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

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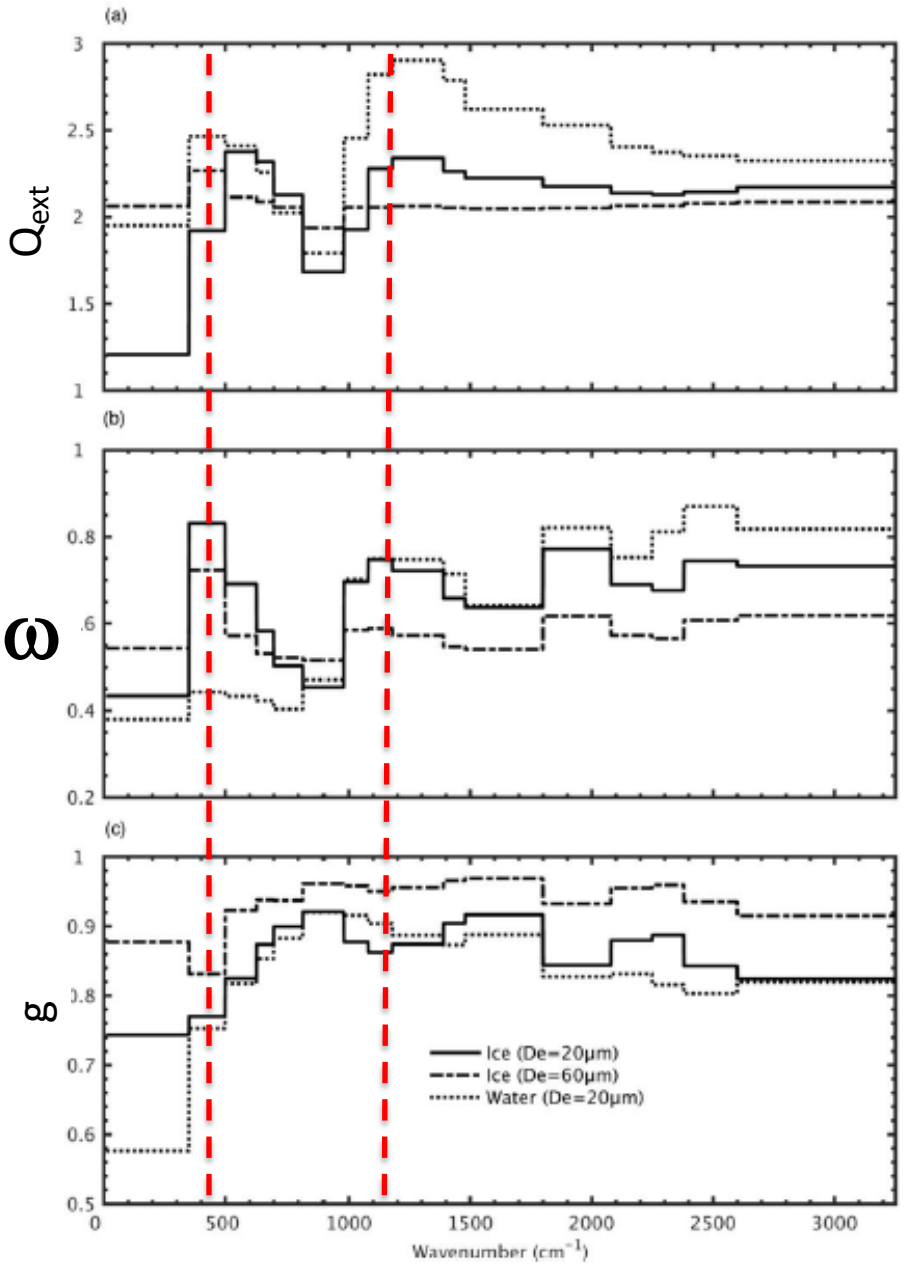
Based on Chen, Y.-H., X. L. Huang, P. Yang, C.-P. Kuo, X. H. Chen, 2020: Seasonal Dependent Impact of Ice-Cloud Longwave Scattering on the Polar Climate, *Geophysical Research Letters*, 47(23), https://doi.org/10.1029/2020GL090534.

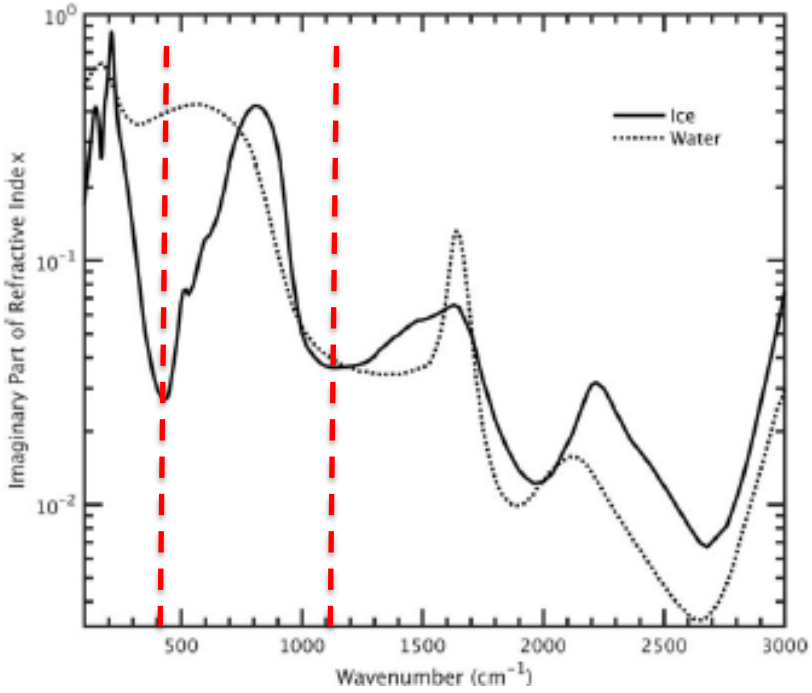
Outline

- 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





Im(**n**) minimum ⟷ Scattering peaks

ω: single-scattering albedo

ω = 1: 100% scattering

ω = 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

$$\epsilon_{cld} = 1 - e^{-D\kappa_{abs}CWP} \tag{4.375}$$

where D is a diffusivity factor set to 1.66, κ_{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

$$\kappa_{abs} = \kappa_l (1 - f_{ice}) + \kappa_i f_{ice} \tag{4.376}$$

where κ_l is the longwave absorption coefficient for liquid cloud water and has a value of 0.090361, such that $D\kappa_l$ is 0.15. κ_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,

