The benefit of far-IR measurements for a better understanding and model representation of the surface-atmospheric radiative coupling

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In collaboration with Ping Yang and his group in TAMU

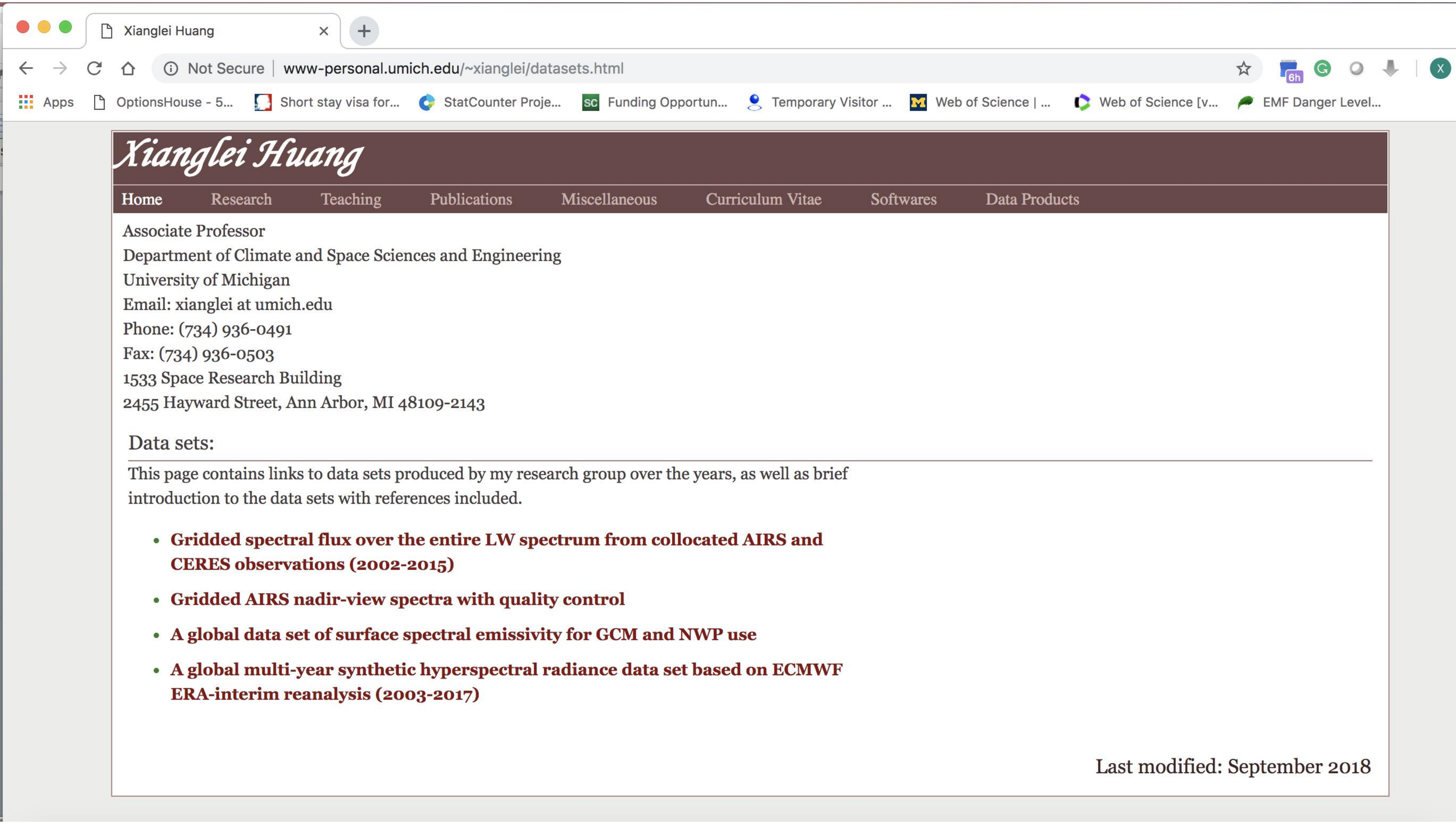
The 1st workshop on the FORUM mission
Florence, Italy, October 25, 2018

Acknowledgements: NASA Earth Science and DoE BER programs

Outline

- (excursus) Resources for the FORUM team
  - Surface emissivity
  - Spectral OLR and radiances
- Defining the problems
- Current progress and understandings
  - Little effect on simulated climate change
  - Effect on simulated mean climate change
- How to position FORUM for such challenges
- Synergy with PREFIRE
- Conclusions and Outlooks

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



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Data sets:

This page contains links to data sets produced by my research group over the years, as well as brief introduction to the data sets with references included.

- **Gridded spectral flux over the entire LW spectrum from collocated AIRS and CERES observations (2002-2015)**
- **Gridded AIRS nadir-view spectra with quality control**
- **A global data set of surface spectral emissivity for GCM and NWP use**
- **A global multi-year synthetic hyperspectral radiance data set based on ECMWF ERA-interim reanalysis (2003-2017)**

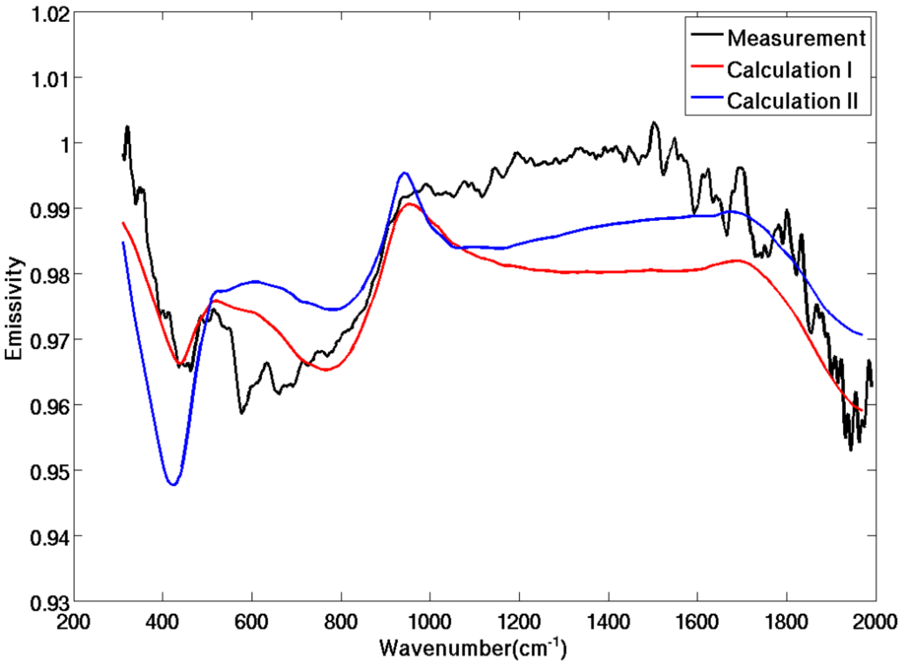
Last modified: September 2018

The 12-hourly full-IR radiances (1.0cm^{-1}) based on ERA-interim is also available upon request

