An improved aerosol wet removal parameterization coupled with an explicit convective cloud scheme in CAM6

Yunpeng Shan, X. Liu, Z. Ke, Z. Lu, L. Lin
Department of Atmospheric Science,
University of Wyoming

Thanks to
L. Gao (OU) K. Yang (CU-Boulder)
P. Ma (PNNL) J. Schwarz (NOAA)
Part 1
Introduction
# Importance of Aerosol and its Vertical Distribution

### Emitted Compound

<table>
<thead>
<tr>
<th>Compound</th>
<th>Resulting Atmospheric Drivers</th>
<th>Radiative Forcing by Emissions and Drivers</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>CO$_2$, H$_2$O, O$_3$, CH$_4$</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH$_4$</td>
<td></td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>O$_3$, CFCs, HCFCs</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>N$_2$O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
</tbody>
</table>

### Anthropogenic

<table>
<thead>
<tr>
<th>Compound</th>
<th>Resulting Atmospheric Drivers</th>
<th>Radiative Forcing by Emissions and Drivers</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>CO$_2$, CH$_4$, O$_3$</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO$_2$, CH$_4$, O$_3$</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>Nitrate CH$_4$, O$_3$</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
</tbody>
</table>

### Short-Lived Gases and Aerosols

<table>
<thead>
<tr>
<th>Compound</th>
<th>Resulting Atmospheric Drivers</th>
<th>Radiative Forcing by Emissions and Drivers</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral Dust, Substrate, Nitrate, Organic Carbon, Black Carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Cloud Adjustments due to Aerosols</td>
<td>-0.59 [-1.33 to -0.06]</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Albedo Change due to Land Use</td>
<td>-0.15 [-0.25 to -0.05]</td>
<td>M</td>
</tr>
</tbody>
</table>

### Natural

<table>
<thead>
<tr>
<th>Compound</th>
<th>Resulting Atmospheric Drivers</th>
<th>Radiative Forcing by Emissions and Drivers</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changes in Solar Irradiance</td>
<td></td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

**Total Anthropogenic RF relative to 1750**

<table>
<thead>
<tr>
<th>Year</th>
<th>Radiative Forcing relative to 1750 (W m$^{-2}$)</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>2.29 [1.13 to 3.33]</td>
<td>H</td>
</tr>
<tr>
<td>1980</td>
<td>1.25 [0.64 to 1.86]</td>
<td>H</td>
</tr>
<tr>
<td>1950</td>
<td>0.57 [0.29 to 0.85]</td>
<td>M</td>
</tr>
</tbody>
</table>

(IPCC5, 2013)
Classifications of Aerosol Wet Scavenging

- Aerosol In-Cloud Wet Removal
- Aerosol Below-Cloud Wet Removal
- Resuspension of Wet Removal

- Snow/Graupel Crystal
- Rain Droplet
- Cloud Droplet
- Aerosol
Aerosol Wet Removal Parameterizations in CAM

Interstitial Aerosols

Stratiform Cloud-borne Aerosols

Wet Removal In Stratiform Clouds
Rac is explicitly parameterized based on MG cloud microphysical scheme

Cloud-borne Aerosol Removal Rate (Rac)

Convective Cloud-borne Aerosols

Wet Removal In Convective Clouds
Rac is empirically parameterized based on ZM cumulus scheme

Below Convective Cloud Wet Removal

Resuspension of Rain Evaporation

Resuspension of Rain Evaporation

Below Stratiform Cloud Wet Removal

Interstitial Aerosols

Prescribed Activated Aerosol Fraction
Part 2
Scheme Improvement and Experiment Setup
Introducing New Schemes

Explicit Convective Cloud Microphysical Scheme by Song and Zhang (2011)

- Convective Cloud-borne Aerosols
- Interstitial Aerosols

- Prescribed Activated Aerosol Fraction

- Rain Producing from ZM95 Cumulus Scheme

- Wet Removal In Convective Clouds
  - Rac is empirically parameterized based on ZM cumulus scheme

- Below Convective Cloud Wet Removal

- Sophisticated Aerosol Removal Scheme by Wang et al. (2013)

