Assessing an improved treatment of the surface-atmosphere longwave radiative coupling in the E3SM v2: the role of longwave cloud scattering

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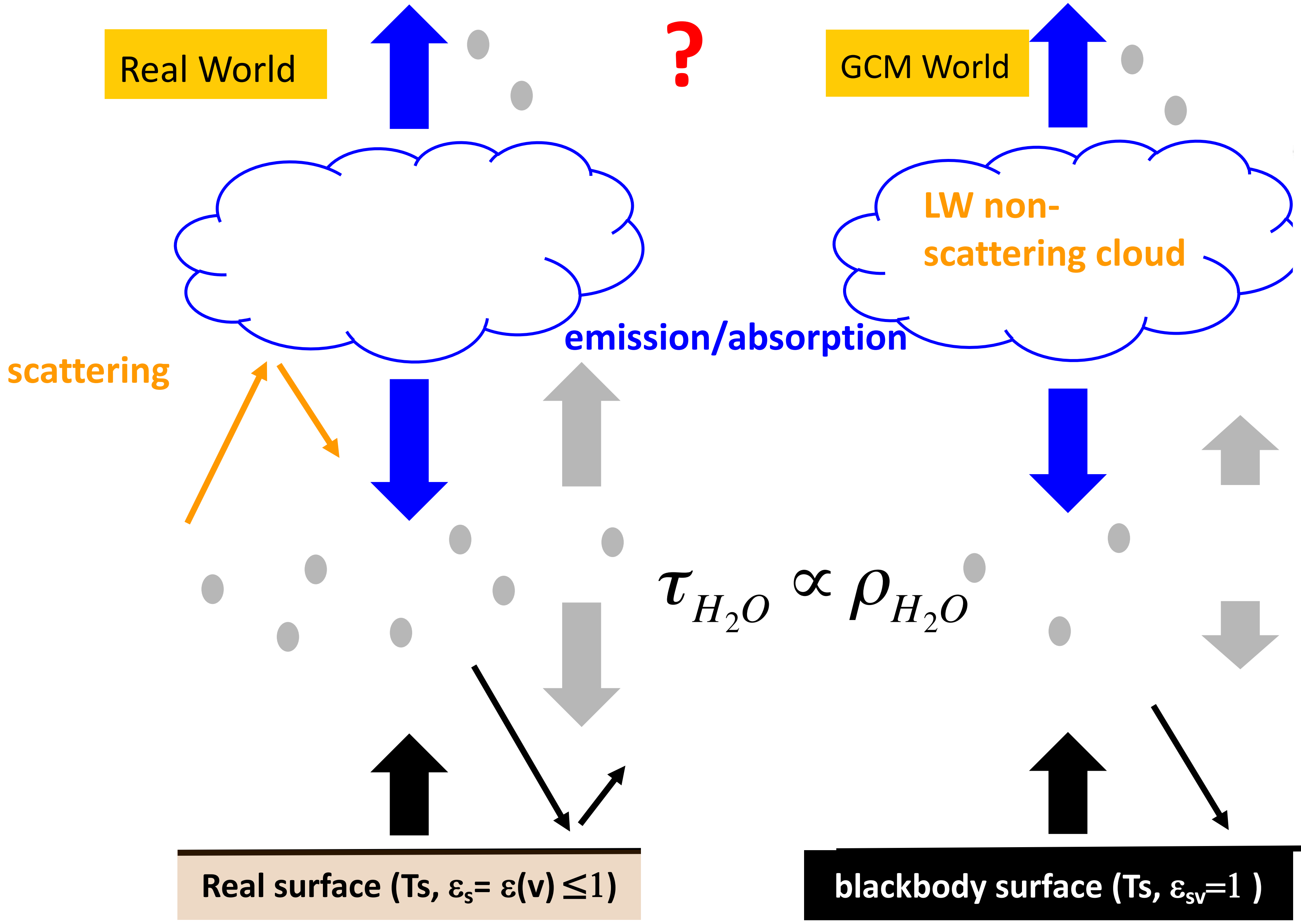
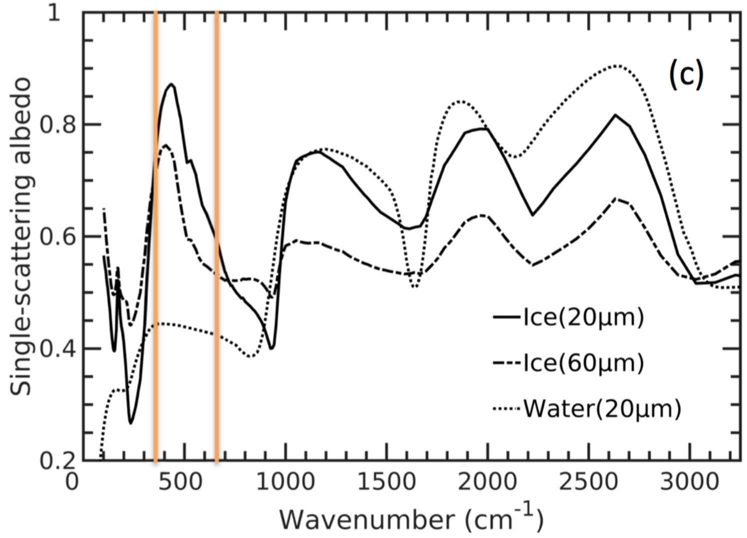
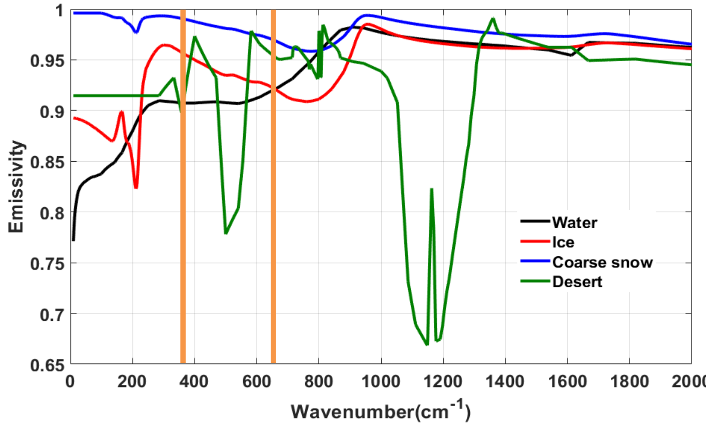
Acknowledgement: E3SM-SciDAC and ESMD programs, Water Cycle and NGD-AtmoPhys teams

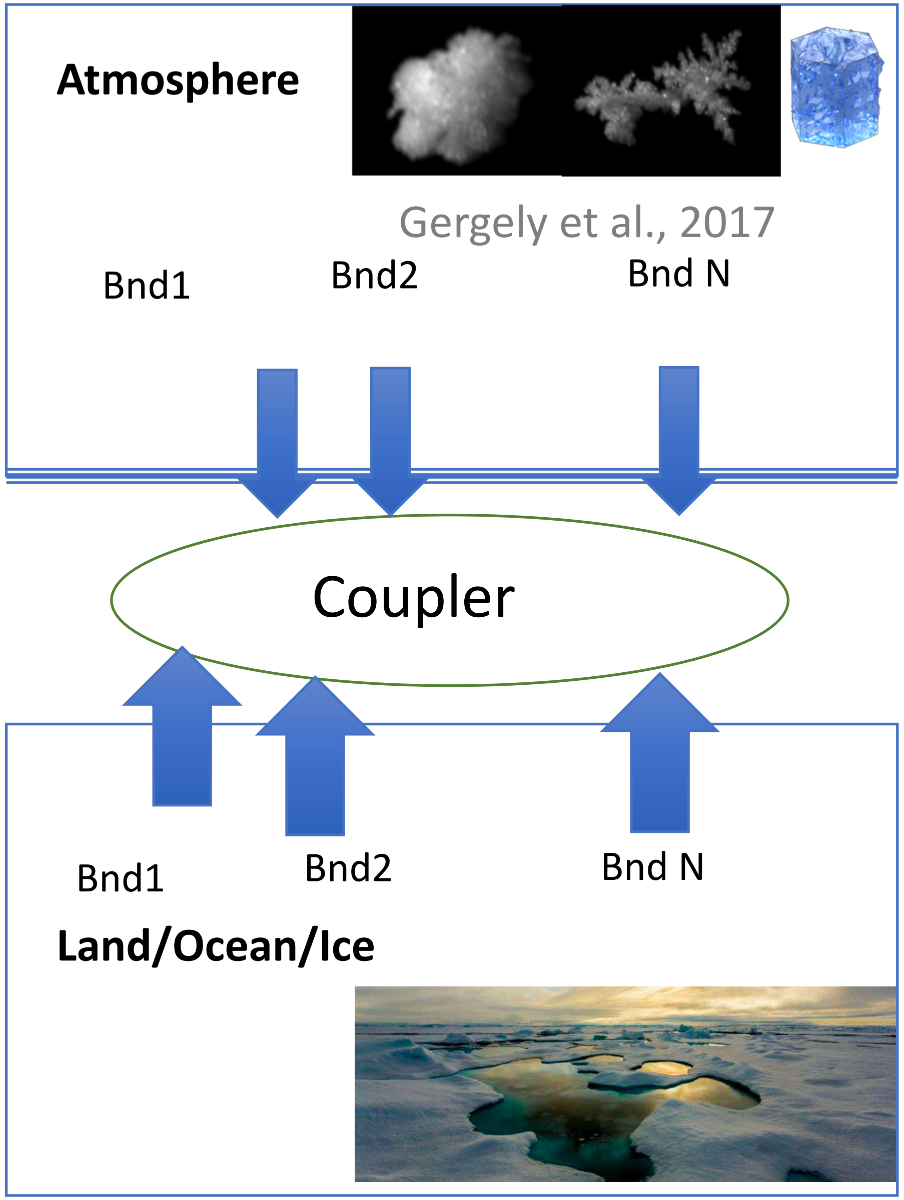
The starting point: Physical consideration about LW radiative transfer