Surface spectral emissivity over full IR

- Chen et al. (2014) first calculated far-IR snow emissivity. Then we calculated the spectral emissivity for other surface types. We provided it to other studies, e.g. Feldman et al. (2014).
- We developed a hybrid approach to estimate surface spectral emissivity in the far-IR (Huang et al., 2016, JAS)
  - First-principle calculation + MODIS fitting
  - Validated against IASI in the mid-IR
  - Used by Earthcare (Jason Cole), Imperial College group, Environmental Canada group, Wisconsin group, UMBC group, Feldman et al.
- More direct validation in the far-IR is needed, e.g. FORUM and PREFIRE.
- Planetary geology community has surface spectral emissivity measurements up to 200 cm^{-1} (lab measurement is available for some minerals)

Far-IR snow emissivity in lab



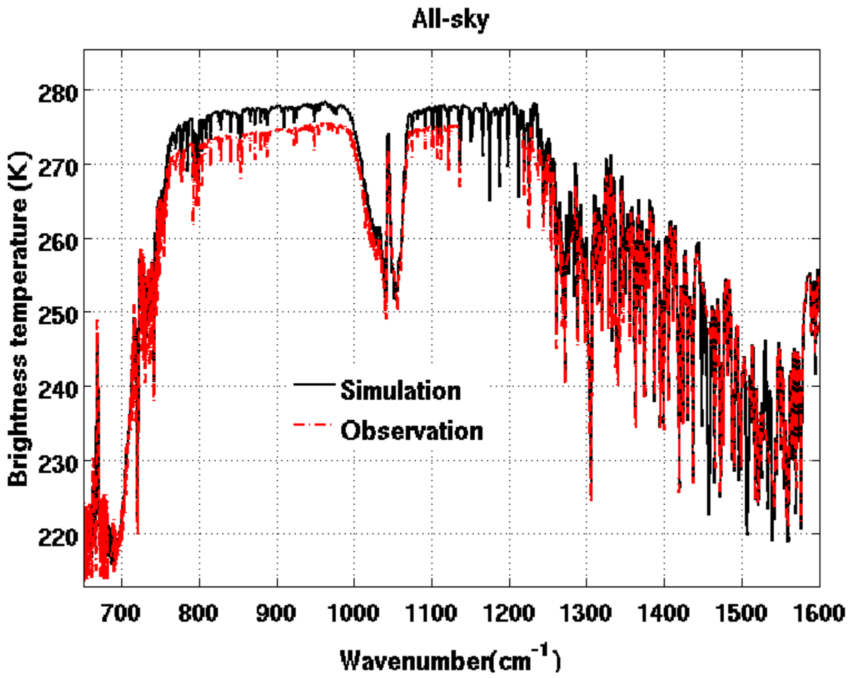
Preliminary results

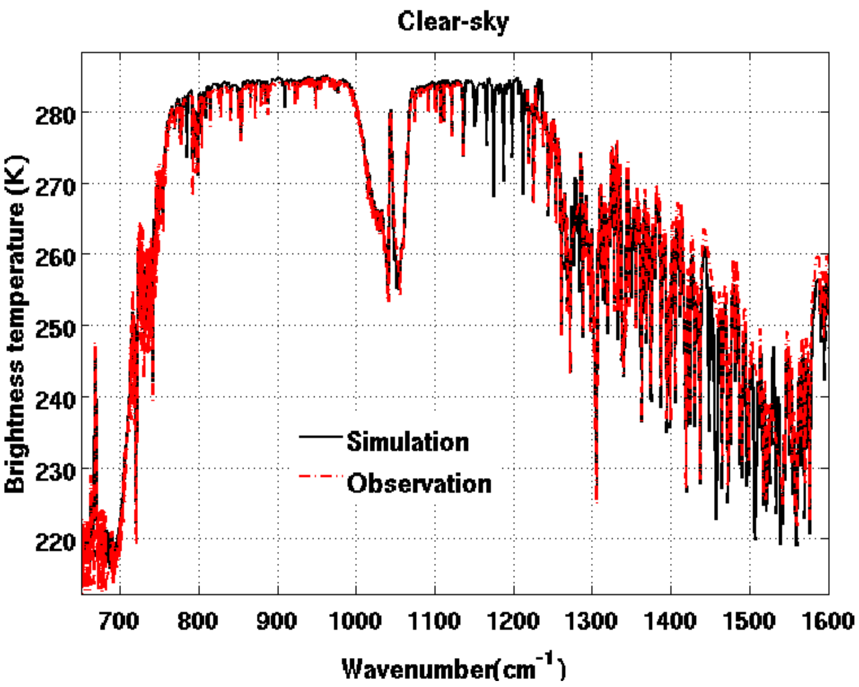
(Measurement from Prof. Glotch)

Spectral radiances: observed and simulated

- We processed AIRS nadir-view radiances in house (2002 to 2018), forms monthly radiance data sets
- Used in spectral fingerprinting study (Pan et al., 2017, J Climate)
- To assist FORUM and PREFIRE, we used ERA-interim 6-hourly output to produce synthetic radiances over the entire globe from 2003 to 2017
  - So far finished 12-hourly results (00/12 UTC)
  - 06/18 UTC results will be done in one month

