Incorporating realistic surface LW spectral emissivity into the CESM Model:

Impact on simulated climate and the potential sea-ice emissivity feedback mechanism

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CESM AWG meeting
February 28, 2017

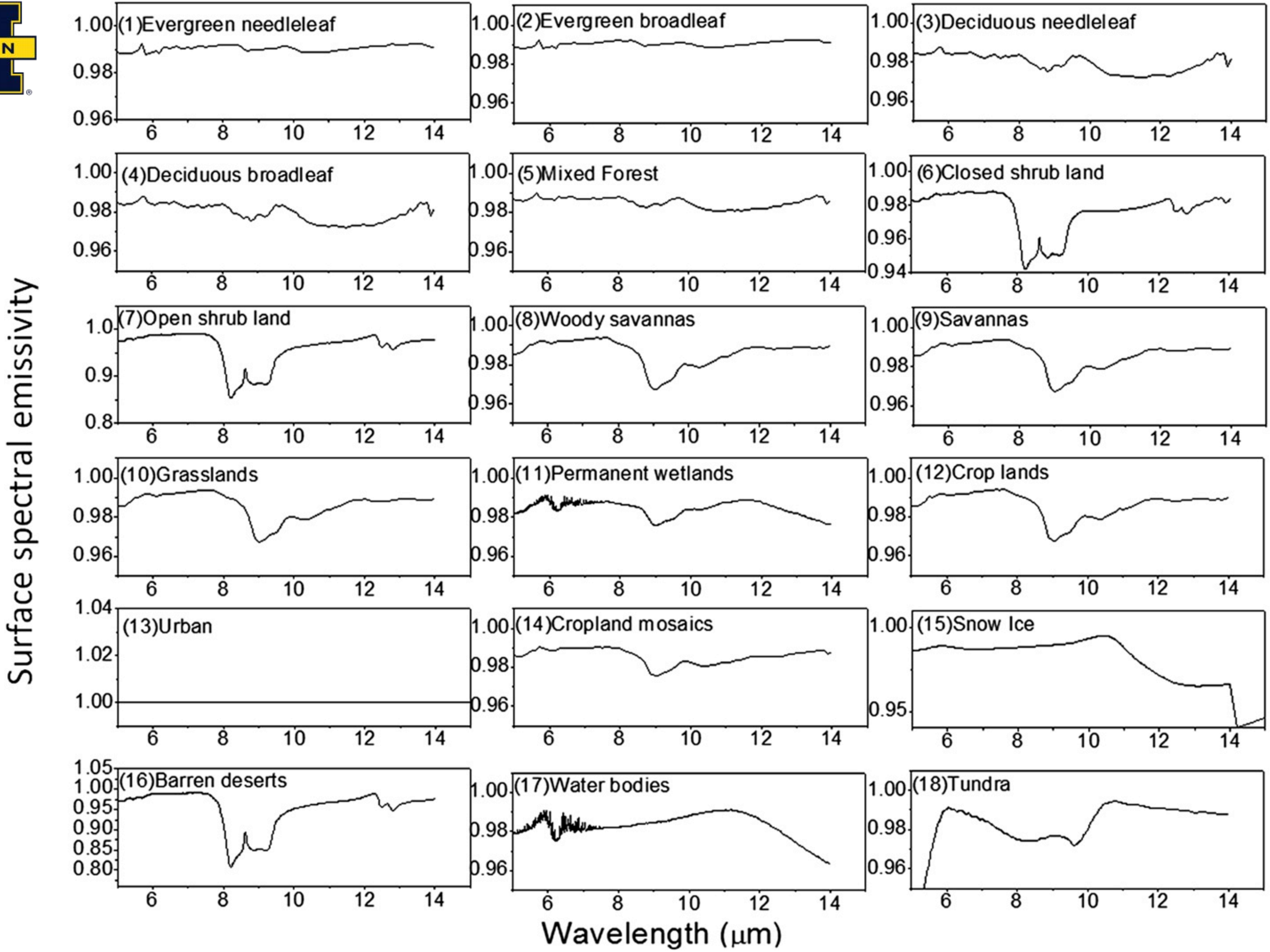
Acknowledgement: DoE BER ESM-SciDAC program

Outline

- Motivation
  - Surface emissivity in general
  - Surface emissivity in climate models
    - How has it been treated
    - What could be biased with such treatments?
- Incorporate surface spectral emissivity into the CESM
  - Global surface spectral emissivity dataset for the entire LW spectrum
  - Consistency with the surface modules
  - “Sanity check”
- Impact on simulated climatology
- Impact on simulated climate change (2xCO2 equilibrium run)
- Conclusions and discussions

Part I: motivations

- Surface emissivity $\varepsilon_v(\theta) = \dfrac{I(\theta)^{\uparrow}_{s_v}}{B_v(T_s)}$
  - 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

Surface emissivity in current models

In Atmospheric model (RRTMG_LW)

- ε_v=1: Surface is always assumed to be a blackbody
- Almost all GCMs and NWP models assume this
  - Exception: NASA GISS models
- Take LW flux from coupler/surface modules

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

Ocean surface is assumed to be blackbody

In Land model (CLM)

- Gray emissivity is assume (NOT a function of *v*)
  - 0.97 for snow and nonurban ground
  - 0.96 for urban ground
- Upward flux at surface is explicitly computed
- Radiative skin temperature is computed and passed onto Atmospheric model

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

Emission **Reflection**

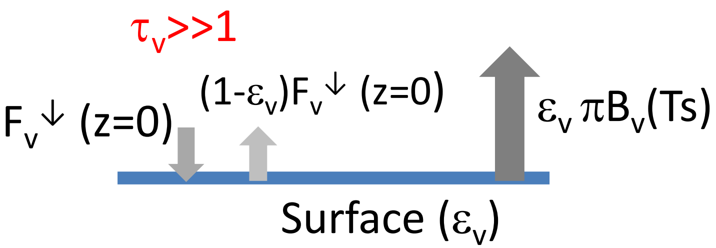
Issues:

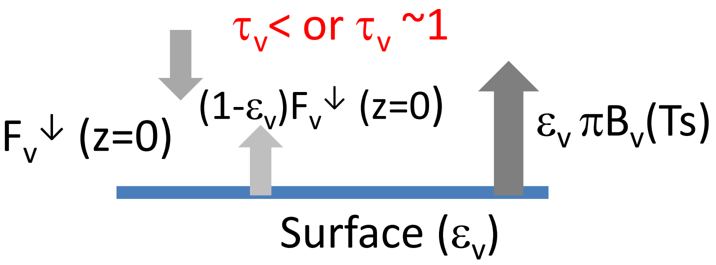
- **Spectral variation of surface emissivity ignored**
- **Cannot simply change ε in RRTMG_LW to realistic values and still using the same T_{skin}**

Surface emissivity

$$\varepsilon_\nu = \frac{F_{s_\nu}^{\uparrow}}{\pi B_\nu(T_s)}$$

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





$$\varepsilon_\nu = A_\nu$$

$$r_\nu = 1 - A_\nu = 1-\varepsilon_\nu$$

Upward flux at surface

$$F^{\uparrow}(z=0) = \varepsilon_\nu \pi B_\nu(T_s) + (1-\varepsilon_\nu)F_\nu^{\downarrow}(z=0)$$

$$\text{if } \varepsilon_\nu \sim 1 \text{ or } F_\nu^{\downarrow}(z=0) \approx \pi B_\nu(T_s) \text{ (e.g. } H_2O \text{ and } CO_2 \text{ band)}$$

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

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

Where does this wisdom break down?

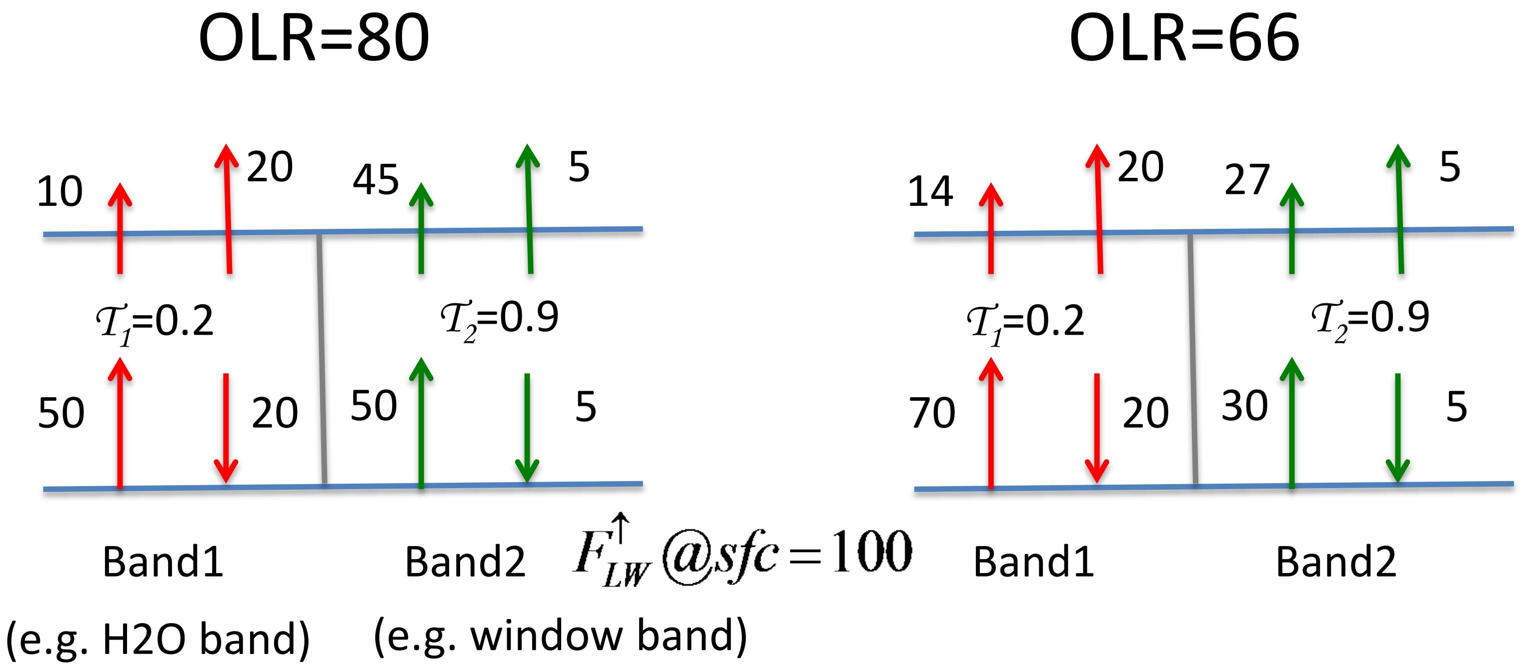
1. IR window region 2. High altitude/High latitude (Chen et al., 2014)

LW coupling between surface and atmosphere

Having the broadband flux @surface correct is not enough.

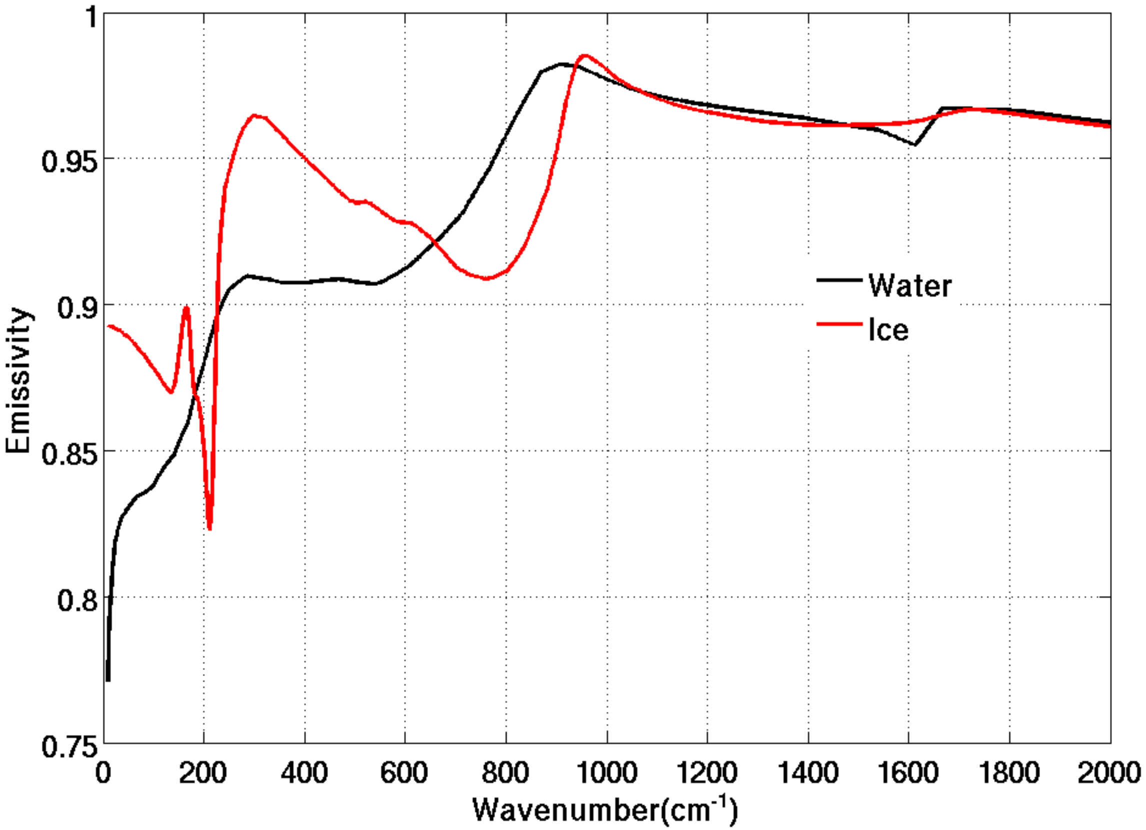
1. The atmosphere absorption and emission is spectrally dependent.
2. A wrong band-by-band partitioning of LW flux at surface could lead to a wrong OLR at TOA. Thus, it could lead to a wrong column radiative cooling rate in the atmosphere as well.