$$\kappa_i = 0.005 + \frac{1}{r_{ei}}. \tag{4.377}$$

NCAR CESM 1.1.1 Technical Description

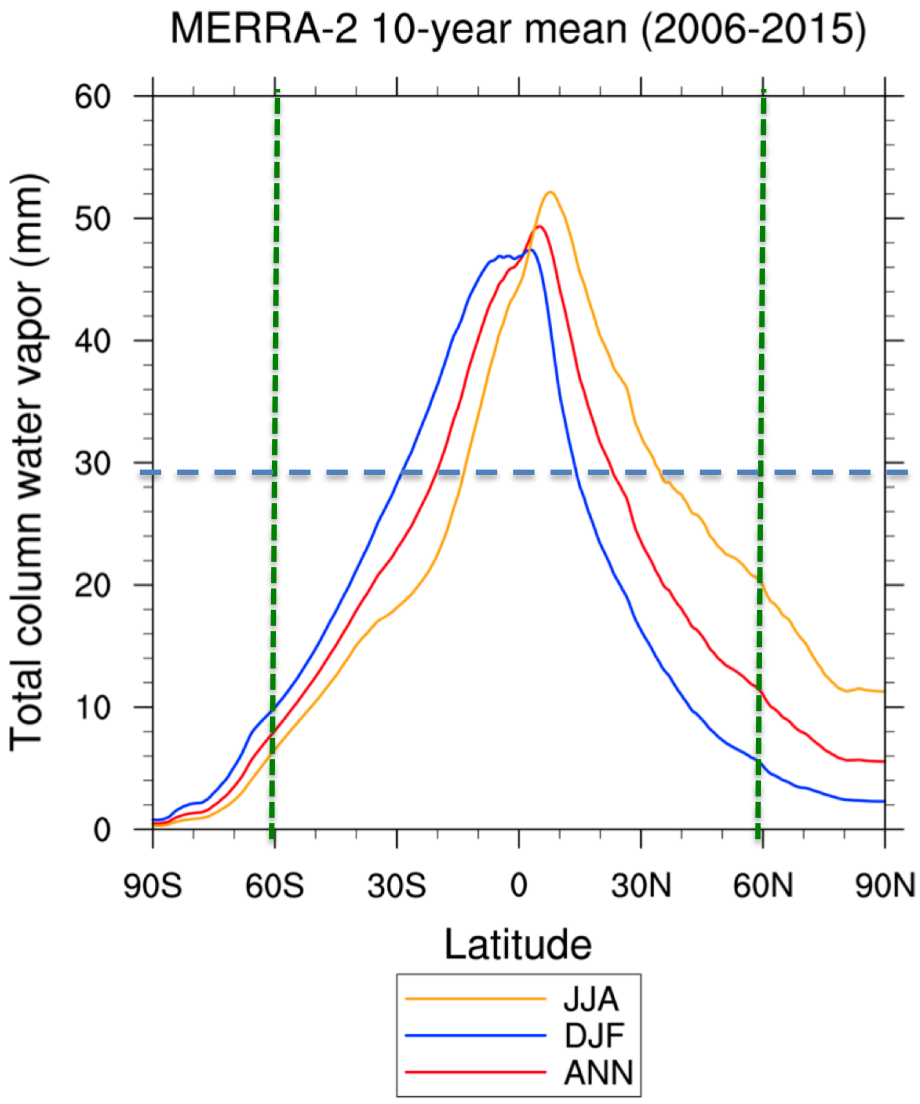
Why do such approximations?

- 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

$$\tau_{H_2O} \propto \rho_{H_2O}$$

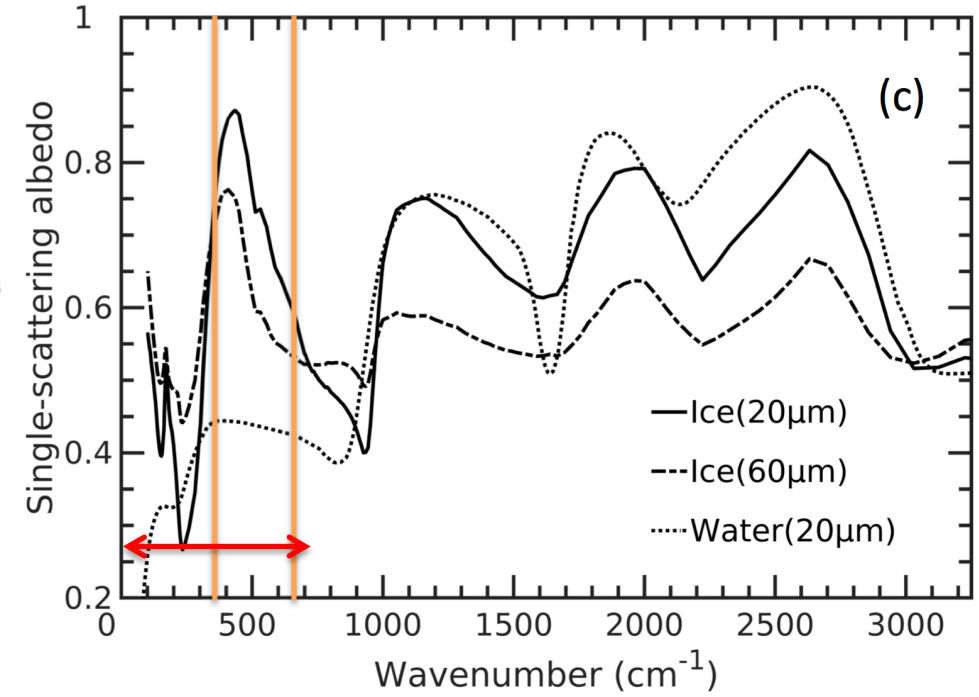


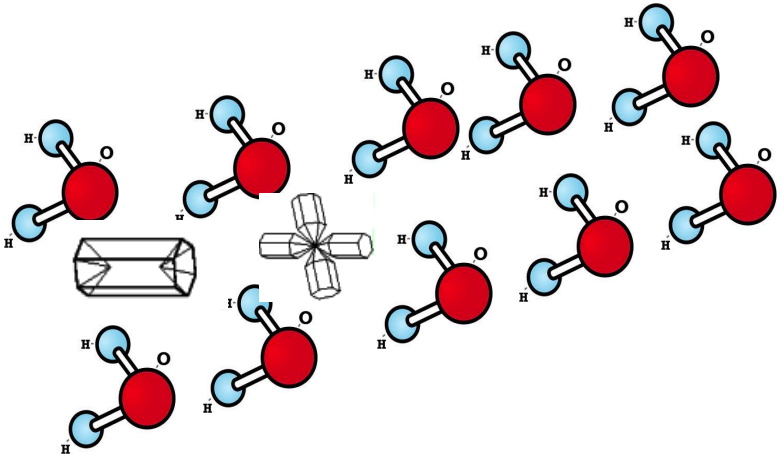
The aftermath of small TCWV in polar regions (I)

$$\omega_{layer} = \frac{\omega_{cld}\tau_{cld}}{\tau_{H_2O} + \tau_{cld}}$$

$\tau_{H_2O} >> \tau_{cld}, \omega_{layer} \rightarrow 0$ Tropics & mid-latitudes

But now τ_{H_2O} reduced by 10 or even more...