Global-mean (80S-80N), Jan. 2016

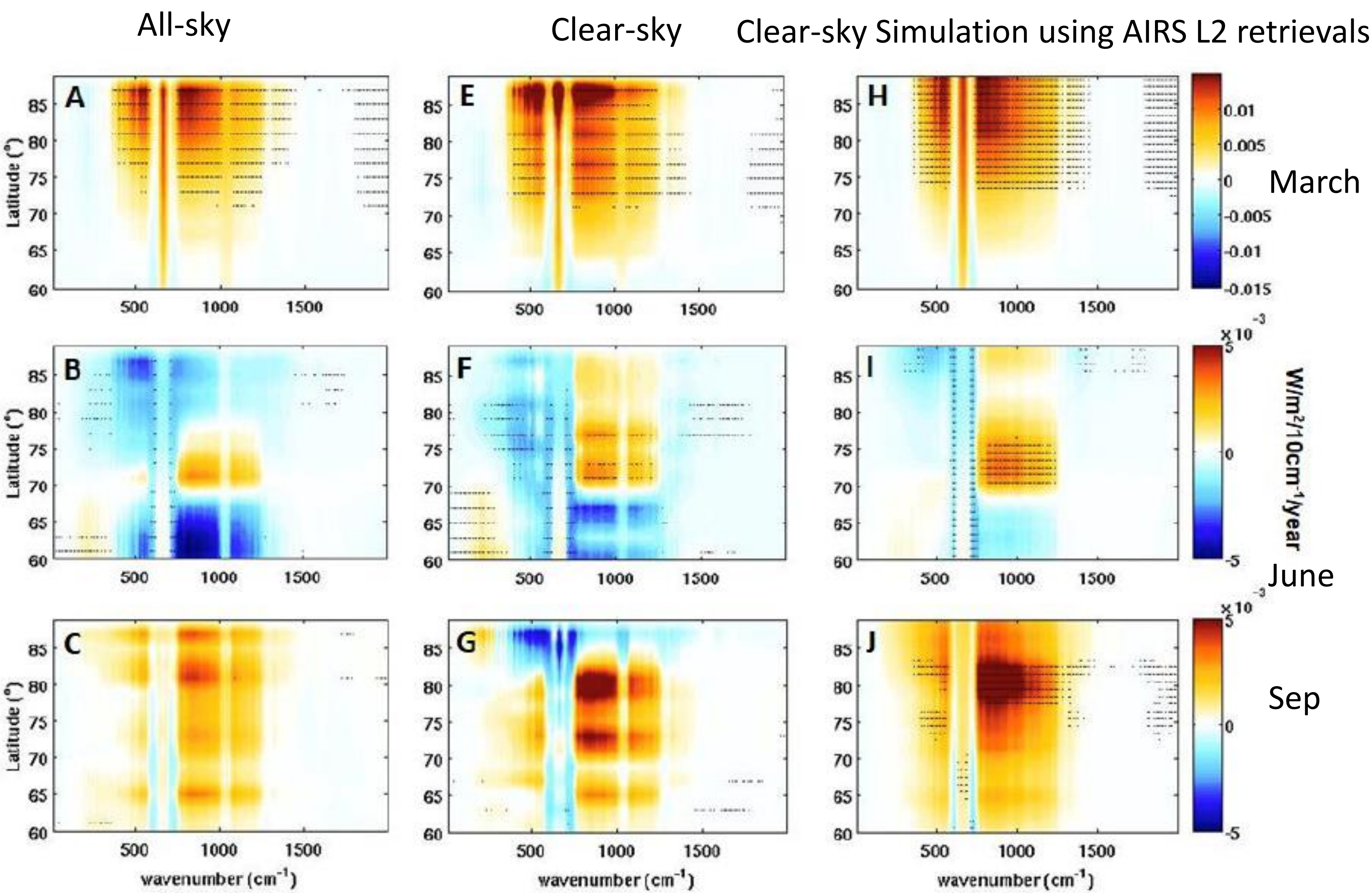




Observations: AIRS 1:30am/1:30pm local time average
Simulation: ERA-interim 00/12UTC average from 2 16-day averaged AIRS in Jan. 2016

AIRS is a grating spectrometer with many gaps in between
Resolving power is 1200.
Simulation: 1cm^{-1} spectral resolution (CLARREO simulator)

Trends of Spectral OLR in the Arctic (2003-2017)

