The Representation of Aerosol Indirect Effects in Global Climate Models

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Role of Aerosols for Global Climate

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m⁻²)</th>
<th>Spatial scale</th>
<th>LOSU</th>
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</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
<td>High</td>
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<tr>
<td>N₂O</td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
<td>High</td>
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<tr>
<td>CH₄</td>
<td>0.16 [0.14 to 0.18]</td>
<td>Global</td>
<td>High</td>
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<tr>
<td>Halocarbons</td>
<td>0.34 [0.31 to 0.37]</td>
<td>Global</td>
<td>High</td>
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<tr>
<td>Ozone</td>
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<tr>
<td>Stratospheric</td>
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<tr>
<td>Tropospheric</td>
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<td>Stratospheric water vapour from CH₄</td>
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<td>Surface albedo</td>
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<td>Land use</td>
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<tr>
<td>Black carbon on snow</td>
<td>-0.2 [-0.4 to 0.0]</td>
<td>Local to continental</td>
<td>Med - Low</td>
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<tr>
<td></td>
<td>0.1 [0.0 to 0.2]</td>
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<td>Total Aerosol</td>
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<td>Direct effect</td>
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<td>Cloud albedo effect</td>
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<td>Linear contrails</td>
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<tr>
<td>Natural</td>
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<tr>
<td>Solar irradiance</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Total net anthropogenic</td>
<td></td>
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</tbody>
</table>

Radiative Forcing (W m⁻²):

-2 -1 0 1 2

Twomey (1st indirect) effect

IPCC (2007)
Aerosol Indirect Effects (IE) in GCMs

1st IE

2nd IE

1st + 2nd IE

Lohmann and Feichter, ACP (2005)
Role of Cloud Droplet Number Concentration for Aerosol/Cloud Effects on Radiation

Cloud Droplet Effective Radius

\[ r_{\text{eff}} = \frac{\int r^3 n(r) \, dr}{\int r^2 n(r) \, dr} = \beta \left( \frac{3 LWC}{4\pi \rho_w N_c} \right)^{1/3} \]

Twomey effect (1\textsuperscript{st} indirect effect, cloud albedo effect):

Aerosol \[\uparrow\] \[\downarrow\] \[N_c\] \[\uparrow\] \[r_{\text{eff}}\] \[\uparrow\]
An Empirical Parameterization for Cloud Droplet Number Concentration (CDNC)

Boucher and Lohmann (1995)
Summary of Empirical Parameterizations for CDNC

- Novakov (1994)
- van Dingenen (1995)
- continental stratus, B&L (1995)
- continental cumulus, B&L (1995)
- marine cloud, B&L (1995)
- all data combined, B&L (1995)
- Saxena and Menon (1999)
- Jones (2001)
- all data combined, Lowenthal (2004)
- GCM15 with NA+ (0)
- GCM15 with NA+ (1)
- GCM15 with NA+ (10)
- GCM15 with NA+ (1)
Adiabatic Parcel Model Simulations

Red line: GCM4 parameterization (Ma and von Salzen, submitted to ACP)

- Dry aerosol mass: 0.01 – 100 µg m⁻³
- Mode radius: 0.01 – 0.1 µm
- Variance: 1.2 – 2.2
- Updraft velocity: 1 m s⁻¹
- Cloud depth: 1000 m

Large scatter in CDNC caused by differences in size distributions for given SO₄²⁻ concentration
CCN Observations for Water Soluble Organic Carbon Aerosol

Predicted vs. measured CCN for different assumptions about water-solubility of organic carbon

0% WSOC

60% WSOC

Systematic effects of organic material on CCN concentrations

Courtesy: Abbatt and Leaitch
Cloud Updraft Velocities

Aerosol indirect effects are linked to cloud dynamical processes and therefore depend on cloud type

Feingold (2003)
Yet Another Cause of Uncertainty: Dispersion Effect

\[ r_{\text{eff}} = \beta \left( \frac{LWC}{CDNC} \right)^{1/3} \]

is used in GCMs to account for the aerosol dispersion effect.

\[ \beta = f(\text{CDNC}) \]

is derived based on field studies (Liu and Daum, 2000)

Peng and Lohmann (2003): Including the dispersion effect reduces the simulated indirect aerosol effect from \(-1.4 \text{ W m}^{-2}\) (const. \(\beta\)) to \(-1.2 \text{ W m}^{-2}\) (\(\beta(N_l)\))
Looking Ahead to the Future: First Principles Based Parameterizations in GCMs
First Principles Based Parameterizations of CDNC

- Realistic dependencies of CDNC on aerosol size and chemical composition.
- **Assumption:** Adiabatically ascending parcels of air.
- **Key parameters:** Dry aerosol size distribution and cloud updraft velocity.
- **Approach:** Provide approximate solution of droplet growth equation for condensation under equilibrium conditions for water vapour, based on Köhler theory.
- **Diagnosis of CDNC** as fraction of activated aerosol at maximum supersaturation. No direct information available on dispersion effect and cloud droplet size.
What About Real Clouds?

