Using a Cloud System Concept to assess bulk ice schemes (fall speed – eff. crystal size) in the LMDZ GCM

Claudia Stubenrauch, Marine Bonazzola, Sofia Protopapadaki, Ionela Musat

LMD/ IPSL, France

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Motivation

In a GCM:

- **mass-weighted ice crystal fall speed** \( (v_m) \)
  strongly influences UT cloud occurrence & properties
  & has potential to influence climate sensitivity (e.g. Sanderson et al. 2008)

- \( D_e \) affects the radiative properties of UT clouds

**Questions:**

- How do existing parameterizations of \( v_m \) and \( D_e \) compare with each other?
- How do they compare with the current parameterizations of the LMDZ GCM?
- How can we use the new “cloud system diagnostics” to assess high clouds in LMDZ?
- What is the effect of including a new bulk ice scheme \( (v_m - D_e) \) in the LMDZ GCM?
1. How do the existing parameterizations of $v_m$ and $D_e$ compare with each other?
Analytical expressions: D -> bulk properties

PSD generally expressed as:

\[ N(D) = N_0 D^\mu e^{-\lambda D} \]

D maximum dimension ice crystals, \( \lambda \) slope, \( \mu \) dispersion; exponential PSD: \( \mu = 0 \)

Cirrus bulk properties = mass- or area-weighted integrals of PSD, with

\[ m = a D^b \quad A = c D^d \]

\( b = 3 \) for sphere, \( b = 2 \) for aggregates, \( b = 1.5 \) for dendrites

\[ \text{IWC} = \int m(D) N(D) \, dD = \int a \, N_0 \, D^{b+\mu} e^{-\lambda D} \, dD = a \, N_0 \, \Gamma(b+\mu+1)/\lambda^{(b+\mu+1)} \]

\[ D_m = \int D^3 N(D) \, dD / \int D^2 N(D) \, dD = (b+\mu+0.67)/\lambda \quad \text{Mitchell et al. 1991} \]

\[ v_t \sim (m/A)^{0.6} D^{0.3} f(p) \quad v_t = AD^B \]

\[ v_m = \int m(D) v_t(D) N(D) \, dD / \int m(D) N(D) \, dD \]

\[ v_m = A'D_m^{B'} \quad \text{Heymsfield et al. 2013} \]

\[ A \& B \text{ for 3 D ranges} \quad \text{(Heymsfield et al. 2013)} \]

\[ A' \& B' \text{ for 2 D ranges} \quad \text{(Furtado et al. 2015)} \]
\( v_m \) and \( D_e \) in literature:
- different retrieval methods
- different meteorological conditions
- different Temperature and IWC ranges

**Empirical parameterizations:** \( v_m = f(T, IWC) \)

**Heymsfield et al. 2007 (H07):** 20000 PSDs from 2 field campaigns
tropical anvils (T > -70°C) & synoptic cirrus (T > -54°C)

**Deng & Mace 2008 (DM08):** from longterm ARM in situ statistics,
retrieved from radar measurements; 1999-2005 -> 30000 hrs
convective: TWP ARM (T > -75°C) synoptic: SGP ARM (T > -65°C)

**Mitchell et al. 2011 (M11):** 3 field campaigns (TC4, NAMMA, ISDAC)
young anvil cirrus, aged anvil cirrus, in situ cirrus, Arctic cirrus
similar behaviour; except Arctic cirrus: \( v_m \) not dependent on IWC

**Elsaesser et al. 2017 (E17):** convective outflow
from 4 field campaigns (TC4, NAMMA, MC3E, SPARTICUS)
- GISS GCM

**Schmitt & Heymsfield 2009 (SH09):** 2 field campaigns of TTL cirrus
(-86°C to -56°C) \( v_m = f(IWC) \)

**Parameterizations of moments/parameters of the PSD**

**Heymsfield et al. 2013 (H13):** 10 recent field campaigns
83000 in-cloud PSDs (tropics to Arctic, -86°C – 0°C)
-> parameterizations of \( a, b, c, d, \lambda, \mu \) as fct of T & \( A, B \) as fct of D

**Field et al. 2007 (F07):** 13000 PSDs, of 4 field campaigns
(tropics & midlatitudes)

\[
M_n = \int D^n N(D) \, dD = A(n) \cdot e^{B(n) \cdot T} \cdot M_2^{C(n)}
\]
\[
M_2 = IWC / a
\]
\[
D_m = M_3 / M_2 = a \cdot M_3 / IWC
\]
\[
v_m = A D_m^B
\]

**Furtado et al. 2015 (F15):** \( v_m \) computed from PSD moment
parameterization of F07
with:
- ice: \( A = 1042 / n= B = 1.0 \) (SI units)
- snow: \( A = 14.3 / n= B = 0.416 \)
for each D the smallest \( v_t \) of both:
- ice D < 600 μm & snow D > 600 μm

**v_m** increases when T increases
when IWC increases
Synthesis: $v_m = f(T, IWC)$

[Graphs showing various IWC (g m$^{-3}$) vs. $v_m$ (cm/s) for different pressures and temperatures: 430 hPa (-15°C), 293 hPa (-35°C), 185 hPa (-55°C), 110 hPa (-75°C).]

