Treatment of surface spectral emissivity: towards a more faithful longwave radiative coupling in the CESM

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What to get at the end of this lecture?

- In addition to dynamical coupling, atmosphere and land/ocean/ice are radiatively coupled together.
- Spectral dependence of such radiative coupling needs to be represented.
  - Why? Because the atmosphere absorption and emission is featured with strong spectral dependence.
- Above two issues can be manifested in the polar regions much more than in the rest of globe.

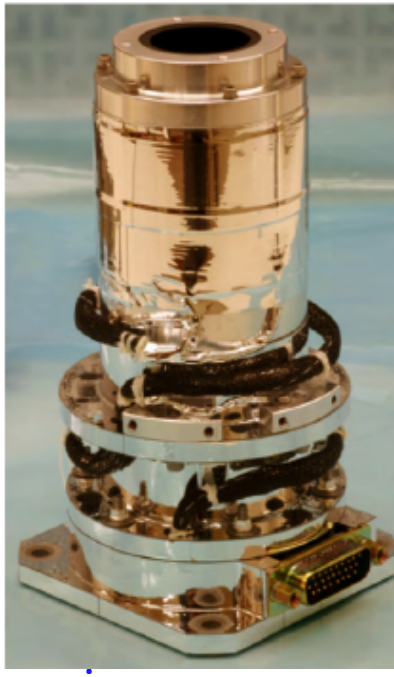
Key reference: Huang, X.L., et al., Improved representation of surface spectral emissivity in a global climate model and its impact on simulated climate, J. Climate, 31(9), 3711-3727, doi:10.1175/JCLI-D-17-0125, 2018.

Roadmap

- Atmospheric Radiative Transfer 101
- Surface emissivity and how it has been treated in the model
  - When does the traditional wisdom break down?
- How to incorporate realistic surface emissivity into the CESM (a bit more detailed illustration)
- Understand the simulations
- Outlooks and perspectives
  - What can be done the next?

Alert: there will be some **simple math** to help making the arguments

Radiative transfer: relevant background knowledge



- First get concepts/jargons clearly defined
- Blackbody: an object absorbs **all** the incident radiation at **all** frequencies
  - Idealized definition
  - Planck Law: describes the emission of blackbody
  - In reality
    - An object can be deemed as blackbody at certain frequencies, but not at other frequencies
- It's a "reference" when we talk about absorption and emission and when we make radiometric measurements.

Radiative transfer: relevant background knowledge

- Broadband flux (F)
  - One type of energy flux
  - Energy budget, radiative forcing/feedback

$$F = \frac{dE}{dAdt},\ unit:\ \frac{J}{s \cdot m^2} = \frac{W}{m^2}$$

- Spectral flux & band flux (F_v)
  - Integrand of broadband flux
  - Band flux computed in the radiation scheme then sum up

$$F_v = \frac{dE}{dAdtdv},\ unit:\ \frac{W}{m^2 \cdot cm^{-1}} (cm^{-1} \text{ is a unit for freq.})$$

$$F(\Delta v) = \int_{\Delta v} F_v\, dv; F = \sum_i F(\Delta v_i)$$

- Spectral radiance (I_v)
  - Directly observed (ground/ space)
  - Not computed in the climate model

$$I_v = \frac{dE_v}{\cos\theta d\Omega \cdot dv \cdot dA \cdot dt} \quad unit: Wm^{-2}sr^{-1}/cm^{-1}$$

$$F_v = \int d\phi \int I_v \cos\theta \sin\theta\, d\theta d\theta \ (d\Omega = \sin\theta d\theta d\phi)$$

$$\text{A blackbody}, I_v = B_v(T); F_v = \pi B_v(T)$$

Note: spectral flux can be defined with respect to wavelength as well ($c/\lambda = v$)

Radiative transfer: relevant background knowledge

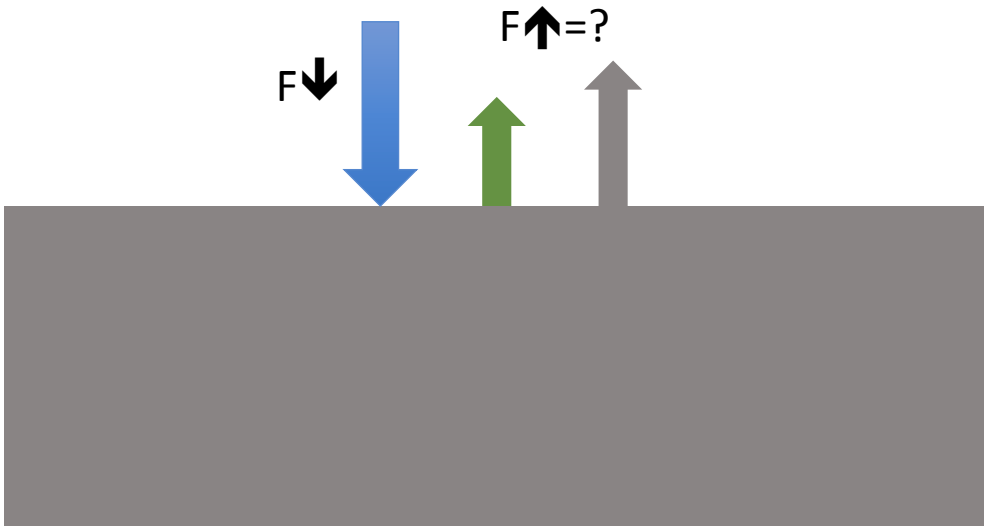
- A few key concepts

Absorptivity $A(v)=\frac{F_{abs}(v)}{F_{incident}(v)}$

Emissivity $\varepsilon(\mathrm{v})=\frac{F_{emis}(v)}{\pi B_v(T)}$; $B_v(T)$ Radiance of blackbody radiation at temperature T of the object

Kirchhoff's Law $A(v)=\varepsilon(v)$

Thus, for a semi-infinite surface, r(v)=1-A(v)=1-ε(v); reflectivity is linked to emissivity.



F↑=Emitted + Reflected

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

$F^{\uparrow}=\varepsilon\sigma T^4+(1-\varepsilon)F^{\downarrow}$ (Broadband version)

Radiative transfer: relevant background knowledge

$\tau(\nu)=0$; z=+∞ (TOA)

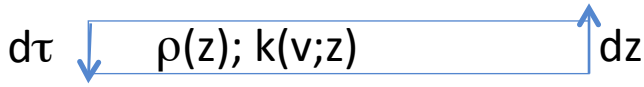
- Optical depth

$$d\tau(\nu) = -\rho(z) \quad k(\nu;z) \quad dz$$

Change in optical depth

Density of the **active** substance

Extinction coefficient



$$\text{Transmissitivty } \mathcal{T}(\nu) = \exp\left[-\tau(\nu)\right]$$

$\tau_s(\nu)>0$; z=0 (surface)

$$\text{Without scattering, } A(\nu)=1-\mathcal{T}(\nu)$$

- τ can be used as a vertical coordinate

- in LW: stronger absorption implies stronger emission in the atmosphere
- Strong non-linearity rises from exp[-τ(ν)]

$\tau(\nu)\sim\rho$	$\mathcal{T}(\nu)$
0.1	0.90
1	0.37
10	0.000045

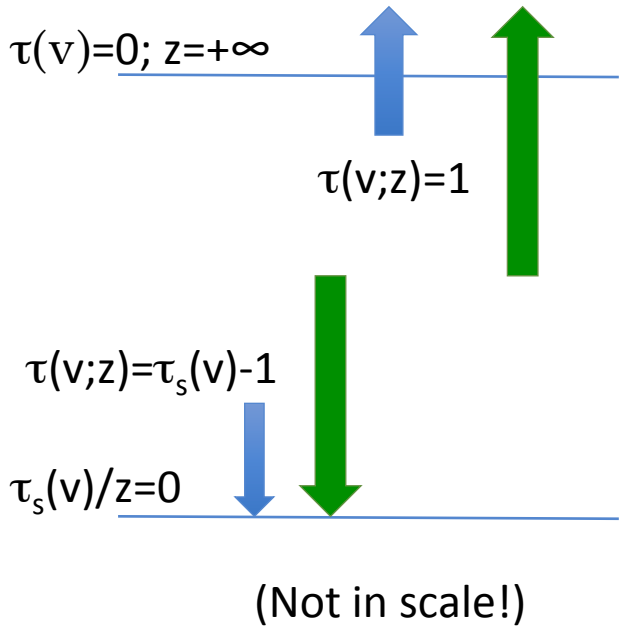
Radiative transfer: relevant background knowledge

- **How deep (high) you can look down (up) ?**
- **Which altitude contribute the most to the flux at any given z_0,**