A toy 1-layer atmosphere to illustrate above points (100 photons from sfc)

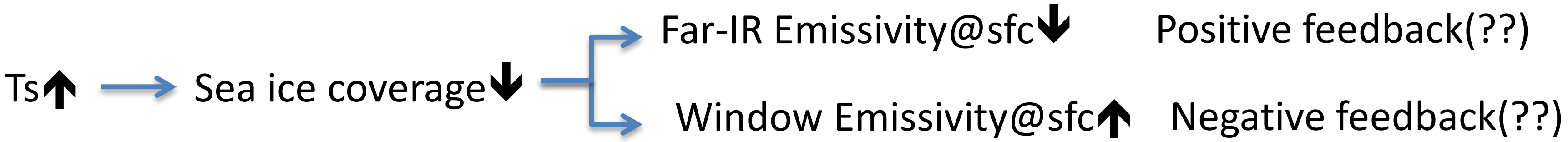


$F_{LW}^{\uparrow} @sfc = 100$

Possible Impact on simulated climate change



- Feldman et al., 2014, PNAS, doi: 10.1073/pnas1413640111.
  - Only looked at far-IR
  - Only modified RRTMG_LW to include emissivity. F_{LW}@sfc not the same in CAM and in surface modules



Ts↑ → Sea ice coverage↓

→ Far-IR Emissivity@sfc↓ Positive feedback(??)

→ Window Emissivity@sfc↑ Negative feedback(??)

Reflection of downward flux can complicate the analysis

Recap

- Surface spectral emissivity treatment can be improved. Know the physics, have (mid-IR) obs.
- Reducing biases due to this treatment can help exposing compensating biases and errors due to other issues.

Incorporate surface spectral emissivity into the CESM

Develop and Validation of a global dataset of surface spectral emissivity (Huang et al., 2016, JAS, doi:10.1175/JAS-D-15-0355.1)

Basic approaches

- First-principle calculations for both far-IR and mid-IR
  - Starting point: Composition and Index of refraction
  - Validate as much as possible with available data set
- Define 11 different surface types (some has subtypes)
- Regress with MODIS retrieved surface emissivity at **8 mid-IR wavelengths** and 0.05°×0.05° spatial resolutions to decide surface type defined in our study
- Averaged onto 0.5°×0.5° grid
- Validation: compare with IASI mid-IR retrievals of spectral emissivity at 0.5°×0.5° grid and at RRTMG_LW bands
- Far-IR as calculated

Usage

- Options 1: Gridded surface spectral emissivity for 12 calendar months
- Options 2: Spectral emissivity for surface types used in GCMs (make it a prognostic variable)

Incorporate surface spectral emissivity into the CESM v1.1.1

ε_i: emissivity in each RRTMG_LW band

$$F_{LW}^{\uparrow} = \sum_i \varepsilon_i \pi \int_{\Delta\nu_i} B_\nu(T_{skin})\,d\nu + \sum_i (1-\varepsilon_i) F_{i\_sfc}^{\downarrow}$$

From surface modules

From CAM

Solve for T_{skin}

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

- 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)

- A note: Cheng et al. (2016, JQSRT) benchmarked RRTMG_LW for the RT calculation in the presence of surface spectral emissivity

Differences between ε_i=1 run and standard CESM run

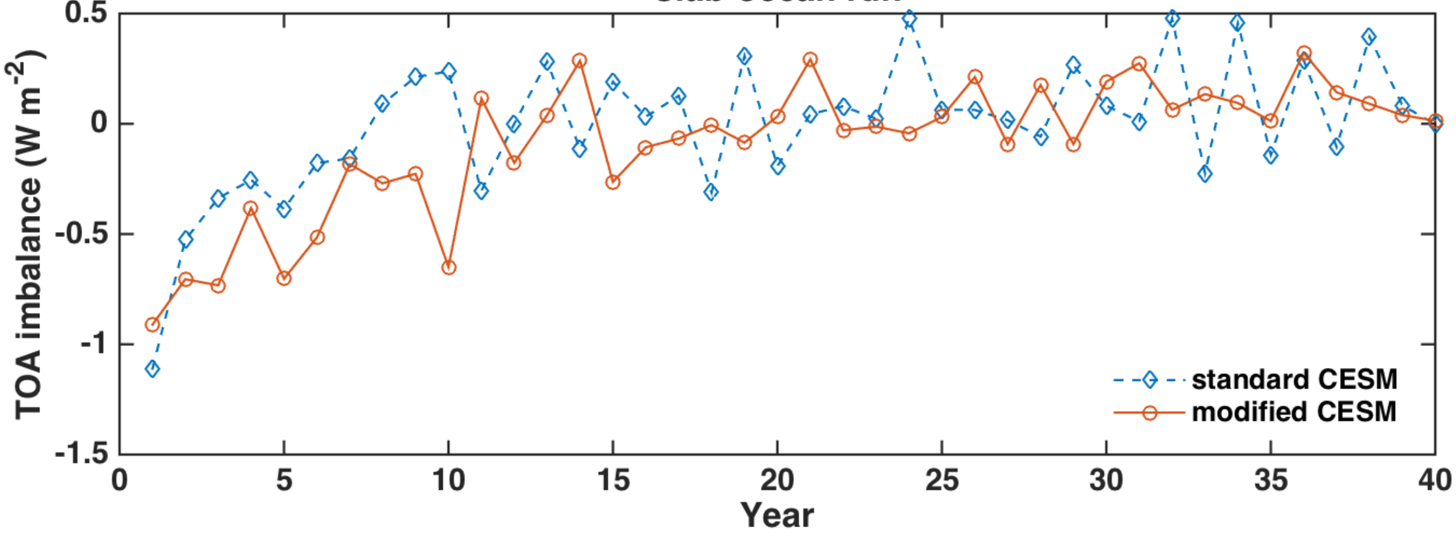
After 3 hours of integration

Simulation set-up

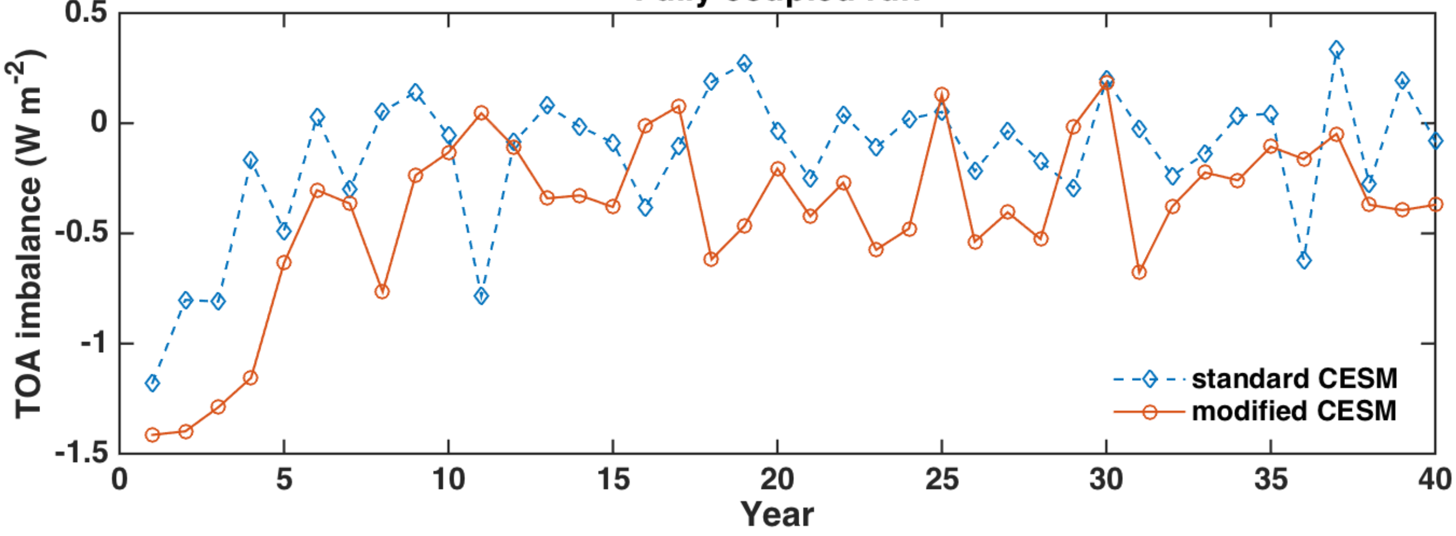
- Land surface spectral emissivity prescribed for each calendar month.
- Spectral emissivity over oceans is weighting sum of $\varepsilon_{\text{water}}$ and ε_{ice}.
- Slab-ocean and fully-coupled run both used. 30-year output analyzed for each.

TOA imbalance: no additional tuning needed

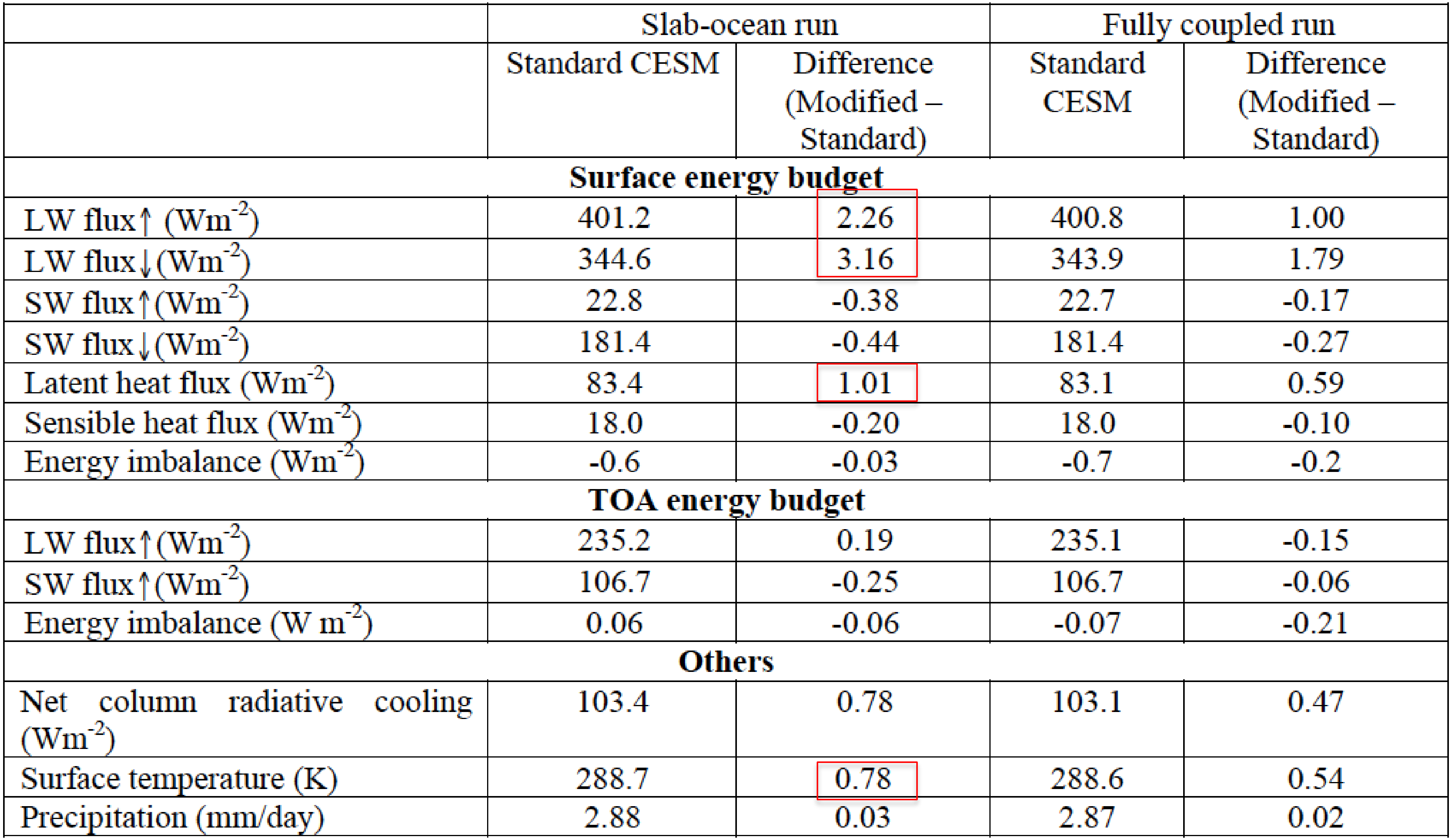
Slab-ocean run



Fully coupled run



Global mean energy budget

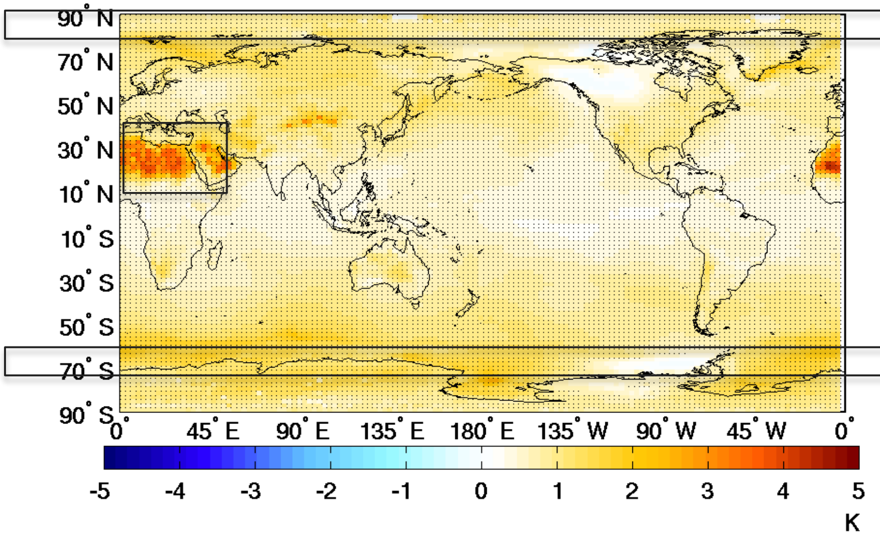


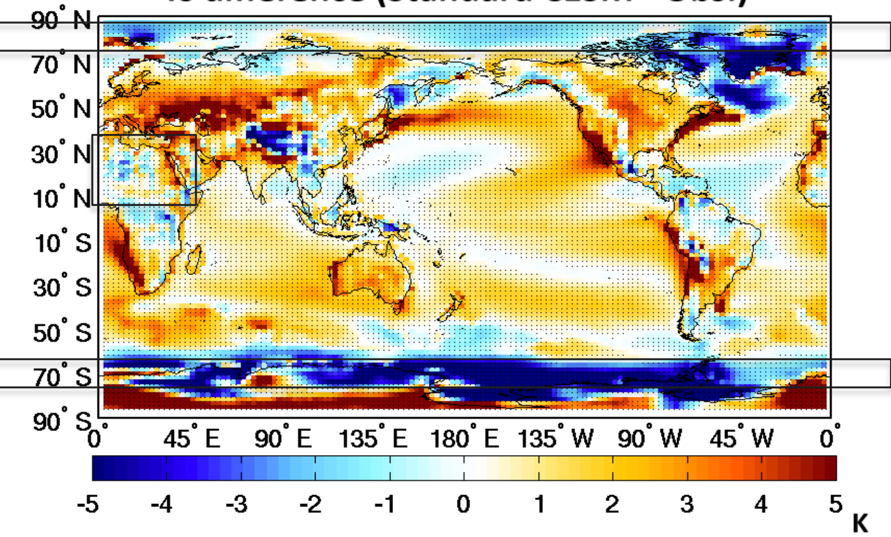
	Slab-ocean run		Fully coupled run	
	Standard CESM	Difference (Modified – Standard)	Standard CESM	Difference (Modified – Standard)
Surface energy budget				
LW flux↑ (Wm^{-2})	401.2	2.26	400.8	1.00
LW flux↓ (Wm^{-2})	344.6	3.16	343.9	1.79
SW flux↑ (Wm^{-2})	22.8	-0.38	22.7	-0.17
SW flux↓ (Wm^{-2})	181.4	-0.44	181.4	-0.27
Latent heat flux (Wm^{-2})	83.4	1.01	83.1	0.59
Sensible heat flux (Wm^{-2})	18.0	-0.20	18.0	-0.10
Energy imbalance (Wm^{-2})	-0.6	-0.03	-0.7	-0.2
TOA energy budget				
LW flux↑ (Wm^{-2})	235.2	0.19	235.1	-0.15
SW flux↑ (Wm^{-2})	106.7	-0.25	106.7	-0.06
Energy imbalance (W m^{-2})	0.06	-0.06	-0.07	-0.21
Others				
Net column radiative cooling (Wm^{-2})	103.4	0.78	103.1	0.47
Surface temperature (K)	288.7	0.78	288.6	0.54
Precipitation (mm/day)	2.88	0.03	2.87	0.02

