Ice Microphysical Properties Below -40°C based on Seven NSF Flight Campaigns and NCAR CAM6 Model Simulations

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Radiative Effects of Cirrus Clouds

Cirrus clouds cover up to 30% - 40% of Earth’s surface. Misrepresenting clear-sky ISS as cirrus clouds: +2.49 W/m² average radiative biases at top of the atmosphere. (Tan et al. 2016)

1. What are effects of thermodynamic, dynamic conditions on cirrus cloud microphysical properties?

2. What are the aerosol indirect effects on cirrus clouds?

3. How well do model simulations represent ice microphysical properties and the key factors affecting them?

Ice supersaturation (ISS) = RH_{ice} – 100%

Prerequisite condition for ice nucleation

Seven National Science Foundation (NSF) Flight Campaigns

Global Map of Campaign Flight Tracks

- **START08 (2008)**
- **HIPPO (2009 – 2011)**
- **PREDICT (2010)**
- **TORERO (2012)**
- **DC3 (2012)**
- **CONTRAST (2014)**
- **ORCAS (2016)**

Extensive spatial coverage from 87°N to 75°S and 128°E to 38°W.

1000 flight hours in total; 84 hr in-cloud and 423 hr clear-sky data at ≤ -40°C.

Analysis restricted to temperature ≤ -40°C at 1 Hz resolution (~230 m resolution).
**Instrumentations and Calibrations**

**Vertical Cavity Surface Emitting Laser (VCSEL) hygrometer**
- Near infrared; 25 Hz -> 1 Hz; Accuracy < 6%; Precision ≤ 1% (Zondlo et al. 2010)
- Combine with ±0.3 K temperature uncertainties, RHice uncertainties are 7.8%–6.9% for -78°C to -40°C, respectively.
- Laboratory calibration of VCSEL hygrometer (Diao, DiGangi, Zondlo, Beaton in 2009 – 2018)

**Cloud probe**
- Fast-Two dimensional cloud (Fast-2DC) probe (62.5–3200 μm);
- In-cloud conditions: Nice > 0 L⁻¹ in 1-second sample  
  (Diao et al., 2013, 2014, 2015, 2017; D’Alessandro et al., 2017)

**Aerosol probe**
- Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) measures aerosols at 0.06 – 1 μm.

**Laboratory Calibrations of the VCSEL Hygrometer**

**Calibration in 2009 – 2013**
- Pressure (100–1013 hPa)
- Temperature (-90–30°C)
- H₂O (0.5–4×10⁵ ppmv)

**Calibration in 2016, 2018**
- RTD temperature probe
- Two temperature probes: VXL, RTD

Thanks to help from Stuart Beaton, Laura Tudor and Hendrik Gilmer
NCAR CESM2/CAM6 Model Simulations

NCAR **CESM2** / Community Atmosphere Model Version 6 (**CAM6**)  
- Two types of simulations  
  - Nudged simulations: towards U,V and T from MERRA2 data.  
  - Free-running simulations  
- MG2 microphysics (Gettelman and Morrison 2015; Gettelman et al., 2010)  
- 0.9° x 1.25° with 32 vertical layers

<table>
<thead>
<tr>
<th>Variable</th>
<th>IWC, Ni, Di</th>
<th>In-cloud</th>
<th>RHice</th>
<th>$\sigma_w$</th>
<th>Aerosols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation</td>
<td>62.5 – 3200 µm</td>
<td>&gt; 1 particle per second</td>
<td>Murphy &amp; Koop, 2005</td>
<td>variance of 200 seconds</td>
<td>Na500 &amp; Na100 (&gt;500nm, &gt;100nm)</td>
</tr>
<tr>
<td>CAM6 model</td>
<td>&gt; 62.5 µm</td>
<td>Ni &gt; $10^{-2}$ L$^{-1}$ &amp; IWC &gt; $10^{-5}$ g m$^{-3}$</td>
<td>same</td>
<td>$w_{sub} = \sqrt{2/3*\text{TKE}}$</td>
<td>same</td>
</tr>
</tbody>
</table>

**Acronyms:**  
**IWC**: ice water content; **Ni**: ice crystal number concentration; **Di**: number-weighted mean diameter  
**RHice**: relative humidity with respect to ice; **w**: vertical velocity; **Na**: aerosol number concentration
Regional variations – Tropics, Midlatitude, Polar Regions in the Northern and Southern Hemispheres (NH and SH)

Observations shows:
• (1) Higher IWC and Ni in NH midlatitude than SH midlatitude;
• (2) Higher Ni in tropics than polar regions.

