Seasonally Dependent Impact of Cloud Longwave Scattering on the Polar climate and Energy Cycle

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Outline

• Define the problem
• The traditional wisdoms in climate/weather modeling
  – Non-scattering cloud in the longwave
  – Blackbody surface in the longwave
• Why and where do the wisdoms break down?
• What is the impact on the simulated climate?
• Conclusions and Outlooks

Take-home messages: traditional wisdom breaks down in the polar region, and (far-IR) LW scattering matters for the surface-atmosphere radiative coupling there.
In reality: Cloud LW properties

\( \omega \): single-scattering albedo
- \( \omega = 1 \): 100% scattering
- \( \omega = 0 \): 100% absorption

Scattering + Absorption = extinction (a.k.a. attenuation)

(Kuo et al, 2017, JAMES)
In models:

only 3 out of 30+ models assumes cloud being non-scattering in the longwave

4.9.5 Cloud emissivity

The clouds in CAM 4.0 are gray bodies with emissivities that depend on cloud phase, condensed water path, and the effective radius of ice particles. The cloud emissivity is defined as

\[ \epsilon_{\text{cl}d} = 1 - e^{-D \kappa_{\text{abs}} \text{CWP}} \]  

(4.375)

where \( D \) is a diffusivity factor set to 1.66, \( \kappa_{\text{abs}} \) is the longwave absorption coefficient \((m^2 g^{-1})\), and CWP is the cloud water path \((gm^{-2})\). The absorption coefficient is defined as

\[ \kappa_{\text{abs}} = \kappa_i (1 - f_{\text{ice}}) + \kappa_{i,\text{ice}} \]  

(4.376)

where \( \kappa_i \) is the longwave absorption coefficient for liquid cloud water and has a value of 0.090361, such that \( D \kappa_i \) is 0.15. \( \kappa_i \) is the absorption coefficient for ice clouds and is based on a broad band fit to the emissivity given by Ebert and Curry’s formulation,

\[ \kappa_i = 0.005 + \frac{1}{r_{ei}}. \]  

(4.377)
Why do such approximations?

• GCMs have been developed for decades. Don’t brush off the traditional wisdoms easily

• Two facts need to be considered
  – Traditional focus in on the tropics and mid-latitude.
    • Polar is a focus only recently.
  – How to make a decision for a scheme related atmospheric physics?
    • Run, compare, and make decision
    • How to run it? AMIP run, SOM run, or fully-coupled run??
When radiation scheme was developed decades ago …

- Polar region is not a focus.
- Water vapor abundance changes a lot from the tropics to polar regions

\[ \tau_{H_2O} \propto \rho_{H_2O} \]
The aftermath of small TCWV in polar regions (I)

\[ \omega_{\text{layer}} = \frac{\omega_{\text{cld}} \tau_{\text{cld}}}{\tau_{H_2O} + \tau_{\text{cld}}} \]

\[ \tau_{H_2O} \gg \tau_{\text{cld}}, \omega_{\text{layer}} \rightarrow 0 \quad \text{Tropics & mid-latitudes} \]

But now \( \tau_{H_2O} \) reduced by 10 or even more...

Far IR: Strong H\(_2\)O absorption
Two RRTMG far-IR bands
The aftermath of small TCWV in polar regions (II)

\[
F^\uparrow(v) = \varepsilon(v)\pi B_v(T) + \left[1 - \varepsilon(v)\right] F^\downarrow(v) \\
= \varepsilon(v)\left[\pi B_v(T) - F^\downarrow(v)\right] + F^\downarrow(v)
\]

Huang et al. (2018, J Climate) incorporated the surface emissivity into the CESM

Dirty window

SAS: subarctic summer (60°N)
Surface spectral emissivity $\varepsilon(v)$ is not one. Broadband emissivity won’t work.

Two RRTMG bands to OLR.