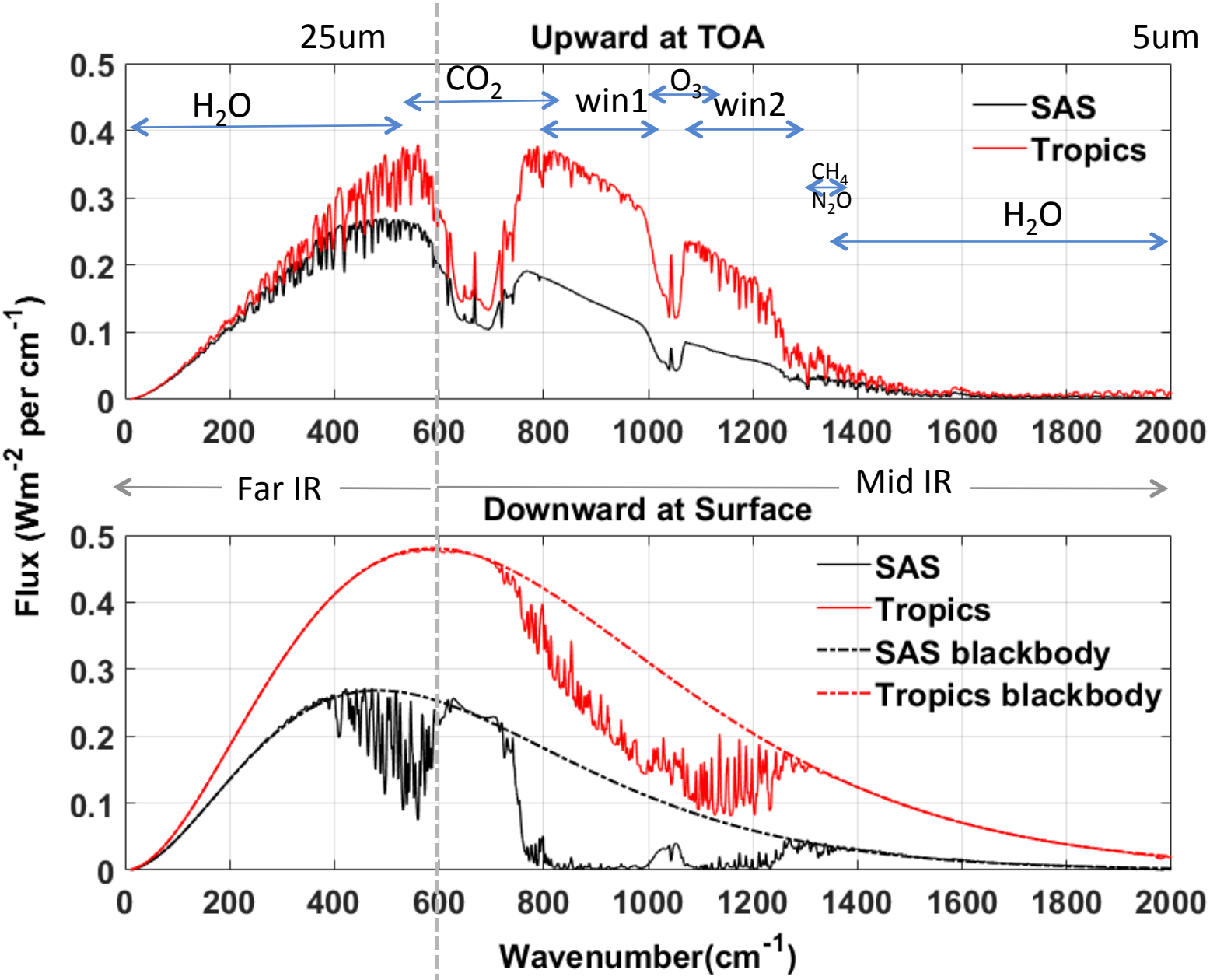
Rule of thumb: $|d\tau| \sim 1$

$$d\tau(v) = -\rho(z)k(v;z)dz$$

Quiz: what if ρ is reduced by a factor of 10 while nothing else changes?

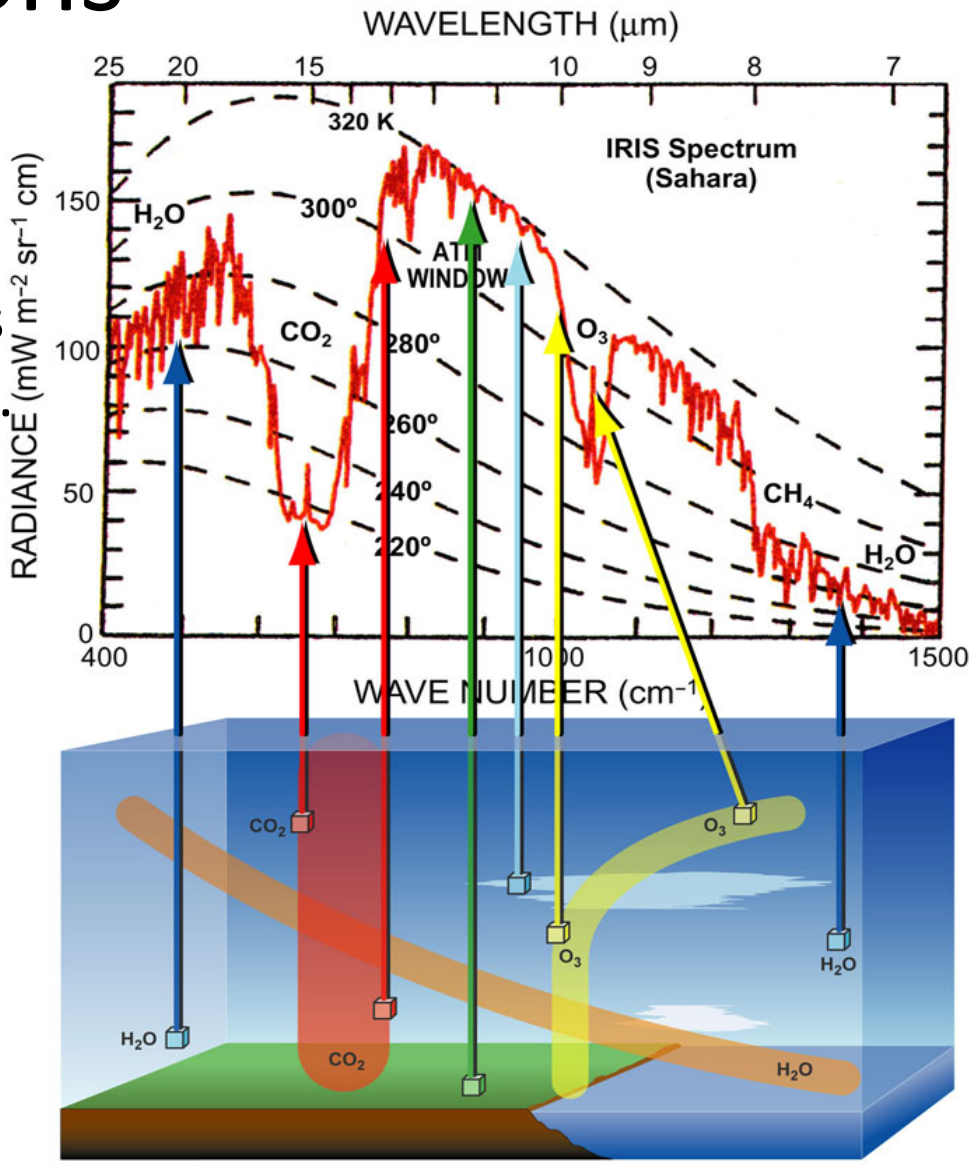


Synthetic clear-sky spectral flux



Implications

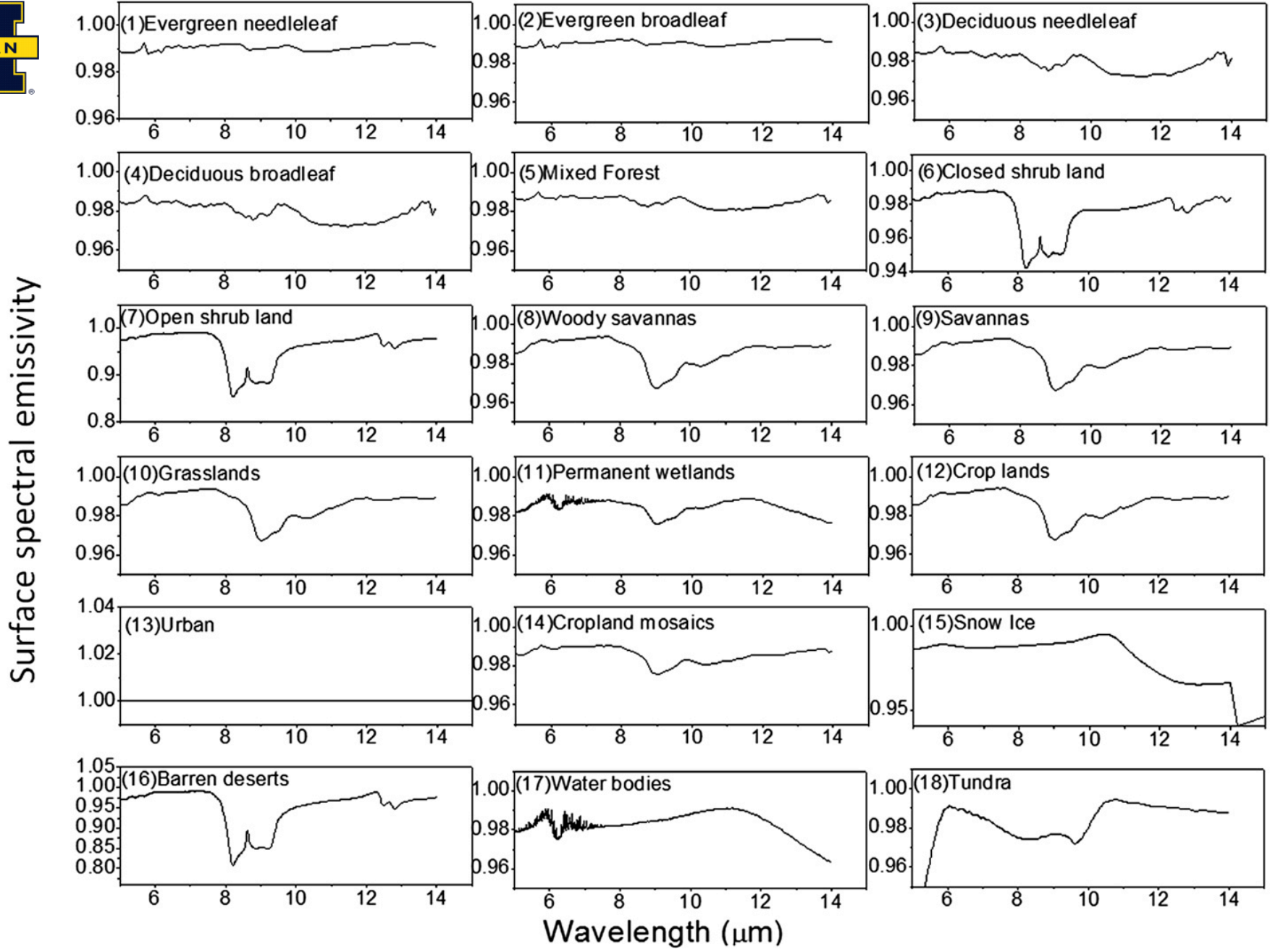
- Atmosphere absorption and emission are strongly varying with frequency.
- Thus, each absorption band has to be parameterized separately. No broadband approach.
- Therefore, the lower B.C. for atmospheric RT, F↑@sfc, should have correct spectral partitioning as well. This is particularly important for LW.
  - Think about two extreme cases
    - All in H_2O band
    - All in window band



(Courtesy of John Dykema)