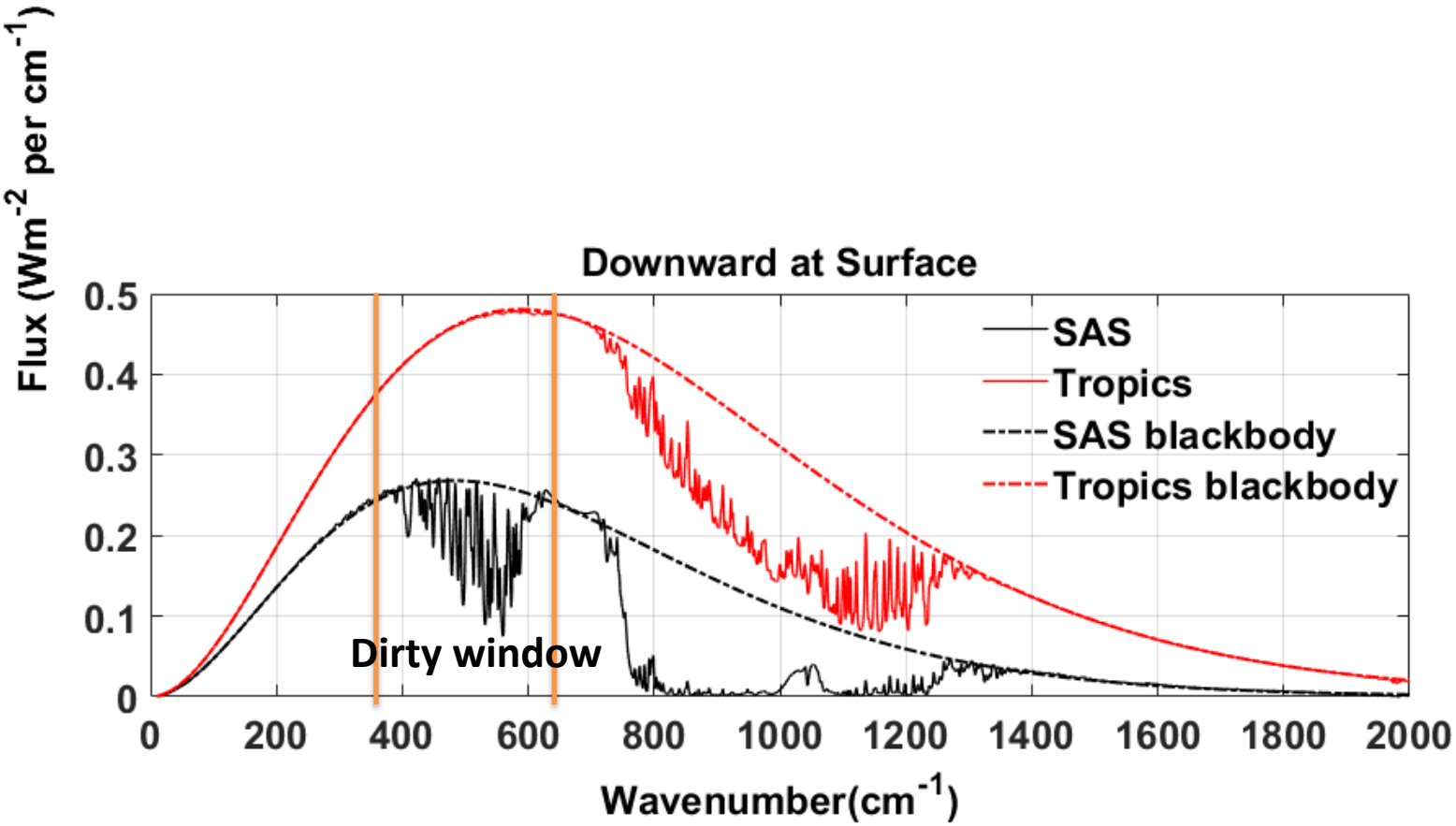
Far IR: Strong H_2O absorption

Two RRTMG far-IR bands

The aftermath of small TCWV in polar regions (II)

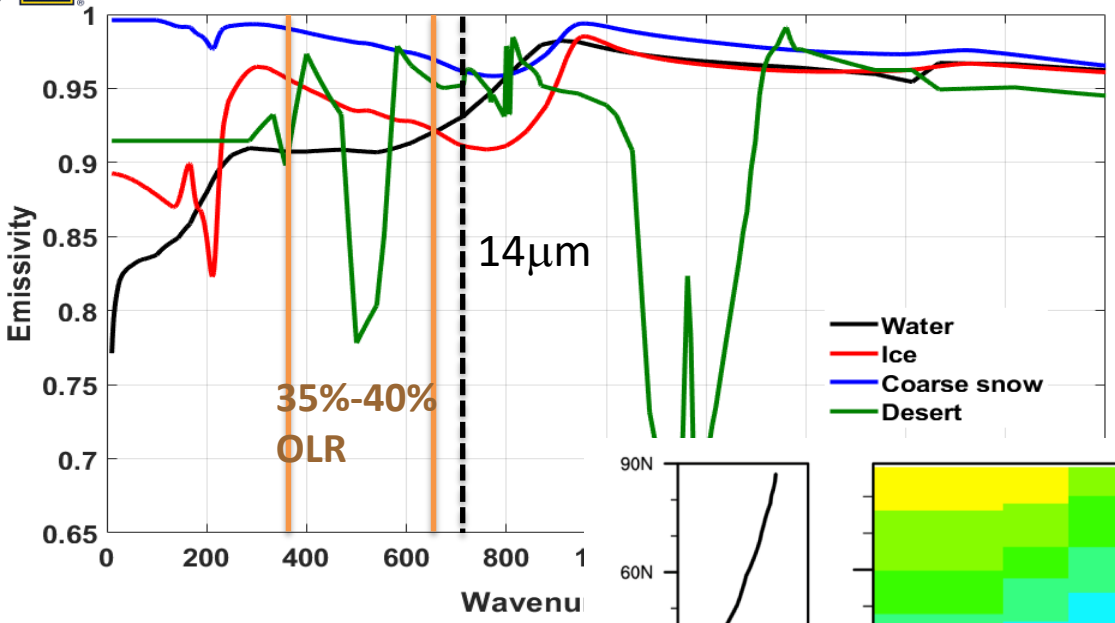
Huang et al. (2018, J Climate) incorporated the surface emissivity into the CESM

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

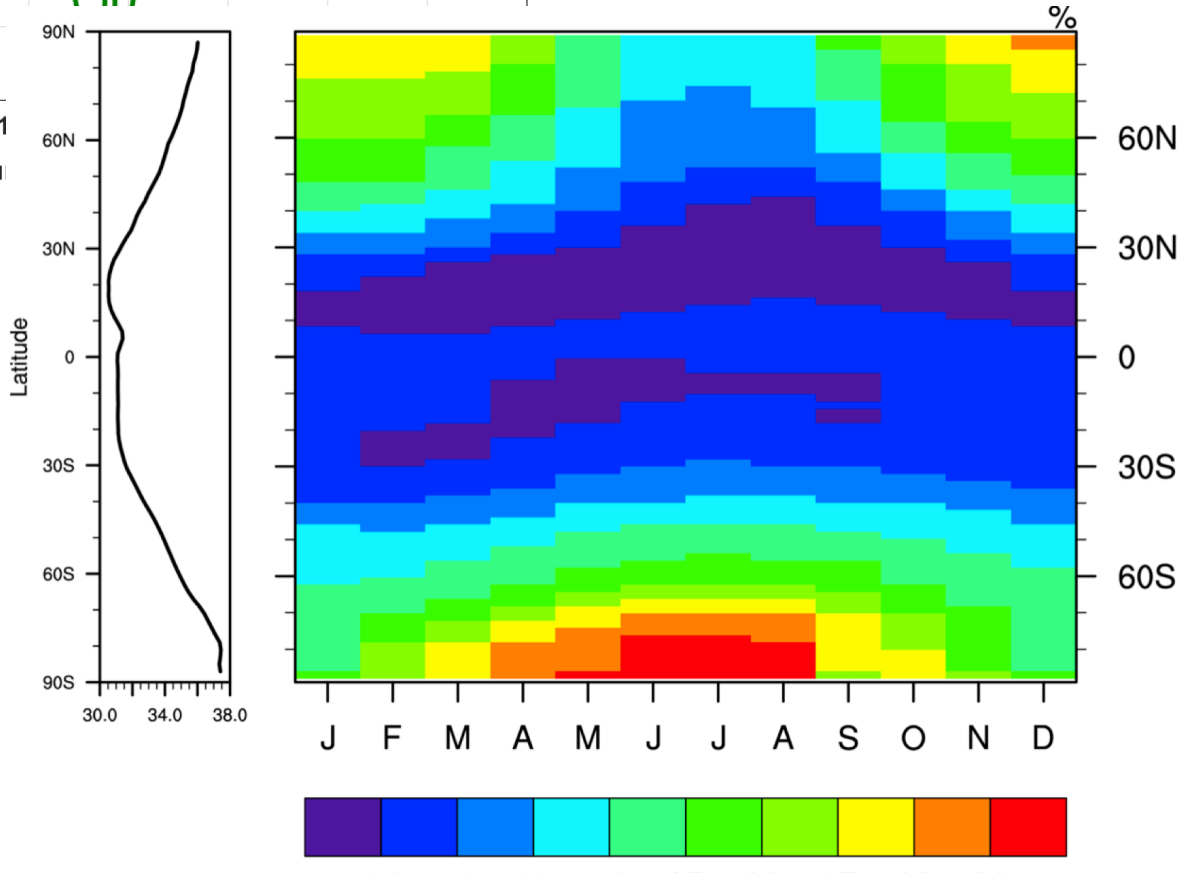


SAS: subarctic summer (60°N)