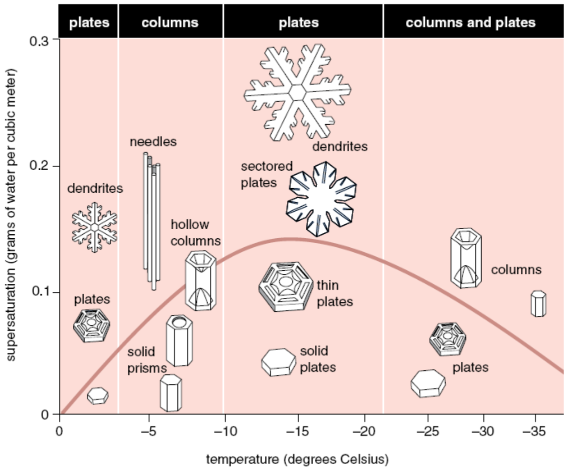






~34% OLR

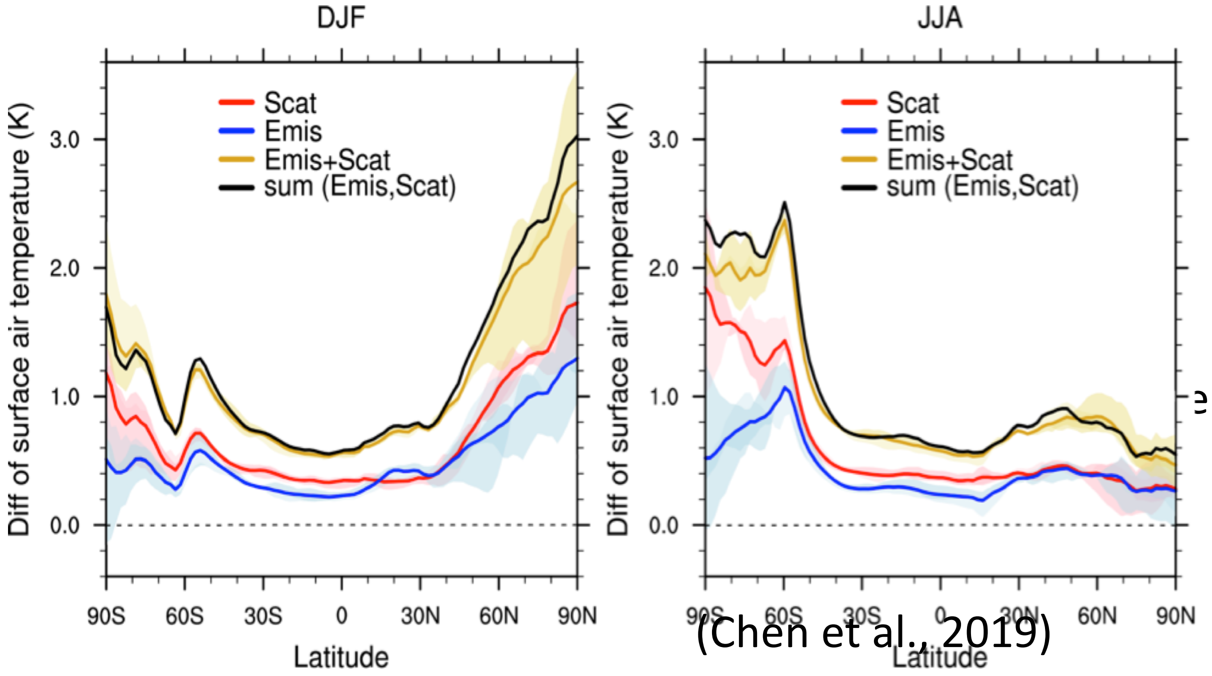




Libbrecht (2007)

- Effects of scattering and emissivity is largely additive

Atmosphere: ice cloud optics, surface emissivity, and their treatments in EAM (UM, Texas A&M, BNL)



(Chen et al., 2019)

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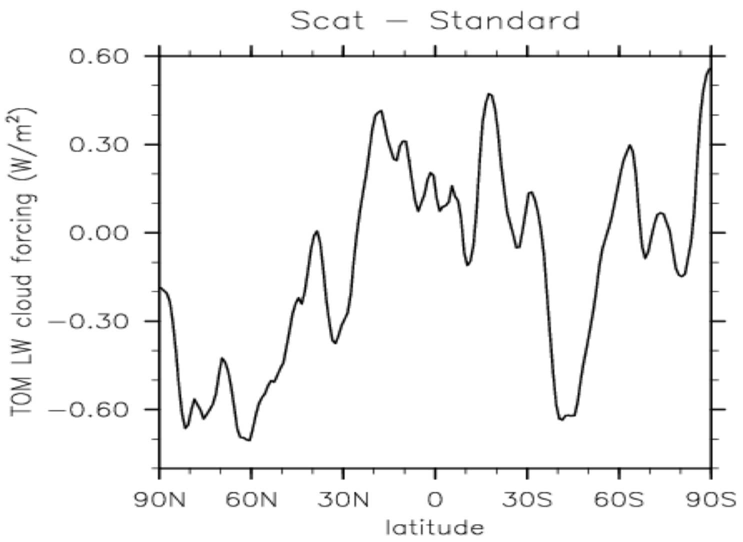
Ice cloud	• MC6 ice cloud optics • A hybrid 2S/4S LW scattering solver into RRTMG_LW (Toon et al., 1989; Kuo et al., 2020)
Surface spectral emissivity	• Based on the spectral emissivity database (Huang et al., 2016) • Prescribed land spectral emissivity • Diagnose spectral emissivity from fractions of sea ice and open water • Major conclusions in Huang et al. (2018, J. Climate)

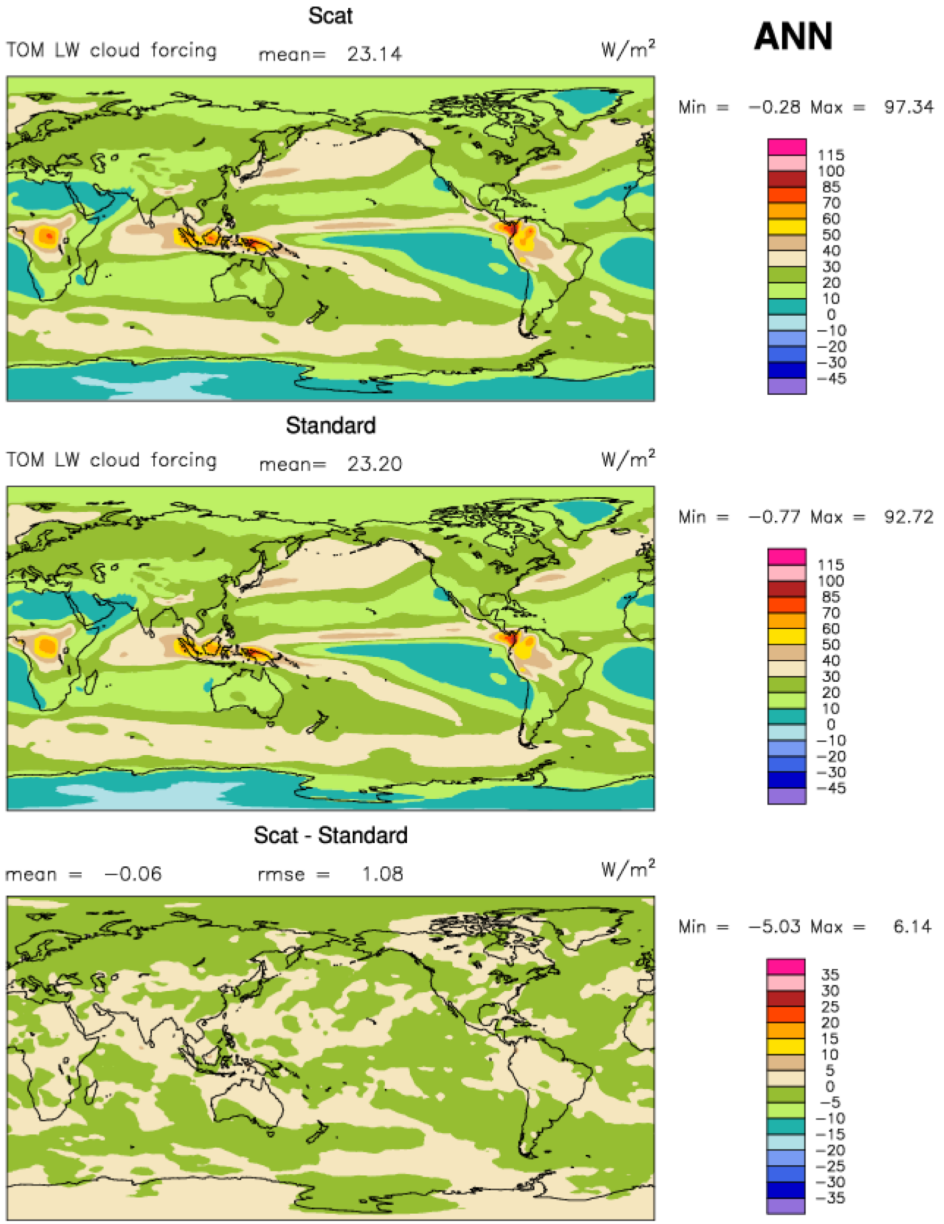
- The role of surface spectral emissivity alone has been described in Huang et al. (2018, J Climate) and presented before
- Following slides will be focusing on understanding the role of longwave ice cloud scattering

AMIP run results (10-year climatology)

	LW CRE	FLUT (OLR)	FLDS
E3SM v2 alpha (standard)	23.2	241.0	345.2
UMRad LW scattering	23.1	239.9	345.2
Obs (CERES EBAF 4.1)	26.1	239.7	345.5

All in Wm^{-2}





A double-call AMIP run

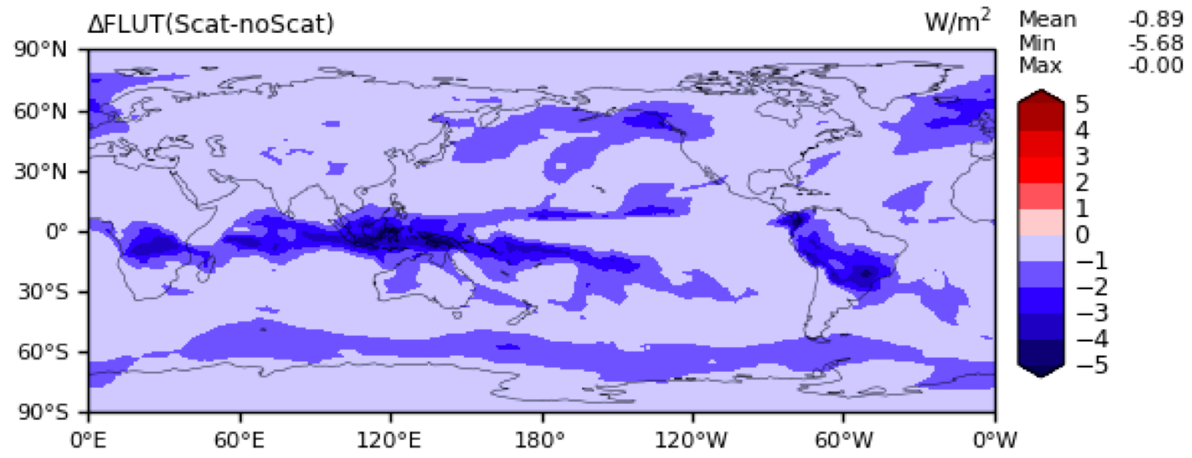
- At each time step, RRTMGP/UMRad is called twice, once to run with scattering and once without scattering.
- Only the results with scattering on were used to further integrate the model forward