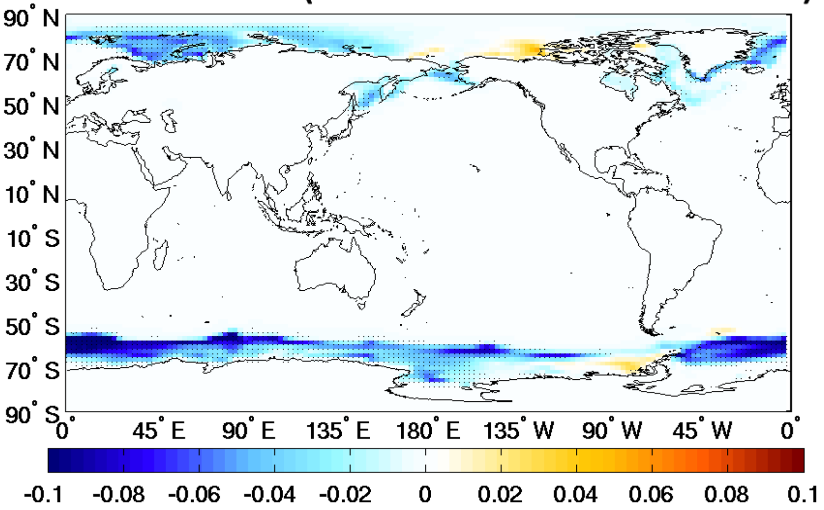
Slab-ocean run

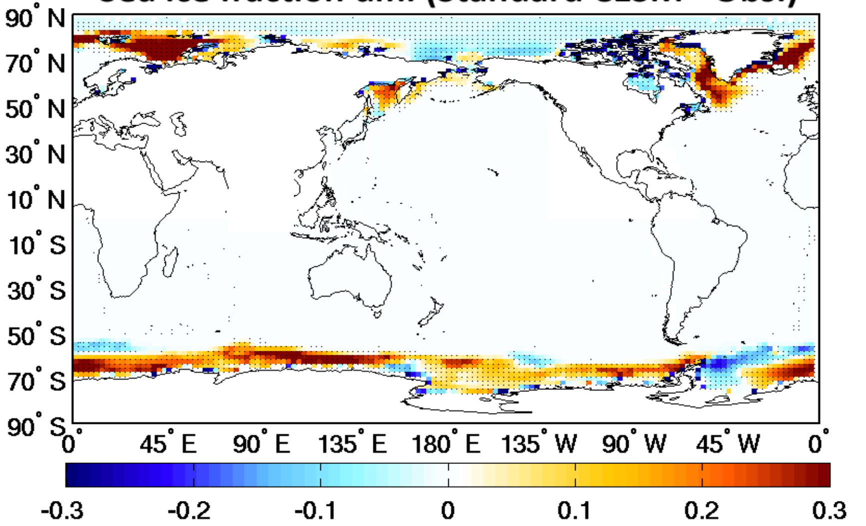
CRU + Hadley SST; NSIDC/NOAA sea ice

High-latitude regions; Sahara desert; Gobi desert (to some extent)

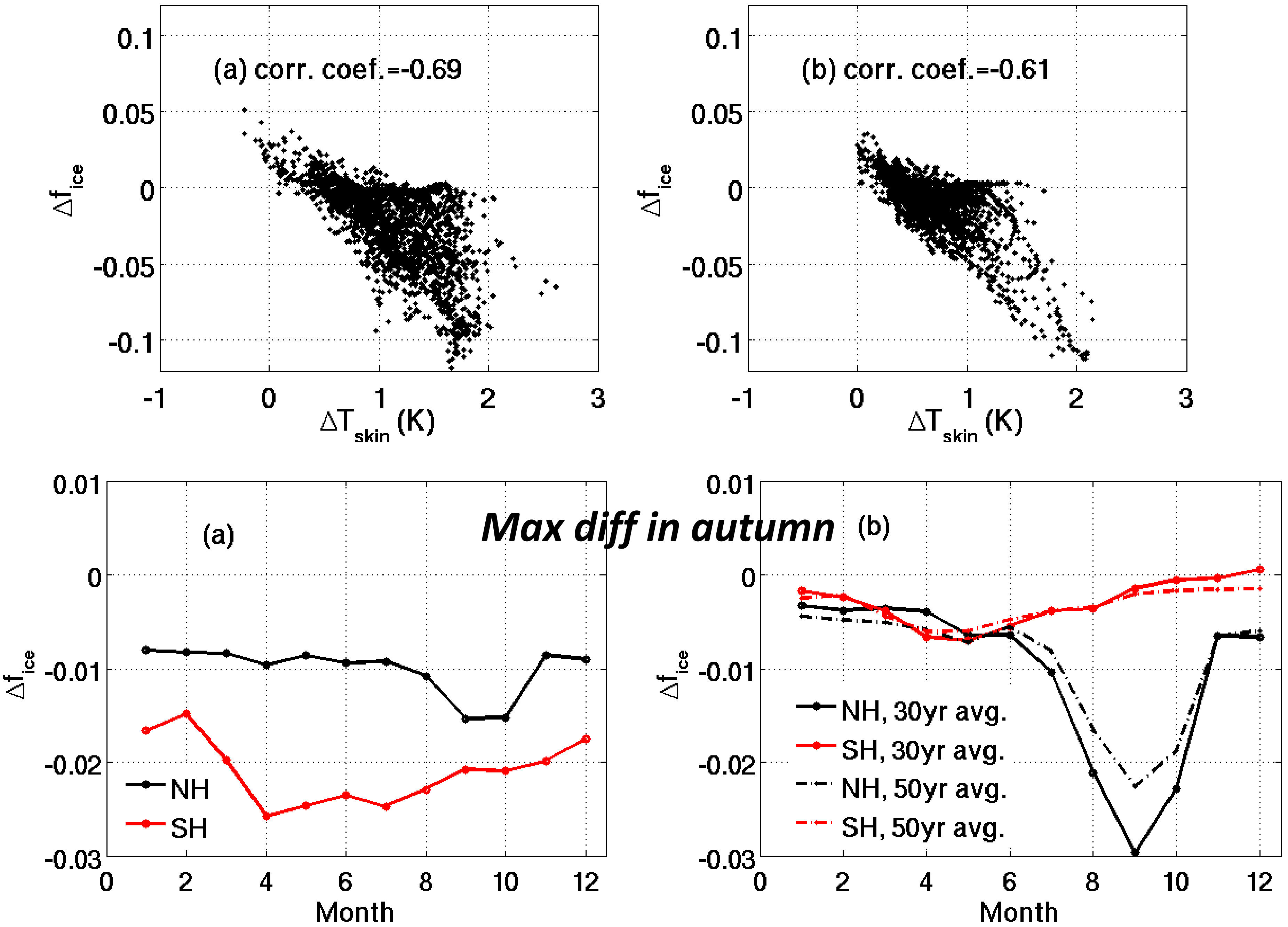

Ts difference (Modified CESM - Standard CESM)


Ts difference (Standard CESM - Obs.)


Sea ice frac. diff. (Modified CESM - Standard CESM)

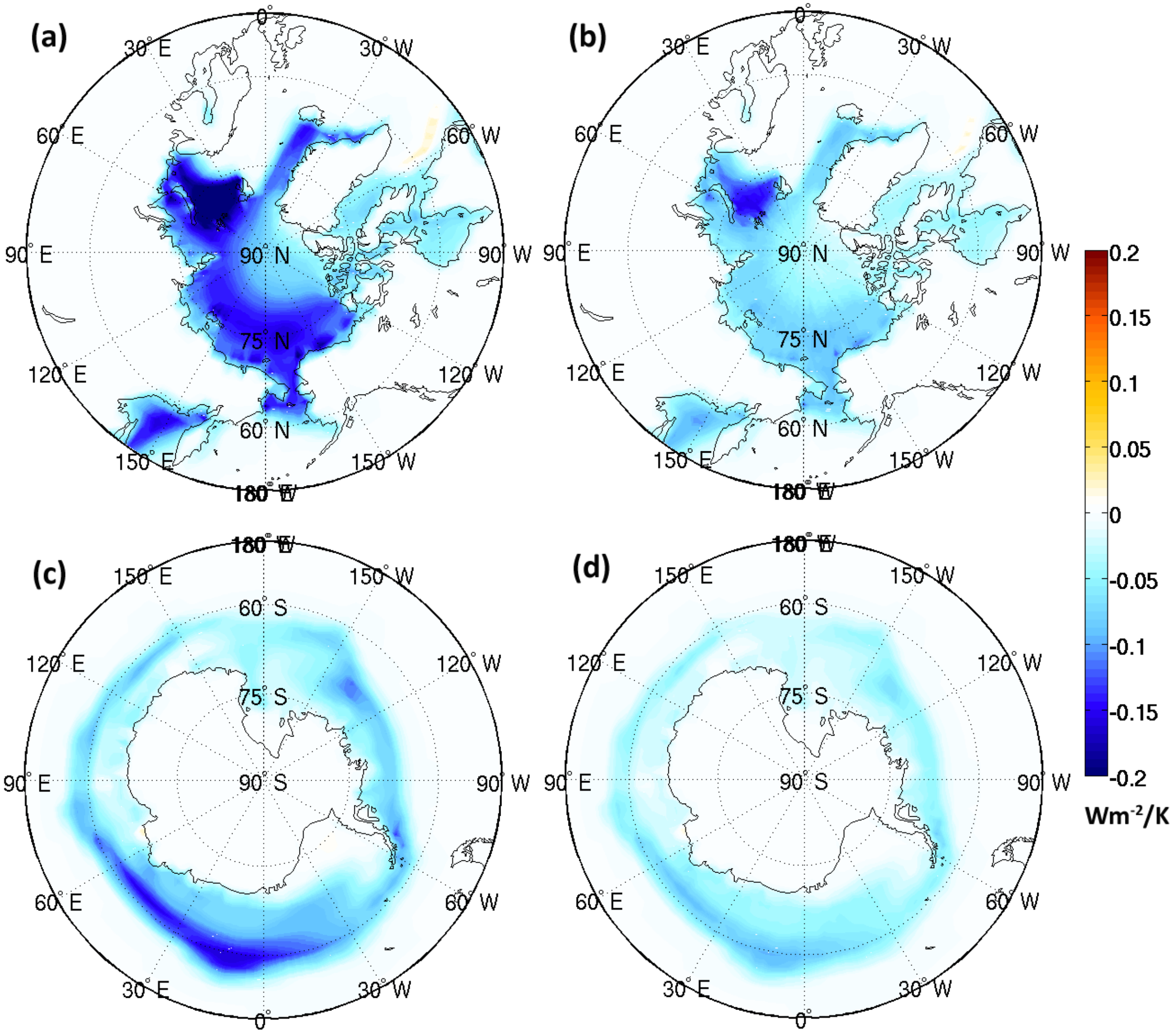

Sea ice fraction diff. (Standard CESM - Obs.)