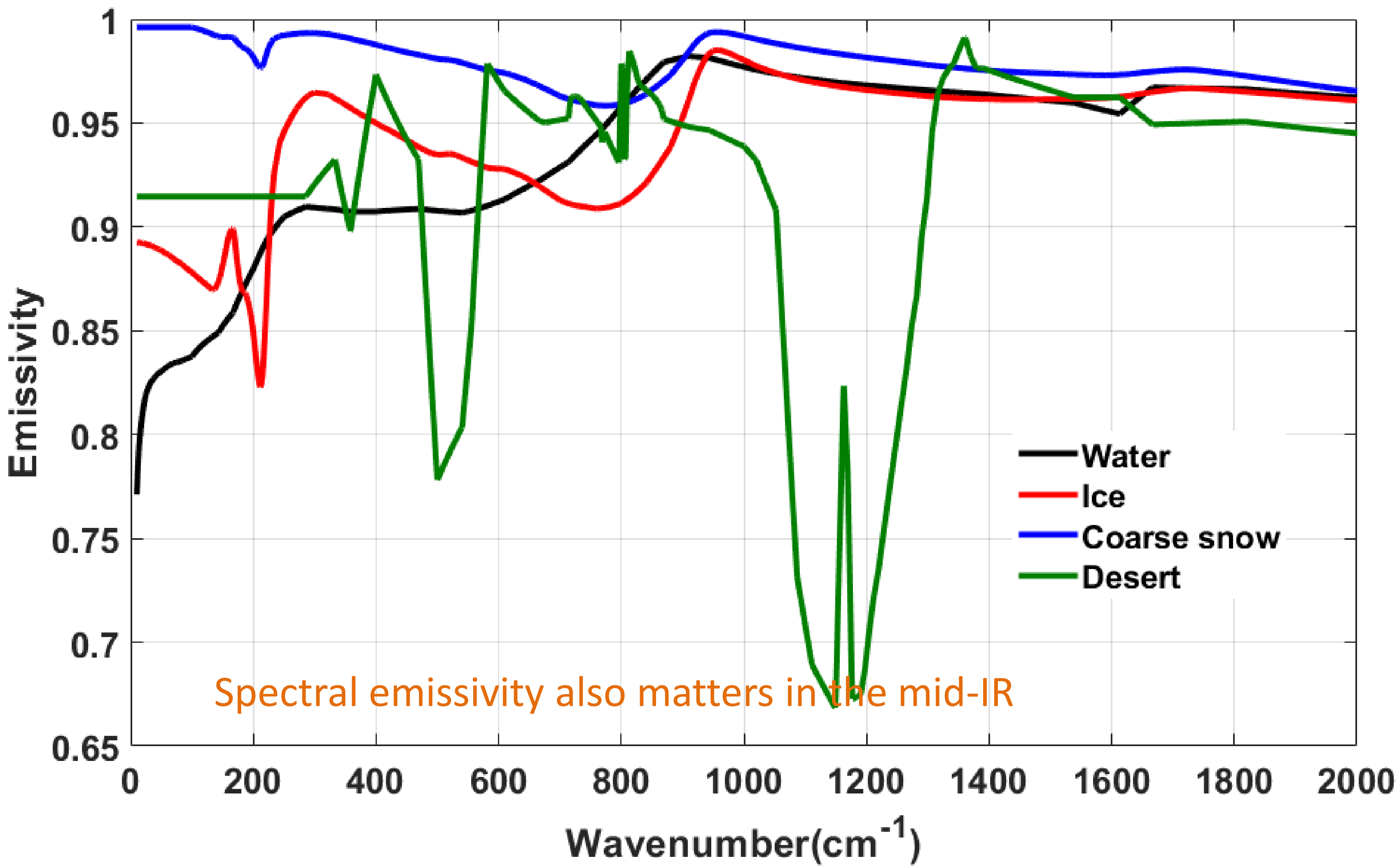


Spectral OLR here is directly derived from AIRS L1B radiances (Huang et al., 2008;2010; 2014)

Go back to the topic: Atmospheric-surface radiative coupling …

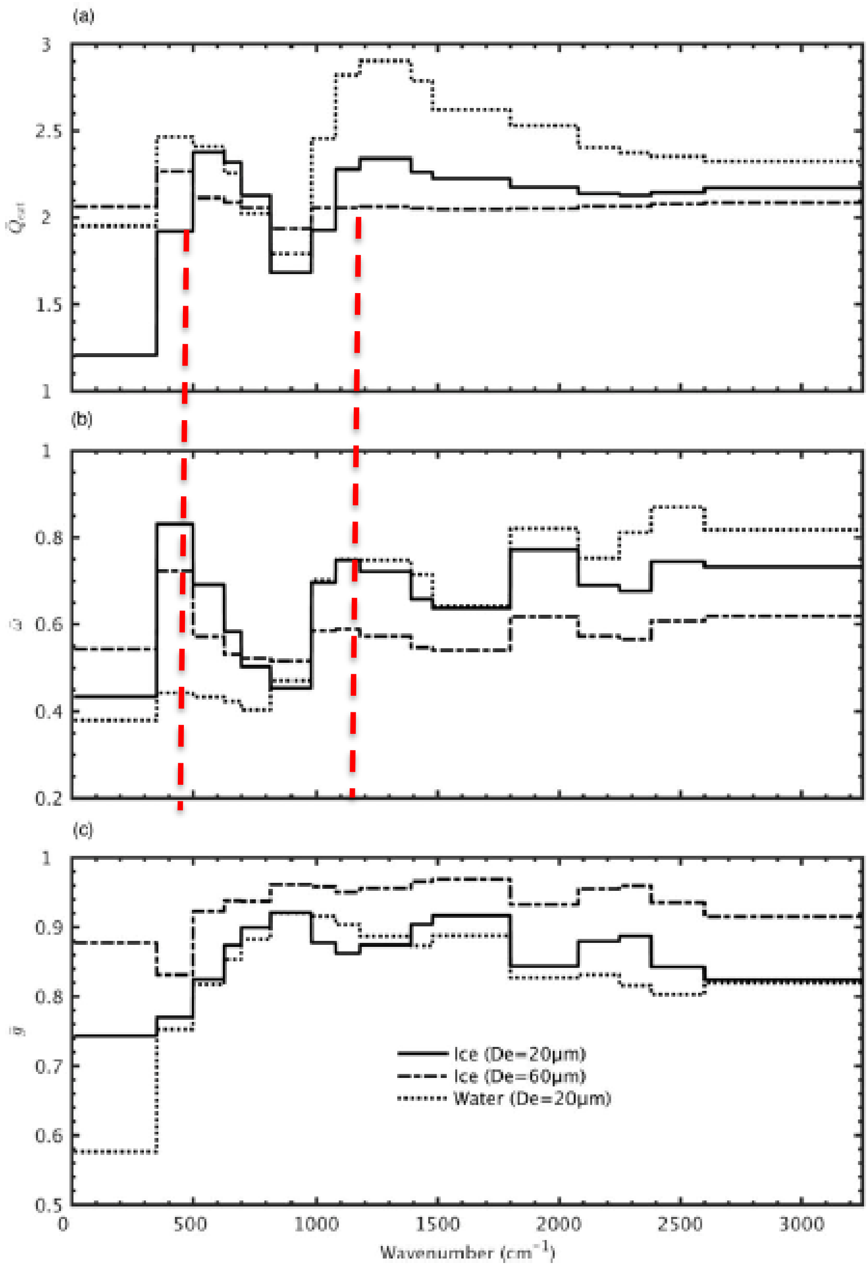
Defining the problems

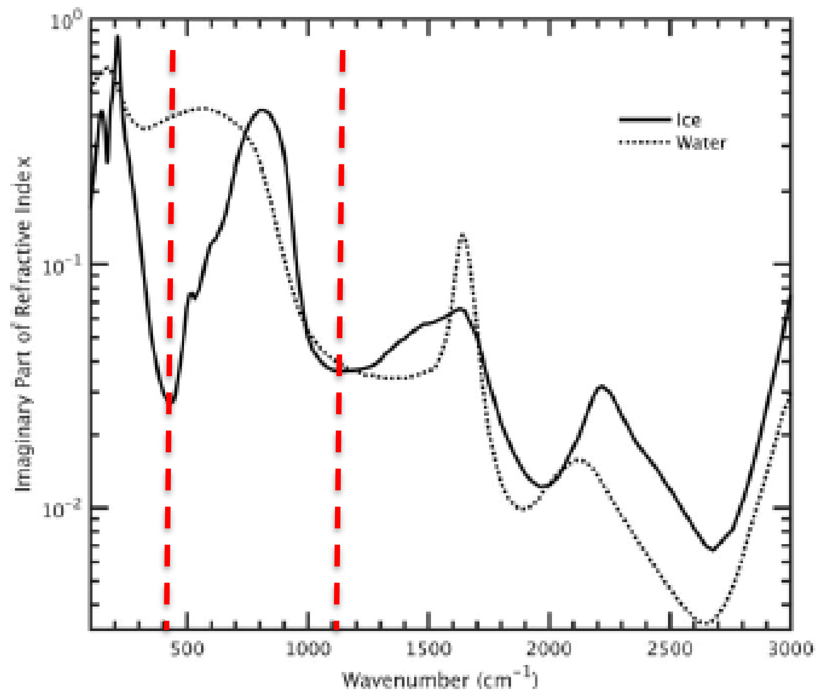
- Surface emissivity $$e_v(q) = \frac{I(q)^{-}_{s_v}}{B_v(T_s)}$$
  - A function of frequency and solid angle
  - A fundamental quantity in LW radiative transfer
- In earth remote sensing community, **Few** measurements in the far-IR (<650cm^{-1})
  - Traditional thoughts:
    - Far-IR water vapor absorption is strong
    - Atmosphere is opaque in the far-IR
    - Surface emissivity is little of important
  - This breaks down at cold and high-elevation region
  - Coupled with cloud scattering, especially in the far-IR, this is what we refer as **the surface-radiative coupling**
  - Chen et al. (2014) was the first to note this issue in modeling and did an off-line estimate of its impact on TOA radiation budget