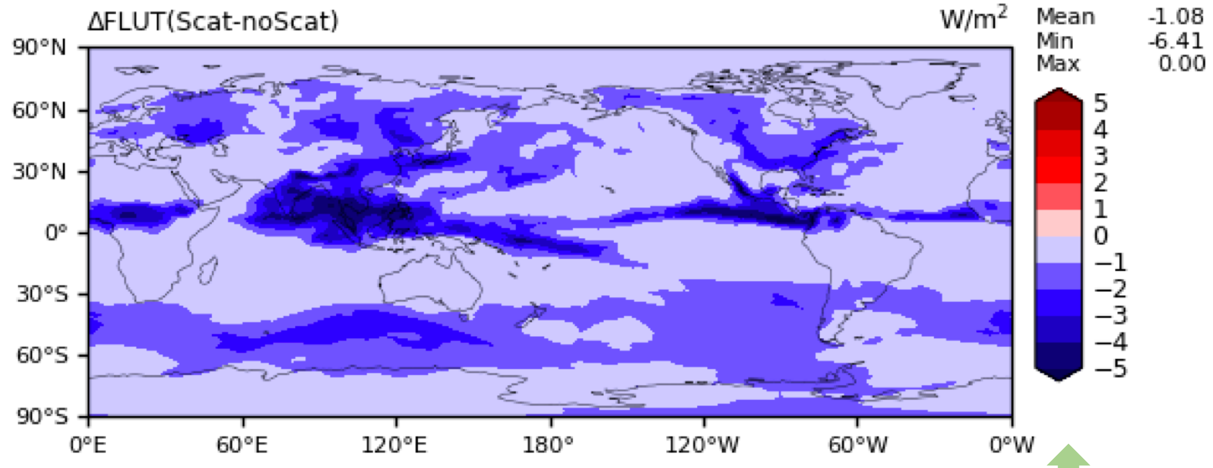
Radiation alone: how much and where the LW ice cloud scattering matters most (before any other components respond to such scattering)?

Double-Call Results

January

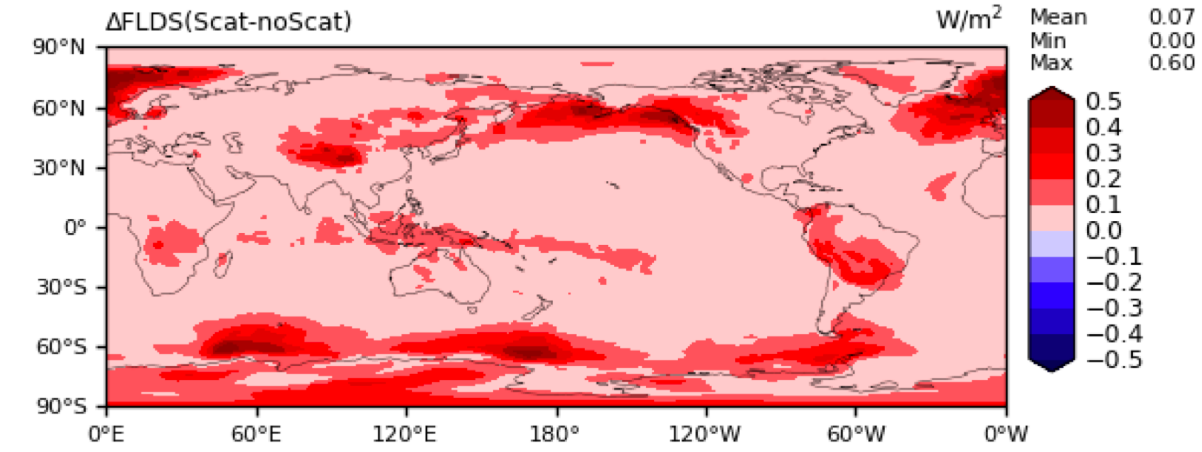
July

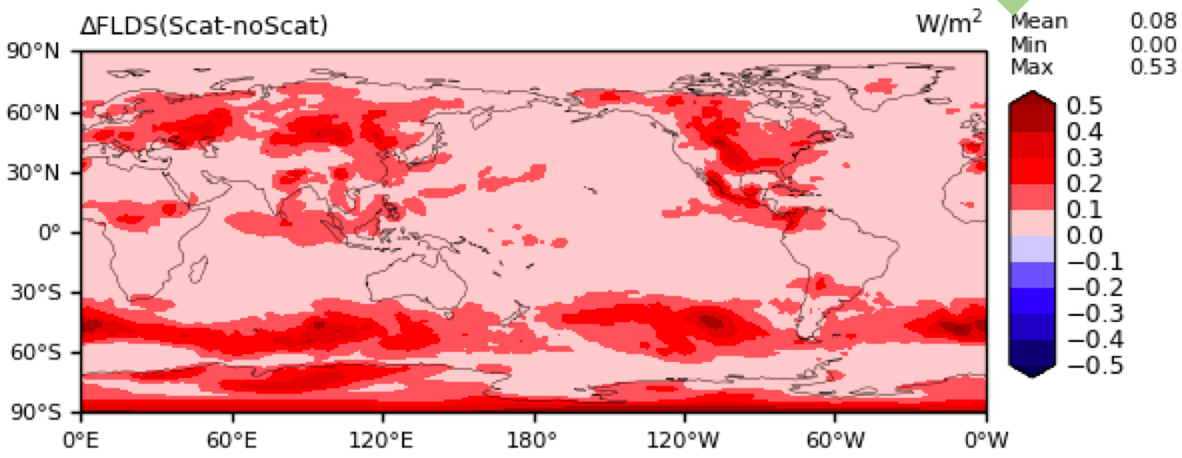




Outgoing Longwave Radiation

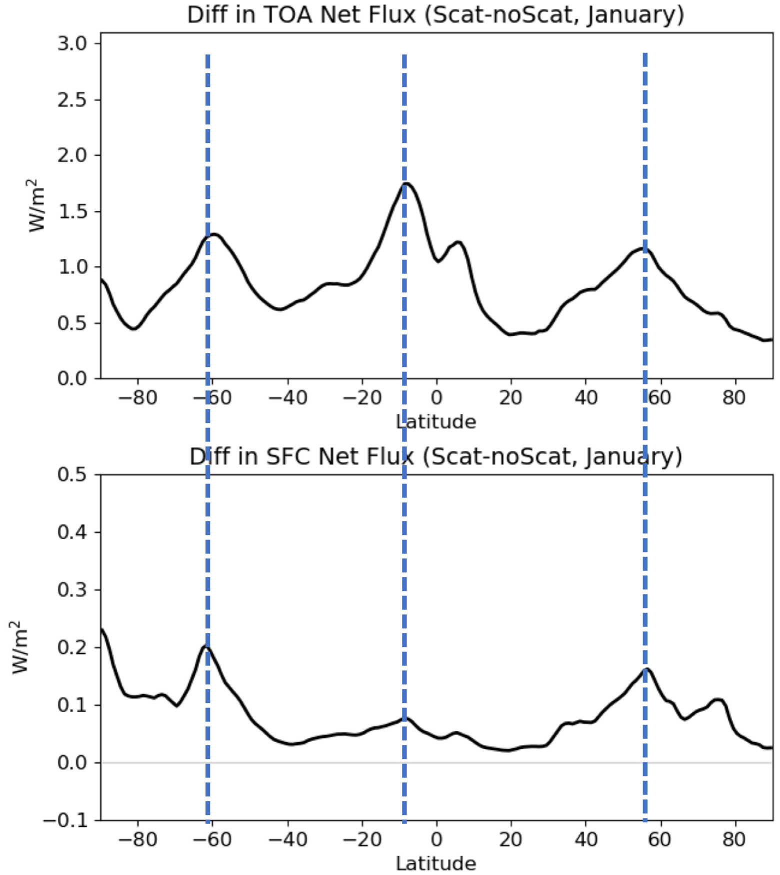
Color scales are difference

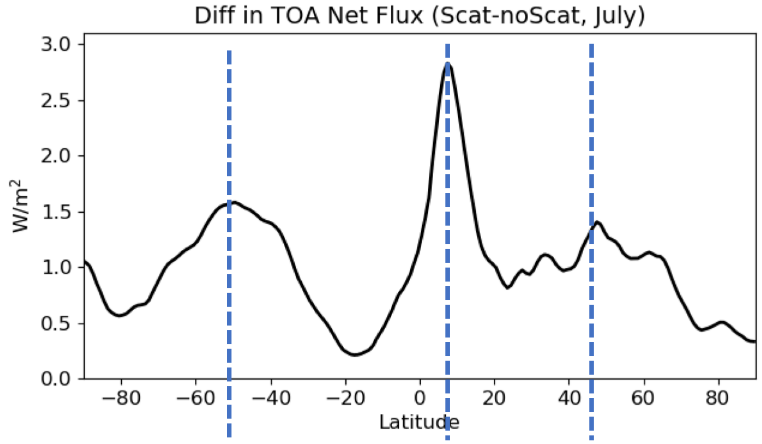


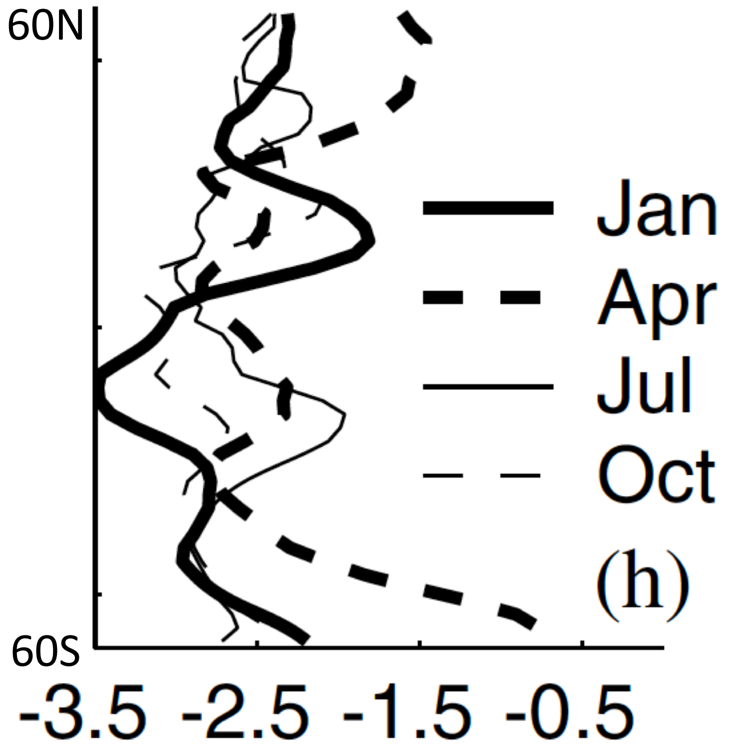


Downward Longwave Flux at the Surface

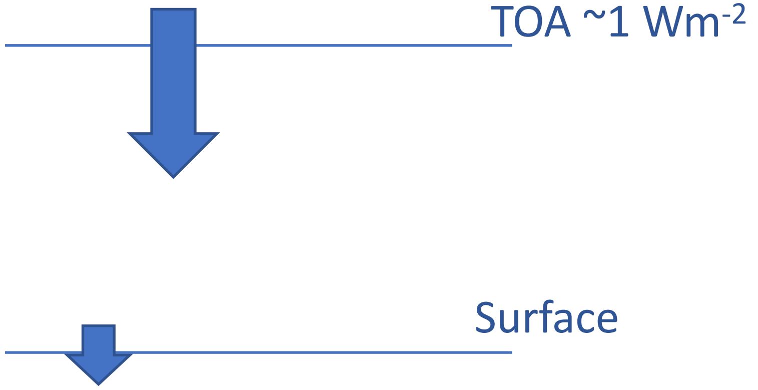
Double-Call Results (Cont)