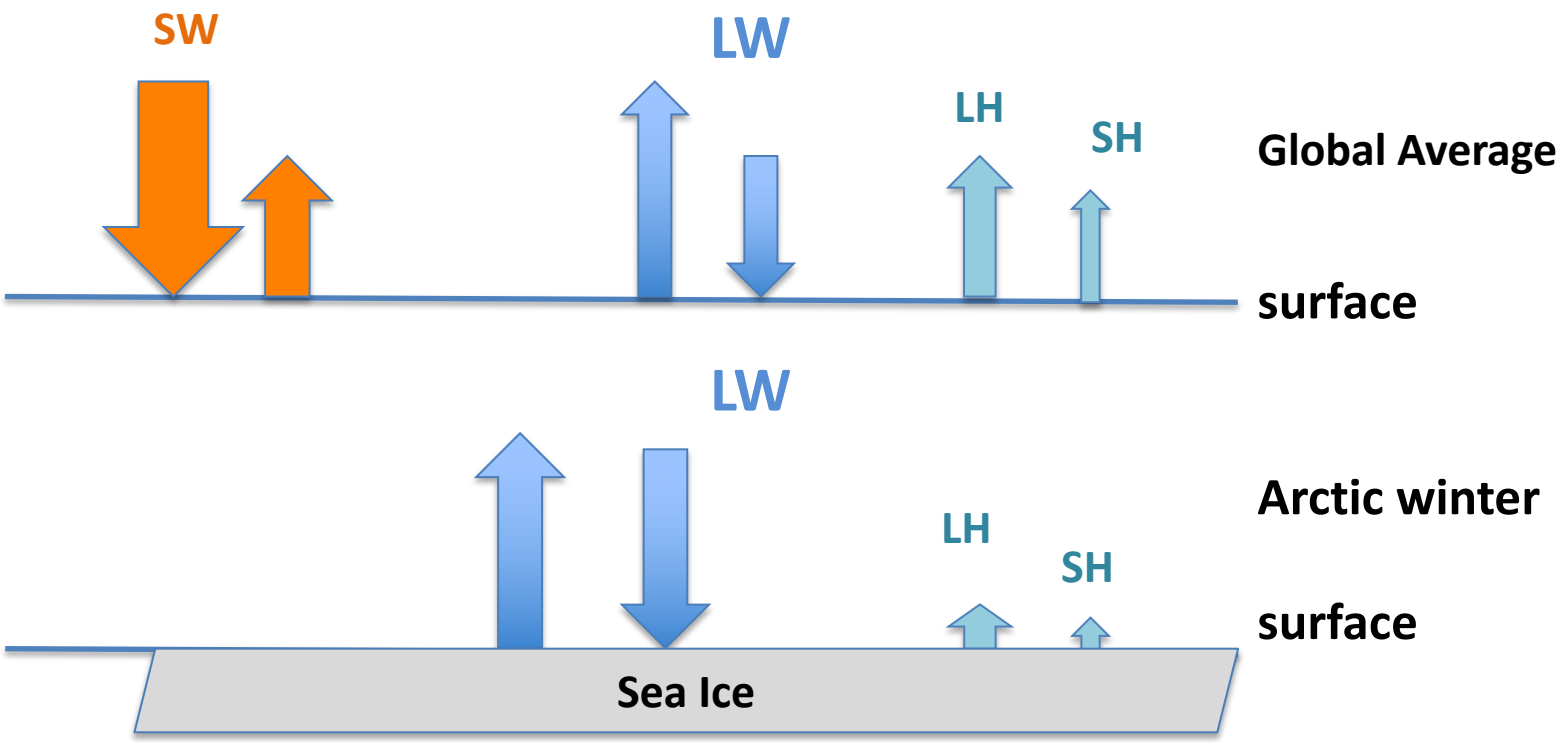
Surface spectral emissivity ε(v) is not one **Broadband emissivity won't work**



Two RRTMG bands to OLR



On top of above considerations: seasonality matters



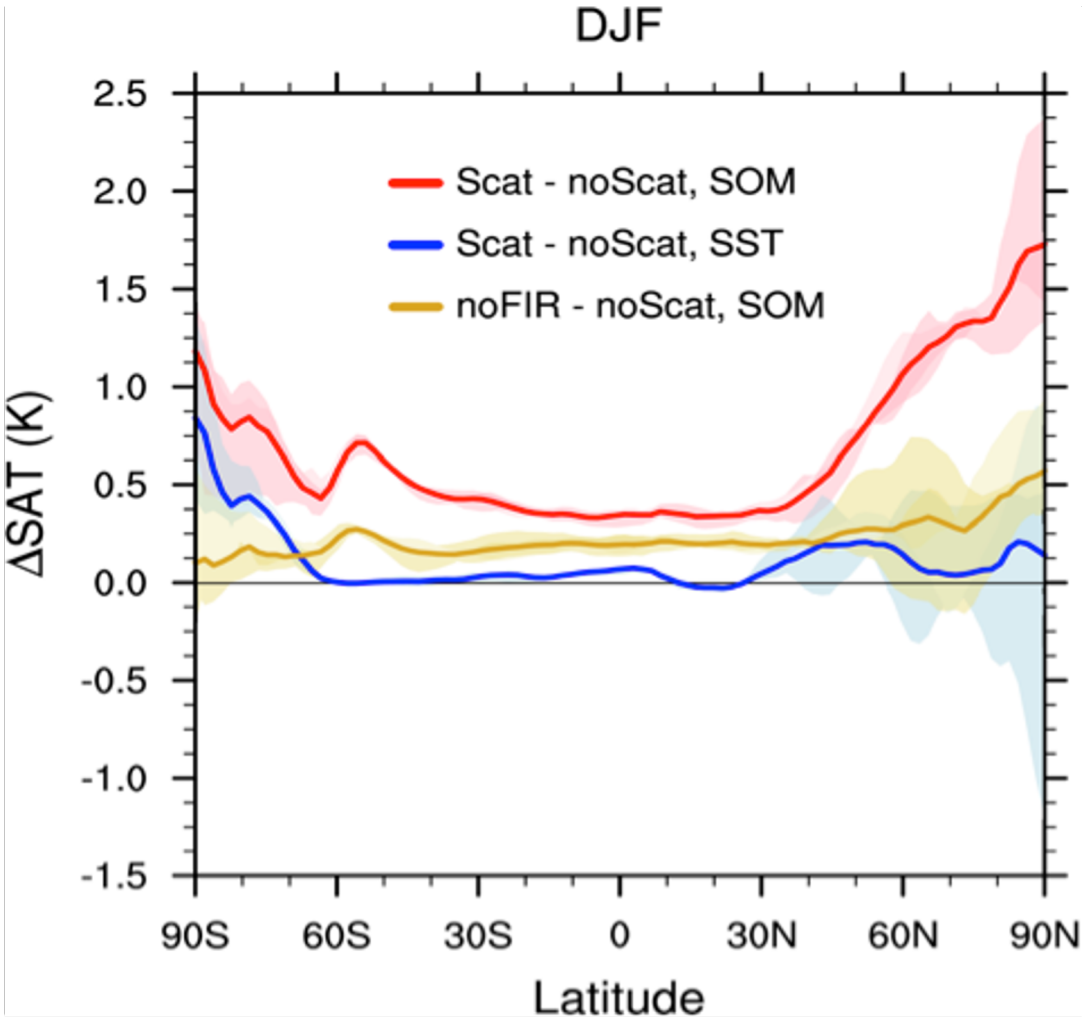
Hypothesis: missing LW processes would affect Arctic winter T_s the most, which then affects subsequent processes and feedbacks.