(Huang et al., 2018, J Climate)

Cloud LW scattering



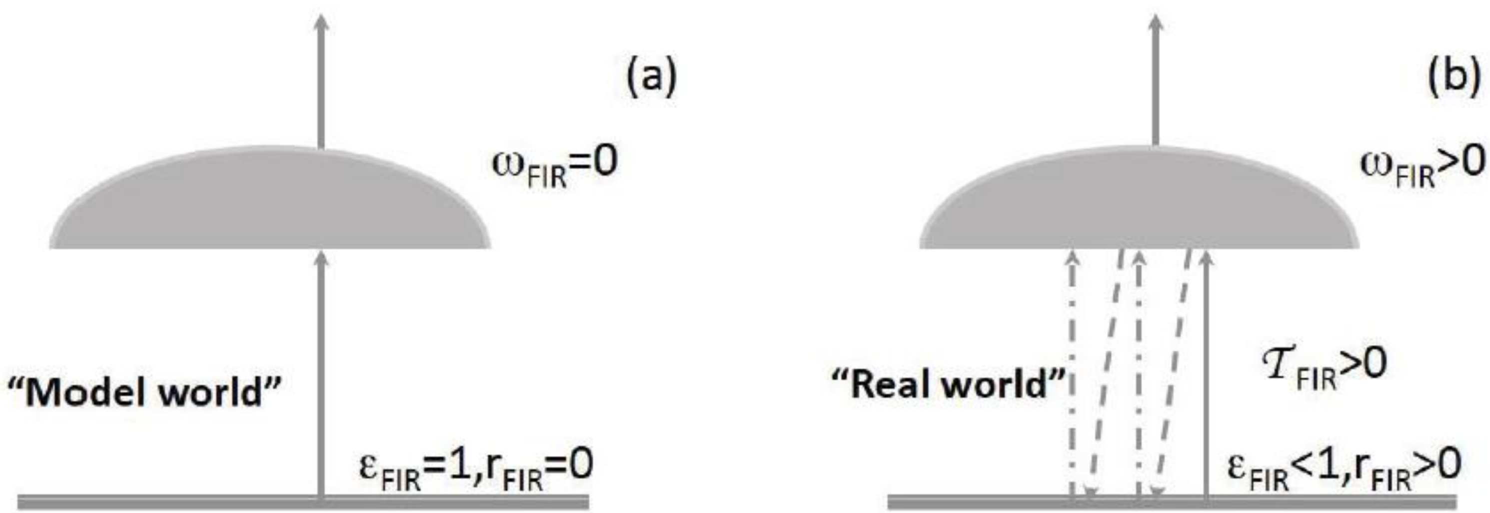


Im(**n**) minimum ⟷ Scattering peaks

Most GCMs assume non-scattering clouds in the LW

(Kuo et al, 2017, JAMES)

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.**
- **Premise: Scattering will lead to more atmosphere absorption, thus more downward LW flux**

How much can such mechanisms affect simulated climatology and simulated climate change?

To answer these questions, we employ a suite of modeling approaches

- Incorporate cloud scattering and new consistent ice cloud optics (MC6/TAMU) into the NCAR CESM and DoE E3SM
- Incorporate surface spectral emissivity into the NCAR CESM (done) and DoE E3SM (ongoing)
- Assess their impacts on simulated radiation budget, mean climate state, and climate change.

First, little impact on climate change (Huang et al., 2018, J Climate)

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 to understand it physically? A back-envelope calculation

$$F_{SW}^{\uparrow} = aF_{SW}^{\downarrow}, \qquad dF_{SW}^{\uparrow} = da \cdot F_{SW}^{\downarrow},\ \text{ice} \leftrightarrow \text{ocean},\ da \sim 0.8$$

