“Improving the representation of clouds in general circulation model (GCM) simulations through analysis of cloud resolving model (CRM) results and field data”

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Methodology

Development of parameterizations of turbulence, convection and clouds

General Circulation Models
$\Delta x = 50-300$ km

1D mode

Large-scale forcings
Surface fluxes

Cloud process analysis

Cloud Resolving Models
$\Delta x = 50$ m - 1 km

Large-scale forcings
Surface fluxes

Khairoutdinov, GCSS 2008
Boundary-layer clouds

**Schematic view from observations**

*LeMone and Pennell, MWR, 1976*

**Thermal plume model**

*Rio & Hourdin, JAS, 2008*

Conservation equations:

- Mass
  \[
  \frac{\partial f}{\partial z} = e - d
  \]

- Conserved variables:
  \[
  \frac{\partial f \psi_u}{\partial z} = e \psi - d \psi_u
  \]

- Momentum:
  \[
  \frac{\partial f w_u}{\partial z} = -d w_u + \alpha g \rho \frac{\theta_{vu} - \theta_v}{\theta_v}
  \]

Internal variables:

- Mass-flux $f$
- Mixing rates: $e$, $d$
- Vertical velocity $w_u$
- $\theta_u$, $qvu$, $qlu$ ...
An example

Boundary-layer clouds

How to select thermals in high resolution simulations?

Couvreux & al., BLM, 2010

Highest Tracer concentration

\[ s' > \sigma_s + w > 0 \]

Rio & al., BLM, 2010

Passive tracer emitted in 1st layer

Traditional samplings of clouds

New sampling

\[
\varepsilon = \max(0, \beta_1 \frac{\partial w_u}{\partial z})
\]

\[
\varepsilon = \max(0, \frac{1}{1 + \beta_1} \frac{B}{w_u^2})
\]

Height (m)

Entrainment rate (1/m)
Intercomparison of CRMs

The Tropical Warm Pool-International Cloud Experiment
Darwin, Australia
January 20 to February 13, 2006

Observations
-Soundings, surface radiative fluxes, surface turbulence flux
Variational analysis (Xie & al., JC, 2010)
- vertical velocity, advective tendencies of temperature and moisture

Fridlind & al., 2010

Bench of cloud resolving model simulations: DHARMA, SAM, MESONH, UKMO
- different dynamics and sub-grid physics (turbulence, microphysics)
- Δx~1km
Observations

Observational picture of tropical squall lines

Zipser (1977)

- shallow convection
- Convective scale updrafts and downdrafts
- mesoscale updrafts and downdrafts
- microphysics of clouds
- Cold pools

GCM issues:
- Heating and moistening profiles
- Rain rates over which area
- Cloud impact on radiation

GISS ModelE

Parameterization of deep convection

Del Genio & Yao, 1993

Microphysics
partitioning of falling and detrained condensate as a function of $w_u$ (Del Genio & al, JC, 2005)

Cloud base height

Surface

**saturated updrafts**
Conservation equations:
- mass: $M_u$
- momentum: $w_u$
- dry static energy: $\theta_u$
- moisture: $q_vu$
- internal variables: $E$, $D$, $M_b$

**downdrafts**
Conservation equations:
- mass: $M_d$
- dry static energy: $\theta_d$
- moisture: $q_vd$
- Internal variables: $E$, $D$, $M_d_{ini}=1/3M_u$

Compensating subsidence in the environment
Convective/stratiform partitioning

Steiner (1995) algorithm based on reflectivity

Convective area (%)

Stratiform area (%)

Figures: A. Mrowiec
Convective/stratiform partitioning

Event A - DHarMA

MSE flux (K m/s) \[ \text{MSE} = C_pT + gz + Lqv - Lfqic \]

- Major part of fluxes occurs in the convective region
- In the stratiform region: fluxes within the anvil and below
- In the subsidence region: dry and shallow convection transport
Traditional samplings of updrafts and downdrafts

Cloudy updrafts: condensate (liquid and ice) + positive w threshold
Precipitating downdrafts: precipitation (rain and graupel) + negative w threshold

Krueger, JAS (1988)
Xu et Randall, JAS (2001)

Images from A. Mrowiec

Moist Static Energy

Equivalent potential temperature at the surface

*Visualization made using VAPOR

Limitations:
do not allow to differentiate convective scale transport from local transport or gravity waves
A sampling based on the observational evidence that:

- Updrafts transport high θe or moist static energy (MSE) up
- Downdrafts transport low θe MSE down (Zipser, 1969; Betts, 1976 ...)