Slab-ocean run **Fully coupled run**



Max diff in autumn

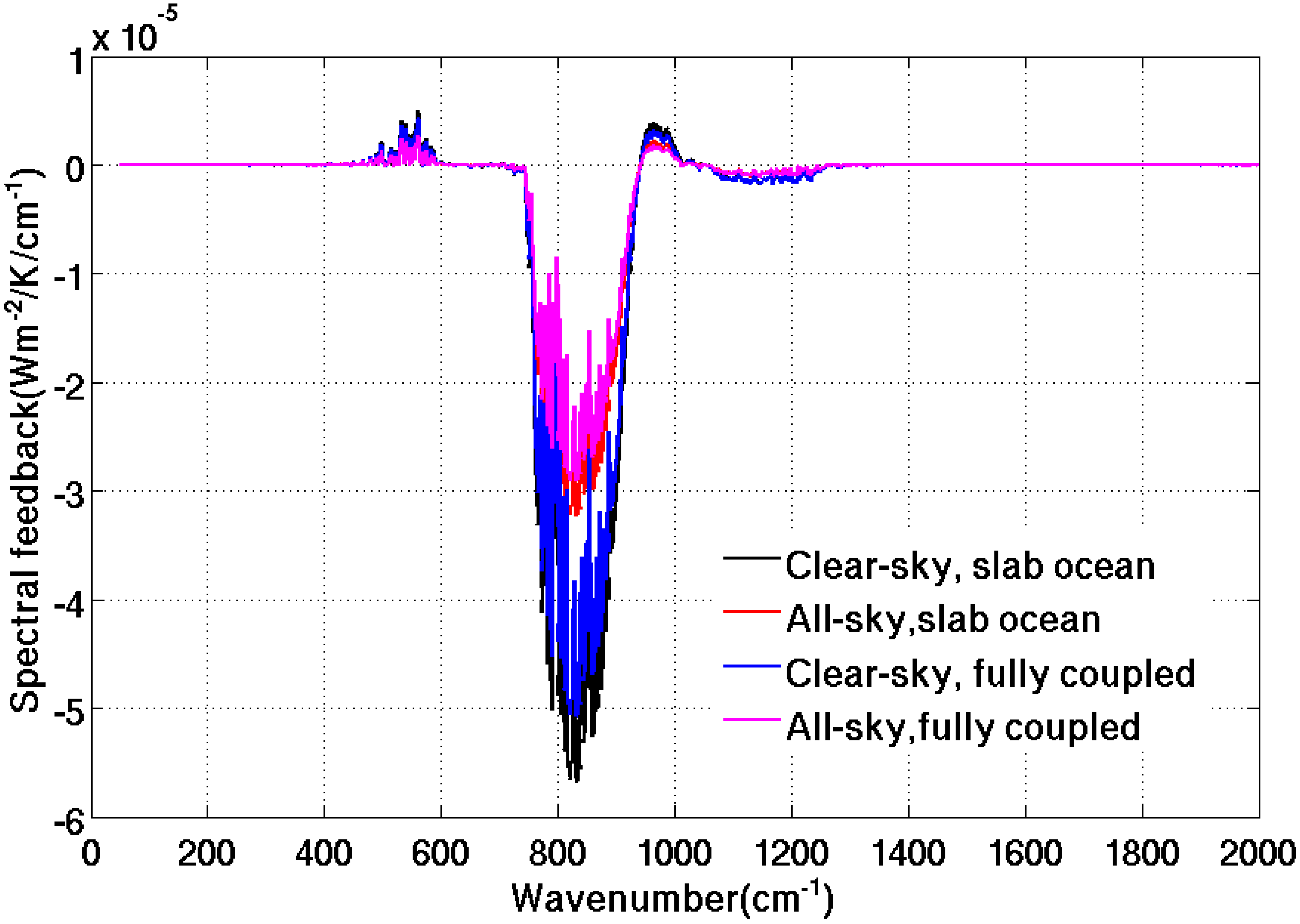
Sea ice emissivity feedback: 2-sided PRP methods for $2xCO_2$ and control run



Clear-sky

All-sky

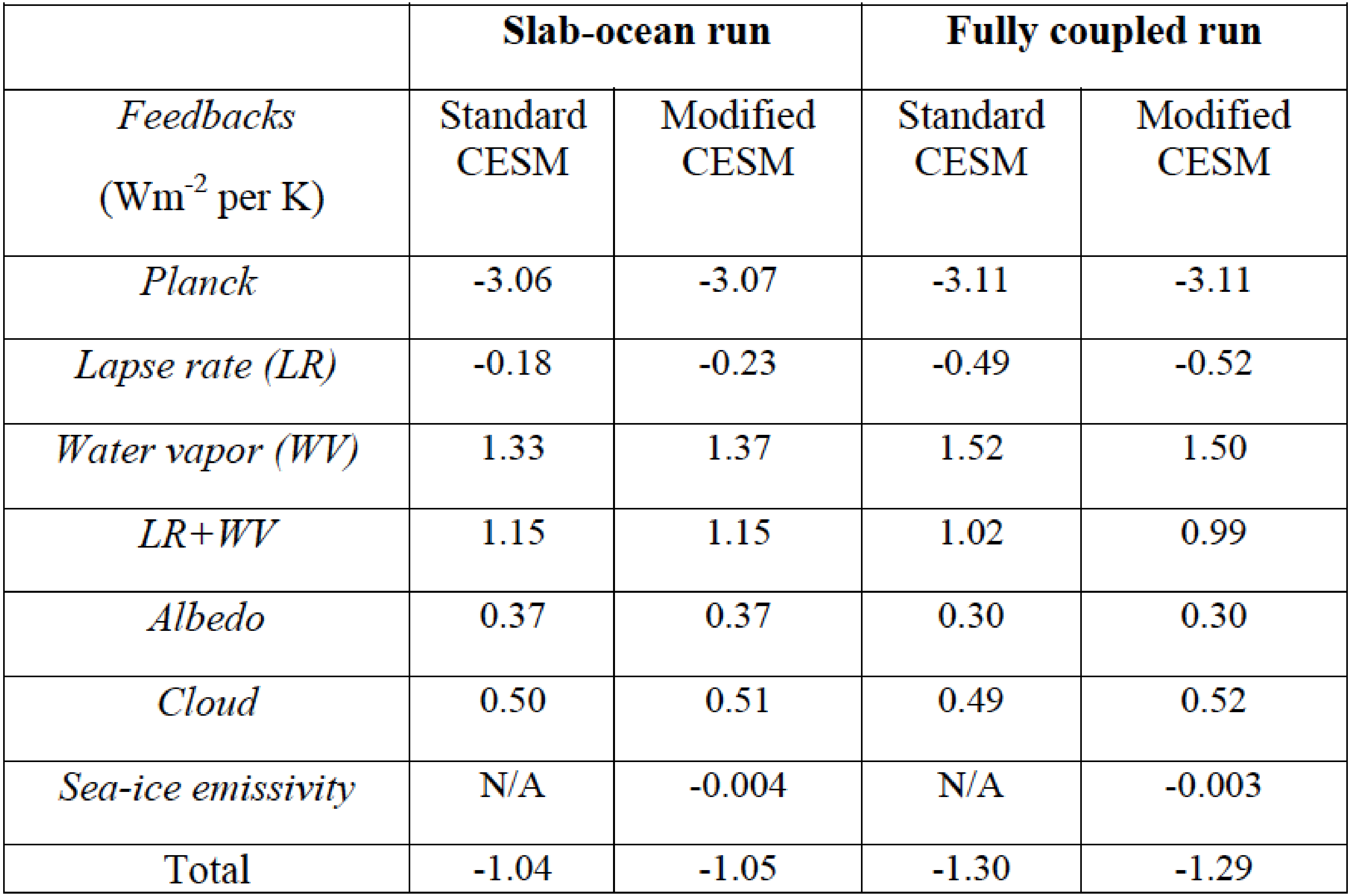
Spectral decomposition of the sea-ice emissivity feedback



Fully Coupled run Clear-sky: -0.007 Wm^{-2}/K

All-sky: -0.003 Wm^{-2}/K

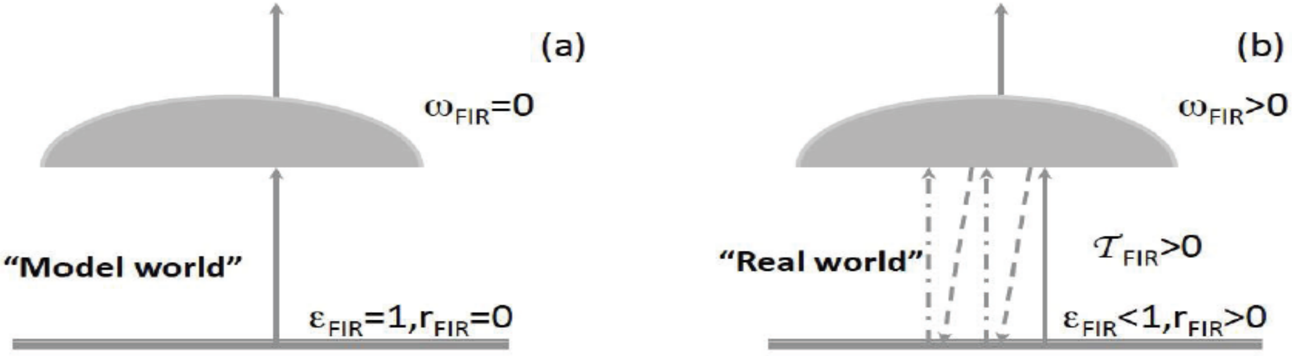
Feedback analysis



	Slab-ocean run		Fully coupled run	
Feedbacks (Wm^{-2} per K)	Standard CESM	Modified CESM	Standard CESM	Modified CESM
Planck	-3.06	-3.07	-3.11	-3.11
Lapse rate (LR)	-0.18	-0.23	-0.49	-0.52
Water vapor (WV)	1.33	1.37	1.52	1.50
LR+WV	1.15	1.15	1.02	0.99
Albedo	0.37	0.37	0.30	0.30
Cloud	0.50	0.51	0.49	0.52
Sea-ice emissivity	N/A	-0.004	N/A	-0.003
Total	-1.04	-1.05	-1.30	-1.29

Conclusions and discussions

- Including surface spectral emissivity
  - Surface energy budget: LW vs. latent heat flux
  - Affect climatology, especially regional Ts and sea ice fraction (reduce some modeled biases)
  - Little impact on simulated global climate change
- Next: Consistency of RT across modules
- Next: When surface in LW is reflective
  - Cold and dry polar regions: BB peak emission shifts to far-IR
  - Ice cloud has a peak of scattering in far-IR (350-450 cm^{-1})
  - Thus, multiple reflection between surface and cloud: possible more absorption along the path!



(Chen et al., 2014, GRL)

Thank you!

References:

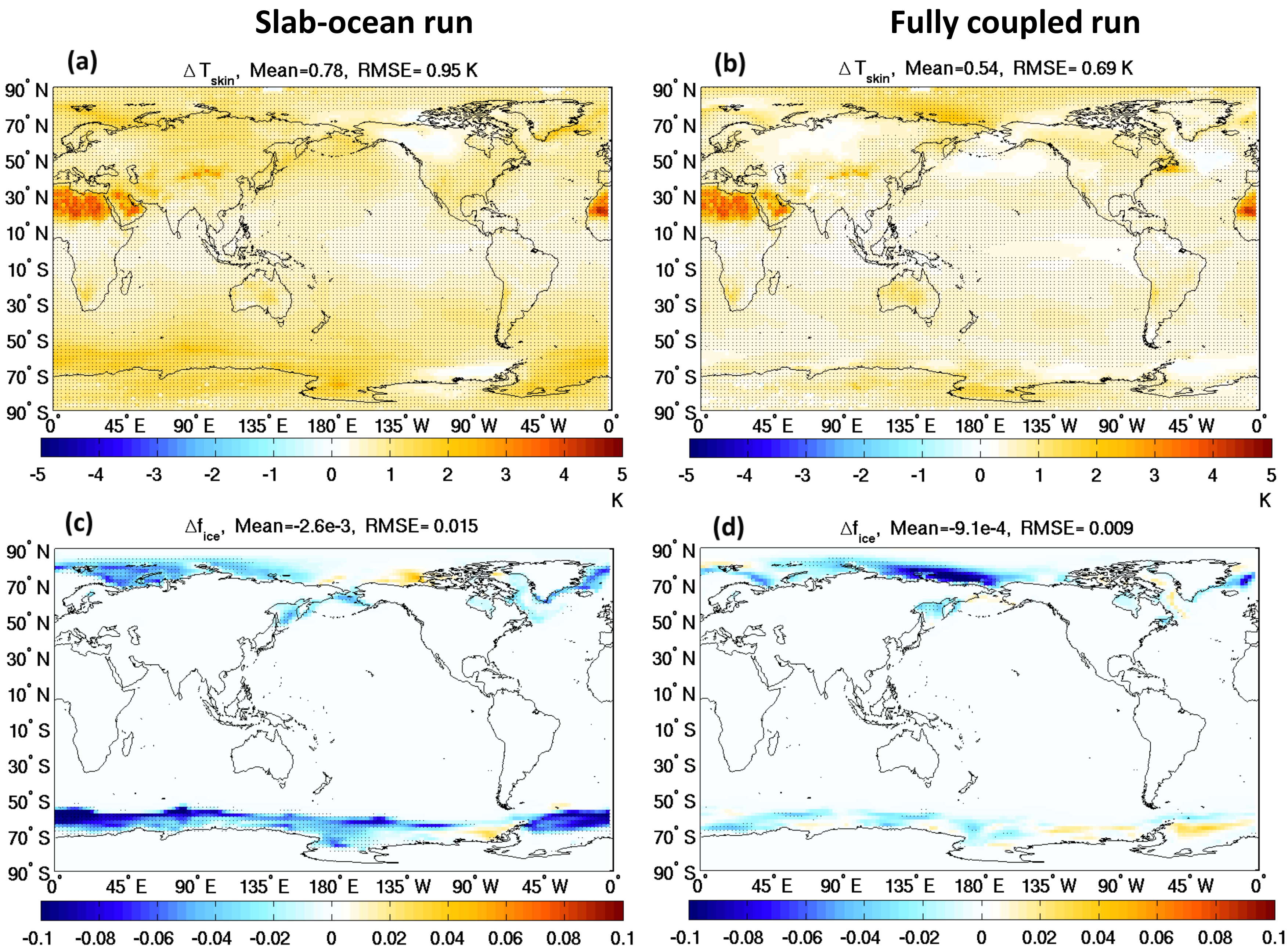
1. Huang et al., An observationally based global band-by-band surface emissivity dataset for climate and weather simulations, *J. Atmos. Sci.*, 73, 3541-3555, doi:10.1175/JAS-D-15-0355.1, 2016.

2. Cheng, H. Z., X.H. Chen, X. L. Huang, Quantification of the Errors Associated with the Representation of Surface Emissivity in the RRTMG_LW, *JQSRT*, 180, 167-176, doi:10.1016/j.qsrt.2016.05.004, 2016.

3. 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, *Geophs. Res. Letts.*, doi:10.1002/2014GL061216, 41(18), 6530-6537, 2014.