Scattering - Non Scattering



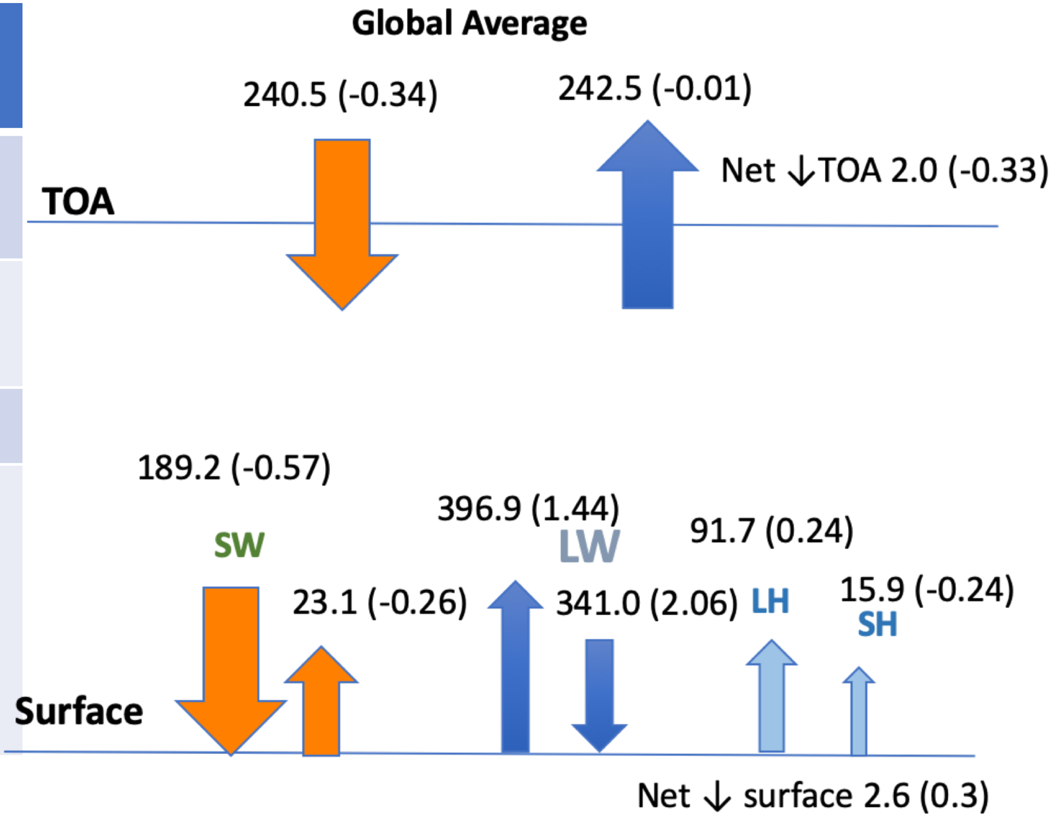
LW scattering directly
(1) leads to more heating of the column atmosphere
(2) increase the LW CRE
Then surface responds, feedbacks start…

Costa & Shine, 2006 (ERA40 + ISCCP)

Coupled ensemble run (10-year climatology)

	LW CRE	FLUT(OLR)	FLDS
UMRad no-scattering	22.3	240.5	341.0
UMRad scattering	23.3	240.2	343.1
Obs (EBAF 4.1)	25.8	240.3	345.5
CMIP 20200410.EAMv1like.piControl.ne30pg2_r05_oECv3_ICG.comp	24.2	242.1	346.5

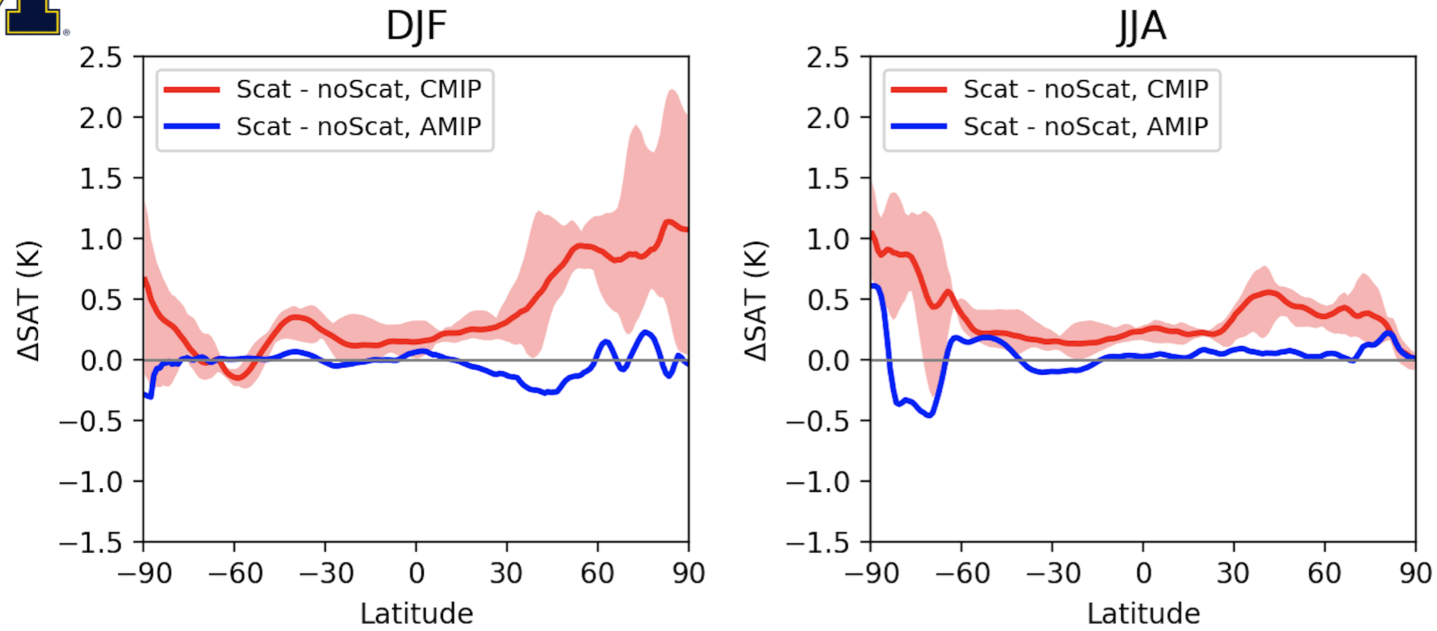
All in Wm^{-2}

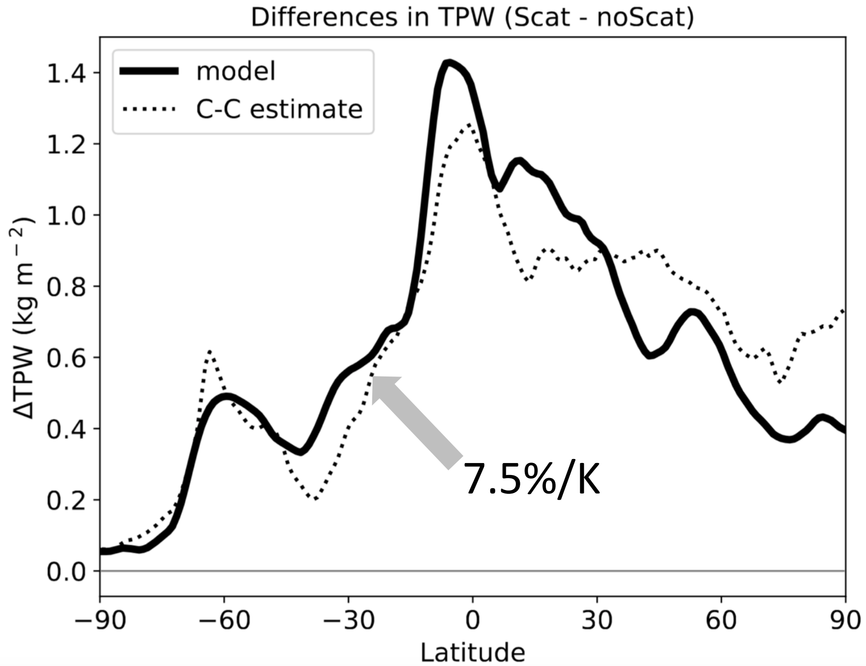


CRE: cloud radiative effect

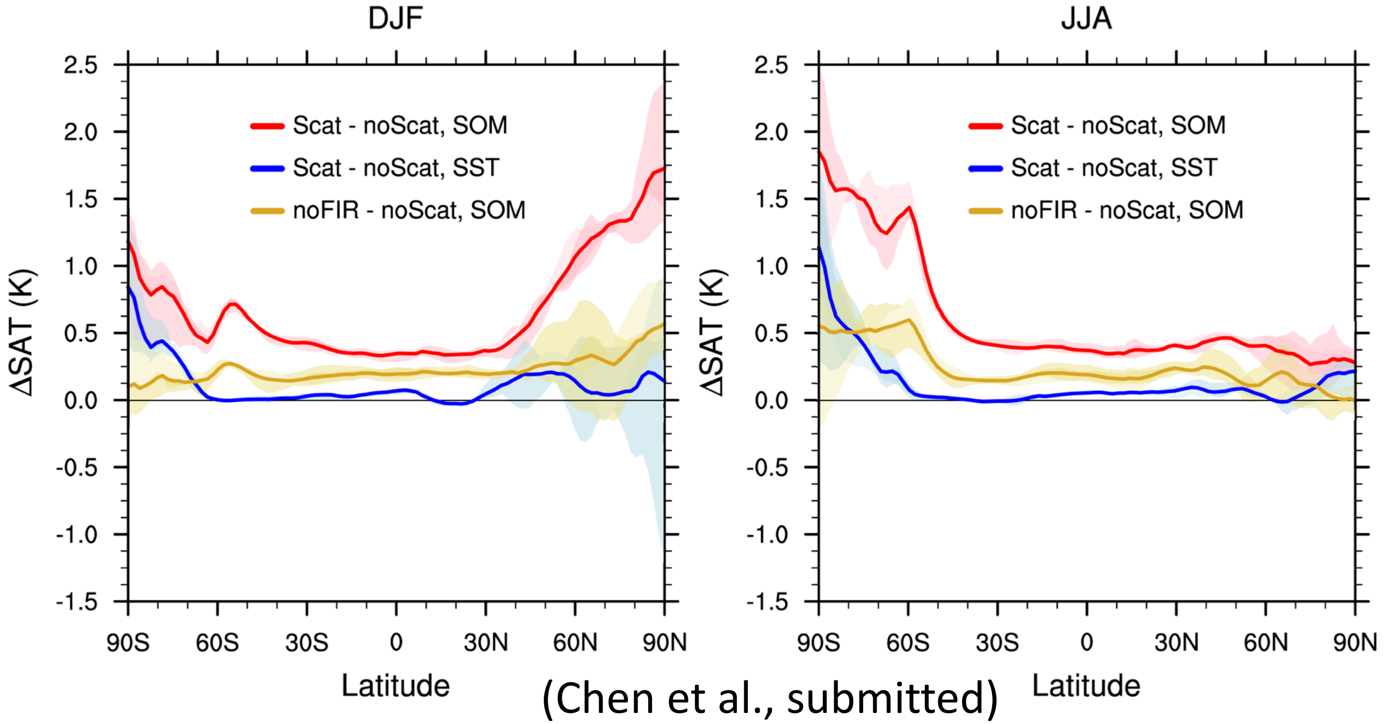
From both physics-based argument and the simulation above, including scattering should
(1) help bringing the E3SM LW CRE closer to the observations
(2) has little impact on OLR, SW flux, and latent/sensible heat flux
(3) Increase the downward LW flux at the surface by ~ $2Wm^{-2}$, which is largely balanced by increased upward LW flux