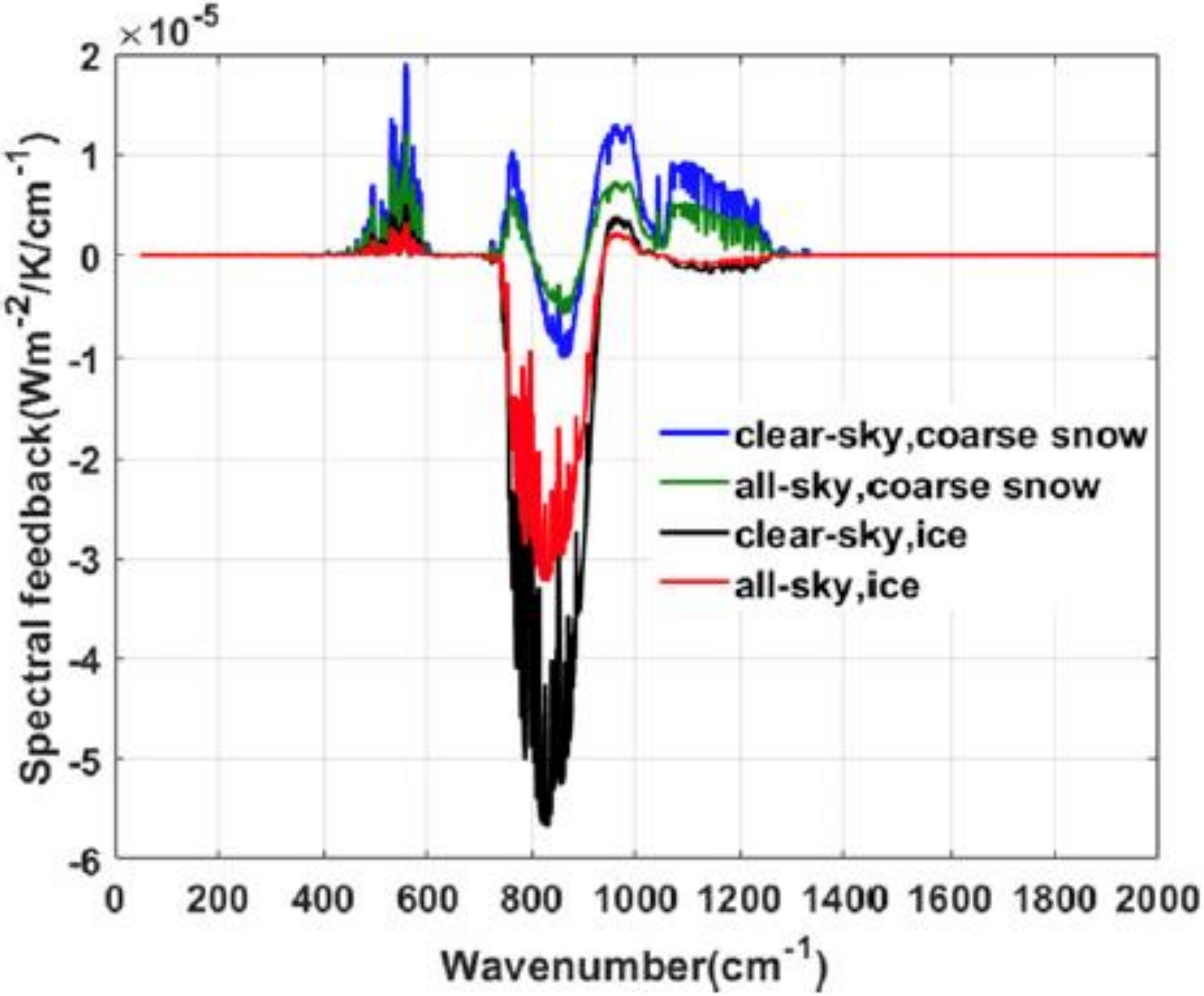
$$F_{LW}^{\uparrow} = e_v B_v(T_s) + (1 - e_v)F_{LW}^{\downarrow}, dF_{LW}^{\uparrow} = de \cdot \left[B_v(T_s) - F_{LW}^{\downarrow} \right], \text{ice} \leftrightarrow \text{ocean}, de \sim 0.1 \text{ or less}$$

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

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

- Feldman et al. (2014) yr 2030 vs. 2000 results were really contrast of two “branch” runs, showing more about mean-state difference than any real climate-change singles.

Spectral details of the sea-ice emissivity feedbacks



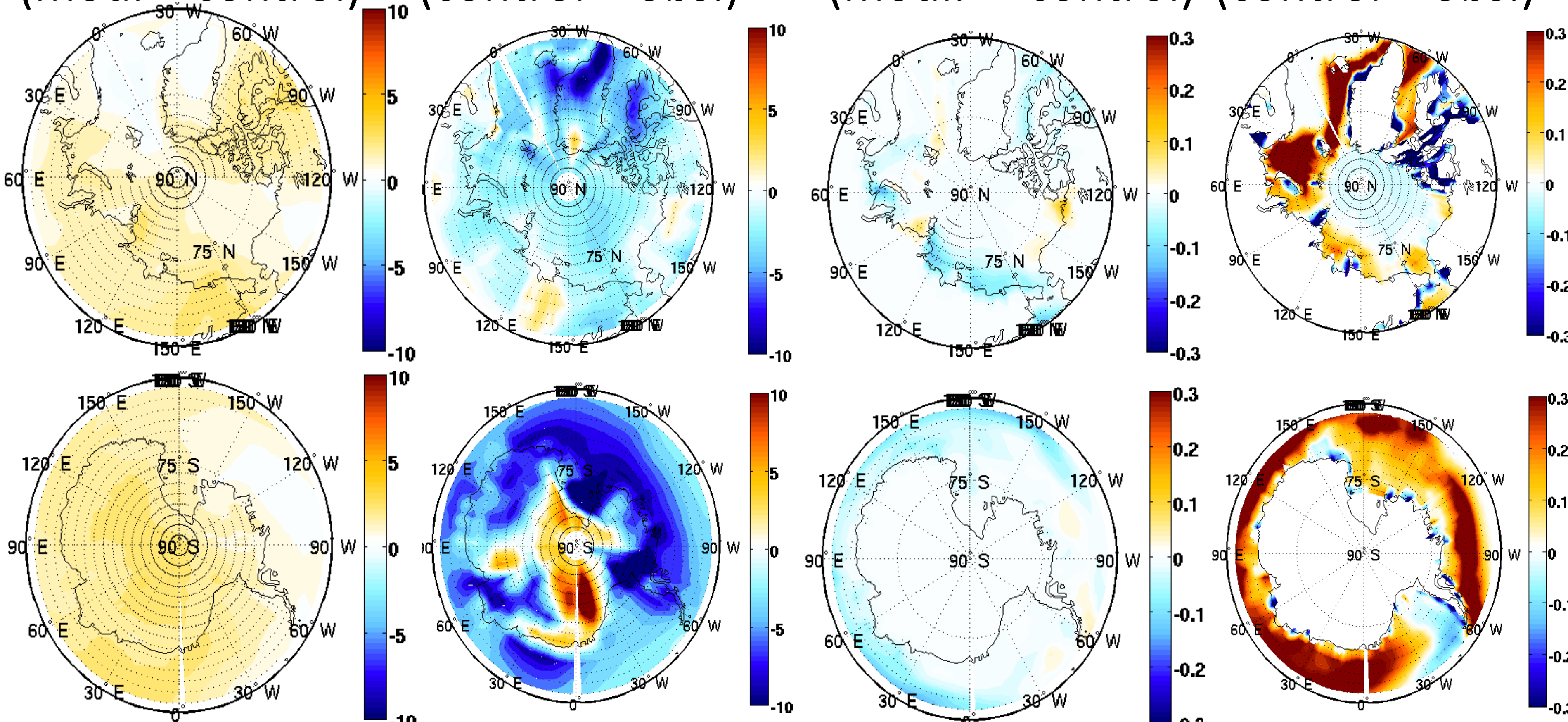
Mid-IR matters

(Huang et al., 2018)