CAM6 model shows:
• (3) Smaller IWC and Di, likely underestimating ice crystal sedimentation and growth.
• (4) Smaller Ni in NH midlat, likely underestimating aerosol indirect effects on Ni.

Patnaude, R., M. Diao, X. Liu, S. Chu, Effects of Thermodynamics, Dynamics and Aerosols on Cirrus Clouds Based on In Situ Observations and NCAR CAM6 Model, Atmos. Chem. Phys., submitted.
Effects of Relative Humidity (RH_{hi}) on Cirrus Clouds

(1) Observations:
- IWC and Ni peak at **110% RH_{hi}**
- Di peaks at 130% RH_{hi}

(2) Simulations:
- IWC and Ni peak at **80% RH_{hi}**, a secondary peak at 100%
- Di peaks at 130% RH_{hi} but much higher at subsaturation
- Simulated ice cloud fraction (CF_{i}) is affected by RH_{min} = 80% and RH_{max} = 110%:

\[
CF_{i} = \min(1, RH_{d}^2)
\]

\[
RH_{d} = \max\left(0, \frac{RH_{ti} - RH_{i_{min}}}{RH_{i_{max}} - RH_{i_{min}}} \right)
\]
Effects of Vertical Velocity ($\sigma_w$) on Cirrus Clouds

- Both observations and simulations show increasing IWC and Ni with increasing $\sigma_w$.

- Simulations show lower maximum $\sigma_w$, likely due to missing gravity waves from topography, fronts, and convection, since only $\sigma_w$ from turbulence is included.
(1) Isolate aerosol indirect effect: Remove T effects by using delta values, i.e., 1-s datum subtracts T-binned averages.

(2) Observations show increasing IWC, Ni and Di, especially when Na500 and Na100 is higher than average by a factor of 3 and 10, respectively.

Aerosol Indirect Effects (AIE) on Ice Microphysical Properties

Linear regression of IWC, Ni, Di wrt. Na$_{500}$ and Na$_{100}$

- Higher slope, larger AIE
- **Na$_{500}$** more effective at higher T (and lower w), possibly heterogeneous nucleation;
- **Na$_{100}$** more effective at lower T (and higher w), possibly homogeneous nucleation.

\[ \frac{d \log_{10}(\text{IWC})}{d \log_{10}(\text{Na}_{500})} = a + b \cdot \frac{d \log_{10}(\text{Na}_{500})}{d \log_{10}(\text{Na}_{100})} \]

- \( b_{\text{Na500}} = 0.18–0.33; \) [1]
- \( b_{\text{Na100}} = 0.23–0.43; \) [1]
- \( b_{\text{model}} = 0.1–0.3. \) [2-4]

[1] Patnaude and Diao, GRL, 2020;
[4] Liu & Shi, 2018
Aerosol Indirect Effects in CAM6 Simulations

(1) Increases of IWC, Ni are seen in CAM6, but much weaker
(2) No sudden increases of aerosol indirect effects (AIE) at higher Na in CAM6
(3) Di is almost constant in CAM6
(1) CAM6 shows smaller IWC, Di especially at $T < -60^\circ$C.

(2) Aerosol indirect effects:

- Obs shows higher IWC, Ni, and Di at higher Na.
- CAM6 shows increase of Ni, smaller increases of IWC, and decrease of Di at higher Na.

(3) CAM6 shows increasing cloud fraction with higher Na, but at 10 times higher Na than obs.

(Patnaude et al., ACP, submitted)
Conclusions

1. Regional variation in two hemispheres
   (a) Obs show higher Ni in NH midlat and tropics
   (b) Model shows smaller IWC, Di everywhere, and smaller Ni in NH midlatitudes

2. Effects of RHi and vertical velocity
   (a) Obs show IWC, Ni peak at RHi = 110%; Model peaks at RHi = 80%
   (b) Narrow range of $\sigma_w$ in the simulation (missing waves, convection)

3. Aerosol indirect effects on cirrus clouds (larger and smaller Na)
   (a) Non-monotonic relationships. Sudden increase of IWC, Ni and Di at higher Na500 and Na100
   (b) Isolate thermodynamic and dynamical impacts when analyzing AIE
   (c) Model shows weaker AIE than obs, and no sudden increases of IWC, Ni or Di

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