E3SM v2 alpha fully coupled run



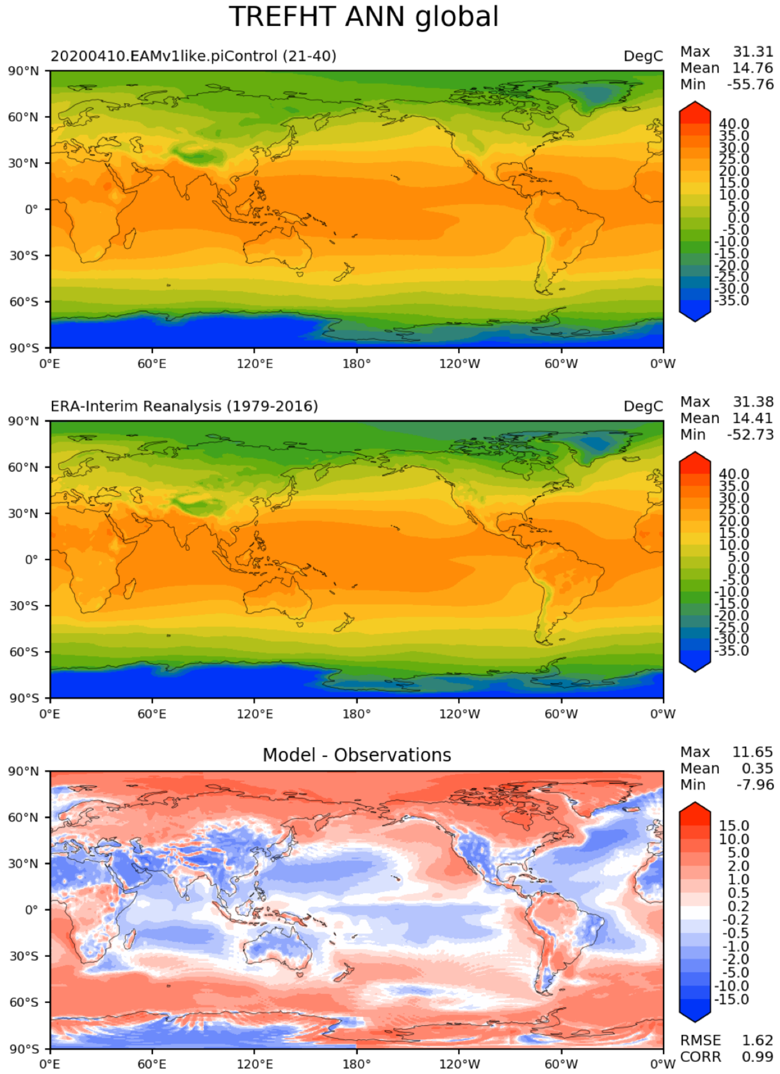


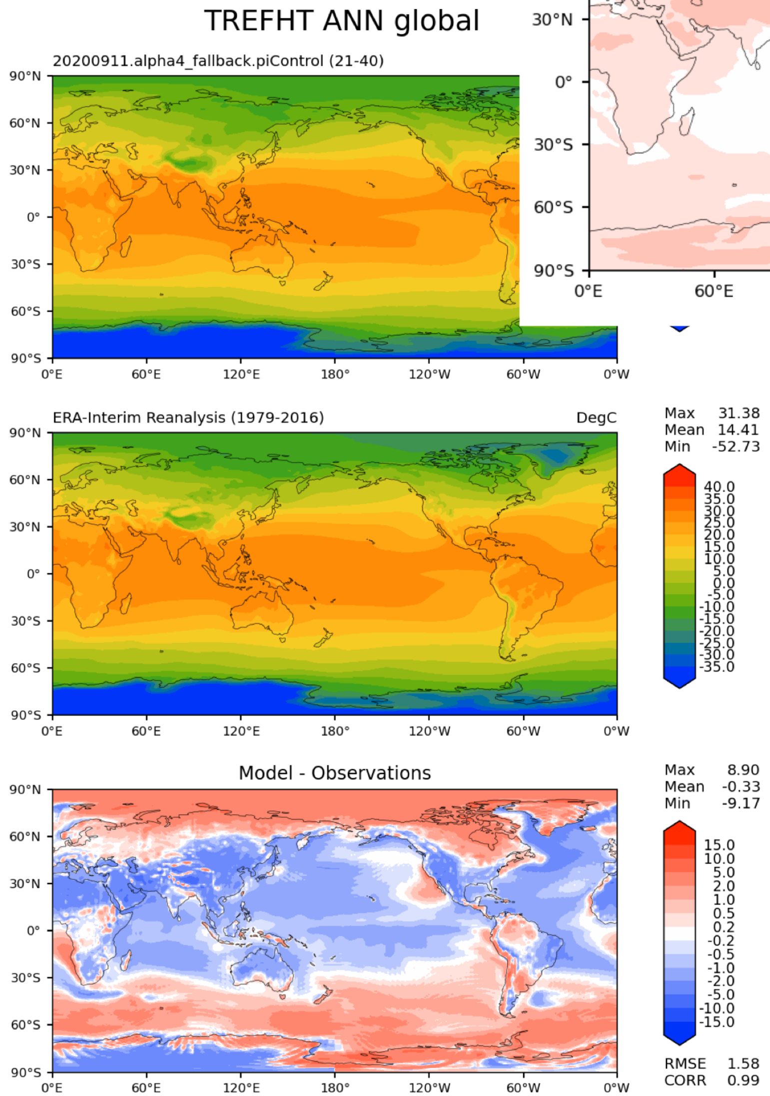
SAT is surface air temperature, a.k.a. reference height temperature

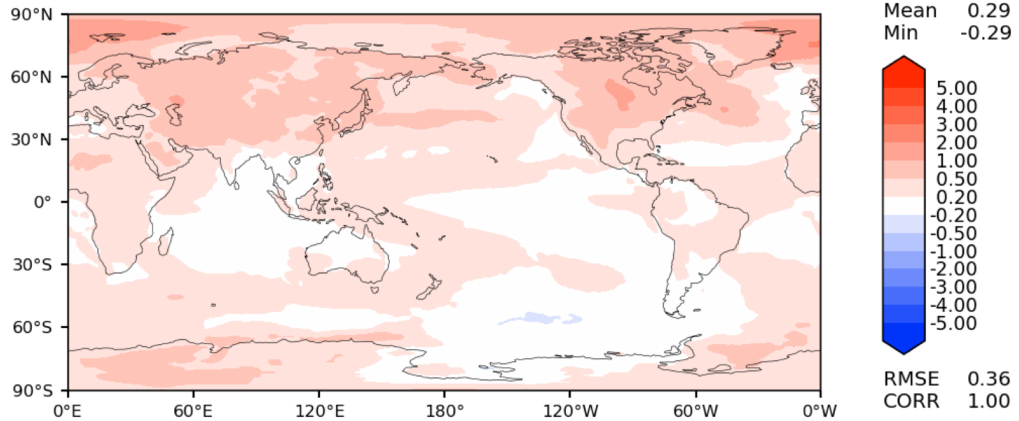


(Chen et al., submitted)

Scattering – Non-scattering







Further thoughts on ice cloud optics in the E3SM

E3SM: default (Mitchell) scheme

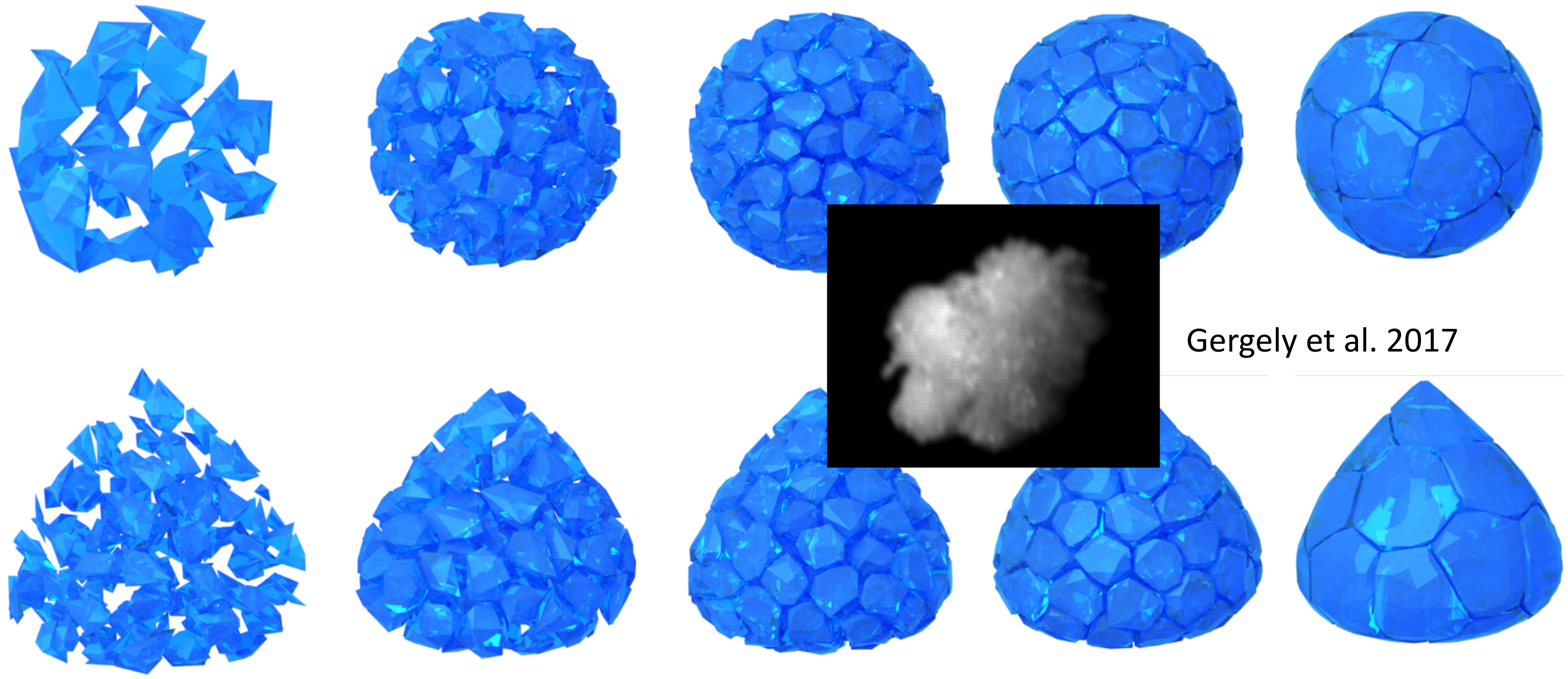
```
! Get relevant pbuf fields, and interpolate optical properties from
! the lookup tables.
call pbuf_get_field(pbuf, i_iciwp, iciwpth)
call pbuf_get_field(pbuf, i_dei,   dei)

call interpolate_ice_optics_lw(state%ncol,iciwpth, dei, abs_od)
```

```
dei_grid = rei_grid * rhoi/rhows * 2._r8
```