Impact on mean climate: help alleviating the polar cold bias (Huang et al., 2018, J Climate)

(Updated figure, with scattering included)

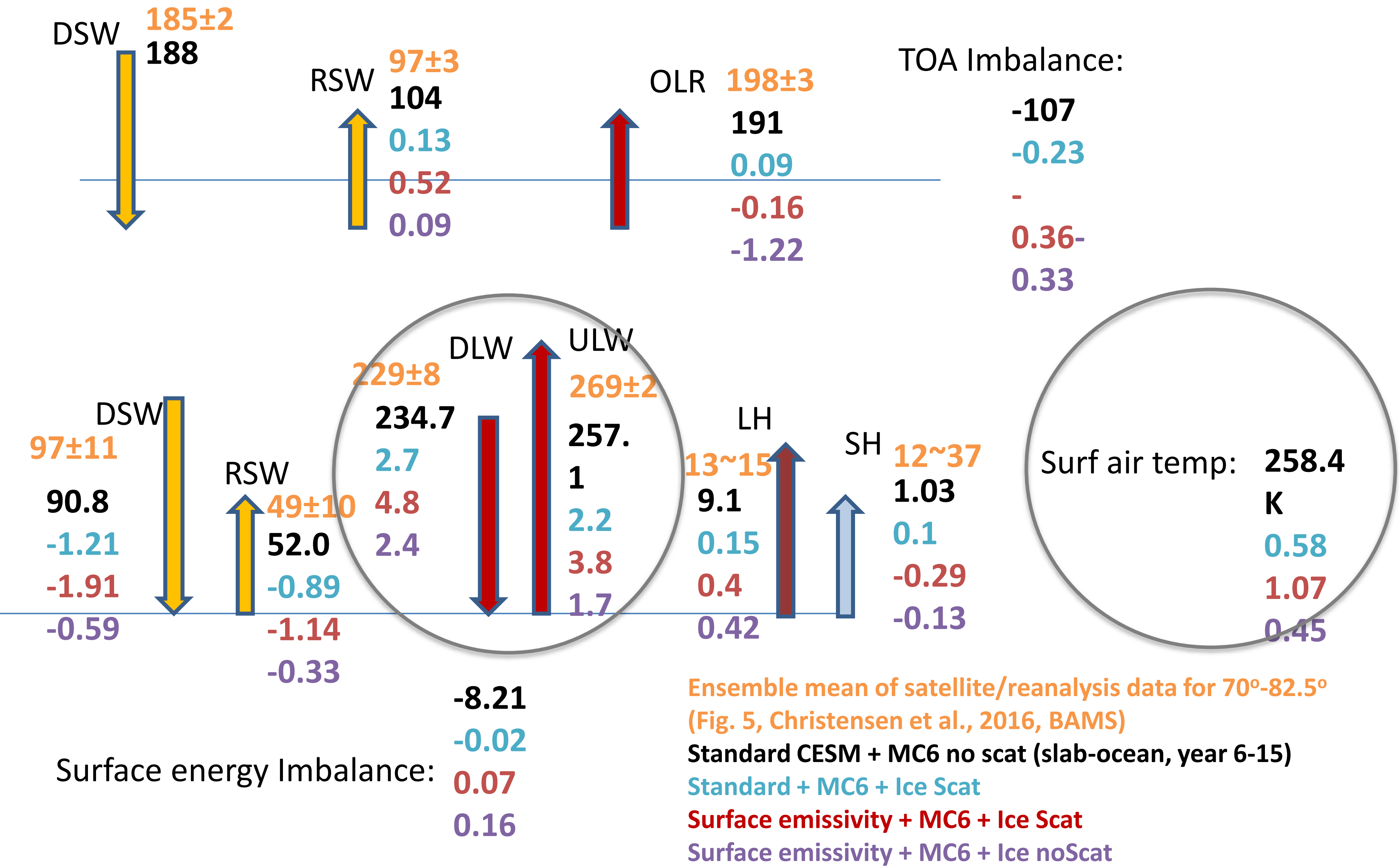
T_{2m} difference (modi – control) | T_{2m} difference (control – obs.) | f_{ice} difference (modi. – control) | f_{ice} difference (control – obs.)



Same color scale | **Same color scale**

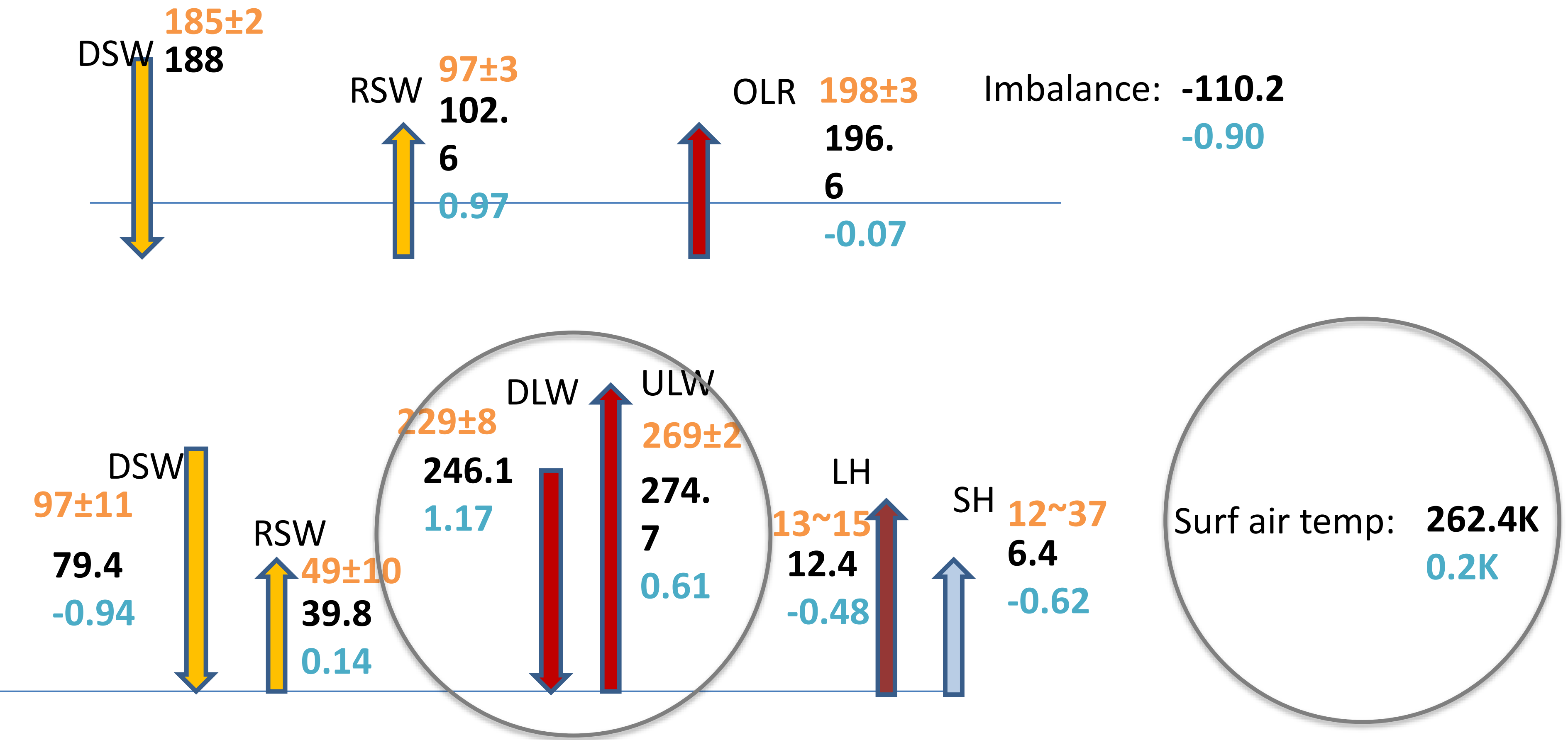
Impact on mean climate: TOA & surface energy budget