Backup slide

Modified – Standard CESM


Slab-ocean run

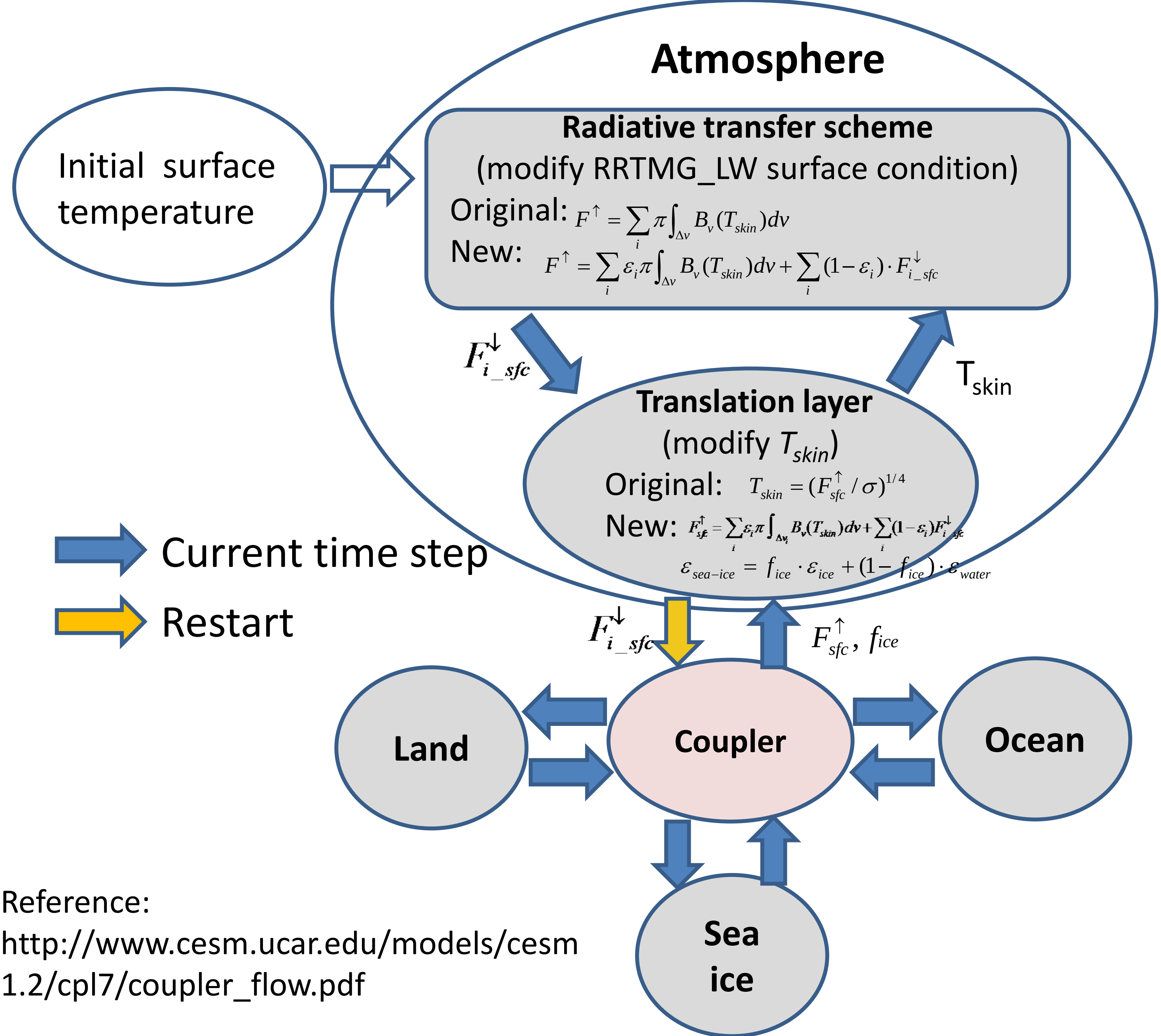
Fully coupled run

(a) ΔT_{skin}, Mean=0.78, RMSE= 0.95 K

(b) ΔT_{skin}, Mean=0.54, RMSE= 0.69 K

(c) Δf_{ice}, Mean=-2.6e-3, RMSE= 0.015

(d) Δf_{ice}, Mean=-9.1e-4, RMSE= 0.009



Atmosphere

Initial surface temperature

Radiative transfer scheme

(modify RRTMG_LW surface condition)

Original: $F^{\uparrow} = \sum_i \pi \int_{\Delta v} B_v(T_{skin}) dv$

New: $F^{\uparrow} = \sum_i \varepsilon_i \pi \int_{\Delta v} B_v(T_{skin}) dv + \sum_i (1-\varepsilon_i) \cdot F_{i\_sfc}^{\downarrow}$

$F_{i\_sfc}^{\downarrow}$

T_{skin}

Translation layer

(modify T_{skin})

Original: $T_{skin} = (F_{sfc}^{\uparrow} / \sigma)^{1/4}$

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

$\varepsilon_{sea-ice} = f_{ice} \cdot \varepsilon_{ice} + (1 - f_{ice}) \cdot \varepsilon_{water}$

$F_{i\_sfc}^{\downarrow}$

$F_{sfc}^{\uparrow}, f_{ice}$

Land

Coupler

Ocean

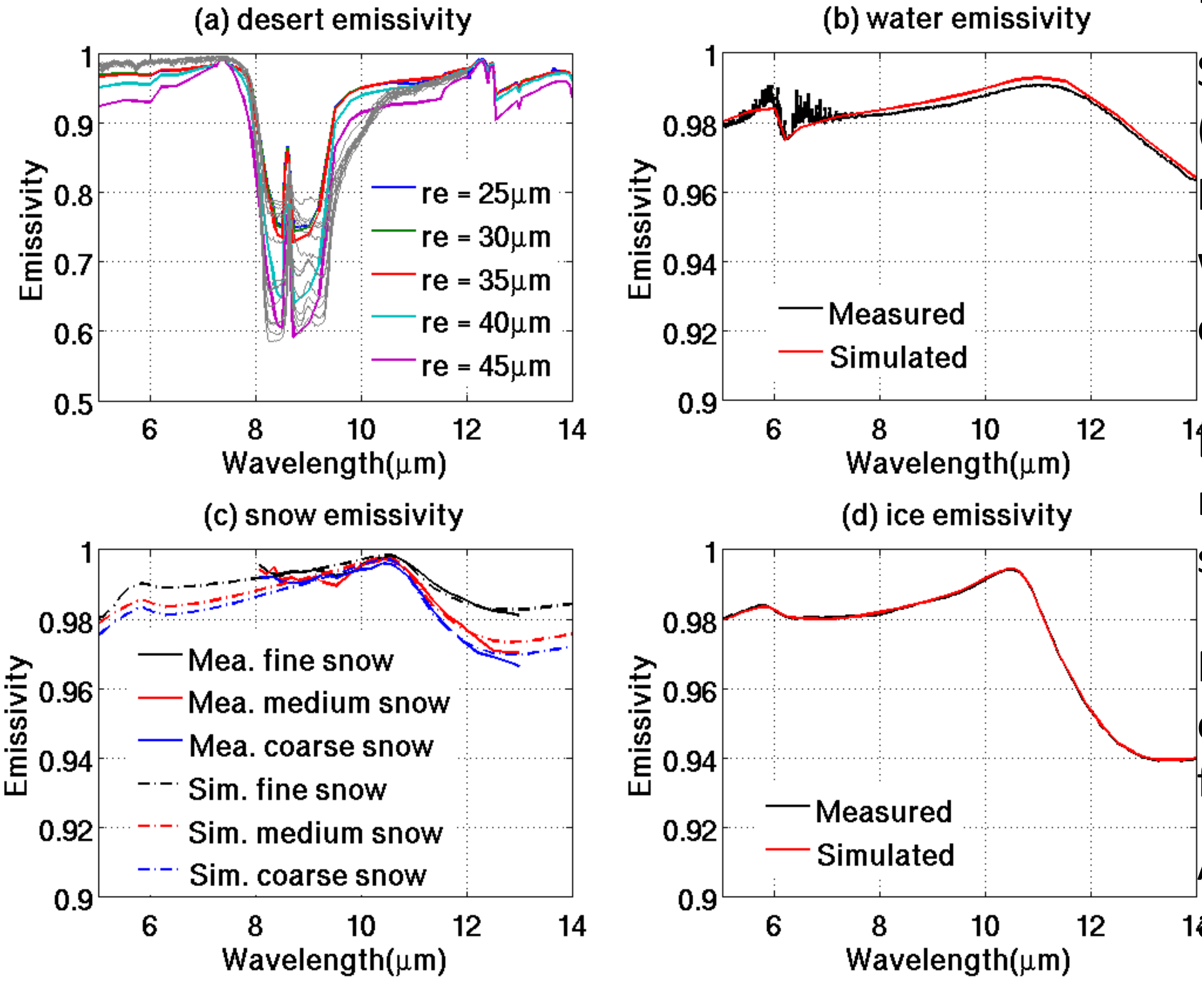
Sea ice

🟦 Current time step

🟨 Restart

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

First-principle simulation of the pan-spectral emissivity



Input: index of refractions

Snow: following Chen et al. (2014), scattering in densely packed medium

Water and Ice: Fresnel equations

Desert: silt (densely packed medium, varying r_e), planar sand grain

Four types (grass, dry grass, conifer, and deciduous) are from ASTER spectral library

A combination (55% of grass and 45% of desert).

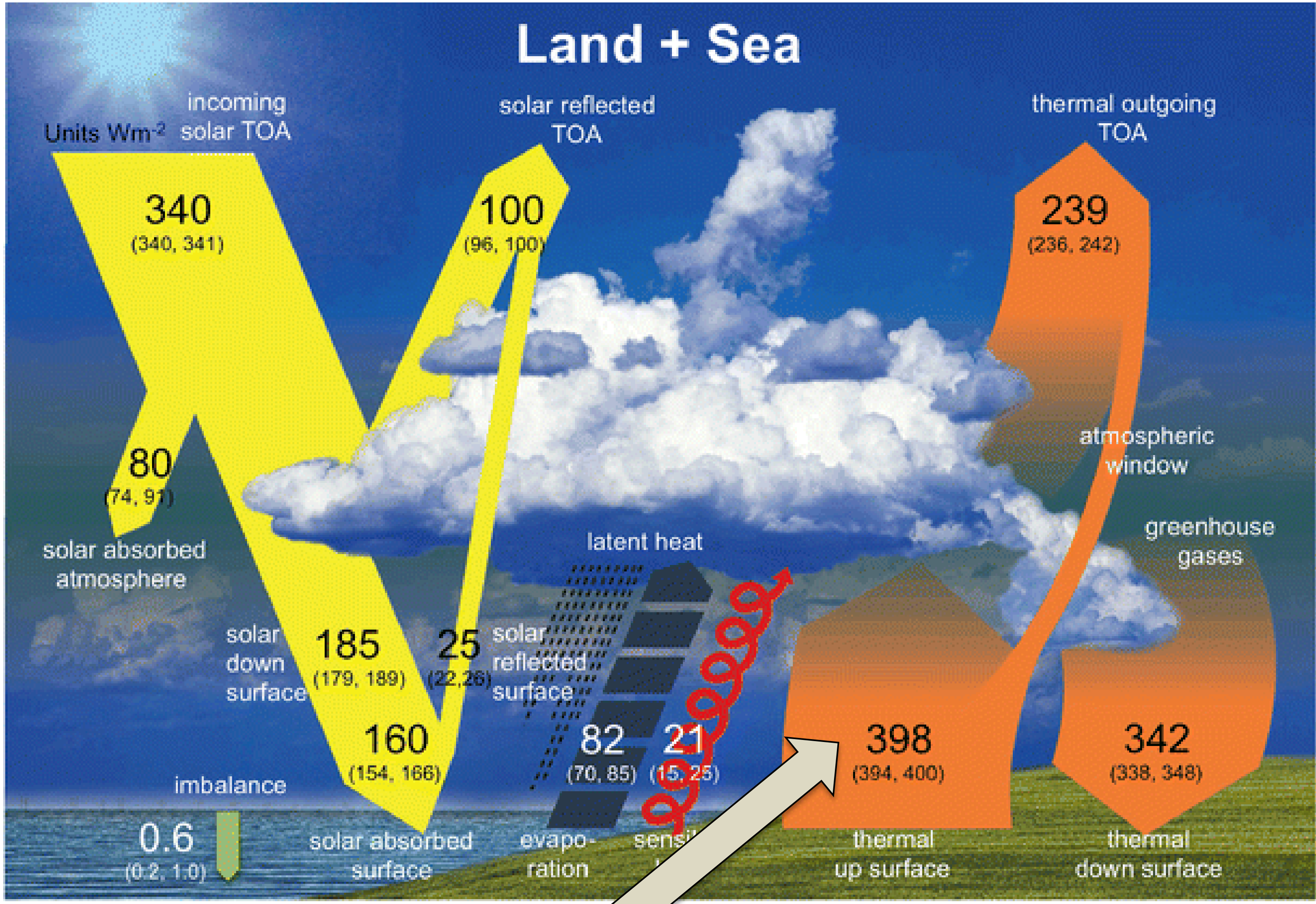
11 types: water, fine snow, medium snow, coarse snow, ice, grass, dry grass, conifer, deciduous, desert (16 sub-types), and a combination of desert and grass.