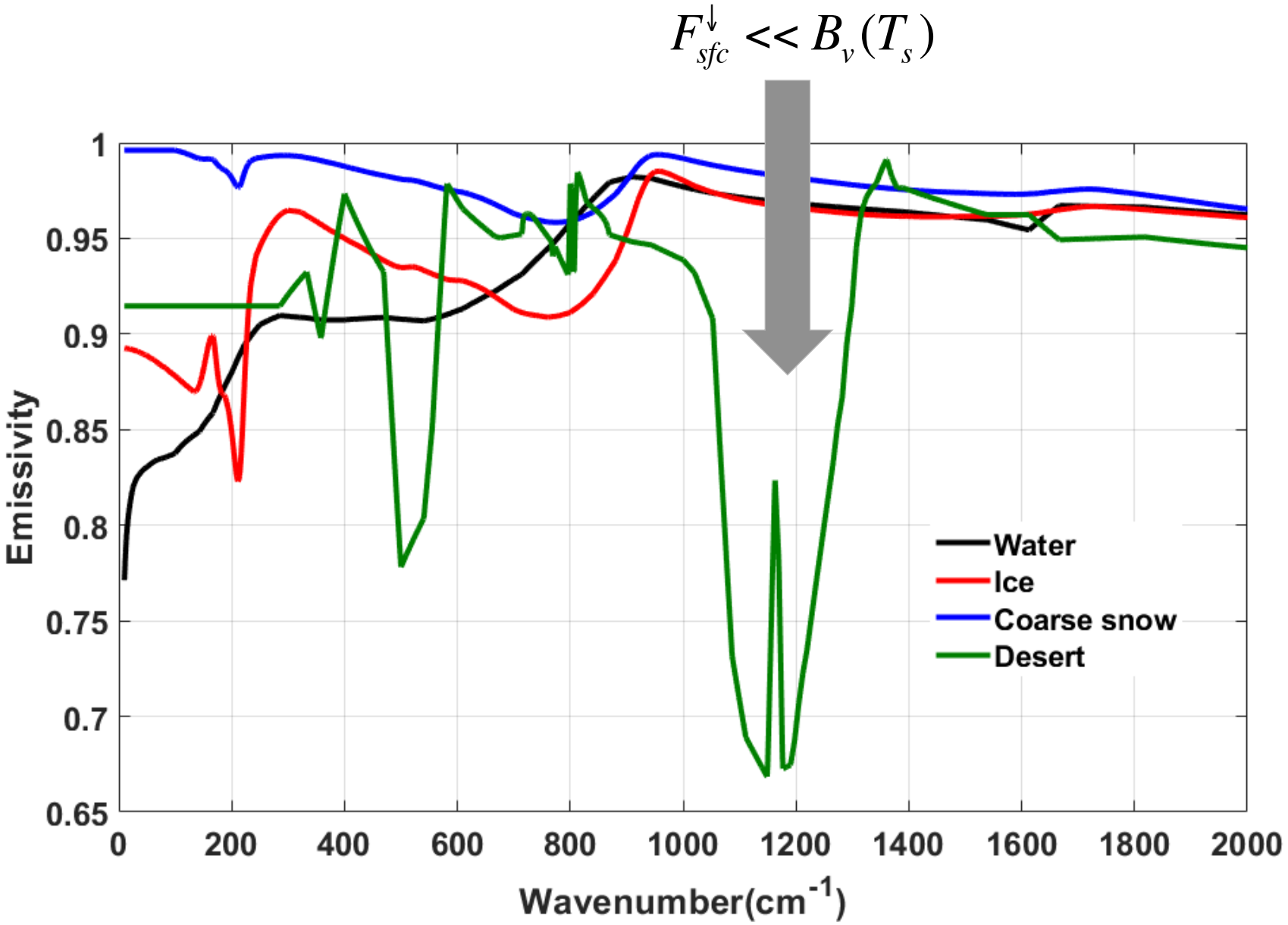
A few facts of surface spectral emissivity

- Surface emissivity $\varepsilon_v(\theta) = \frac{I(\theta)^{\uparrow}_{s_v}}{B_v(T_s)}$; $\varepsilon_v = \frac{F_{v\_emis}}{\pi B_v(T_s)}$ (flux form)
  - A function of frequency and solid angle
- Routine retrieval products from hyperspectral soundings (e.g. AIRS, IASI, CrIS) but only in mid-IR
- Also measureable in-situ or in the lab (ASTER Spectral Library)
- But **Few** measurements in the far-IR (<650cm^{-1})
  - Traditional thoughts:
    - Far-IR water vapor absorption is strong
    - **Atmosphere is opaque**
    - Surface emissivity is little of important



From ASTER Spectral Library (Chen et al. 2013)

No far-IR (>15μm) measurements



Far-IR spectral emissivity is calculated using suitable compact medium radiative transfer model.

(Huang et al., 2016, JAS)
(Huang et al., 2018, J Climate)

Next …

- How F↑@sfc has been represented in current models?
- What's the traditional wisdom behind it?
- When the traditional wisdom can break down…
- If it breaks down, how large the impact could be?

Atmosphere module

- Lower B.C. for radiation scheme is $F^{\uparrow}_{LW\_SFC}(\Delta\nu)$

$$F^{\uparrow}_{LW\_sfc} = \sigma T^4_{skin}$$

$$\varepsilon\sigma T^4_{ground} + (1-\varepsilon)F^{\downarrow}_{sfc} = F^{\uparrow}_{LW\_sfc}$$

- The input to radiation scheme is not lower B.C., but $\mathbf{T_{skin}}$
- **All GCMs always assume blackbody (except GISS model)**

Coupling: $F^{\uparrow}_{LW\_SFC}$

Emission **Reflection**

An example: CLM in the CESM

- 0.97 for snow and nonurban ground
- 0.96 for urban ground

Surface modules

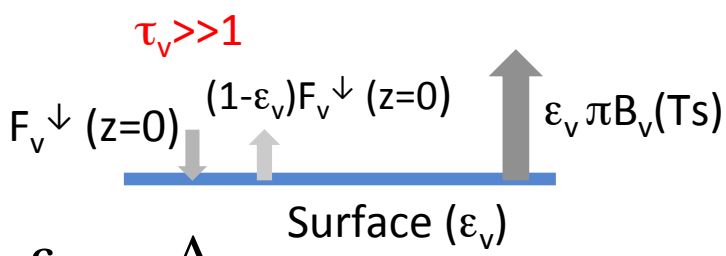
- Some module assumes blackbody (ε=1)
- Some assumes graybody (ε<1)
- Either way, ε does not vary from band to band

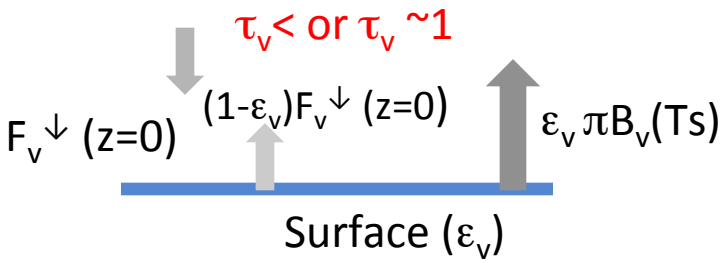
Issues: 1. Broadband flux is passed through correctly. But inconsistent in the spectral decomposition. Right for broadband, but could be wrong each spectral band.

2. This can be an issue, because atmospheric absorption and emission is VERY spectrally dependent. When a wrong lower B.C. is provided ……

$$\varepsilon_v = \frac{F_{s_v}^{\uparrow}}{\pi B_v(T_s)}$$

Models: what's the traditional wisdom to assume BB in AGCM?





$$\varepsilon_v = A_v$$

$$r_v = 1 - A_v = 1 - \varepsilon_v$$

Upward flux at surface

$$F^{\uparrow}(z=0) = \varepsilon_v \pi B_v(T_s) + (1-\varepsilon_v) F_v^{\downarrow}(z=0)$$

$$\text{if } \varepsilon_v \sim 1 \text{ or } F_v^{\downarrow}(z=0) \approx \pi B_v(T_s) \text{ (e.g. } H_2O \text{ and } CO_2 \text{ band)}$$

$$F^{\uparrow}(z=0) \cong \pi B_v(T_s)$$

- Chen et al., 2014, GRL, doi: 10.1002/2014GL061216

Where does this wisdom break down?

1. **IR window region (Chen et al., 2019)**
2. **High altitude/High latitude (Chen et al., 2014; where TCWV ~0.1 or less than mid-latitude)**

Incorporate surface spectral emissivity into the CESM v1.1.1

ε_i: emissivity in each RRTMG_LW band

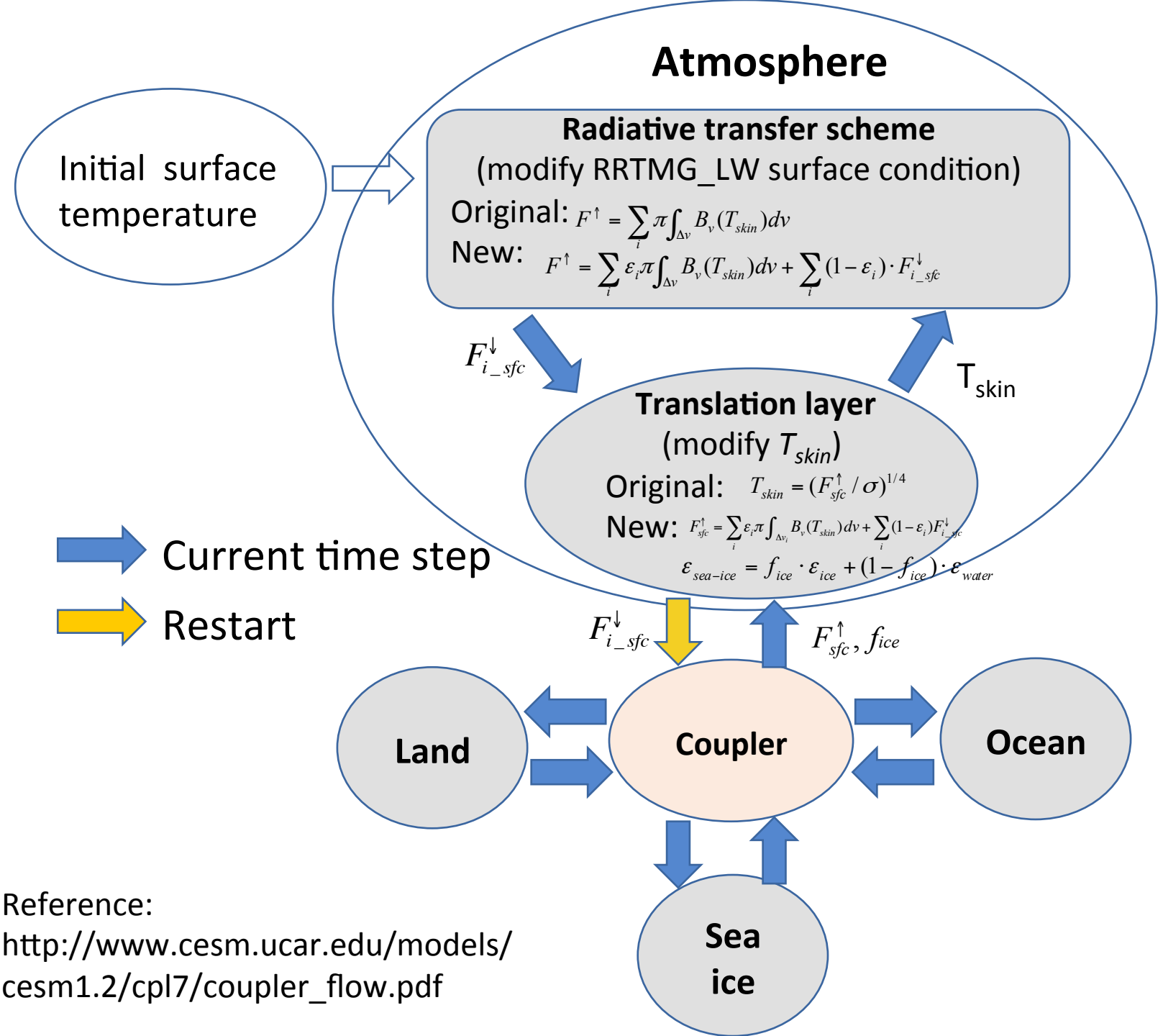
$$F_{LW}^{\uparrow} = \sum_i \varepsilon_i \pi \int_{\Delta v_i} B_v(T_{skin})\,dv + \sum_i (1-\varepsilon_i) F_{i\_sfc}^{\downarrow}$$

From surface modules

From CAM

Solve for T_{skin}

- This treatment ensures $F^{\uparrow}_{LW}$ being the same across different modules.