At a given (z,t):

- ✓ MSE threshold:

- ✓ Vertical velocity threshold?
  3 categories: 0.1-0.5-1m/s
Updraft categorization in the convective region

\[ P(MSE) \]

- \( MSE-m\sigma \)
- \( MSE \)
- \( MSE+m\sigma \)

\( 0.1 < w < 0.5 \)
\( 0.5 < w < 1 \)
\( w > 1 \)

\( m = 1 \)
Event A - DHARMA

Updraft properties

MSE sampling:
- same qv flux
- with less points

Selected updraft:
- moister
- faster
- higher buoyancy
Updraft properties

Event A - DHRAMA

- qv turbulent flux (g/kg m/s)
- area (%)
- vertical velocity (m/s)
- qv perturbation (g/kg)
- mass flux (kg/m2/s)
- buoyancy (m/s2)

Related processes:
- Entrainment
- P perturbations
- Detrainment

Overestimated:
- mass-flux
- vertical velocity

cloudy updrafts
high MSE updrafts
GISS updrafts
**Parameterization issues**

**Event A - DHARMA**

- Entrainment overestimated at low levels
- Detrainment underestimated above 2km
- Buoyancy ok > underestimation of pressure perturbation impact on velocity field

\[
\epsilon = \frac{1}{\psi - \psi_u} \frac{\partial \psi_u}{\partial z}
\]

\[
\delta = -\frac{1}{f} \frac{\delta f}{\delta z} + \epsilon
\]

\[
\frac{1}{2} \frac{\partial w_u^2}{\partial z} = a_1 B - a_2 \epsilon \nu w_u^2
\]
Downdraft categorization in the convective region

\[ P(MSE) \]

\[ MSE-m_x \sigma \]

\[ MSE \]

\[ MSE+m_x \sigma \]

\[ m=0.5 \]

\[-0.5 < w < -0.1\]

\[-1 < w < -0.5\]

\[ w < -1\]
Downdraft properties

**Event A - DHRAMA**

- **qv turbulent flux (g/kg m/s)**
- **mass flux (kg/m²/s)**
- **vertical velocity (m/s)**
- **qv perturbation (g/kg)**
- **area (%)**
- **buoyancy (m/s²)**

**Low MSE downdraft:**
- positive qv flux
- low qv, qr, w
- negative buoyancy
Downdraft properties

**Event A - DHRAMA**

- **qv turbulent flux (g/kg m/s)**
- **mass flux (kg/m²/s)**
- **vertical velocity (m/s)**
- **qv perturbation (g/kg)**
- **area (%)**
- **buoyancy (m/s²)**

**Low MSE downdraft:**
- Positive qv flux
- Low qv, qr, w
- Negative buoyancy

**High MSE downdraft:**
- Negative qv flux
- High qv, qr, w
- Positive buoyancy
Downdraft properties

Event A - DHRAMA

- qv turbulent flux (g/kg m/s)
- mass flux (kg/m²/s)
- vertical velocity (m/s)
- qv perturbation (g/kg)
- area (%)
- buoyancy (m/s²)

Related processes:
- downdraft initiation
- downdraft mass-flux at initiation level
- entrainment
- detrainment
- vertical velocity equation?

- overestimated mass-flux
- Above cloud base: high MSE downdraft
- Below cloud base: low MSE downdraft
Parameterization issues

Downdraft initiation

- High MSE downdrafts: 60% env – 40% up
  
  Md: 20 to 40% of Mu

- Low MSE downdrafts

- High MSE updrafts

MSE (K)

$qv$ (g/kg)

Mass flux (kg/m²/s)

Height (m)

Height (m)

Fraction of environmental air inside downdrafts

Md/Mu
Event C - SAM

**Updrafts**
- 150m
- 1km
- 2km
- 4km

**Downdrafts**

- High MSE downdrafts right under cloud base
- Low MSE downdrafts at low levels under the tilting updrafts
Structure visualization

Event C - SAM

Are they the same structure from 8km to the surface?

Low MSE downdrafts spread into the stratiform region
Low MSE downdrafts = cold pools?
Conclusions

“Improving the representation of clouds in general circulation model (GCM) simulations through analysis of cloud resolving model (CRM) results and field data”

1. Identify a key physical process in clouds life cycle that matters at global scale
   *Downdrafts: strongly modify the boundary layer + deep convection triggering*

2. Understand the mechanisms behind this process from observations or high resolution modeling
   *Water loading, melting, evaporation, mixing*

3. Evaluate existing parameterizations
   *Parameterization hypothesis: downdraft initiation, mass-flux, microphysics*

4. Develop or improve parameterizations

5. Run GCM and study the impact of the development at global scale

6. Identify GCM weaknesses

*Long is the road...*