Rhoi (bulk density of ice)=500. (kg/m3) Reinser et al. (1998, QJRMS)
Rhows (bulk density of water solid)=917. (kg/m3)

Radiation scheme considers pure ice solid, i.e., not graupel, not snow

Examples: Graupel

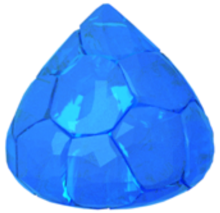


Gergely et al. 2017

(From TAMU team)

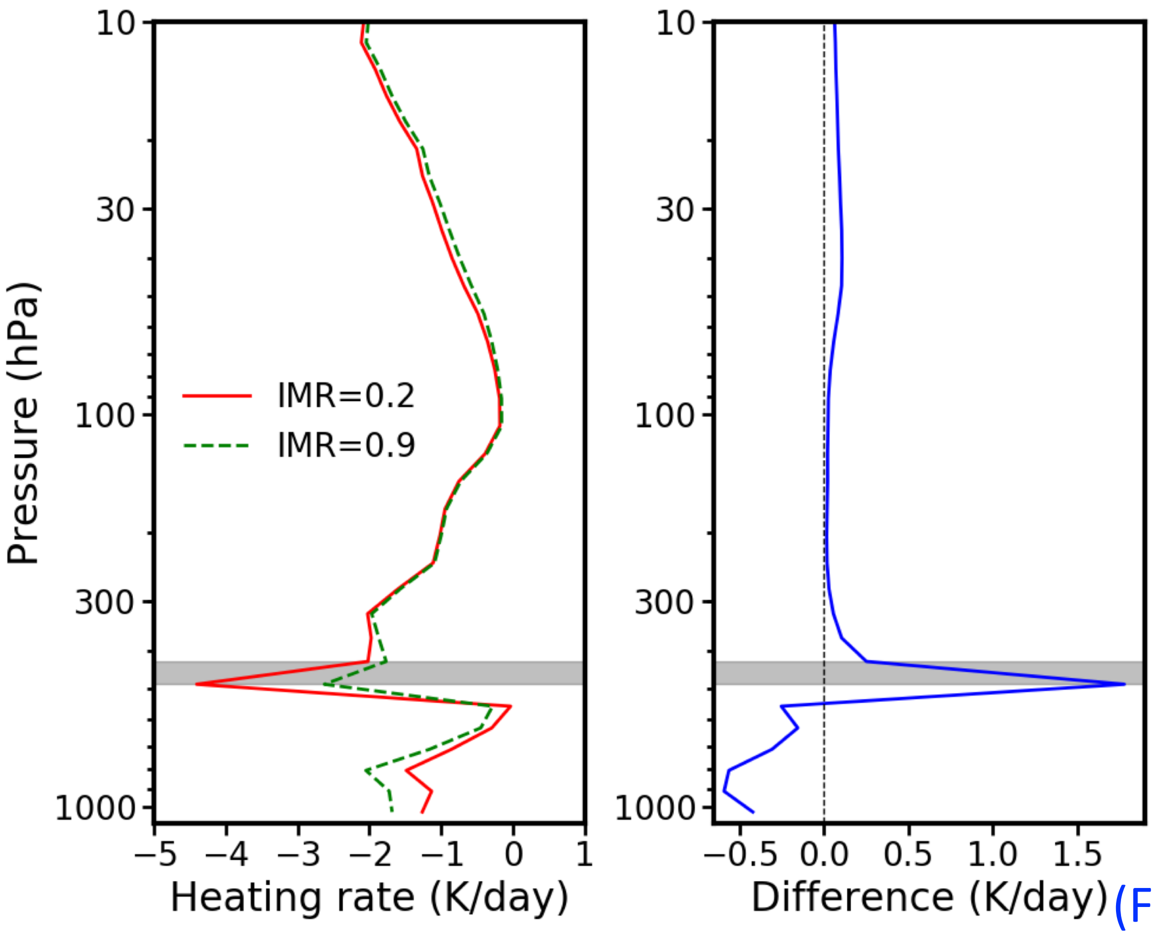
We can treat graupel, snow flakes, etc

- IMR=0.2
- D_m=17 mm



- IMR=0.9
- D_m=28 mm

LW heating rate



Cloud layer

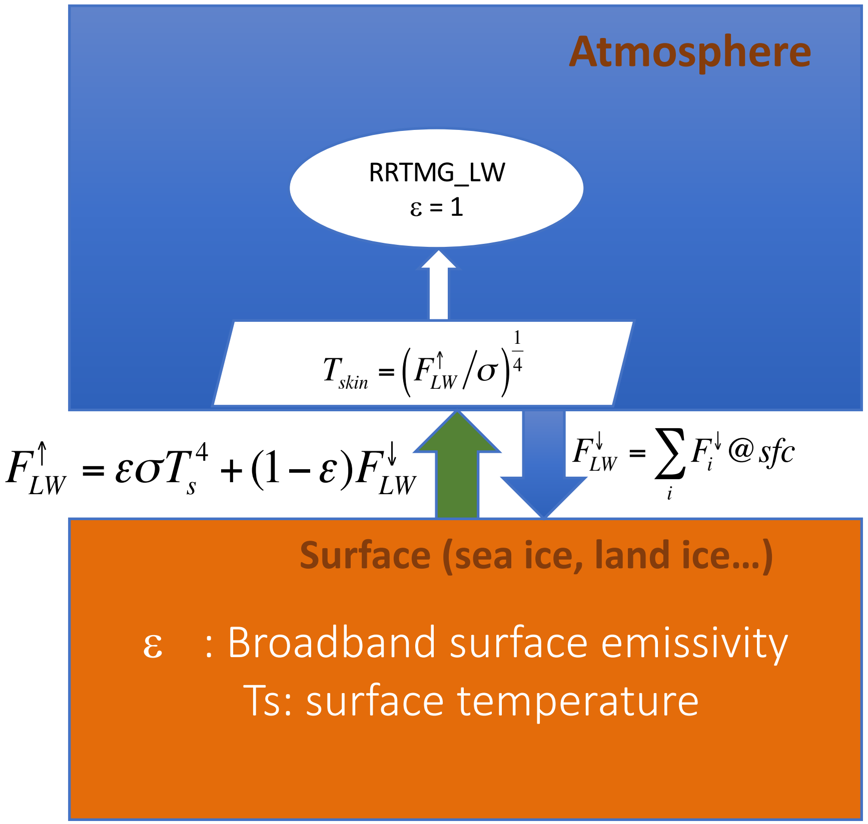
(From TAMU team)

RRTM heating rate simulations

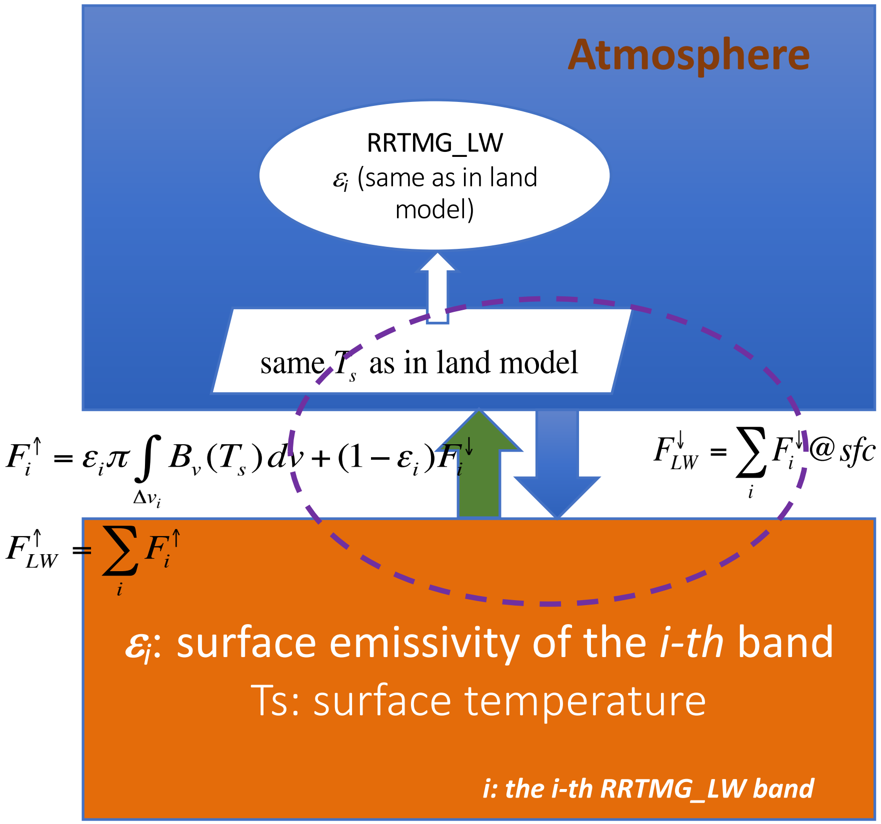
- Ice water path (IWP): 400 g/m^2;
- The graupel is taken as a cloud layer;
- 16-stream DISORT

Forward Looking ...