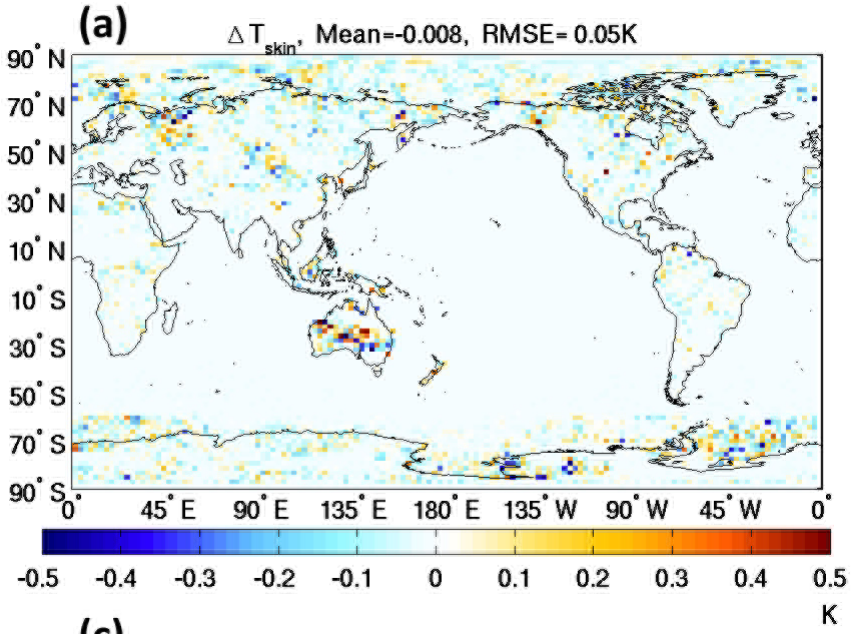
Reference:
http://www.cesm.ucar.edu/models/cesm1.2/cpl7/coupler_flow.pdf

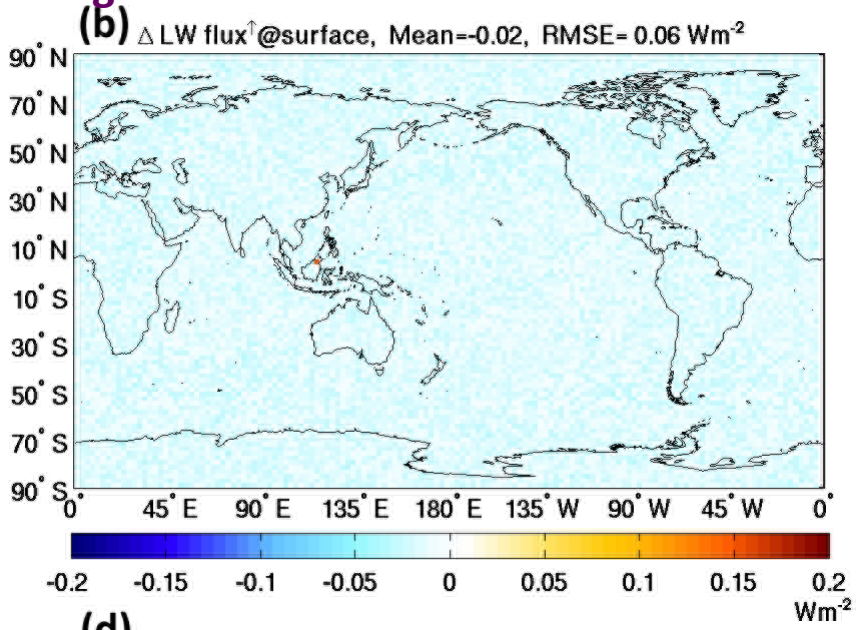
How could we know that we get it right?

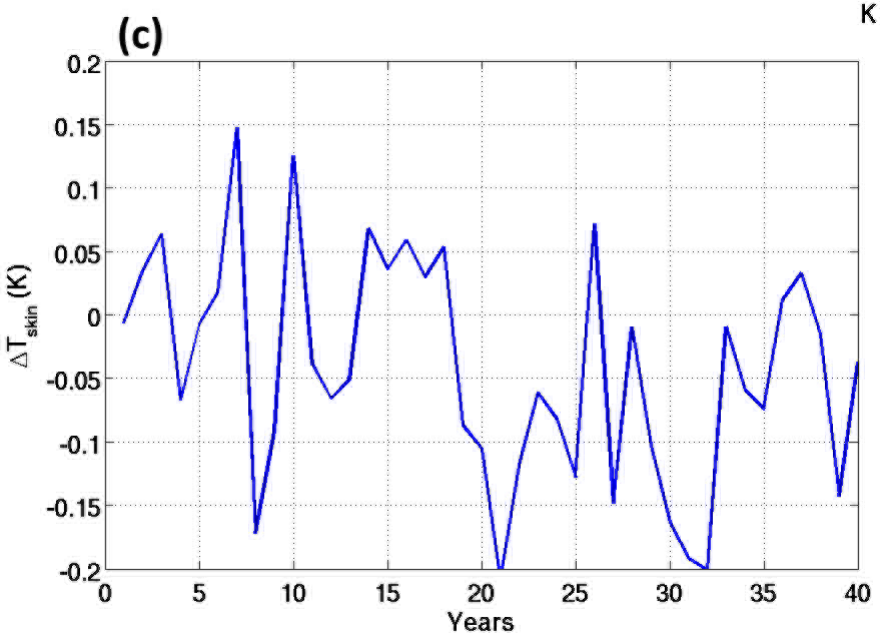
- A sanity check: if we set ε_i =1, the simulation should be the same as the standard CESM simulation (up to numerical errors in solving the equation above)

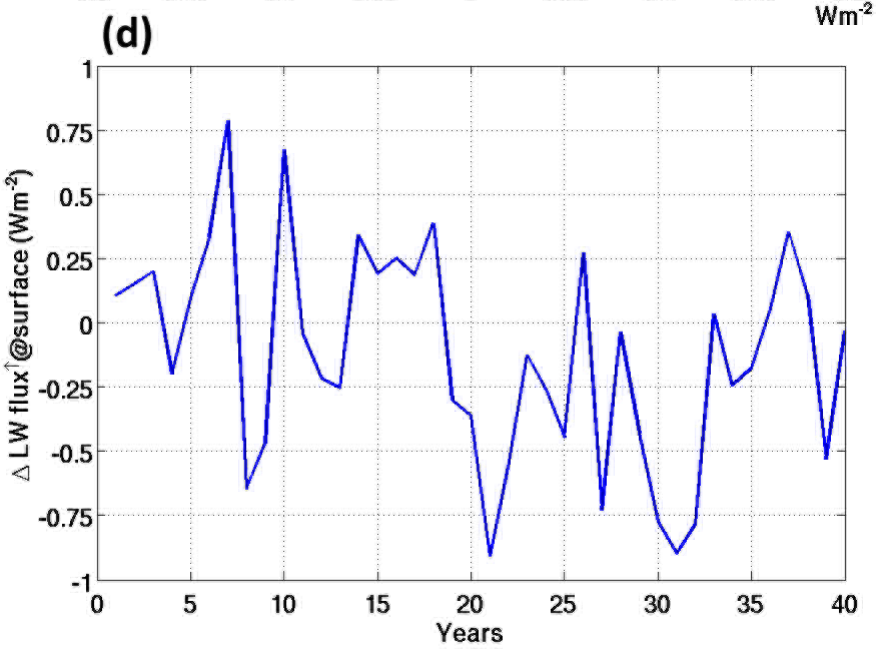
Differences between ε_i=1 run and standard CESM run