--- all  --- convective outflow  ---- synoptic cirrus

Stubenrauch & Bonazzola, JAMES, subm. 2018
Synthesis: \( v_m - D_e \)

Analytical expression of \( D_e: \)
\[
D_e = \frac{3}{2} \text{IWC} / (\rho_{\text{ice}} \int A(D) N(D) \, dD) = \frac{3}{2} \frac{\alpha \Gamma(b+\mu+1)}{2 \rho_{\text{ice}} c \Gamma(d+\mu+1)}
\]

*uncertainties: \( \alpha: 54\%, \ c: 11\%, \ b \ & \ d: < 10\% \) (e.g. Erfani & Mitchell 2016)*

\[ \rightarrow D_e - v_m \text{ relationships from field campaigns:} \]

\[
D_{\text{eff}} = f(v_m) \text{ of H03 (mean between synoptic & anvil cirrus)}
\]
\[
D_m \text{ of F07 PSD momentum, } D_{\text{eff}} = 0.17 \times D_m \text{ (Baran et al. 2016)}
\]
\(v_m - D_e \) Strategies for LMDZ GCM

- \(v_m = f(IWC, T)\) of DM08 & SH09
  \(D_{eff} = f(v_m)\) of H03 (mean between synoptic & anvil cirrus)

- \(v_m = F07\) PSD momentum & F15 A-B couples for ice / snow
  \(D_m = F07\) PSD momentum
  \(D_{eff} = 0.17 \times D_m\) (assumed aggregates, Baran et al. 2016)

Next step: use for radiative transfer instead of \(D_{eff}\) directly
single scattering property (SSP) parameterization \(f(IWC,T)\) of Baran et al. 2016
(same PSDs as in F07)
2.

How do these parameterizations of $v_m$ and $D_e$ compare with the LMDZ parameterizations?
In literature:

- \(v_m\) depends on \(T\) and IWC
- Relation between \(D_e\) and \(v_m\)

In LMDZ:

- \(v_m\) only depends on IWC
- \(D_e\) only depends on \(T\)
- For high clouds \(T\) and IWC are not perfectly correlated
- Relation between \(D_e\) and \(v_m\) different from those found in literature
$v_m$ & $D_{\text{eff}}$ as function of IWC & T

with scaling factor $\text{FALLICE} = \alpha = 0.3$, LMDZ $v_m$ is very small compared to realistic $v_m$

$\rightarrow$ integrating new bulk ice schemes needs retuning of remaining unconstrained parameters (RQH, EPMAX) to achieve radiation balance
3. How can we use the new “cloud system diagnostics” to evaluate high clouds in LMDZ?
From cloud retrieval to cloud systems

Clouds are extended objects, driven by dynamics -> organized systems.

**Method:**
1) group adjacent grid boxes with high clouds of similar height ($p_{cld}$)

2) use $\varepsilon_{cld}$ to distinguish convective core, thick cirrus, thin cirrus (only IR sounder)

30N-30S: UT cloud systems cover 25%, those without convective core 5%
50% of these originate from convection (Luo & Rossow 2004, Riihimaki et al. 2012)
Process-oriented UT cloud system behaviour
convective core fraction within system proxy for system life stage

Convective core size increases up to system maturity & then decreases
Convective rain rate and anvil emissivity decrease

Protopapadaki et al. 2017
Process-oriented UT cloud system behaviour

convective core temperature proxy for convective depth (mature systems)

cloud system size / max rain rate increase with convective depth,
**land – ocean differences** : difference in entrainment (Takahashi et al. 2017)

Thin cirrus in/around anvil increases with convective depth
(UT environmental predisposition or UT humidification from cirrus outflow ?)
Methodology: The AIRS/IASI simulator

Maximum overlap for adjacent cloud layers

Random overlap between independent clouds

\( \varepsilon_{\text{cl}d}^1 \) detected

\( \varepsilon_{\text{cl}d}^2 \) detected

\( \varepsilon_{\text{cl}d}^3 < 0.1 \) not detected

P=440 hPa

Cb, Ci and thinCI in the model grid cell
UT Cloud System Concept to assess GCM parameterizations

analyze GCM clouds as seen from AIRS/IASI, via simulator & construct UT cloud systems

-> evaluation of GCM convection schemes / detrainment / microphysics

Cloud systems are constructed from AIRS data and LMDZ outputs at the same spat. resolution
4. What is the effect of including new $v_m$ – De parameterizations in the LMDZ GCM?
Tuning parameters concerning high clouds for radiation balance