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

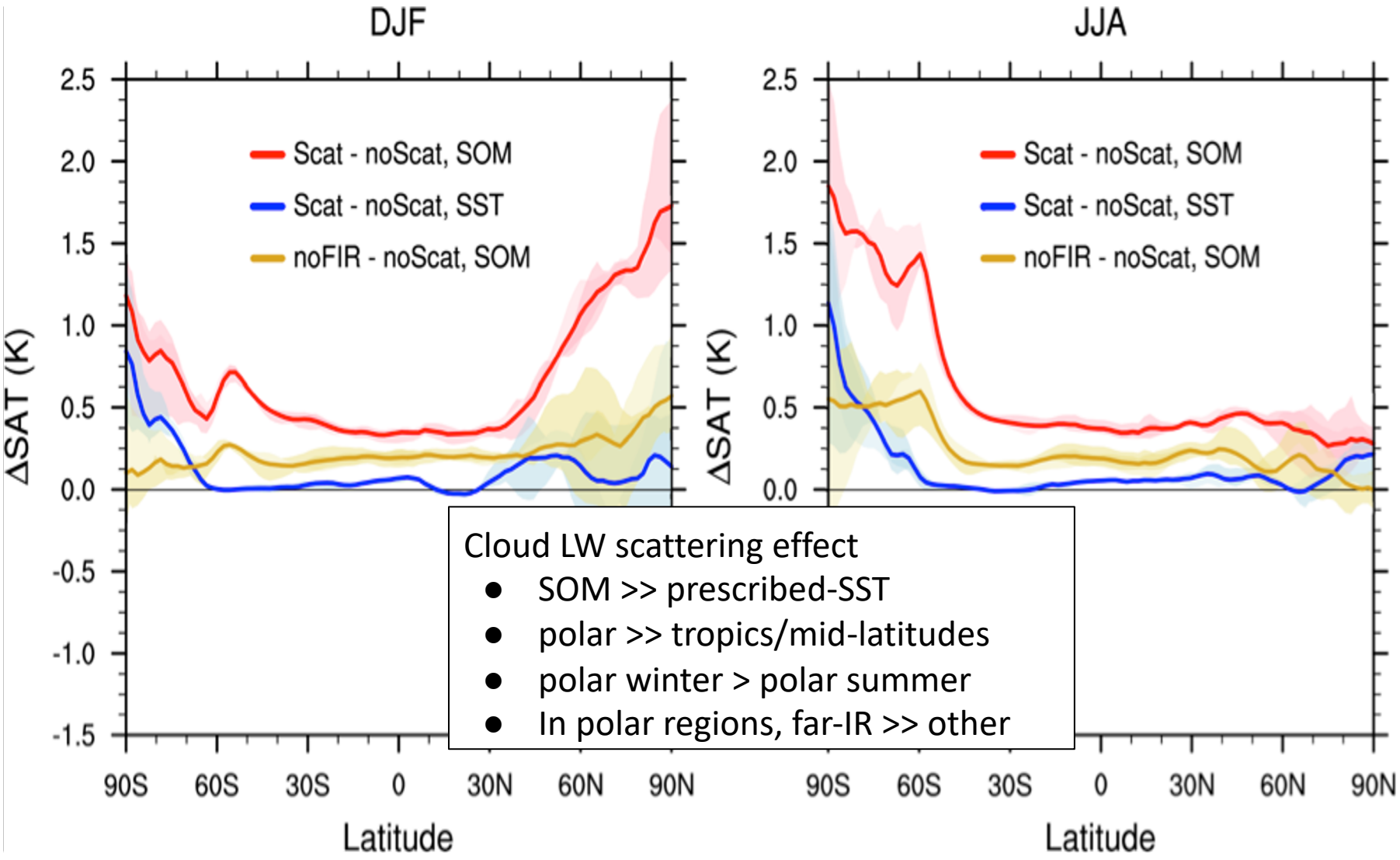
Codes available at
https://github.com/Huang-Group-UMICH/LW-scattering-polar-climate

Diff of surface air temperature



SST: prescribed SST run
SOM: slab-ocean run (surface-atmosphere coupling enabled)

Diff of surface air temperature

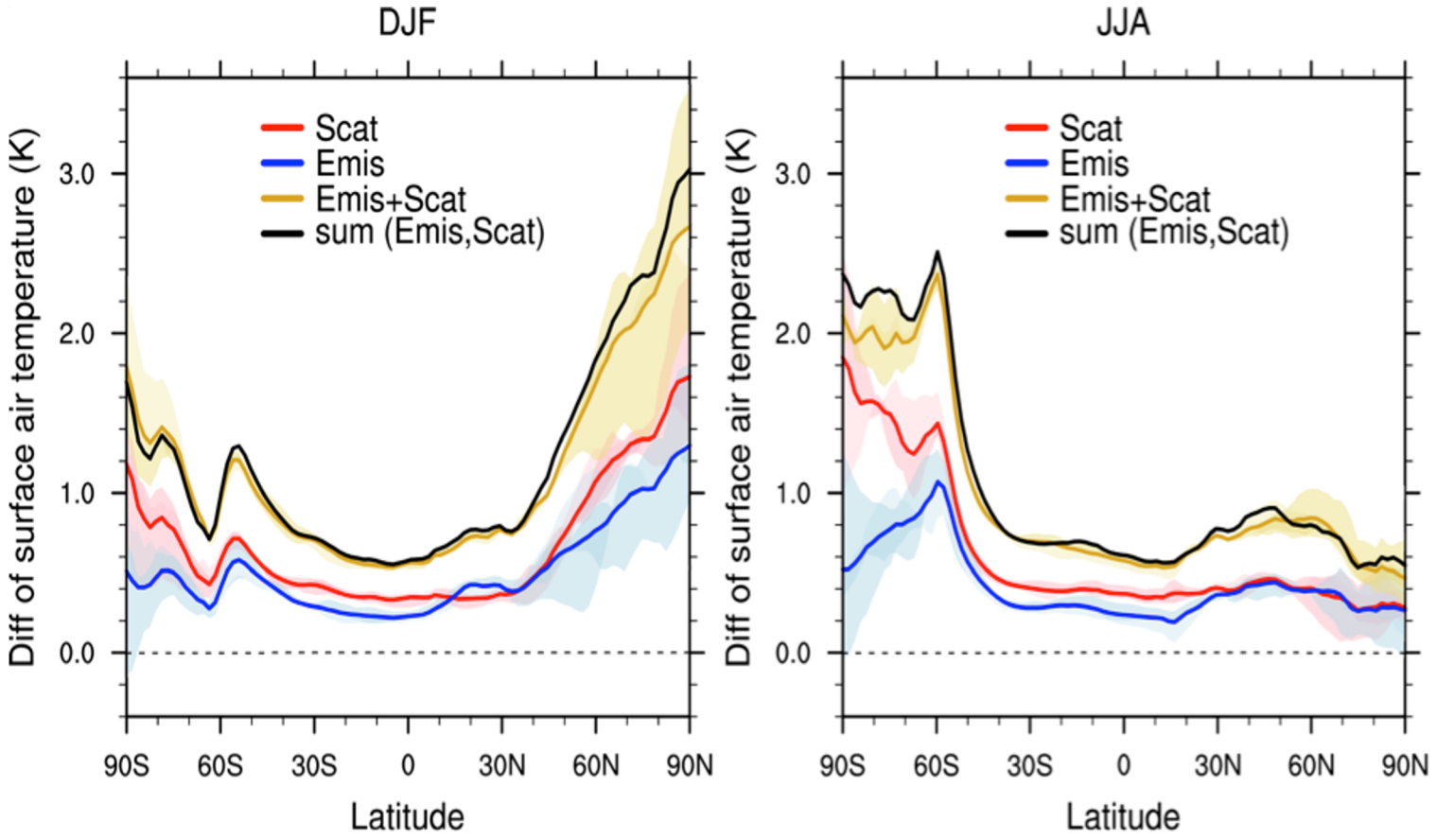


Cloud LW scattering effect

- SOM >> prescribed-SST
- polar >> tropics/mid-latitudes
- polar winter > polar summer
- In polar regions, far-IR >> other