After 3 hours of integration



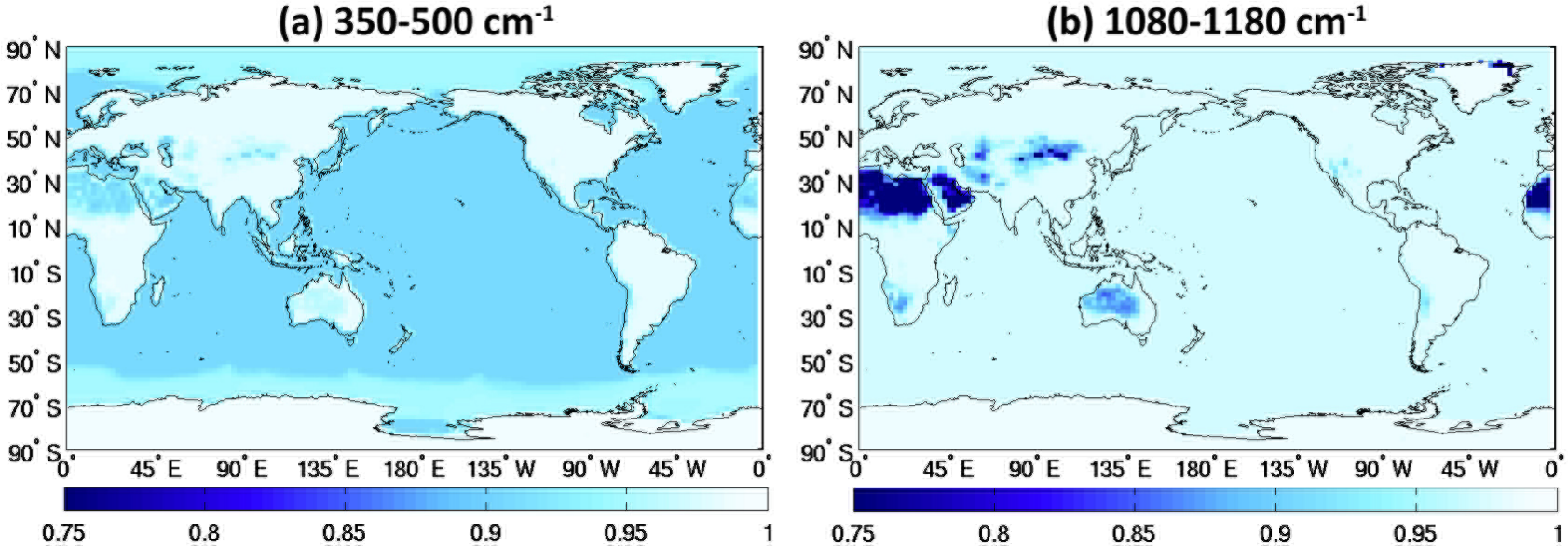




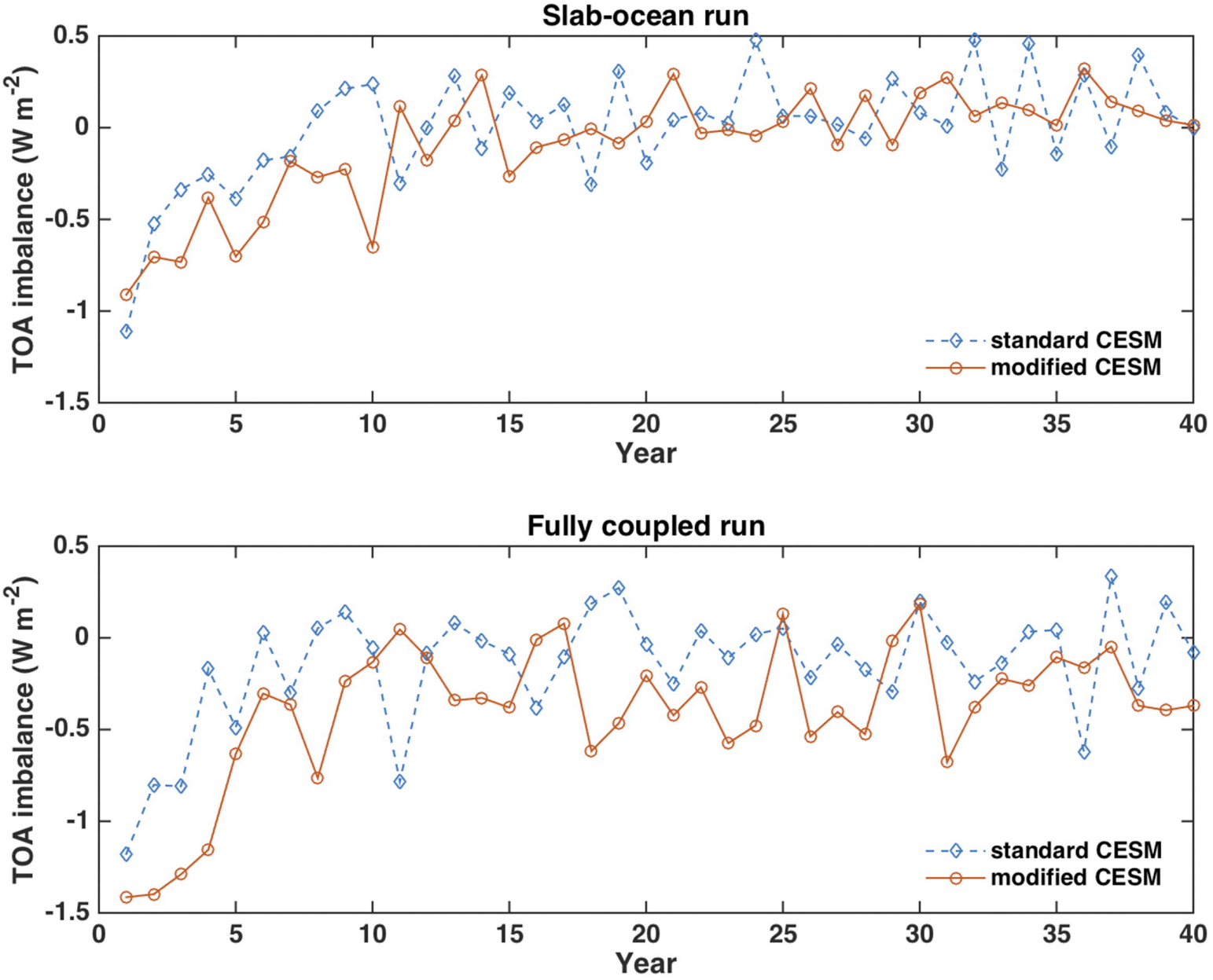


Simulation set-up

- Land surface spectral emissivity prescribed for each calendar month.
- Spectral emissivity over oceans is prognostic, weighting sum of $\varepsilon_{\text{water}}$ and ε_{ice} .
- Slab-ocean and fully-coupled run both used. 30-year output analyzed for each.

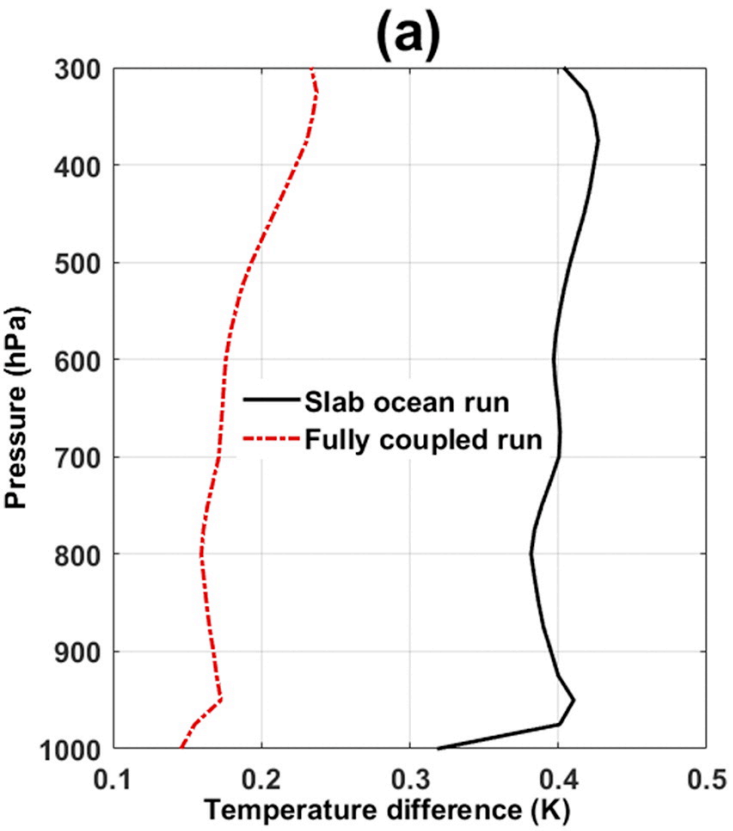


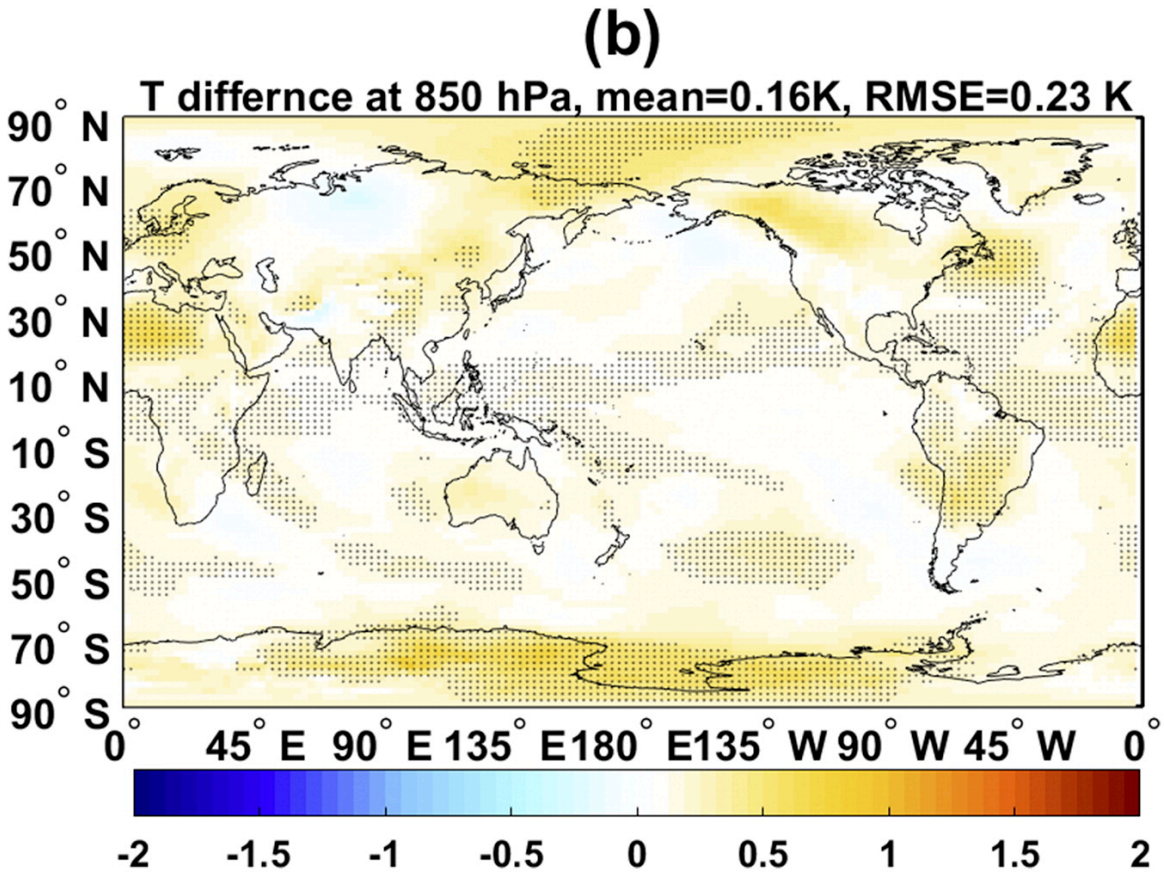
Another sanity check: TOA imbalance/No need of “retune” of the model