- Aerosol Wet Removal by Precipitation Producing

- Resuspension of Rain Evaporation

- Interstitial Aerosols
Explicitly Parameterized Rain Producing Rate

\[
\left( \frac{\partial q_{ec}}{\partial t} \right)_{up} = \frac{\partial (M_u q_{uc})}{\partial p} - \frac{\partial (M_u q_{ec})}{\partial p} + Act \cdot q_{ul} - Wet \cdot q_{uc} + Res \cdot q_{uc}
\]

Bergeron Releasing by Bergeron Process

\[
Wet = \frac{Pr_{ec}}{Pr_{ec} + cldm}
\]

\[
Wet = \frac{Pr_{ec} - P_{Berg}}{Pr_{ec} + cldm}
\]
Aerosol Releasing by Rain droplet Entire Evaporation

\[
\frac{\partial q_{ec}}{\partial t}_{up} = \frac{\partial (M_u q_{uc})}{\partial p} - \frac{\partial (M_u q_{ec})}{\partial p} + \text{Act} \cdot q_{ul} - \text{Wet} \cdot q_{uc} - \text{Re s} \cdot q_{uc}
\]

Predicted SS

Aerosol Secondary Nucleation in Cumulus

\[
\text{Re s} = \frac{P_{eva}}{Pr ec + cldm}
\]
## Model Configuration and Experiment Setup

<table>
<thead>
<tr>
<th></th>
<th>Convective removal</th>
<th>Bergeron Releasing</th>
<th>Rain Evaporation</th>
<th>Secondary Nucleation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>St</td>
<td>Conv</td>
<td>St</td>
<td>Conv</td>
</tr>
<tr>
<td><strong>CTL</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>CONV</strong></td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>WBF</strong></td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>SN</strong></td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>EE</strong></td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>ToMod</strong></td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

**Runtime period:** 18 month free run (first 6 months are spin-up time)

**CESM2 configuration:** 30 levels, MG2, MAM4, CLUBB

**Modified schemes:**
- SZ11 Convective Cloud Microphysics (Song and Zhang, 2011)
- WH13 Convective In-cloud Aerosol Wet Removal (Wang et al., 2013)
Part 3
Results and Discussions
Sensitivities of Sulfate Aerosol Distribution

A) CTL (mg/m³)

B) CONV (mg/m³)

C) ToMod (mg/m³)

D) (CONV-CTL)/CTL %

E) (ToMod-CTL)/CTL %

F) (ToMod-CONV)/CONV %
Sulfate Aerosol Transports
Elevations of Sulfate Aerosol Transport Path

(Yang et al., 2018)
Sensitivities of Dust Aerosol Distribution
Dust Aerosol Transports
Observed Dust Transport

Averaged dust occurrence from CALIPSO observation (2007-2009)

(Yang et al., 2019)
Evaluation of Aerosol Vertical Profile Simulations

A) A

B) B

C) C

No In-cloud removal

 HIPPO

 ATOM

CTL

CONV

ToMod

20S-25N, 60W-120W

20S-25N, 0-60W

20S-25N, 120W-180W

A) A

B) B

C) C

CTL

 CONV

 ToMod

 No In-cloud removal

Sea Salt (μg/m³)

Sea Salt (μg/m³)

Sea Salt (μg/m³)
Toward a Uniform Representation of Cloud-borne Aerosol

- **Intersetitial Aerosol**
  - **Stratiforms**
    - Nucleation
    - Wet Removal
    - Resuspension
    - Cloud -> Rain by Coalescence
    - Evaporation of rain releases aerosols

- **Convective clouds**
  - Nucleation
  - Wet Removal
  - Resuspension
  - Entrainment
  - Song & Zhang (2011)

- **Ice Nucleation**
- **Increasing by Impaction removal**

- Steven Ghan (2000)

References:
- Song & Zhang (2011)
Part 4

Conclusions
Conclusions

Sensitivities of the Aerosol Distributions

• Both aerosols in remote areas are sensitive to scheme changes.
• Aerosol transport to Arctic should be at lower layers.

Evaluations of Simulated Aerosol Profiles

• Profiles of sea salt aerosols with high hydrophilia are improved.
• Improvement of BC vertical distribution may need to IN scavenge.

Uniform Representations of Cloud-borne Aerosols

• Detrainment should transport convective cloud-borne aerosols into Stratiform.
• A comprehensive cloud-borne aerosol resources are required.
Questions?

Thank you for your attention