Shallow Cumulus

Overwhelming evidence for non-adiabatic conditions in clouds from observations:

Implications for cloud droplets?

Warner (1955)

Gerber (2006)

Overwhelming evidence for non-adiabatic conditions in clouds from observations:

Implications for cloud droplets?
A Prognostic Approach for Cloud Droplet Nucleation: Droplet Growth Equation and Köhler Theory

\[ R_p \frac{dR_p}{dt} = \frac{s - s_p}{C} \]

\[ s_p = \frac{A}{R_p} - \frac{B}{R_p^3} \]

\[ A = \frac{2M_w \sigma_w}{RT \rho_w}, \quad B = \frac{3M_w \nu M_s}{4\pi \rho_w M_s \left[ 1 + \left( \frac{1 - \varepsilon}{\varepsilon} \right) \left( \frac{\rho_s}{\rho_u} \right) \right]}, \quad C = \frac{\rho_w RT}{e' D_v M_w} + \frac{L_v \rho_w}{k_a T} \left( \frac{L_v M_w}{RT} - 1 \right) \]

supersaturation in ambient air

supersaturation at droplet surface

droplet radius

curvature (Kelvin) term

solute (Raoult) term
A Prognostic Approach for Cloud Droplet Nucleation: Generalized Droplet Growth Equation (GDGE)

For quasi-steady supersaturation:

\[
\frac{dR_p}{dt} \rightarrow \frac{dx}{du} = \delta - \hat{B} \left( \frac{F}{\sqrt{x}} - \frac{1}{x^{3/2}} \right)
\]

\[
x = \frac{R_p^2}{2} = \text{generalized droplet size}, \quad u = \frac{|s|t}{C} = \text{generalized time}
\]

\[
\hat{B} = \frac{B}{2^{3/2}|s|}, \quad F = \frac{2A}{B}, \quad \delta = \frac{s}{|s|}
\]

Look-up tables for solutions of the GDGE are available for applications in GCMs
A Prognostic Approach for Cloud Droplet Nucleation: Basic Algorithm

initial supersaturation, size distribution

predicted size distribution (GDGE)

implied supersaturation (from mass and energy continuity)

supersaturation estimate

convergence

no convergence

diagnose CDNC, $r_{\text{eff}}$, etc. from predicted size distribution
Piecewise Log-normal Approximation (PLA)

Representation of aerosol number distribution:

for section boundaries at \( \varphi_{i\pm 1/2} = \ln\left( \frac{R_{i\pm 1/2}}{R_0} \right) \).

von Salzen (2006)
Comparisons with Detailed Parcel Model
...in Progress

Courtesy: Nicole Shantz

Canadian Centre for Climate Modelling and Analysis
Centre canadien de la modélisation et de l'analyse climatique
Environment Canada
Environnement Canada
GCM Simulation of Cloud Droplet Nucleation in Shallow Cumulus Clouds
Mixing in Shallow Cumulus: The Mixing Line

**Linear mixing** for cloud properties (e.g. total water, liquid water static energy)

\[ \chi = f \chi_e + (1-f) \chi_c \]

where \( f = 0 \ldots 1 \)

Cloud Environment  Cloud core

Mixing fraction probability distribution \( p(f) \)

Fig. 4. Comparisons of the total mixing ratio \( Q \) and the wet equivalent potential temperature \( \theta_e \) computed from data collected inside a growing cumulus cloud with \( Q \) and \( \theta_e \) values of a representative sounding. The dashed line refers to the sounding; the points connected by lines represent the in-cloud observations. The data correspond to the first half-kilometer shown in Fig. 3. Air with the observed properties could have been formed by mixing air from the surface levels with air from \( \approx 8 \text{ km} \) as indicated by the dot-dashed line. The observation level was \( 5.2 \text{ km} (\sim 2^\circ C) \). Cloud base (CB) was at \( 3.8 \text{ km} \).

Paluch (1979)
Mixing in Shallow Cumulus: Implications for Cloud Droplets

• Relevant time scales:
  - $\tau_e = (1/R)(d R/d t)$  Droplet evaporation time scale
  - $\tau_t = (L^2/\varepsilon)^{1/3}$  Turbulent mixing time scale

• Homogeneous mixing: $\tau_e \gg \tau_t$, Efficient turbulent mixing means that droplets are exposed to the same humidity and temperature. Sizes of individual droplets are reduced by evaporation. Spectral broadening from mixing line.