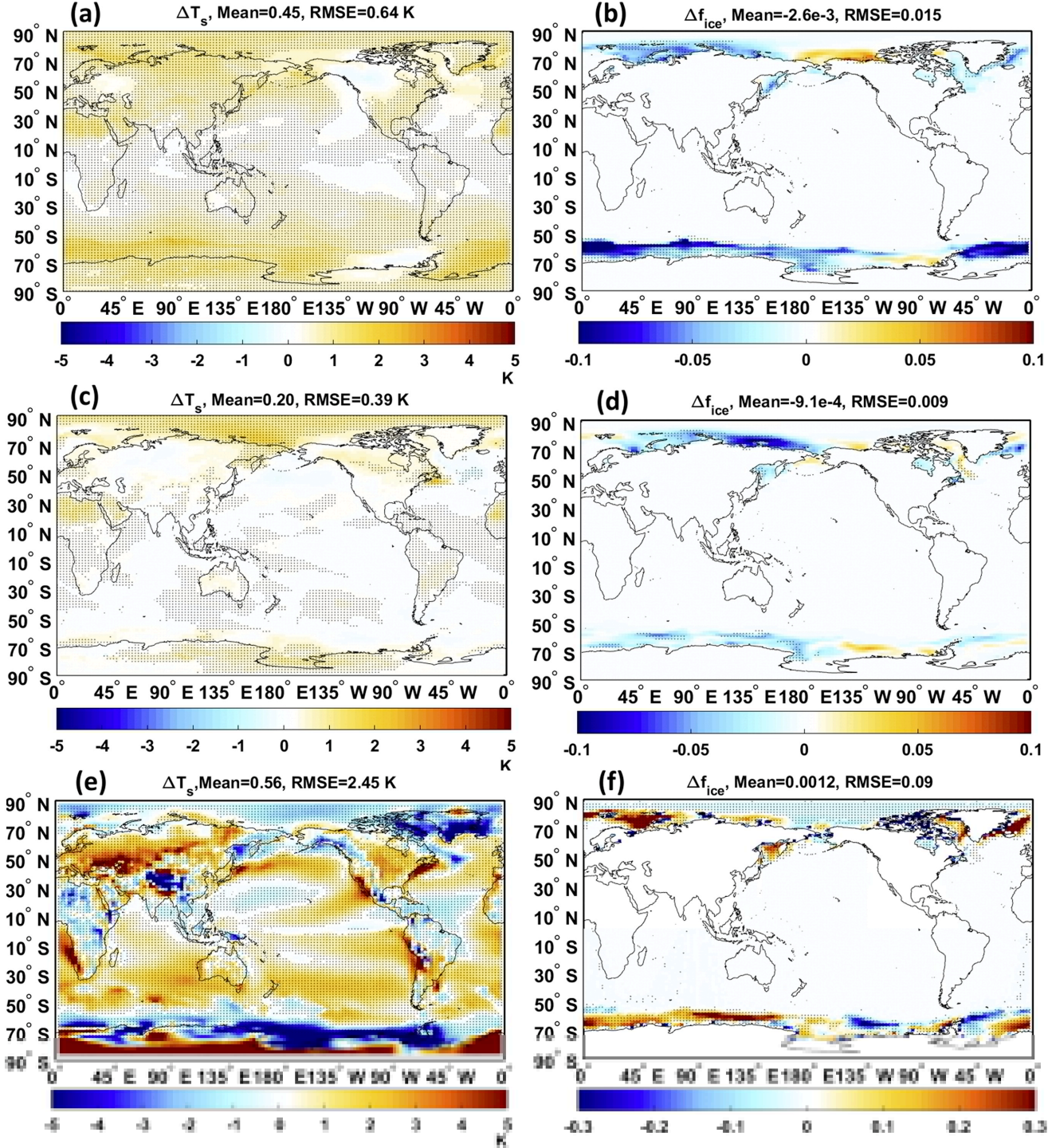
(Huang et al., 2018)

Global-mean





(Huang et al., 2018)



30-year average

Slab Ocean run
Modified - Control

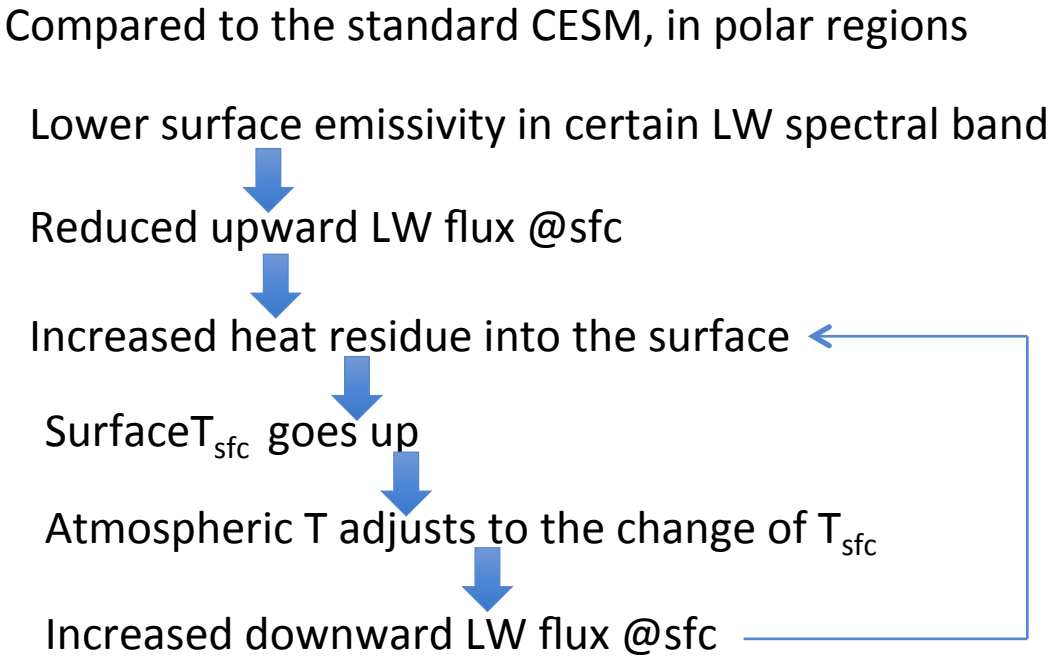
Fully-coupled run
Modified - Control

Control − Obs climatology

All CESM1.1.1 results
(Huang et al., 2018)

Understand the simulations (based on CESM 1.1.1)

Compared to the standard CESM, in polar regions



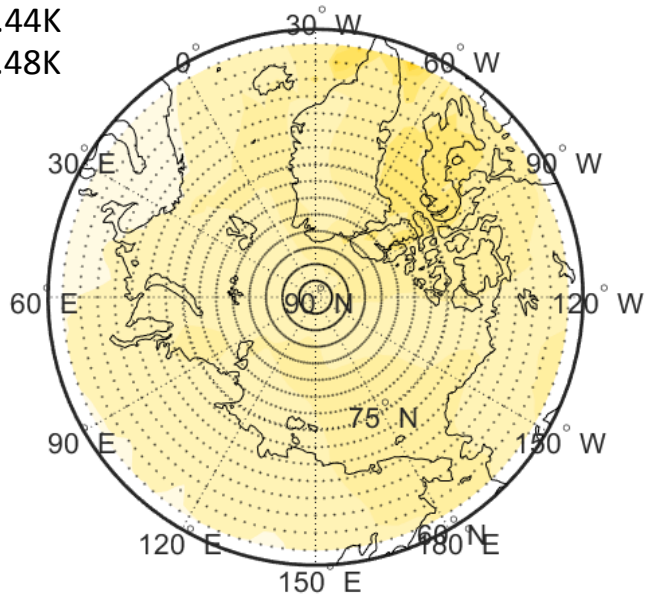
At polar region

- Surface energy rebalance is achieved primarily by upward and downward LW offset
- **Note that** this might not be the case in other regions (e.g. Sahara desert; Chen et al., 2019, J. Climate)
- Globally, LW upward/LW downward/latent heat flux are leading three terms for changes.

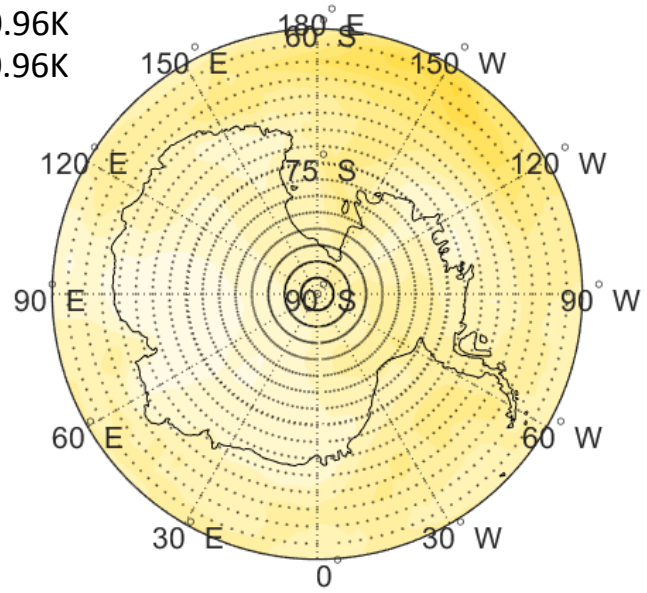
Surface air temp. difference (K); CESM 2.1.1; slab ocean; 6-35-year mean

Modified – Standard

Mean=1.44K
RMSE=1.48K

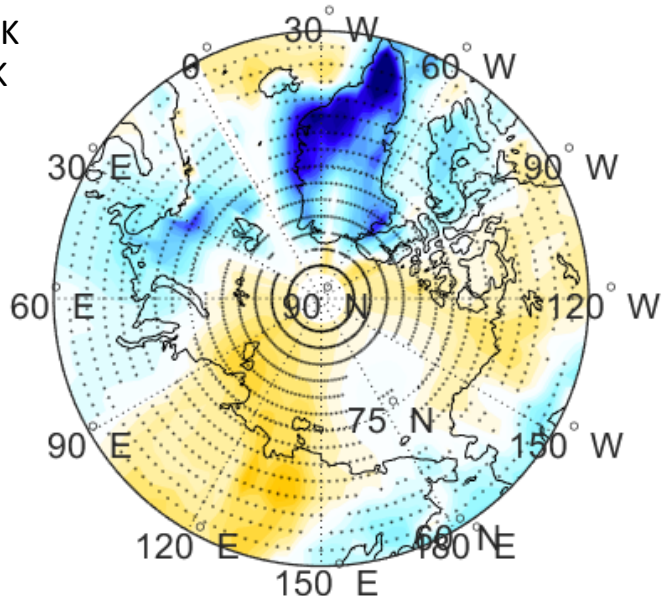


Mean=0.96K
RMSE=0.96K

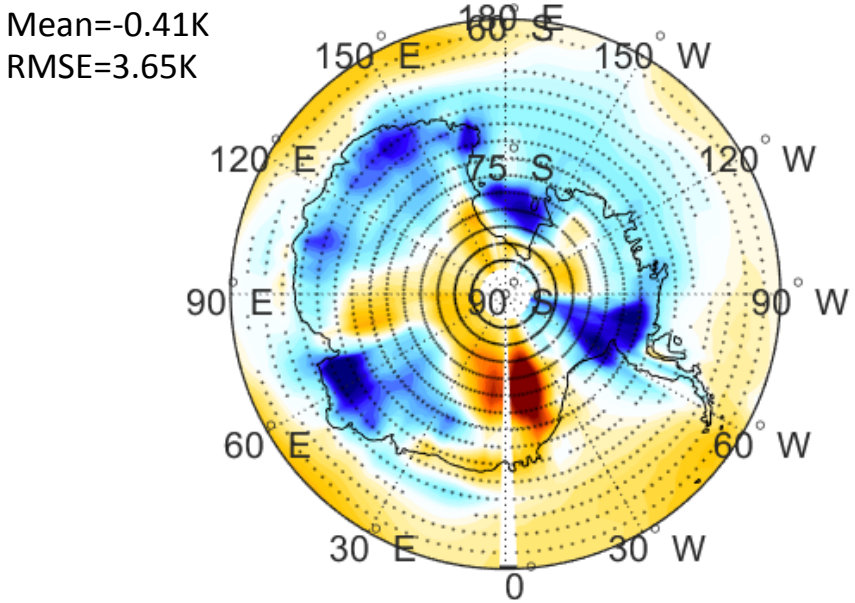


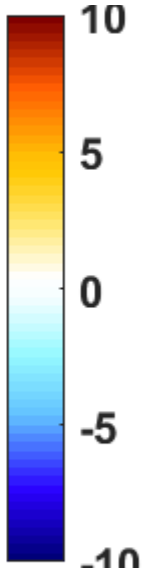
Standard – Obs.