35%-40% OLR at 14μm.
Hypothesis: missing LW processes would affect Arctic winter $T_s$ the most, which then affects subsequent processes and feedbacks.
## Implementations

| Ice cloud | • MC6 ice cloud optics  
• A hybrid 2S/4S LW scattering solver into RRTMG_LW (Toon et al., 1989; Kuo et al., 2020) |
|-----------|----------------------------------------------------------------------------------------------------------------------------------|
| Surface spectral emissivity | • Based on the spectral emissivity database (Huang et al., 2016)  
• Prescribed land spectral emissivity  
• Prognostic spectral emissivity over sea ice and ocean  
• Major conclusions in Huang et al. (2018, J. Climate) |
| Control case: | CESM v1.1.1/DoE E3SM v1 |

Codes available at https://github.com/Huang-Group-UMICH/LW-scattering-polar-climate
Diff of surface air temperature

SST: prescribed SST run
SOM: slab-ocean run (surface-atmosphere coupling enabled)
Diff of surface air temperature

Cloud LW scattering effect
- SOM >> prescribed-SST
- polar >> tropics/mid-latitudes
- polar winter > polar summer
- In polar regions, far-IR >> other
When realistic surface emissivity is also included

Changes in surface air temp

Emissivity and scattering effect is comparable and the combined effect is largely linear additive.
DJF climatology energy budget over the Arctic (66.5°-90°N)

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Standard Deviation</th>
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<tbody>
<tr>
<td>DSW</td>
<td>7.15</td>
<td>-0.01±0.01</td>
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<tr>
<td>RSW</td>
<td>4.40</td>
<td>+1.70±0.13</td>
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<tr>
<td>OLR</td>
<td>163.05</td>
<td>+0.80±0.55</td>
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<tr>
<td>Clear-sky OLR</td>
<td>171.26</td>
<td>+0.84±0.43</td>
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<tr>
<td>TOA net upward</td>
<td>160.29</td>
<td>+2.29±0.40</td>
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</tbody>
</table>

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<thead>
<tr>
<th>Component</th>
<th>Value</th>
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<tbody>
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<td>DSW</td>
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<td>RSW</td>
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<td>OLR</td>
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<td>Clear-sky DLW</td>
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<tr>
<td>DLW</td>
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<td>+3.37±0.49</td>
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<tr>
<td>ULW</td>
<td>6.09</td>
<td>+4.52±0.41</td>
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<tr>
<td>LH</td>
<td>0.66±0.14</td>
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<tr>
<td>SH</td>
<td>0.38±0.34</td>
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</tbody>
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Surf air temp: 244.07
+2.17±0.18
+1.02±0.14
+1.35±0.13

Surface net upward: 37.79
+0.74±0.63
+0.51±0.36
+0.65±0.23

- Emis+Scat effect (Emis_Scat – noEmis_noScat)
- Emis effect (Emis_noScat – noEmis_noScat)
- Scat effect (noEmis_Scat – noEmis_noScat)
Conclusions and discussions

- LW scattering and surface spectral emissivity: two missing LW physics in most GCMs
- Together, they matters the most for polar surface energy budget and surface climate
  - But through radiative coupling between surface and atmosphere
- The Far-IR matters the most for the LW cloud scattering here
  - The last uncharted territory in the spectral observations
- Globally, LW scattering increases DLW by \( \sim 2 \text{ Wm}^{-2} \)
References


CESM implementation at
https://github.com/Huang-Group-UMICH/LW-scattering-polar-climate
Real World

emission/absorption

scattering

surface emissivity

GCM World

non-scattering cloud

\[ \tau_{H_2O} \propto \rho_{H_2O} \]

blackbody surface

(Chen et al., 2014)
E3SM v2 alpha fully coupled run

SAT is surface air temperature, a.k.a. reference height temperature

(Chen et al., submitted)
Two far-IR Satellite Missions that I have participated in

**PREFIRE:** NASA 4th EV-I mission
- $35M project for 1-year nominal operation
- Target Launch date: late 2021/early 2022
- Think it as a "far-IR MODIS"

**FORUM:** ESA 9th Earth Explorer mission
- Current budget ~ 350M euros
- Target Launch date: 2025/2026
- Fourier Spectrometer with 0.5cm⁻¹ resolution

- My role: L2 spectral flux and surface spectral emissivity retrievals, modeling support
Previous studies on cloud LW scattering always used AMIP-type prescribed SST/sea ice runs. Hypothesis: without surface responses to the cloud LW scattering, its effect cannot be fully revealed.
Why LW scattering was ignored?

- Tropics/mid-latitude focus
- The decisions were made with AGCM run only: prescribed SST/sea ice
- The surface-atmosphere LW coupling manifests the LW scattering effect

Turn on LW scattering

Increases of LW absorption & downward LW flux

Not allowed in prescribed SST runs

Feedback to increase (T, q)