• Extremely inhomogeneous mixing: $\tau_t \gg \tau_e$, Filaments of cloudy and non-cloudy air. Droplets inside and outside filaments experience different environmental conditions and may either have nearly adiabatic sizes or evaporate completely. Little spectral broadening, relatively large cloud droplets.
Cloud Droplet Sizes in RICO Shallow Cumulus

Gerber, 12th AMS Conference on Cloud Physics, Madison, 2006
Parameterization of Shallow Convection in CCCma AGCM4

- Based on continuity equations for mass, energy, and vertical momentum
- Idealized cumulus lifecycle with variable cloud top heights
- Lateral and cloud-top mixing processes
- Non-homogenous clouds: Probability distributions of cloud properties
- Simple warm microphysics (no precipitation processes)
- Suitable for cloud droplet nucleation parameterizations

von Salzen and McFarlane (2002)
von Salzen et al. (2005)
GCM Sensitivity Experiments for Shallow Convection

- Combination of new approach for cloud droplet nucleation with shallow cumulus parameterization to test effects of different assumptions about mixing between cloud core and environment on cloud droplets.

- Prognostic calculation of vertical profiles of cloud droplet size distributions for cloud core conditions. Parameterization of droplet size for mixed cloudy air.

- Prognostic sulphate and sea salt aerosol size distributions based on PLA approach (simplified):
  
  $\text{SO}_4^\ominus$: Binary homogeneous nucleation $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$; Condensation of $\text{H}_2\text{SO}_4$, $\text{NH}_3$, $\text{H}_2\text{O}$; gravitational settling; cloud removal; in-cloud production (bulk); transport

  **Sea salt**: Ocean production (Lewis and Schwartz, 2004); gravitational settling; cloud removal; transport

- No feedbacks of simulated cloud droplets on climate yet.
GCM Sensitivity Experiments for Shallow Convection

- **HOM: Homogeneous mixing:** Variable cloud liquid water content and droplet concentration (mixing line)

\[
\text{LWC} = \text{LWC}_c + \frac{d \text{LWC}}{df} f \\
\text{CDNC} = \text{CDNC}_c + \frac{d \text{CDNC}}{df} f
\]

- **INHOM: Extremely inhomogeneous mixing:** Adiabatic, cloud-core conditions for cloud droplet size

\[
\langle \text{CDNC} \rangle = \int_{f=0}^{1} \text{CDNC} \, p(f) \, df \\
\langle r_{\text{eff}} \rangle = \beta \int_{f=0}^{1} \left( \frac{\text{LWC}}{\text{CDNC}} \right)^{1/3} \, p(f) \, df
\]
Adiabatic Fraction in Simulated Shallow Cumulus (JJA)

Distance above cloud base:

1000 m

700 m

50 m

\[
\frac{\text{LWC}}{\text{LWC}_a}
\]
Cloud Droplet Number Concentration (JJA)

New approach for cloud droplet nucleation

Adiabatic cloud core, CDNC\textsubscript{c}

Mean, \langle CDNC \rangle

Nenes and Seinfeld (2003) (modified for PLA method)

Adiabatic cloud core, CDNC\textsubscript{c}

700 m above cloud base

(cm\textsuperscript{-3})
Mean Cloud Droplet Effective Radius (JJA)

**HOM**

700 m

50 m

**INHOM**

700 m

50 m

(µm)
Mean Cloud Droplet Effective Radius (JJA)

CERES SRBAVG2
(Terra, non-GEO, V. 2d)
low clouds

Mean Cloud Droplet Effective Radius (JJA)
Cloud Top Pressure (JJA)

GCM
Shallow convection

CERES SRBAVG2
(Terra, non-GEO, V. 2d)
low clouds

700 m

50 m

How to compare results for $r_{eff}$ for variable cloud tops and different types of clouds?
Conclusions

• Empirically based parameterizations of CDNC and aerosol indirect effects are inherently uncertain in GCMs.

• Currently available first principles based parameterizations of CDNC are considerably more realistic but assumptions of adiabatic conditions and steady updrafts are not yet fully evaluated.

• GCM simulations for simplified aerosol cycles give evidence for sensitivity of shallow cumulus cloud droplet sizes to entrainment mixing assumptions.

• Role of shallow cumulus cloud droplet sizes for radiation and climate still needs to be addressed in GCM.

• Future GCM studies for stratiform clouds, including fog.

• Ideally, studies of cloud droplet size should distinguish between different types of clouds and cloud vertical extend (e.g. cloud-type specific diagnostics from CERES for model validation? Field experiment comparisons?).