Mean=-0.25K
RMSE=2.32K



Mean=-0.41K
RMSE=3.65K

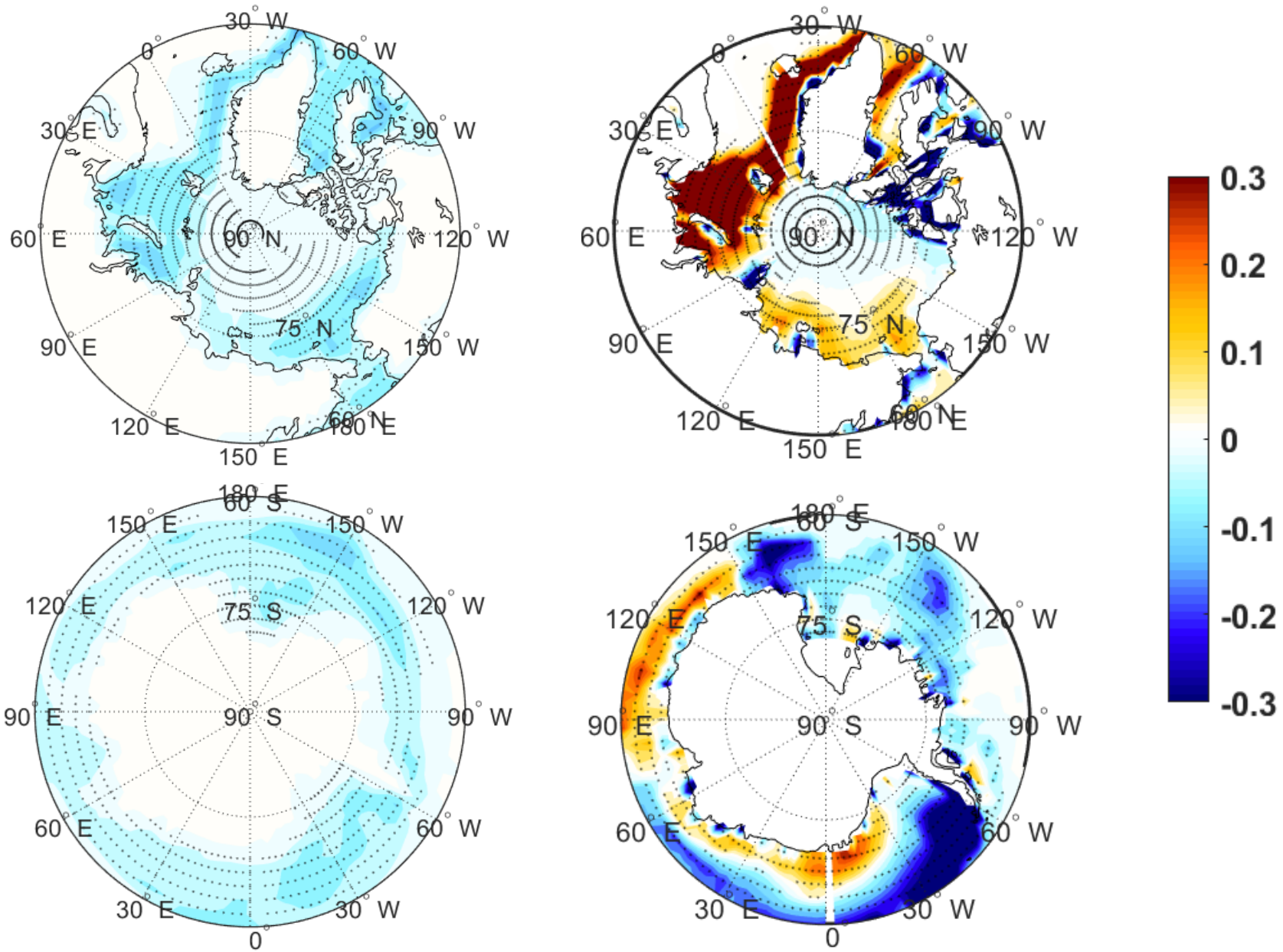




Sea-ice fraction diff.; CESM version 2.1.1; slab ocean run; 6-35-year mean

Modified – Standard

Standard – Obs.



Globe (all SOM runs)

	CESM 2.1.1 (6-35-yr mean)		CESM 1.1.1 (6-35-yr mean)	
	Control run	Modified –control	Control run	Modified-control
Surface energy budget				
LW flux↑ (Wm^{-2})	398.3	3.5	401.2	2.3
LW flux↓(Wm^{-2})	343.8	4.4	344.6	3.2
SW flux↑(Wm^{-2})	23.4	-0.5	22.9	-0.4
SW flux↓(Wm^{-2})	184.9	-0.08	181.4	-0.4
Latent flux (Wm^{-2})	84.5	1.6	83.4	1.0
Sensible flux (Wm^{-2})	21.4	-0.2	17.8	-0.2
Imbalance (Wm^{-2})	-1.1	-0.01	-0.56	-0.03
TOA energy budget				
LW flux↑(Wm^{-2})	238.2	0.9	235.2	0.2
SW flux↑(Wm^{-2})	103.0	-0.9	106.7	-0.3
Imbalance ($W\ m^{-2}$)	-0.31	-0.05	0.03	-0.06
Others				
Net column radiative cooling (Wm^{-2})	108.2	1.3	103.4	0.8
Tskin (K)	288.2	1.0	288.7	0.8
Surface air temp. (K)	288.0	0.9	288.5	0.5
Precipitation (mm/day)	2.92	0.05	2.88	0.03

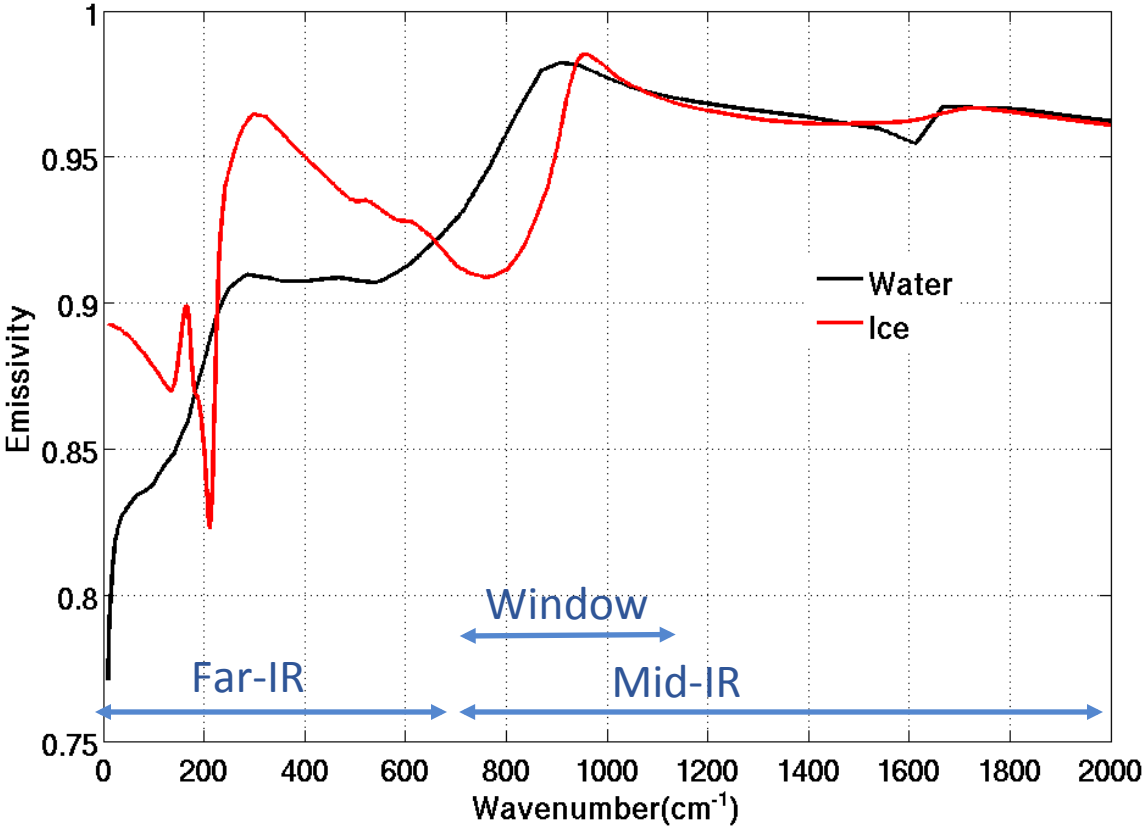
Arctic DJF

	CESM 2.1.1 (6-35-yr mean)		CESM 1.1.1 (6-35-yr mean)	
	Control run	Modified –control	Control run	Modified –control
Surface energy budget				
LW flux↑ (Wm^{-2})	226.8	6.5	223.3	3.6
LW flux↓(Wm^{-2})	198.2	6.4	186.6	3.7
SW flux↑(Wm^{-2})	4.6	-0.1	4.8	-0.1
SW flux↓(Wm^{-2})	7.1	-0.1	7.6	-0.1
Latent flux (Wm^{-2})	11.0	1.3	11.4	0.7
Sensible flux (Wm^{-2})	9.2	0.9	-0.4	-0.3
Imbalance (Wm^{-2})	46.3	2.3	44.9	0.3
TOA energy budget				
LW flux↑(Wm^{-2})	170.7	1.9	168.7	0.6
SW flux↑(Wm^{-2})	10.5	-0.02	10.3	-0.03
Imbalance ($W\ m^{-2}$)	163.0	1.9	160.9	0.5
Others				
Net column radiative cooling (Wm^{-2})	137.8	1.8	127.8	0.6
Tskin (K)	250.5	2.0	249.4	1.2
Surface air temp. (K)	250.5	1.9	249.9	1.0
Precipitation (mm/day)	1.10	0.06	1.21	0.07

Arctic JJA

	CESM 2.1.1 (6-35-yr mean)		CESM 1.1.1 (6-35-yr mean)	
	Control run	Modified – control	Control run	Modified -control
Surface energy budget				
LW flux↑ (Wm^{-2})	330.3	3.1	338.8	1.3
LW flux↓(Wm^{-2})	302.4	3.5	302.5	2.0
SW flux↑(Wm^{-2})	68.7	-7.0	60.5	-2.5
SW flux↓(Wm^{-2})	172.6	-4.2	178.3	-2.7
Latent flux (Wm^{-2})	20.8	0.6	23.1	0.4
Sensible flux (Wm^{-2})	11.2	0.2	15.4	-0.4
Imbalance (Wm^{-2})	-44.1	-2.4	-43.0	-0.4
TOA energy budget				
LW flux↑(Wm^{-2})	220.4	1.3	224.4	-0.07
SW flux↑(Wm^{-2})	219.3	-3.4	207.5	-0.04
Imbalance ($W\ m^{-2}$)	14.9	-2.1	7.3	-0.1
Others				
Net column radiative cooling (Wm^{-2})	92.9	1.1	90.6	0.3
Tskin (K)	276.1	0.7	277.7	0.4
Surface air temp. (K)	275.9	0.7	277.7	0.3
Precipitation (mm/day)	1.45	0.04	1.59	0.04

Possible Impact on simulated **current** climate change?