Usage of the data set

- Use data set for 2000-2015 period (MODIS era)
- Use data set for each calendar month
- Use the surface emissivity by type in the model (prognostic)

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

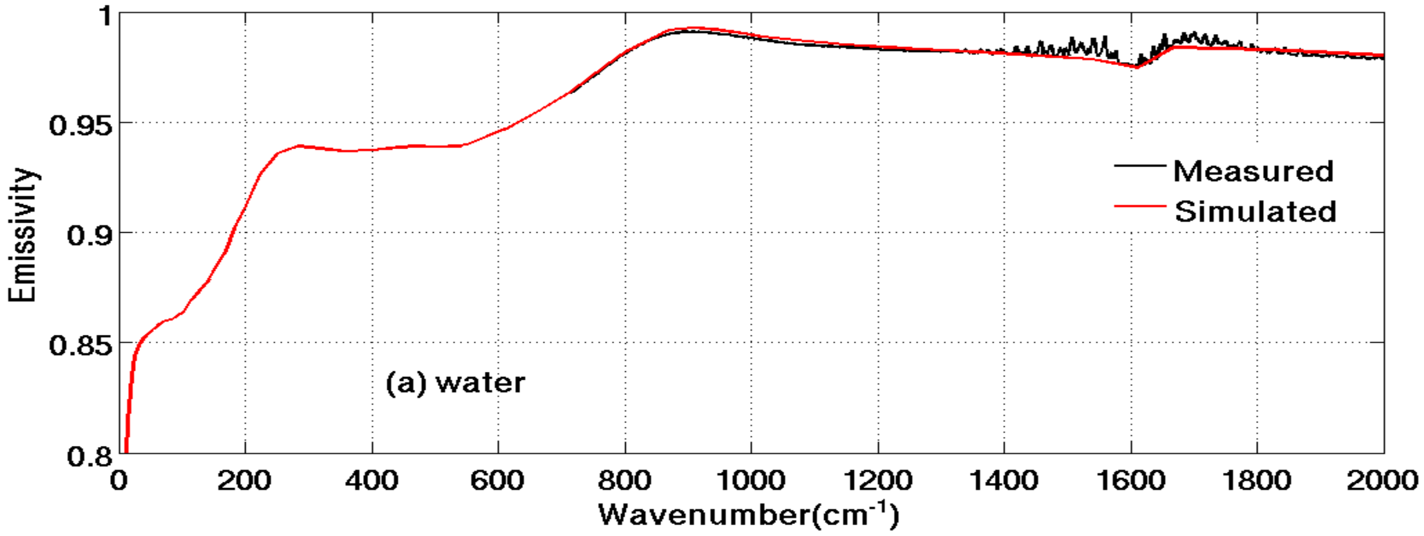
Surface ID	Surface Type
1	Grass
2	Dry grass
3	Decidous
4	Confier
5	Water
6	Fine snow
7	Medium snow
8	Coarse snow
9	Ice
10	Desert (subtypes included for fitting observations)
11	45% desert and 55% grass



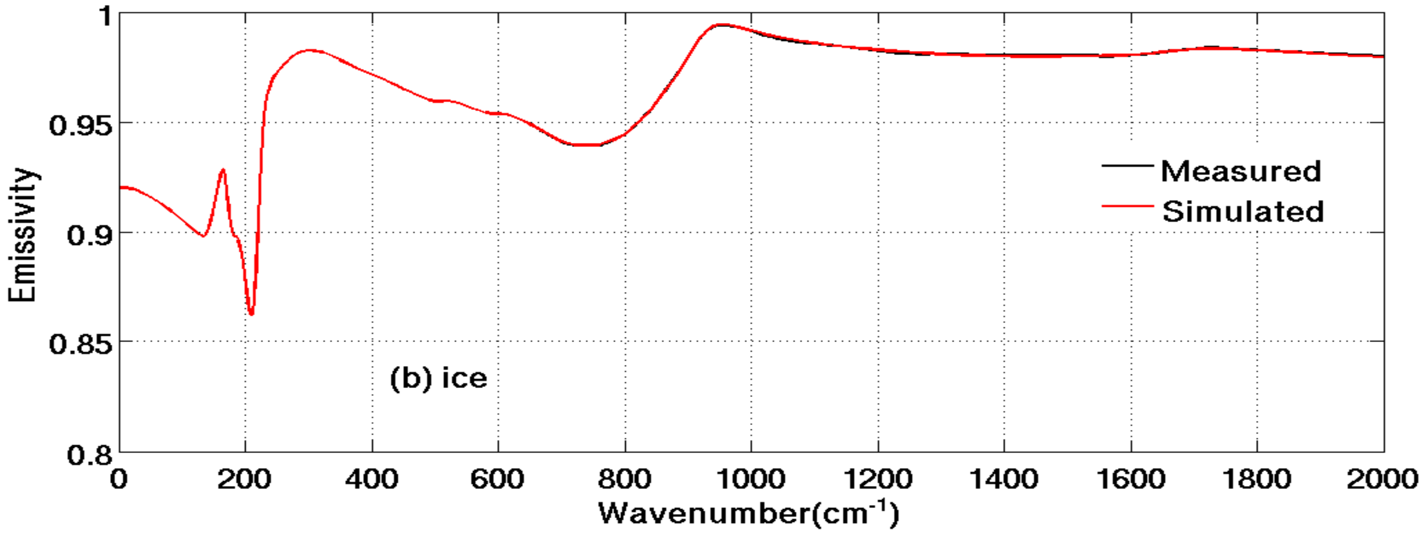
(Wild, 2015)

Has this LW_UP_FLUX been computed correctly in the GCMs? If not, by how much and what's the impact?

Water and Ice surface: Fresnel equation



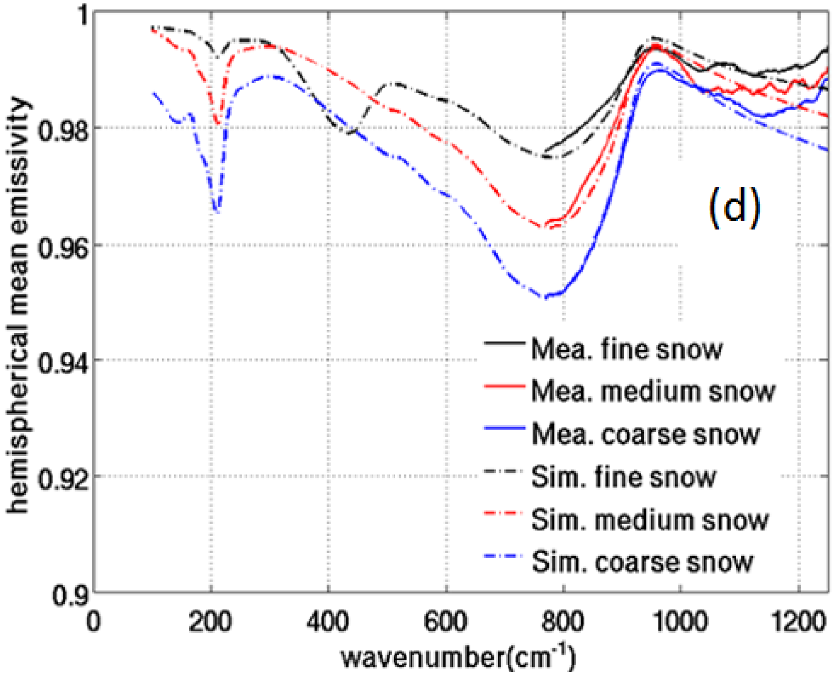
θ=10^o



Measured:
ASTER library

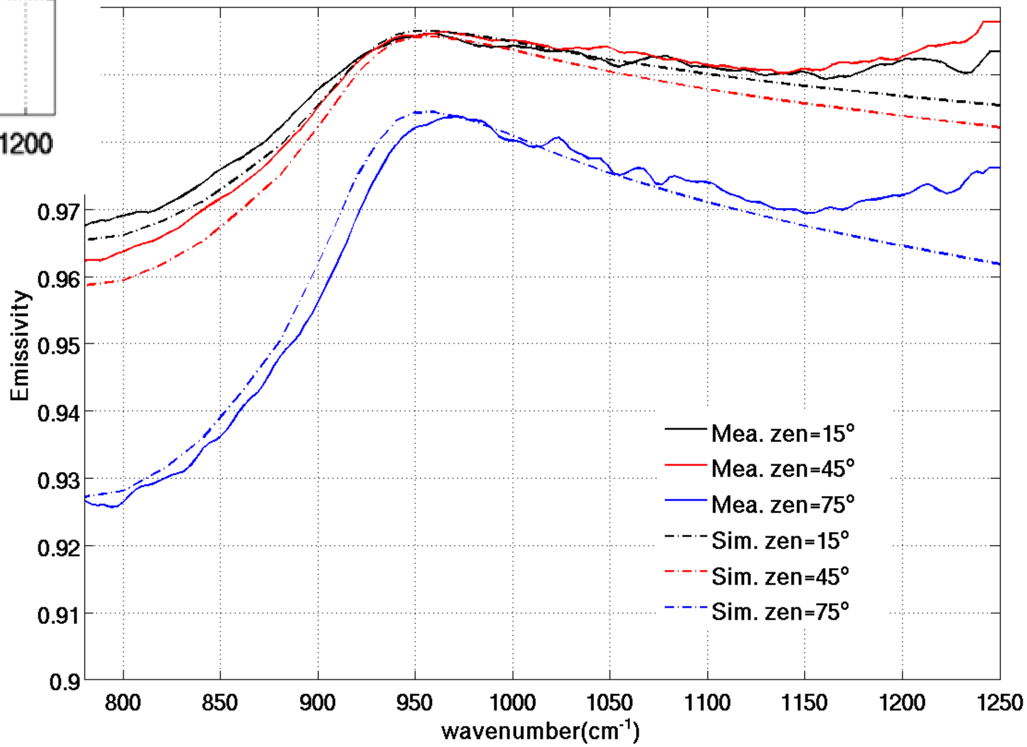
Modeling the snow surface emissivity

Different snow grain sizes
Measurement from Hori et al (2006)



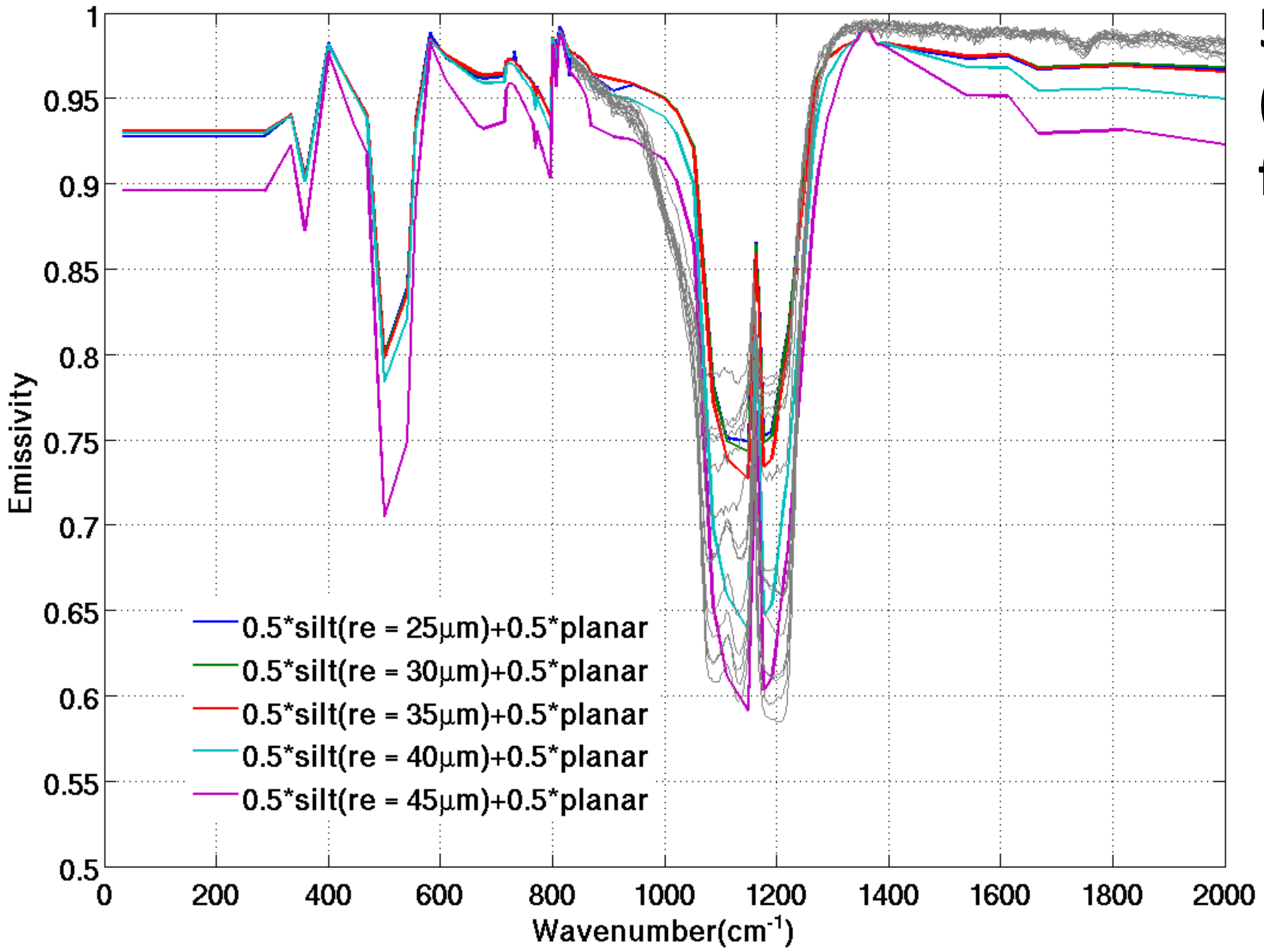
(Chen et al., 2014, GRL doi:10.1002/2014GL061216)