Current broadband coupling



Proposed **consistent spectral-band** coupling



Cloud optics
3-D RT

Snow impurity
(snow algae, black carbon, etc)

Conclusions and discussion

- The roles of LW ice cloud scattering in the E3SM simulation are thoroughly assessed
  - Locally, increase the LW CRE
  - Globally, increase the surface temperature, esp. in high latitude
- Together with surface emissivity, they are missing physics in current LW surface-radiative coupling in virtually all climate models.
  - Including them help exposing a myriad of compensating biases (for the right reasons)
- Ongoing work
  - Code optimization
  - Assessing fully coupled runs with both LW scattering and surface emissivity schemes on

Two poster presentations from the team members

- Effects of Spectrally Varying Cryospheric Surface Emissivity on Atmospheric Longwave Radiation by *Zach Wolff and Charles S. Zender* (JGR, under revision)
- Impact of cloud longwave scattering on radiative fluxes associated with the Madden-Julian Oscillation in the Indian Ocean and Maritime Continent by *Tong Ren, Ping Yang, et al.* (JGR, 2020)

References:

1. Chen, X. H., X. L. Huang, M. G. Flanner, Sensitivity of modeled far-IR radiation budgets in polar continents to treatments of snow surface and ice cloud radiative properties, *Geophys. Res. Letts.*, doi:10.1002/2014GL061216, 41(18), 6530-6537, 2014.
2. Kuo, C.-P., P. Yang, et al., Assessing the accuracy and efficiency of longwave radiative transfer models involving scattering effect with cloud optical property parameterizations, JQSRT, 240, 106683, 10.1016/j.jqsrt.2019.106683, 2020.
3. Chen et al., Seasonal Dependent Impact of Ice-Cloud Longwave Scattering on the Polar Climate, under revision.
4. Huang et al., 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.

Back-up slides

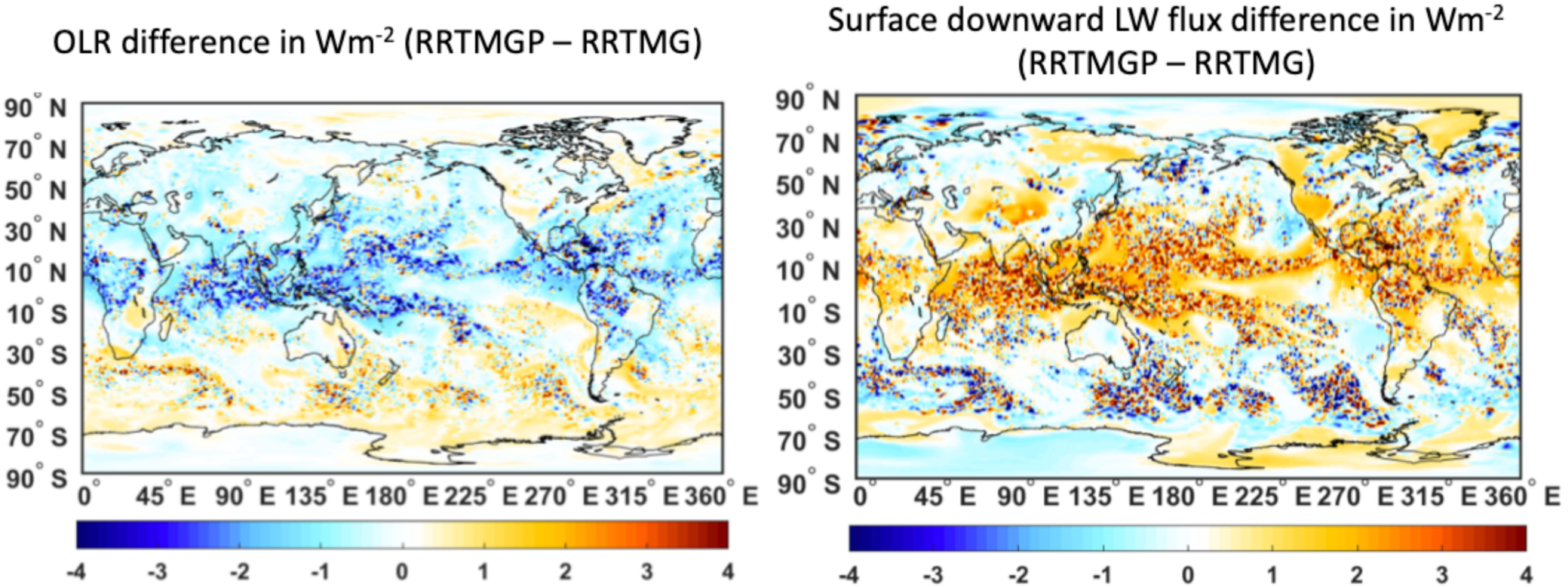


Figure 9. The longwave flux difference after one-time step when the E3SM v2 alpha version is interfaced with RRTMGP and RRTMG, respectively. Note that, due to the nature of Monte-Carlo Independent Column Approximation (MCICA), the flux difference for cloudy grids (i.e. ITCZ) can show certain degree of randomness. Nevertheless, persistence contrast between left and right panels is still recognizable.

Why both physical processes have been ignored before in model development?

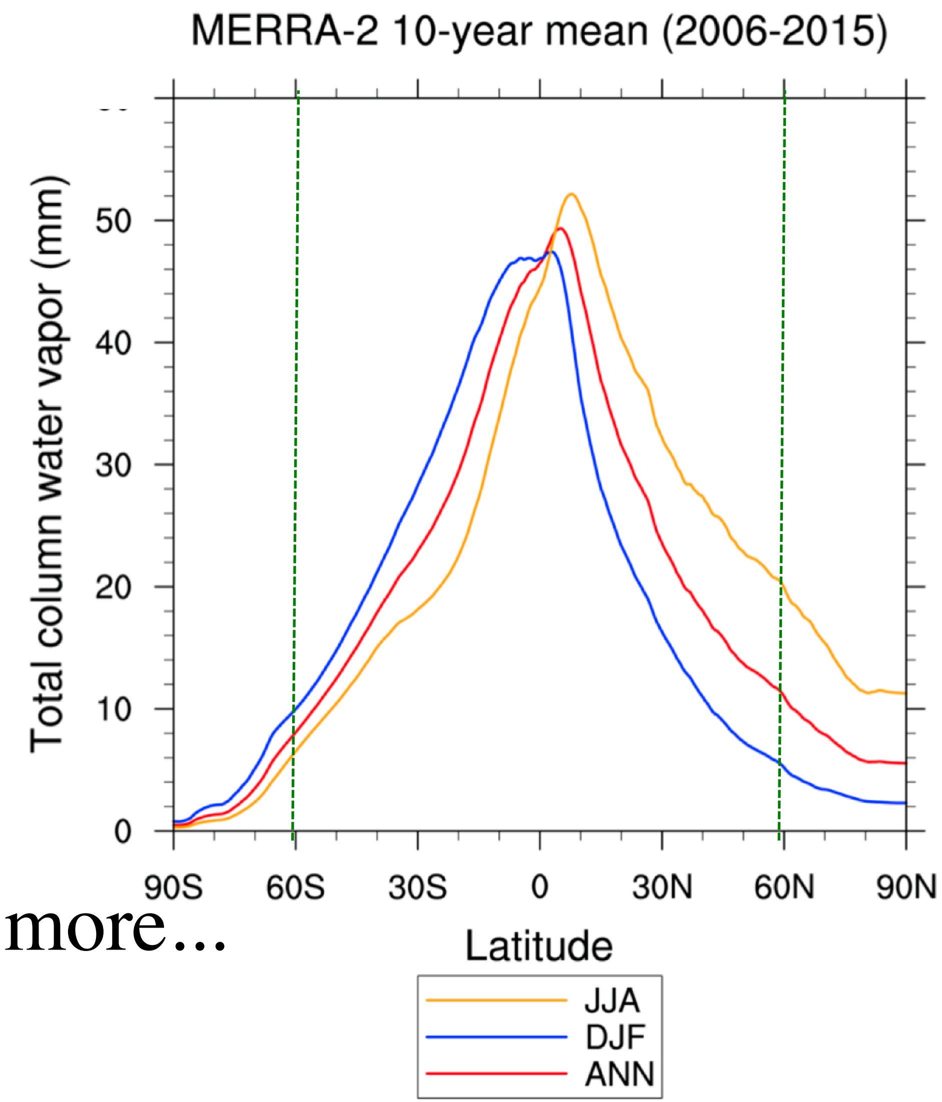
- Polar region is not a focus.
- The contrast of TCWV between polar vs. extra-polar regions

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

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

$$\tau_{H_2O} >> \tau_{cld}, \omega_{layer} \to 0$$

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



The spectral parameters N_0 and λ are derived from the predicted N'' and q'' and specified μ:

$$\lambda = \left[\frac{\pi\rho N''\Gamma(\mu+4)}{6q''\Gamma(\mu+1)}\right]^{(1/3)} \tag{4.152}$$

$$N_0 = \frac{N''\lambda^{\mu+1}}{\Gamma(\mu+1)} \tag{4.153}$$

where Γ is the Euler gamma function. Note that 4.152 and 4.153 assume spherical cloud particles with bulk density ρ = 1000 kg m^{-3} for droplets and ρ= 500 kg m^{-3} for cloud ice following Reisner et al. [1998].

The effective size for cloud ice needed by the radiative transfer scheme is obtained directly by dividing the third and second moments of the size distribution given by 4.150 and accounting for differenceds in cloud ice density and that of pure ice. After rearranging terms, this yields