Ts↑ → Sea ice coverage↓ → Far-IR Emissivity@sfc↓ Reflectivity@sfc↑

Sea ice coverage↓ → Window Emissivity@sfc↑ Reflectivity@sfc ↓

$$\varepsilon\sigma T_{ground}^{4} + (1-\varepsilon)F_{sfc}^{\downarrow} = F_{LW\_sfc}^{\uparrow}$$

Emission Reflection Upward LW flux from surface

Sea-ice emissivity feedback: a back-envelope calculation

$$F_{SW}^{\uparrow} = \alpha F_{SW}^{\downarrow}, \qquad \delta F_{SW}^{\uparrow} = \delta\alpha \bullet F_{SW}^{\downarrow}, \ \text{ice} \leftrightarrow \text{ocean}, \ \delta\alpha \sim 0.8$$

$$F_{LW}^{\uparrow} = \varepsilon_v B_v(T_s) + (1-\varepsilon_v) F_{LW}^{\downarrow}, \delta F_{LW}^{\uparrow} = \delta\varepsilon \bullet \left[B_v(T_s) - F_{LW}^{\downarrow} \right], \text{ice} \leftrightarrow \text{ocean}, \delta\varepsilon \sim 0.1 \text{ or less}$$

$$\text{moreover}, \left[B_v(T_s) - F_{LW}^{\downarrow} \right] \sim 0.1 F_{SW}^{\downarrow}$$

$$\text{Therefore}, \delta F_{LW}^{\uparrow} \sim 0.01 \delta F_{SW}^{\uparrow},$$

The CESM calculation (Huang et al., 2018)

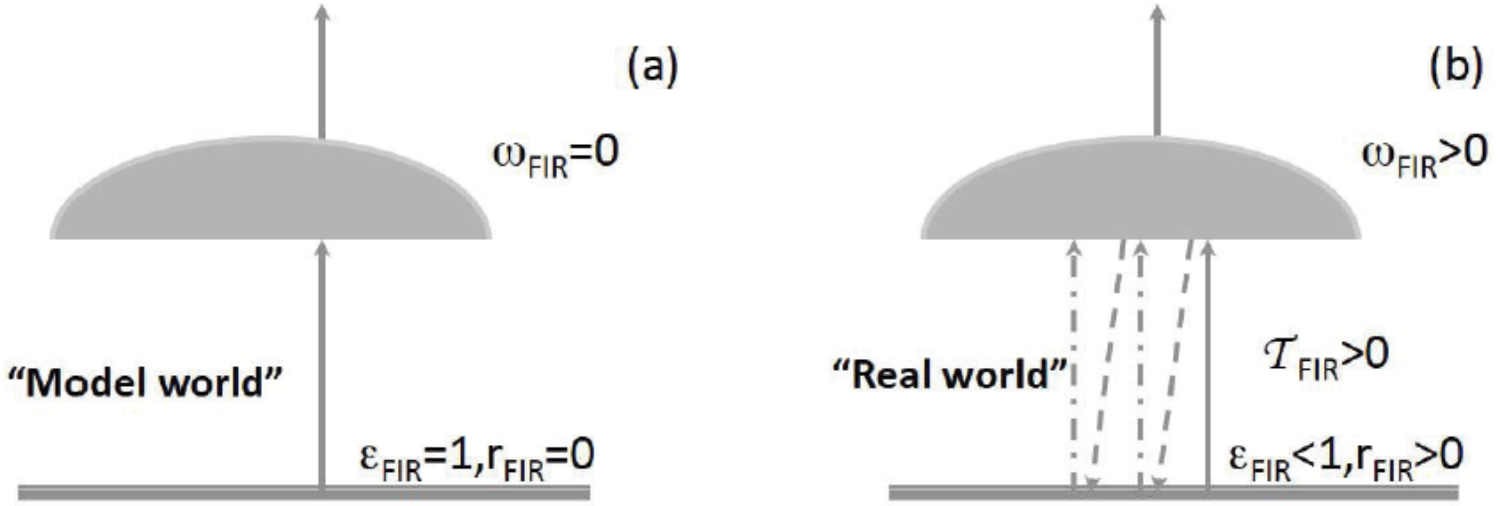
Sea ice emissivity feedback
Clear-sky: [-0.007, 0.003] Wm^{-2}/K
All-sky: [-0.003, 0.002] Wm^{-2}/K

Sea ice shortwave albedo feedback: 0.3 Wm^{-2}/K

How about snowball earth and ice age? The paleoclimate implication?

Outlooks and Opportunities (I)

When surface spectral emissivity and cloud scattering are both enabled….



(Chen et al., 2014, GRL)

- **The less water vapor, the model the IR scattering matters here.**
- **Scattering will lead to more atmosphere absorption, thus more downward LW flux**
- **Only 3 out of 20+ GCMs consider LW scattering now**
- **Cloud scattering plus surface emissivity can change the delicate surface energy balance around melting season…**
- **Current CESM (with RRTMG_LW) cannot handle scattering**
  - **We have a modified version with LW scattering/new ice optics…**

Outlooks and Opportunities (II)

- What we modified is only for the CAM component
- We “re-interpreted” the radiative flux from all surface modules
- Ideally, radiative flux from all surface modules should be band-by-band
  - Spectral consistency across models
  - Take spectral dependence into account for ocean/sea ice/land ice/lands
  - UCI on CICE/ Edinburgh on JULES (land model for HadCM)
- Together with (I), these will improve the radiative coupling in the model
- Applications in paleoclimate modeling?

Outlooks and Opportunities: far-IR

- Far-IR (>15um) accounts for >50% of OLR
  - The colder the scene, the more the far-IR contributes
- We never had band-resolved obs in far-IR from space
  - **The last uncharted territory** in radiation budget measurements
- Two opportunities
  - NASA PREFIRE
    - A $35M EV-I mission selected in 2018
    - Slated to launch in 2021/2022
    - Dedicated for polar regions/surface emissivity is a target
    - **Field measurements for validation are needed**

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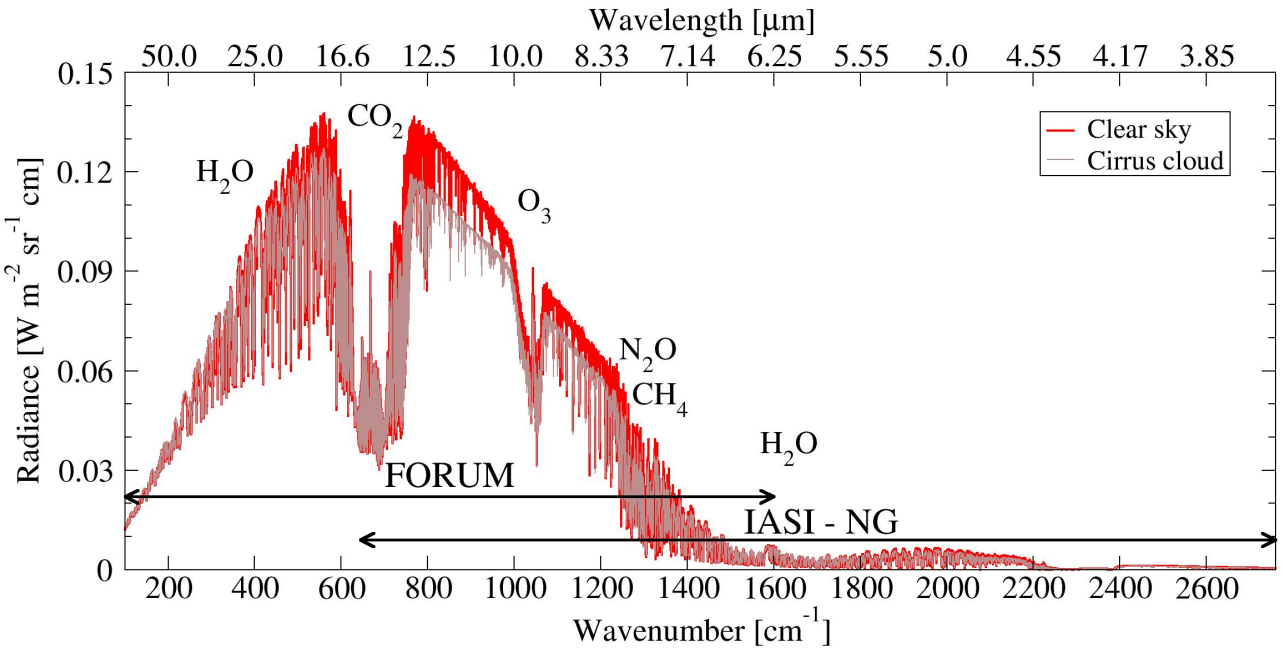
Outlooks and Opportunities: far-IR



Far-infrared Outgoing Radiation Understanding and Monitoring (FORUM)

- One of two finalists for ESA 9th Earth Explorer
- Selection has been made; will be announced in September
- Scheduled launch: 2024/2025 (but…)
- Polar LW radiation budget/surface emissivity are also the targeted variables: *how to make best use of PREFIRE and FORUM obs.?*

Remarks

- Sometimes atmospheric parameterizations are “tuned” for mid-lat, which might not be equally applicable to polar region.
- The intrinsic spectral dimension of the radiative process.
- How many physical processes do we need to include in the model?
- Hidden offsetting biases in the model: how to expose them?

Useful resources

- Global surface spectral emissivity data set

http://www-personal.umich.edu/~xianglei/datasets.html

For each surface type, as well as for each grid/ calendar month

- Modified CESM2.1.1 with surface spectral emissivity included

/glade/p/cesm/pcwg/PWS2019_DATA/day3/morning/

Back-up slides