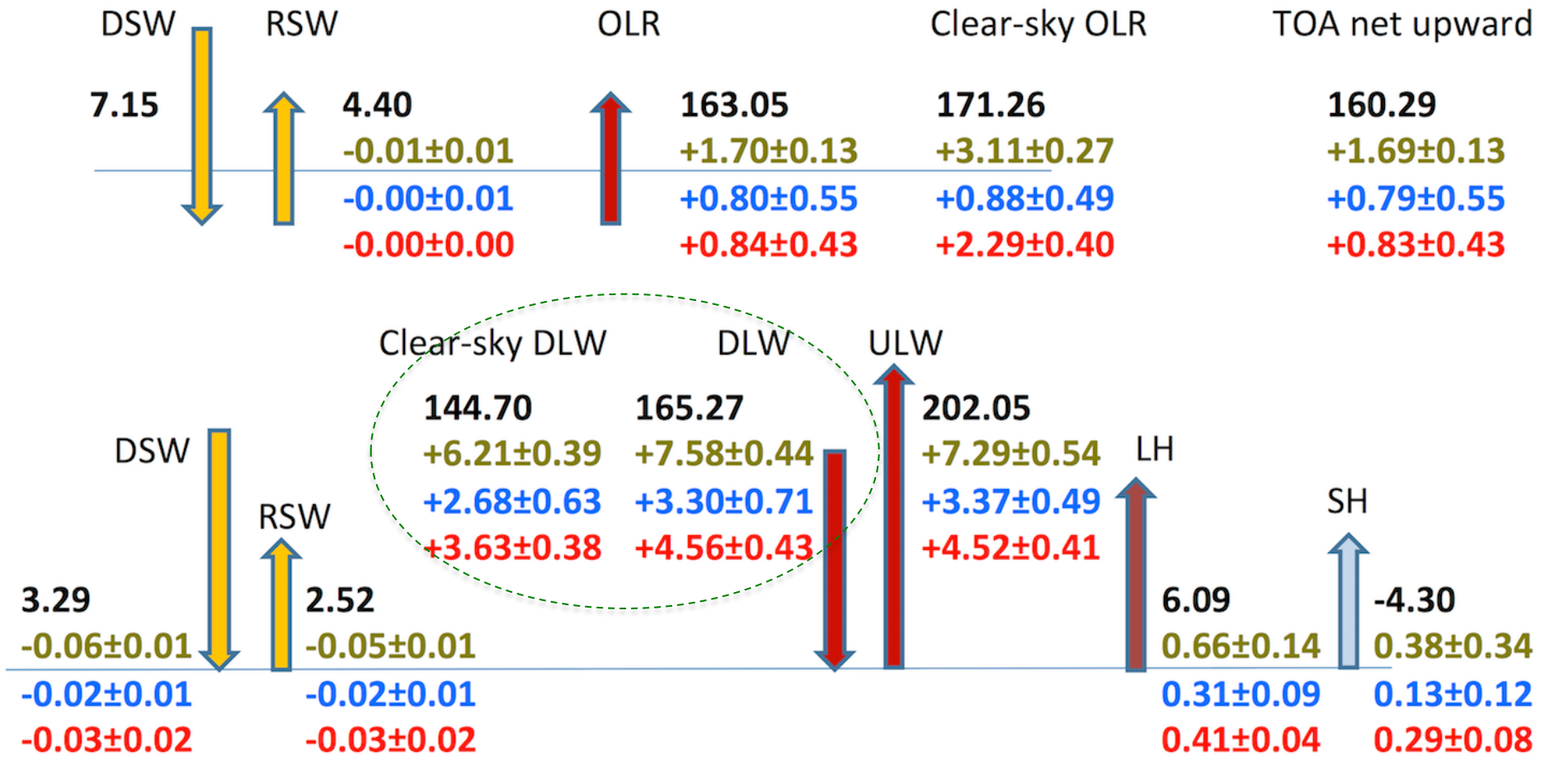
When realistc surface emissivity is also included

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)



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

noEmis_noScat
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 ~2 Wm^{-2}

References

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- Huang, X. L., X. H. Chen, M. G. Flanner, P. Yang, D. Feldman, C. Kuo, Improved representation of surface spectral emissivity in a global climate model and its impact on simulated climate, J. Climate, 31(9), 3711-3727, doi:10.1175/JCLI-D-17-0125, 2018.
- Chen, Y.-H., X. L. Huang, P. Yang, C.-P. Kuo, X. H. Chen, 2020: Seasonal Dependent Impact of Ice-Cloud Longwave Scattering on the Polar Climate, *Geophysical Research Letters*, 47(23), https://doi.org/10.1029/2020GL090534.

CESM implementation at
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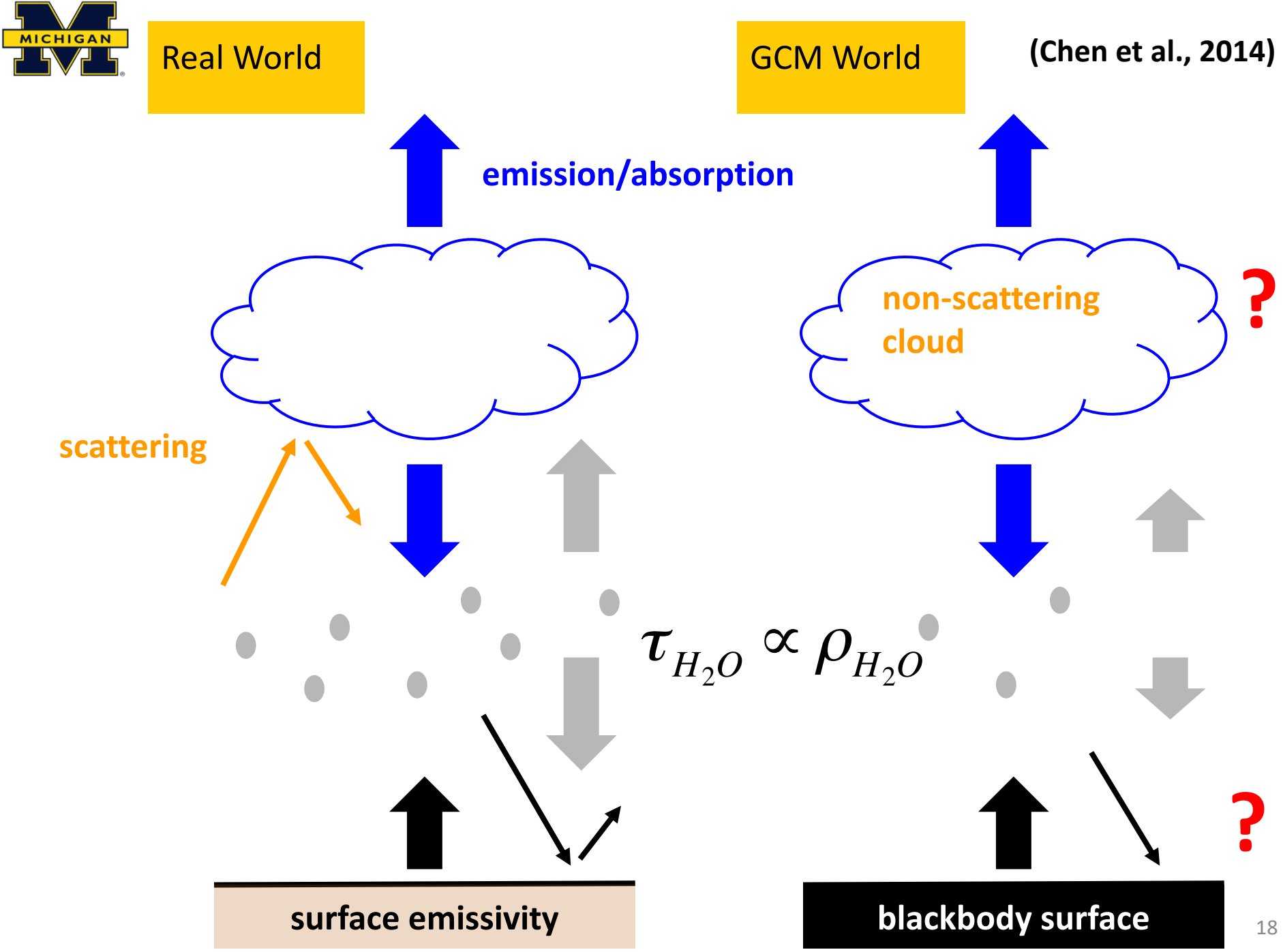
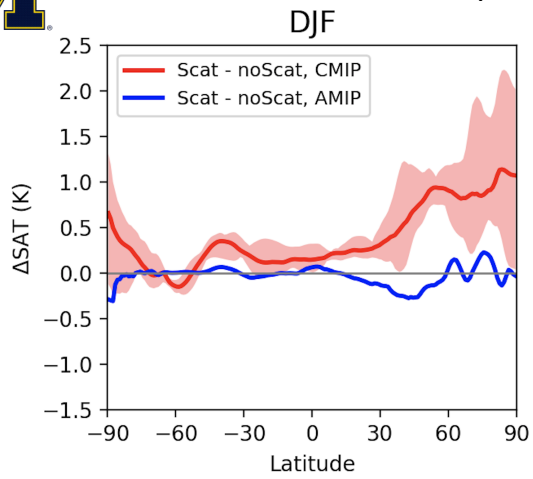
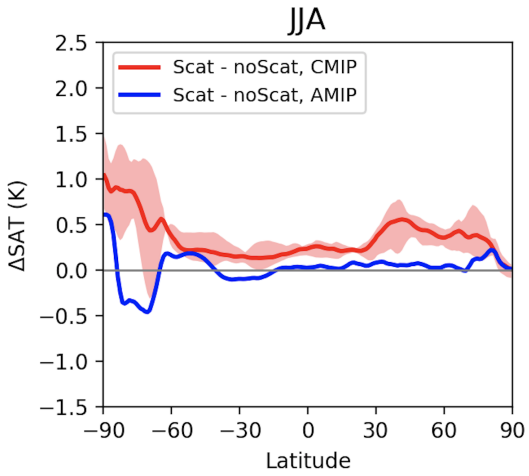
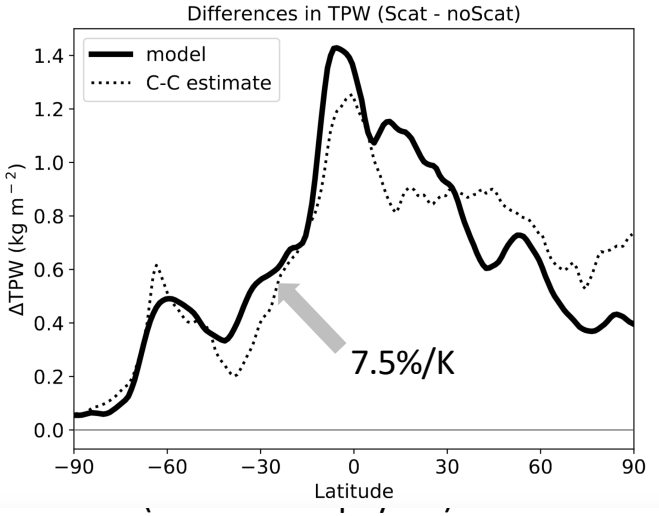