Emissivities at different viewing angles



Scattering in densely packed medium

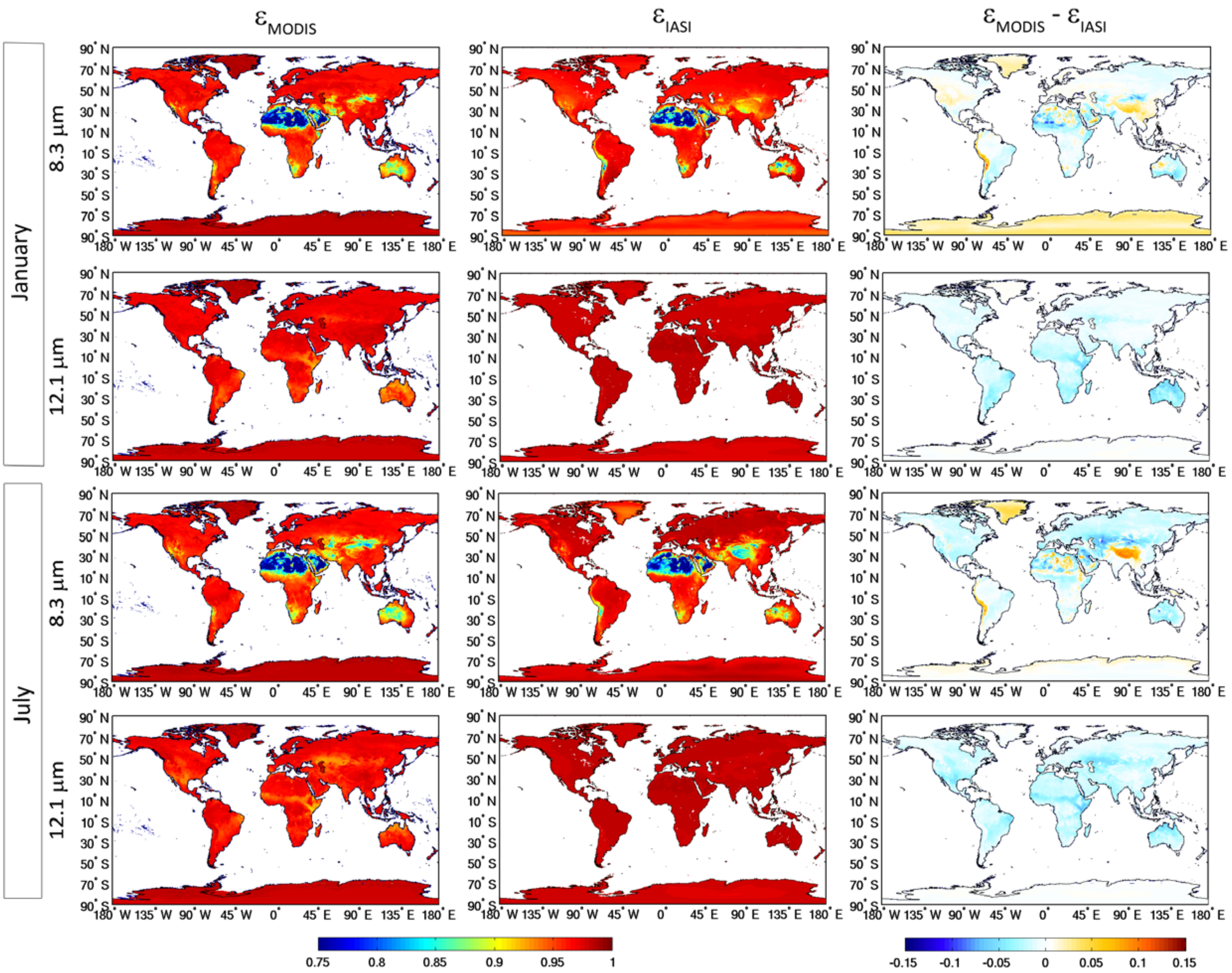
Deserts



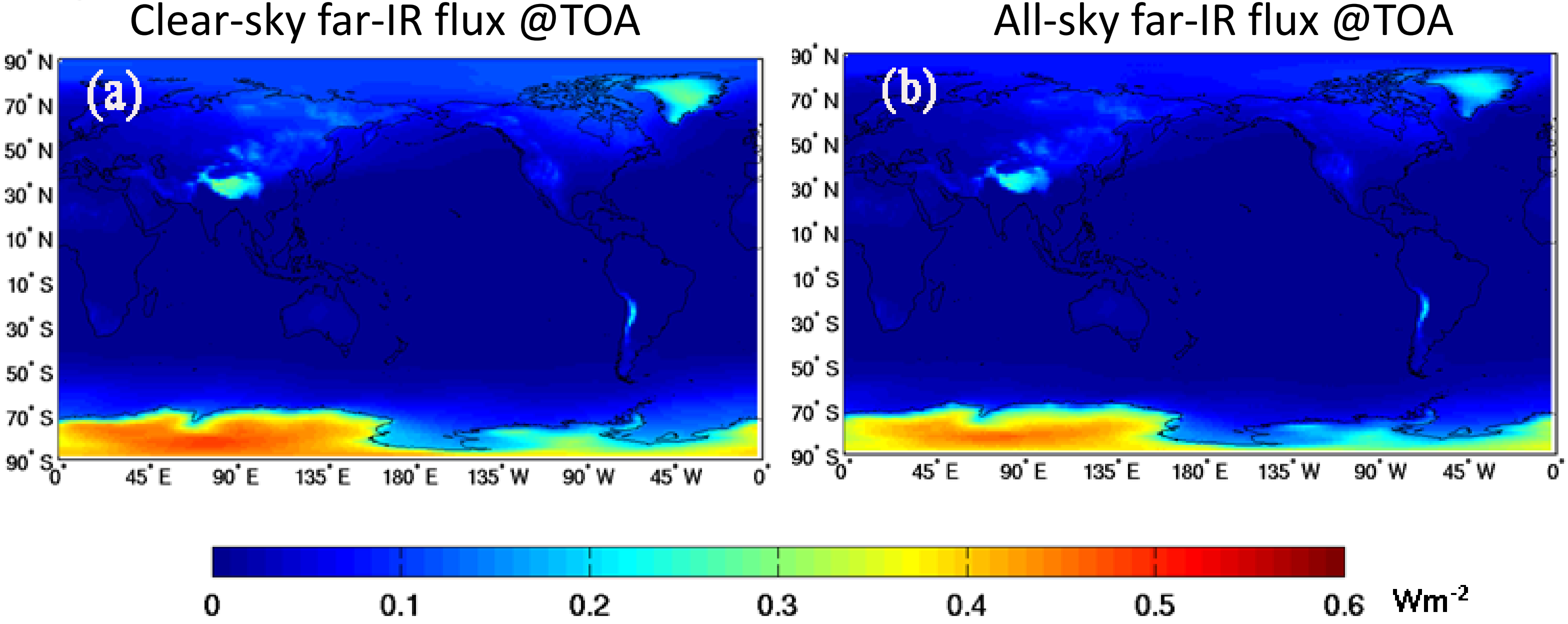
50% sand grain (planar) and 50% find grain (silt)

6 sites in Namib Desert and 8 sites in Kalahari Desert

Differences between two retrievals in January



At far-IR, Surface can be “visible” from space

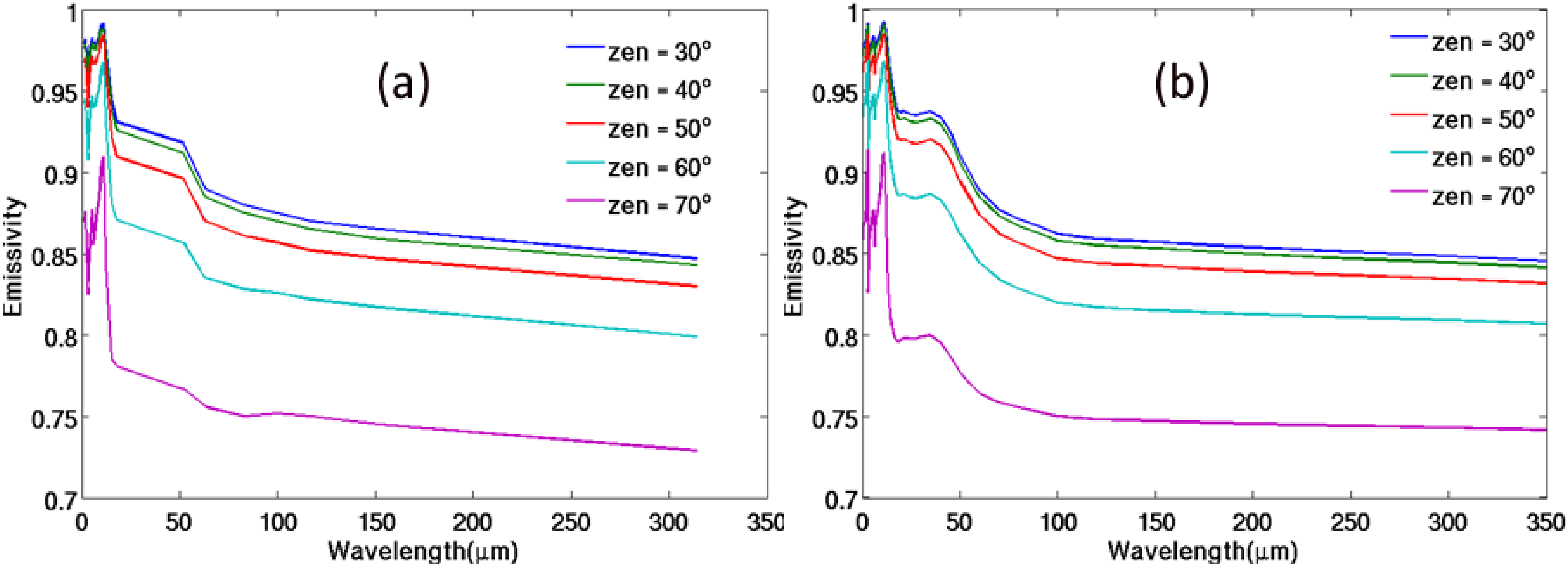

Clear-sky far-IR flux @TOA

All-sky far-IR flux @TOA

(Chen et al., 2014)

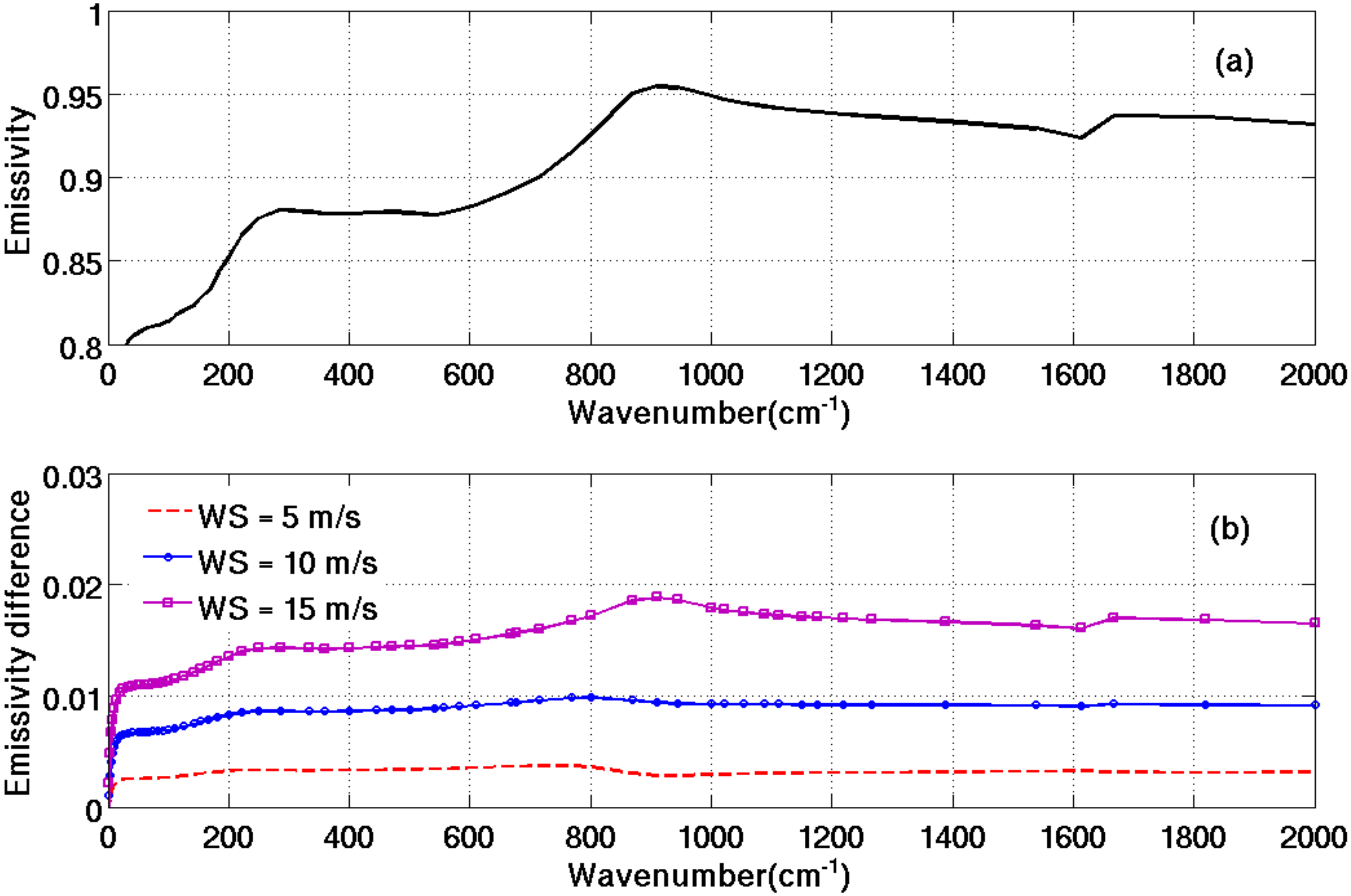
- Change of far-IR flux alone at TOA due to 1K change of surface temperature
- Surface emissivity can be important in far-IR for high-elevation regions (cold and dry)
- Chen et al. (2014) assessed the impact of surface emissivity and LW cloud scattering on far-IR radiation budget (off-line evaluation)
  - Chen, X. H., X. L. Huang, M. G. Flanner, 2014: Sensitivity of modeled far-IR radiation budgets in polar continents to treatments of snow surface and ice cloud radiative properties, ***Geophysical Research Letters***, 41, doi:10.1002/2014GL061216.

