processes within them are of sub grid-scale size.
Neglecting this subgrid variability causes biased errors in a number of key processes:

• Moist convection of heat and moisture

• Cloud Properties

• Radiative Transport
Neglecting Cloud inhomogeneity causes a positive bias in the cloud albedo.
Subgrid variability (at least the 2\textsuperscript{nd} moment) for the thermodynamic variables needs to be taken into account in any GCM for parameterizations of convection, clouds and radiation in a consistent way.

At present this has not be accomplished in any GCM.

Large Eddy Simulations (LES) in combination with observations is a useful tool to obtain this subgrid variability and to help develop GCM parameterizations for these cloud related processes.

GEWEX Cloud System Studies (GCSS) explores this avenue (www.gewex.org/gcss.html)
How to obtain a parameterization for the variance?

Link it to the convection/turbulence schemes using a variance budget:

Production Dissipation

$$w' q_t' \frac{\partial q_t}{\partial z} = \tau^{-1} q_t'^2$$

$$M (q^{cu}_t - \bar{q}_t) \frac{\partial \bar{q}_t}{\partial z} \equiv \frac{w^{cu}_*}{l_{cloud}} q_t'^2$$

$$\tau = \frac{l_{cloud}}{w^{cu}_*}$$

$$w^{cu}_* = \int_{\text{cloud}} \frac{g}{\theta} M \Delta \theta_v dz$$

Grant & Brown QJRMS 1999

Final Result: $$q_t'^2 \equiv \frac{M (q^{cu}_t - \bar{q}_t)}{w^{cu}_*} l_{cloud} \frac{\partial \bar{q}_t}{\partial z}$$
LES domain size: How large is large enough?

Spectra in stratocumulus

- Different domain sizes $L$