Real World
GCM World
(Chen et al., 2014)
emission/absorption
scattering
non-scattering cloud
?
$\tau_{H_2O} \propto \rho_{H_2O}$
surface emissivity
blackbody surface
?

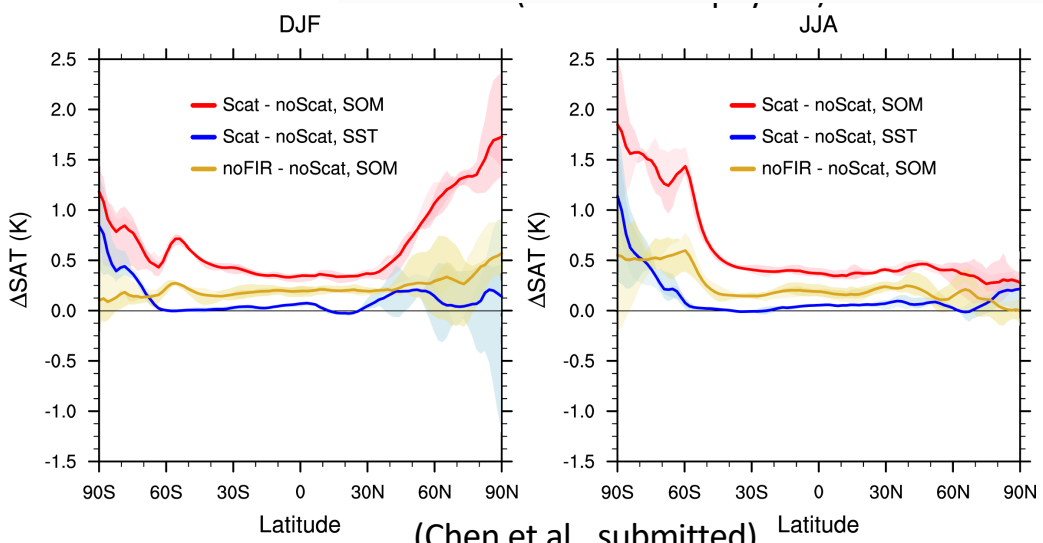
E3SM v2 alpha fully coupled run







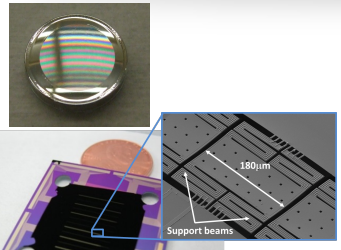
SAT is surface air temperature, a.k.a. reference height temperature



(Chen et al., submitted)

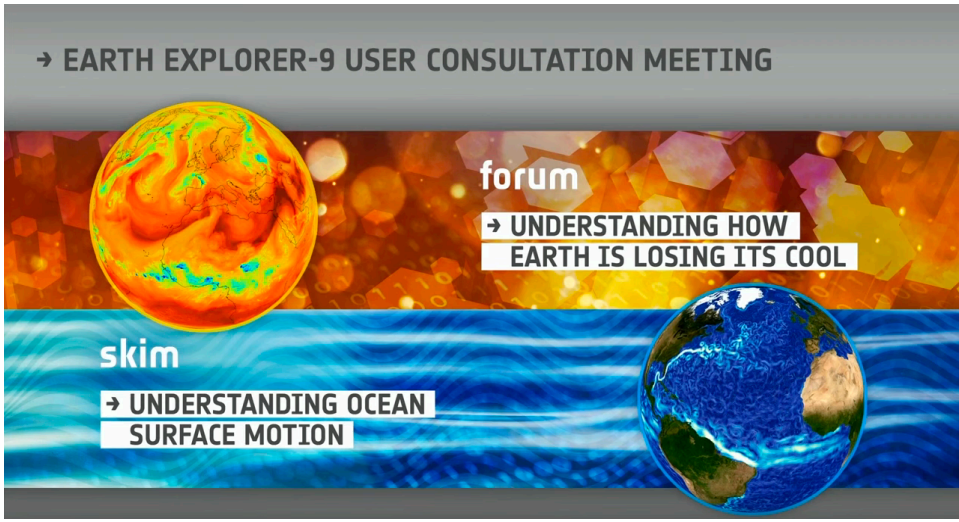
Two far-IR Satellite Missions that I have participated in

GRATING



THERMOPILE

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”