<table>
<thead>
<tr>
<th></th>
<th>FALLICE</th>
<th>EPMAX</th>
<th>RHQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>0.6</td>
<td>0.9985</td>
<td>0.4</td>
</tr>
<tr>
<td>DM08+De($v_m$)</td>
<td>0.9</td>
<td>0.9991</td>
<td>0.05</td>
</tr>
<tr>
<td>F07F15+De($v_m$)</td>
<td>0.9</td>
<td>0.9992</td>
<td>0.002</td>
</tr>
<tr>
<td>F07F15+De(IWC,T)</td>
<td>0.9</td>
<td>0.9991</td>
<td>0.05</td>
</tr>
</tbody>
</table>

FALLICE: scaling of fall speed  
EPMAX: maximum precipitation efficiency  
RQH: Rel. width of sub-grid water distribution above 250 hPa
CRE and total radiative budget at TOA

Total radiative budget TOA (W/m²)
- CTRL: 3.67
- F07F15+De\(v_m\): 3.51
- F07F15+De(IWC,T): 3.45
- DM08+De\(v_m\): 3.62
New parameterizations: More high cloud cover than in CTRL, in better agreement with observations (except at higher latitudes)
Improvement: Less Cb in midlatitudes

Improvement for F07F15: more Ci

Improvement: more thinCi
(more thinCi in polar regions than in obs., but thin clouds over ice difficult to detect)
UT Cloud System Concept to assess GCM parameterizations

analyze GCM clouds as seen from AIRS/IASI, via simulator

& construct UT cloud systems

-> evaluation of GCM convection schemes / detrainment / microphysics

Goal: build coherent $v_m$ - De parameterization

nominal fall speed

$v_m = 0.3 \times f(IWC)$

De = $f(T)$, $\varepsilon = f(De, IWC)$

scaled $v_m$ too small compared to observations

$v_m = 0.9 \times f(IWC, T)$

De = $f(v_m)$

Heymsfield et al. 2003

$v_m$ increases with IWC & T, $v_m$ closely related to De

Deng & Mace 2008

$v_m$ increase with IWC weaker towards warm T

Field et al. 2007, Furtado et al. 2015

PSD moment parameterization

Rad. balance -> precip. efficiency, UT hum variability

horizontal cloud system emissivity structure sensitive to $v_m$, De

AIRS 7 Jan 2008
Analysis of cloud systems

Improvement of:
- emissivity (less emissive cloud systems),
- Temperature (warmer cloud systems).

CTRL
F07F15+De(ν_m)
F07F15+De(IWC,T)
DM08+De(ν_m)
Analysis of cloud systems

Improvement of cloud system sizes

<table>
<thead>
<tr>
<th></th>
<th>Tropics</th>
<th></th>
<th>Mid-latitudes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>data</td>
<td>233</td>
<td>88 (132)</td>
<td></td>
</tr>
<tr>
<td>CTRL</td>
<td>66 (143)</td>
<td>16</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>F07F15+De(v_m)</td>
<td>98 (427)</td>
<td>47</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>F07F15+De(IWC,T)</td>
<td>91 (376)</td>
<td></td>
<td>47 (108)</td>
<td></td>
</tr>
<tr>
<td>DM08+De(v_m)</td>
<td>142 (446)</td>
<td></td>
<td>38 (83)</td>
<td></td>
</tr>
</tbody>
</table>

For convective/ frontal cloud systems
process-oriented UT cloud system behaviour

including T dependency of $v_m \rightarrow$ larger spread in T
more realistic $v_m$ –De very promising: leads to more realistic anvil size development and thin Ci increasing

Next steps: integrate single scattering properties developed by Baran et al. 2016 from PSD’s of F07
more realistic UT humidity variability threshold (AIRS climatology of Kahn et al. 2009, 2011)
precipitation – detrainment efficiency parameterization

Data
control $v_m = 0.3 \times f(IWC)$
$De = f(T)$
DM08 $v_m = f(IWC,T)$
$De = f(v_m)$
F07-F15 $v_m = f(IWC,T)$
$De = f(v_m)$
F07-F15 $v_m = f(IWC)$
$De = 0.17(D_m)$
preliminary
Conclusions

- 2 bulk ice cloud schemes which coherently couple $v_m$ (cloud physics) and De (cloud radiative effects) have been constructed from existing parameterizations.

The new schemes use a **realistic** $v_m$ (about 3 x larger than the original, tuned $v_m$ in LMDZ), which also depends on IWC & T, instead of IWC alone.

De is now linked to (IWC,T) or directly to $v_m$.

  - $UT$ water sub-grid variability had to be reduced for radiation balance

- Cloud System diagnostics provides additional constraints:
  - new bulk ice schemes -> larger cloud systems & slightly less emissive anvils, in better agreement with AIRS observations

- Cloud System Concept links anvils to convection
  - *allows process-oriented evaluation*
    - (behavior of anvils with increasing convective depth, along statistical life cycle)

- new ice cloud schemes seem to improve this behavior, compared to observational cloud system analysis

- AIRS-IASI cloud observational simulator will be made available in COSP