Water emissivity: change with θ

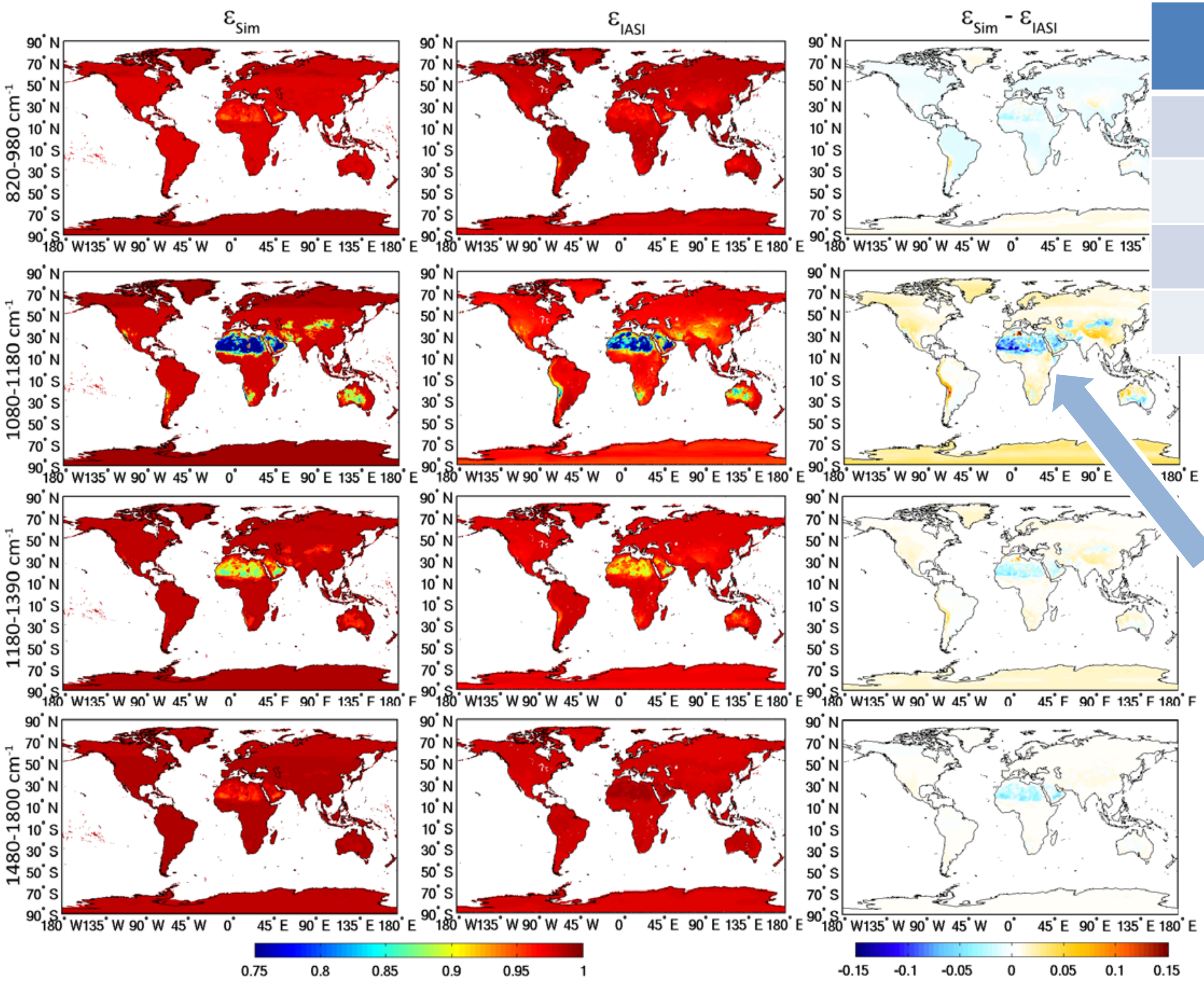


Measurements compiled by Mironova (1973),

Water emissivity: changes with wind speed



Difference between our data set and IASI retrievals in January

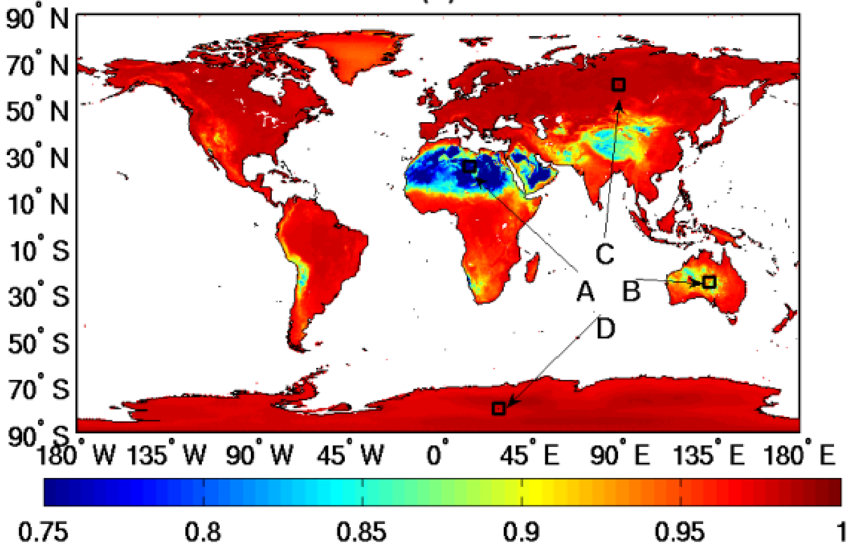


Mean (ε_{sim}-ε_{IASI})	RMS (ε_{sim}-ε_{IASI})
-0.005	0.01
0.006	0.03
0.006	0.01
0.005	0.01

Attributable back to the MODIS vs. IASI differences

Similar comparison results in other calendar months

(a)



Four places (A to D).

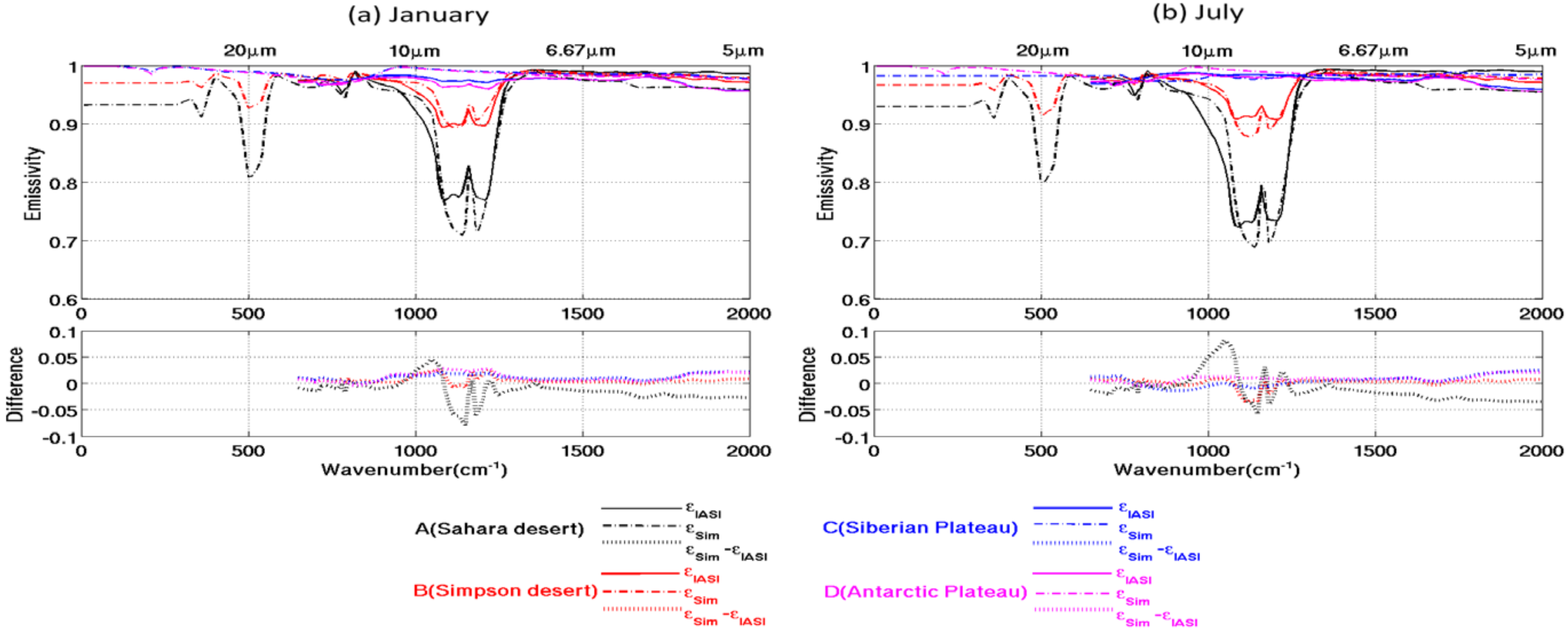
Place A (desert surface at 23°N,27°E

Place B (combined desert
and grass surface at
25°S,135°E)

Place C (grass surface at 60°N,90°E)

Place D (snow surface at 80°S,30°E).

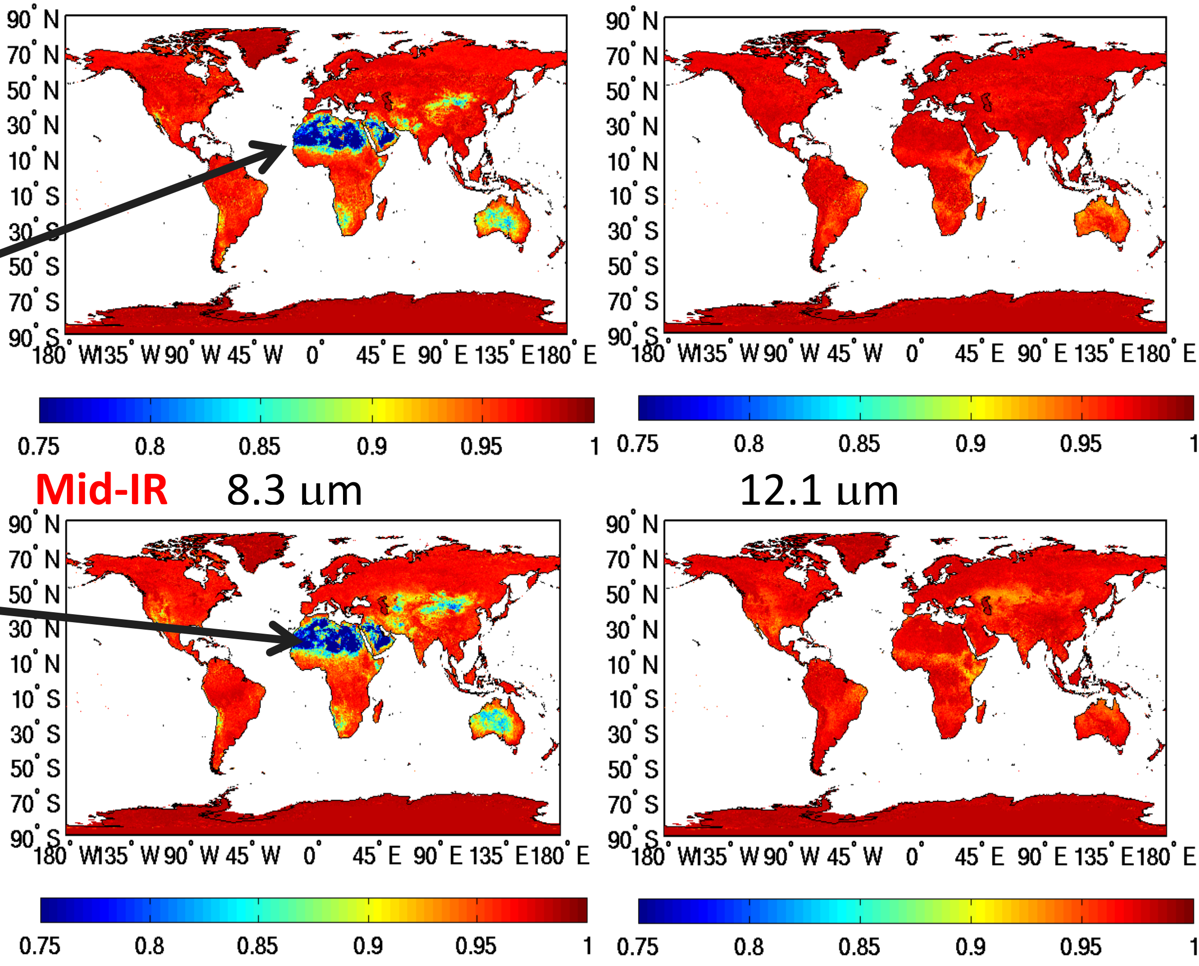
(b)



Surface emissivity

$$\varepsilon_\nu = \frac{F_{s_\nu}^{\uparrow}}{\pi B_\nu(T_s)}$$

Reality: emissivity changes with frequency/wavelength; it can also changes with time.



Jan2008

Jul2008

Mid-IR 8.3 um

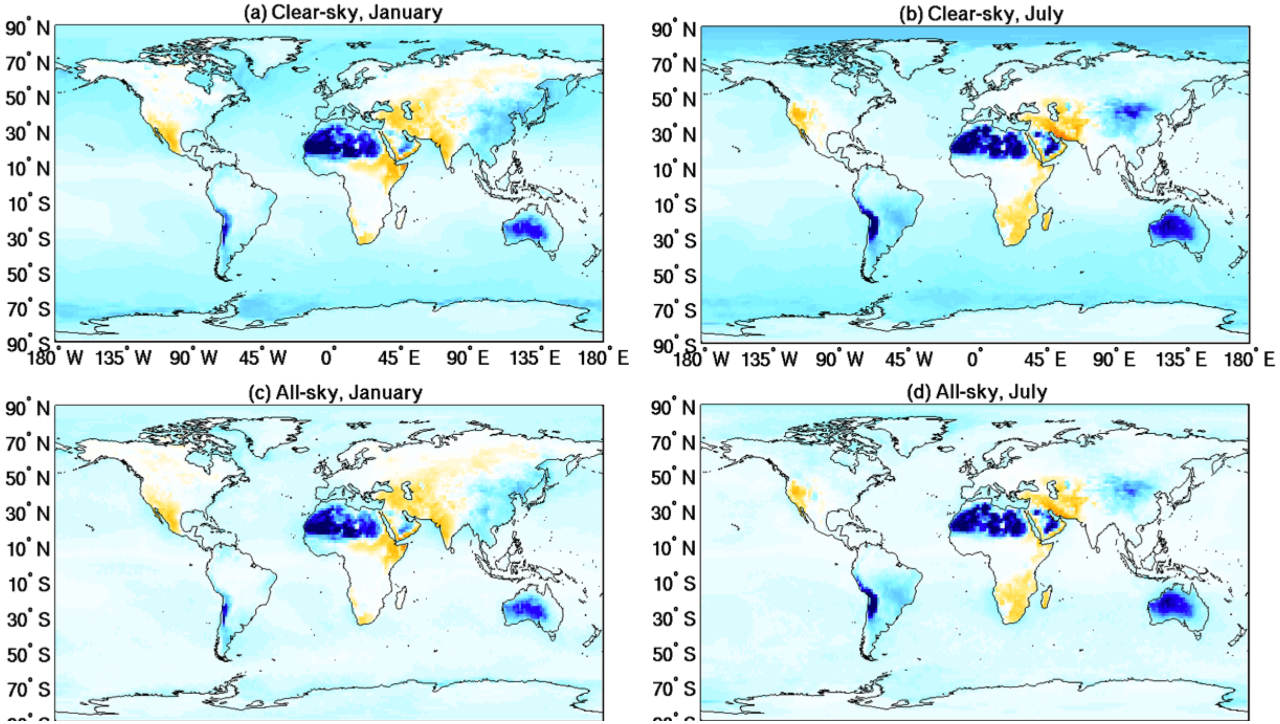
12.1 um

weak H2O continuum absorption

$\tau_\nu < 1$, thus $F_\nu^{\downarrow}(z=0) < \pi B_\nu(T_s)$?

$(1-\varepsilon_\nu)$ is not small

MODIS retrievals http://cimss.ssec.wisc.edu/iremis/data/



	Mean Diff (Wm^{-2})	RMS (Wm^{-2})
a	-1.19	1.83
b	-1.28	2.04
c	-0.66	1.28
d	-0.76	1.41

OLR difference