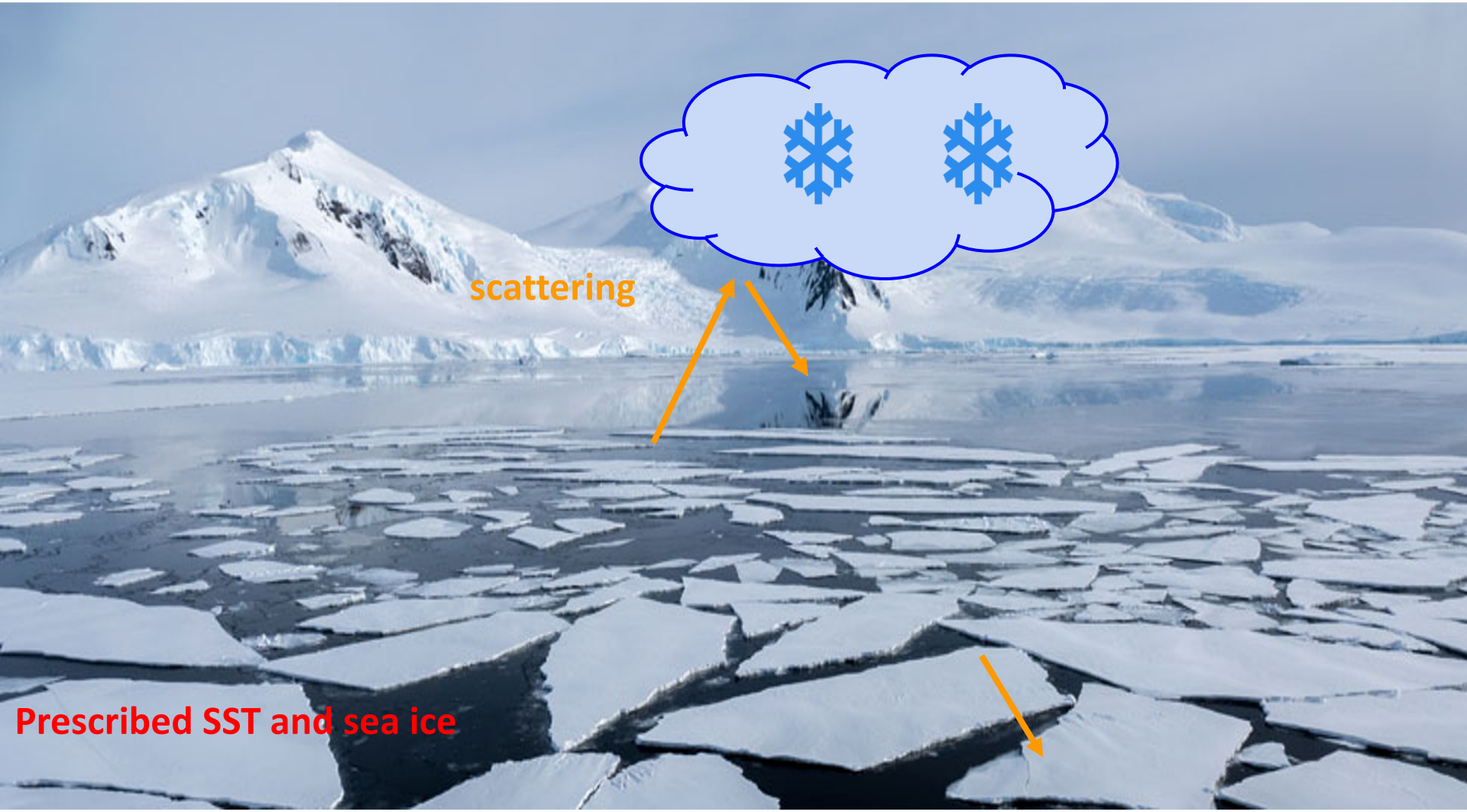


FORUM: ESA 9th Earth Explorer mission
Current budget ~ 350M euros
Target Launch date: 2025/2026
Fourier Spectrometer with 0.5cm^{-1} resolution

- My role: L2 spectral flux and surface spectral emissivity retrievals, modeling support

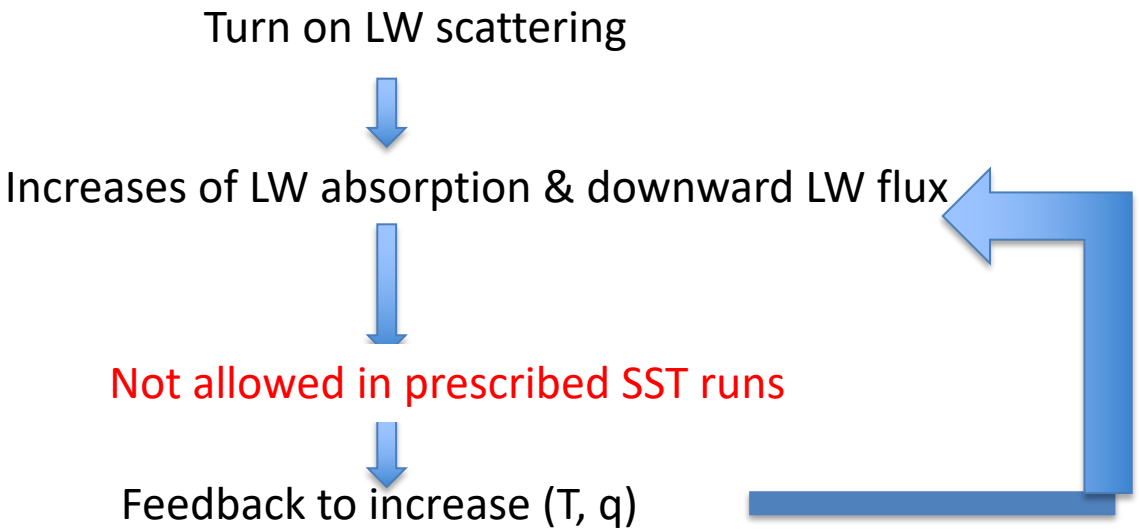
Previous studies on cloud LW scattering always used AMIP-type prescribed SST/sea ice runs.

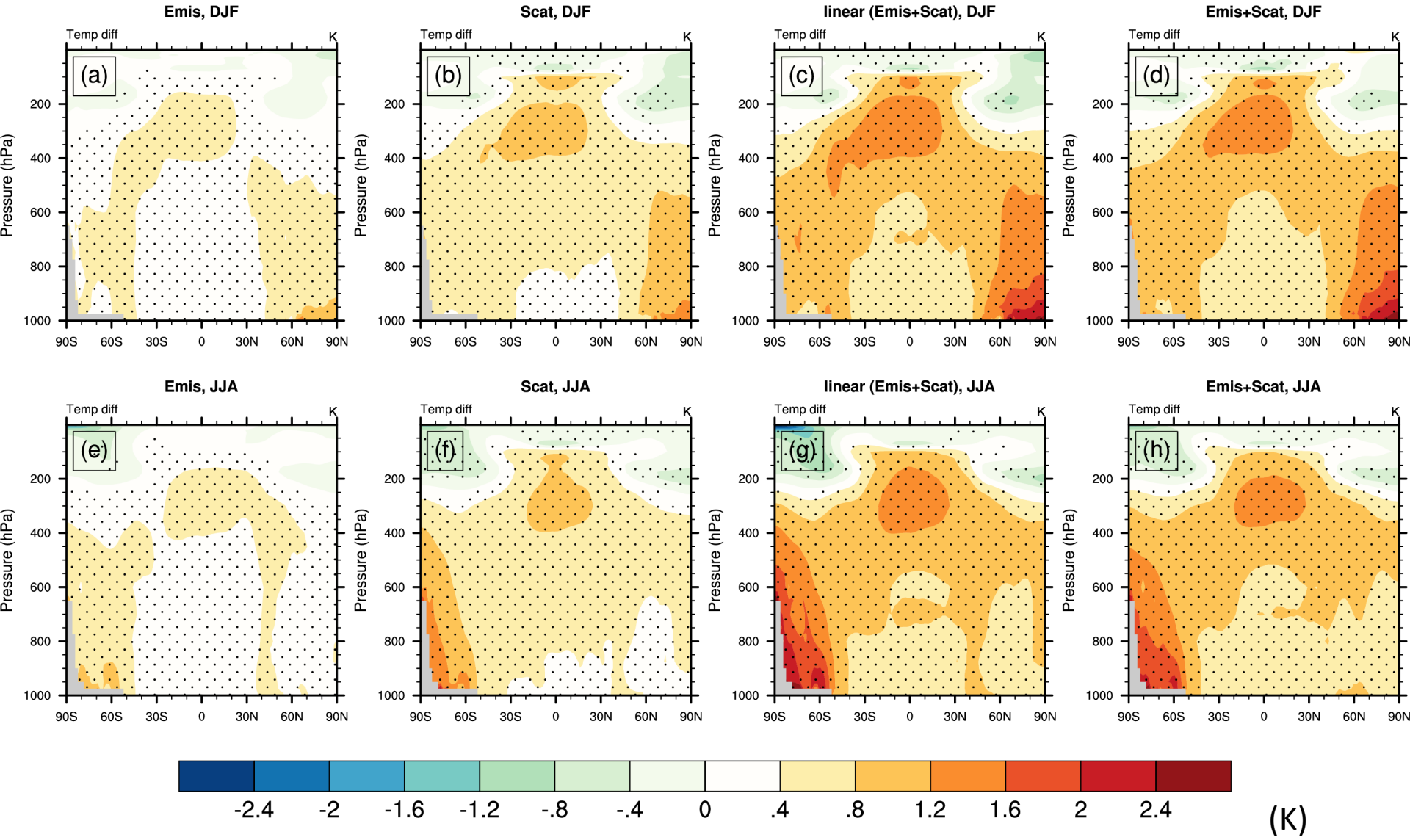
Hypothesis: without surface responses to the cloud LW scattering, its effect cannot be fully revealed.



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




Emis, DJF
Scat, DJF
linear (Emis+Scat), DJF
Emis+Scat, DJF
Emis, JJA
Scat, JJA
linear (Emis+Scat), JJA
Emis+Scat, JJA
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Temp diff
K
Pressure (hPa)
200
400
600
800
1000
90S
60S
30S
0
30N
60N
90N
-2.4
-2
-1.6
-1.2
-.8
-.4
0
.4
.8
1.2
1.6
2
2.4
(K)