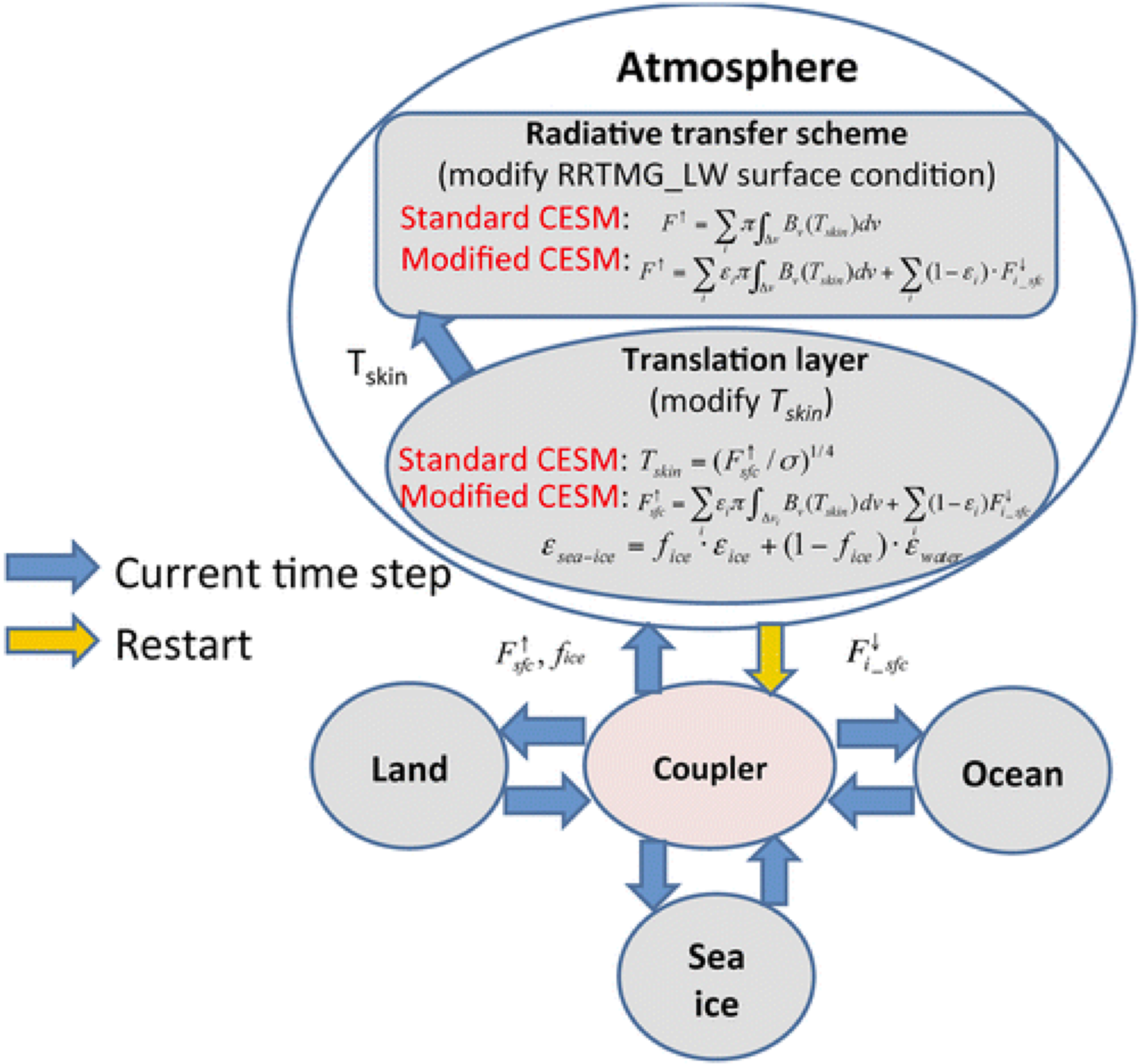
$$d_ei = \frac{3\rho}{\lambda\rho_i} \tag{4.154}$$

where ρ_i = 917 kg m-2 is the bulk density of pure ice. Note that optical properties for cloud droplets are calculated using a lookup table from the N_0 and λ parameters. The droplet effective radius, which is used for output purposes only, is given by

$$r_ec = \frac{\Gamma(\mu+4)}{2\lambda\Gamma(\mu+3)} \tag{4.155}$$

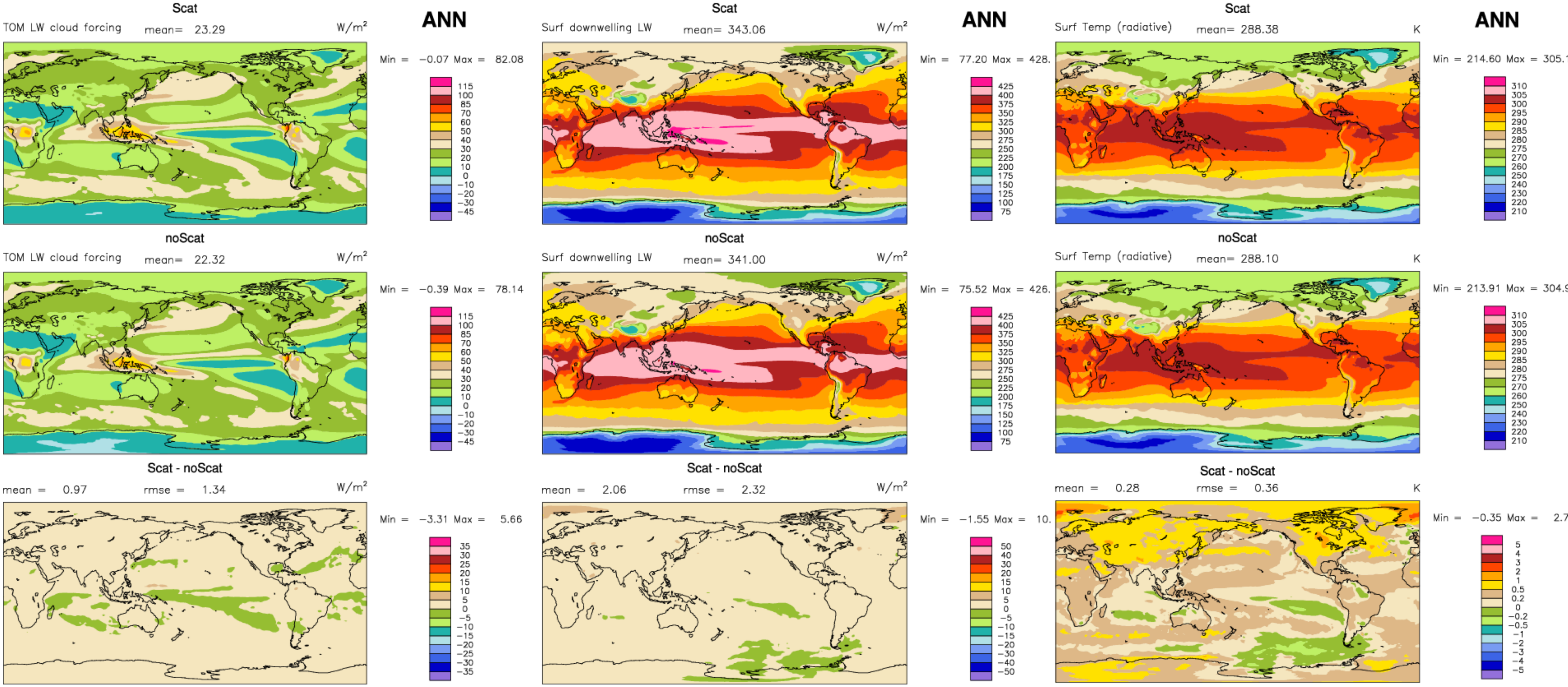
Neale et al., 2010, Description of the NCAR Community Atmosphere Model (CAM 5.0), NCAR Tech. Note NCAR/TN-486+STR, p129

Surface spectral emissivity alone



To modify surface modules requires a lot of additional work

(Huang et al., 2018)



ANN
Scat
TOM LW cloud forcing mean= 23.29 W/m²
Min = −0.07 Max = 82.08
115 100 85 70 60 50 40 30 20 10 0 −10 −20 −30 −45
noScat
TOM LW cloud forcing mean= 22.32 W/m²
Min = −0.39 Max = 78.14
115 100 85 70 60 50 40 30 20 10 0 −10 −20 −30 −45
Scat - noScat
mean = 0.97 rmse = 1.34 W/m²
Min = −3.31 Max = 5.66
35 30 25 20 15 10 5 0 −5 −10 −15 −20 −25 −30 −35
ANN
Scat
Surf downwelling LW mean= 343.06 W/m²
Min = 77.20 Max = 428.
425 400 375 350 325 300 275 250 225 200 175 150 125 100 75
noScat
Surf downwelling LW mean= 341.00 W/m²
Min = 75.52 Max = 426.
425 400 375 350 325 300 275 250 225 200 175 150 125 100 75
Scat - noScat
mean = 2.06 rmse = 2.32 W/m²
Min = −1.55 Max = 10.
50 40 30 20 15 10 5 0 −5 −10 −15 −20 −30 −40 −50
ANN
Scat
Surf Temp (radiative) mean= 288.38 K
Min = 214.60 Max = 305.
310 305 300 295 290 285 280 275 270 260 250 240 230 220 210
noScat
Surf Temp (radiative) mean= 288.10 K
Min = 213.91 Max = 304.
310 305 300 295 290 285 280 275 270 260 250 240 230 220 210
Scat - noScat
mean = 0.28 rmse = 0.36 K
Min = −0.35 Max = 2.7
5 4 3 2 1 0.5 0.2 0 −0.2 −0.5 −1 −2 −3 −4 −5

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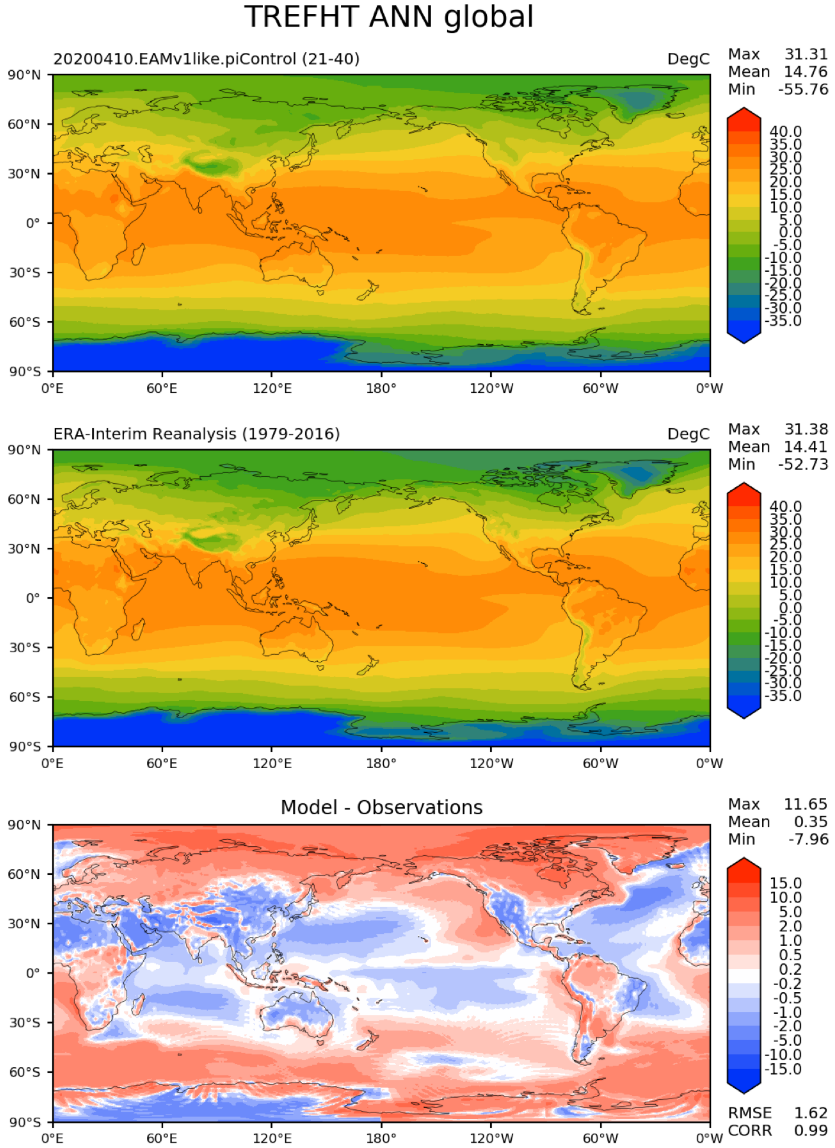
ne30pg2_r05_oECv3_ICG.compy



Scattering – Non-scattering