NCAR CESM Annual-mean energy budget over the Arctic (66.5°-90°N)



As expected, including both surface emissivity and cloud LW scattering warms up the surface more

DoE E3SM Annual-mean energy budget over the Arctic (66.5°-90°N)



Ensemble mean of satellite/reanalysis data for 70°-82.5° (Fig. 5, Christensen et al., 2016, BAMS)

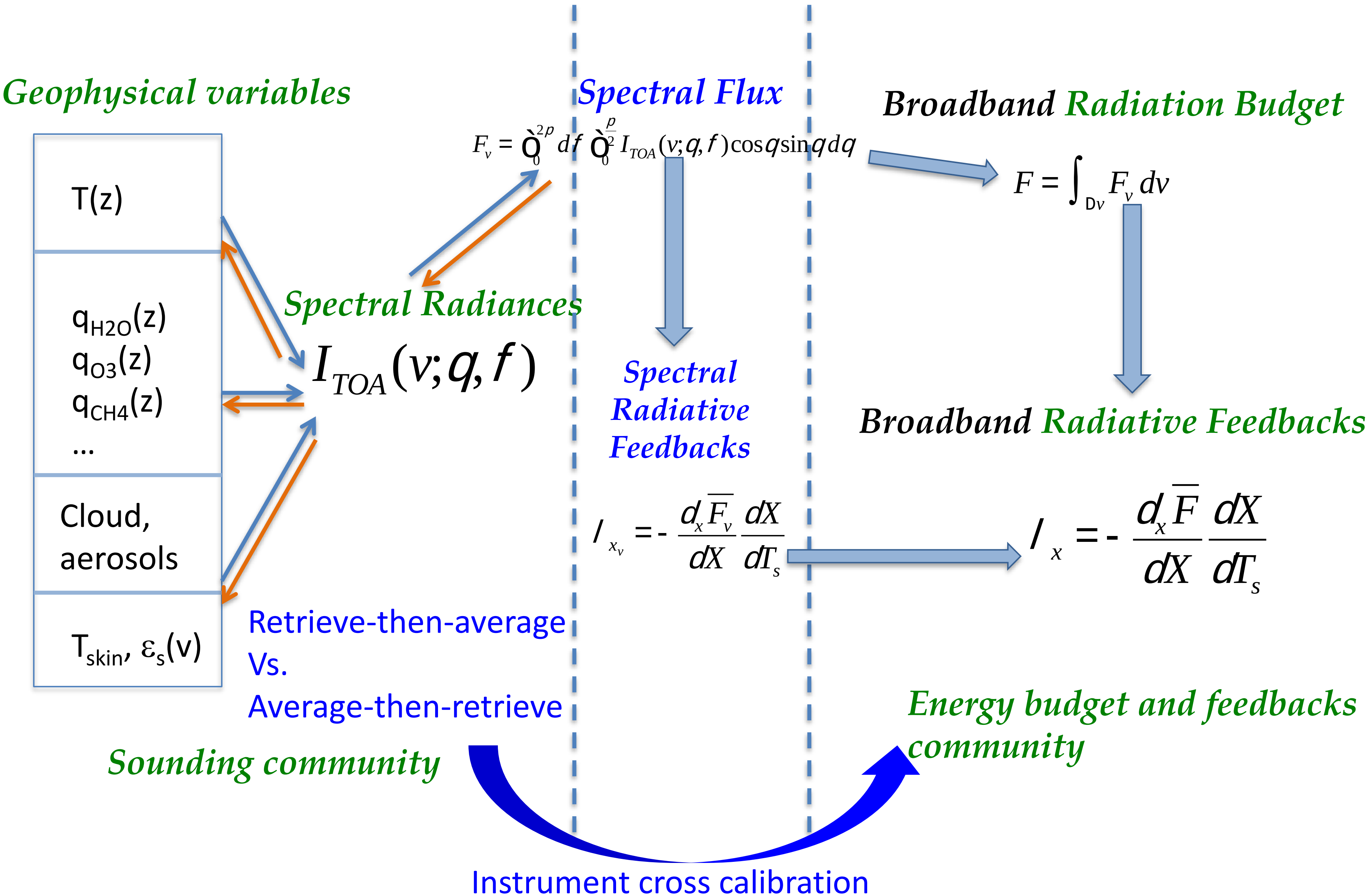
Standard E3SM + MC6 no scat (fixed SST run)

Standard + MC6 + Ice Scat

In terms of model evaluation and testing climate models, what can FORUM be valuable for?

- With IASI, provide DIRECT estimate of full spectral OLR.
- Spectral OLR can reveal **compensating biases** in the climate model that cannot be revealed by OLR diagnostics alone.
- This bridges model diagnostics…

Synthesis: my view

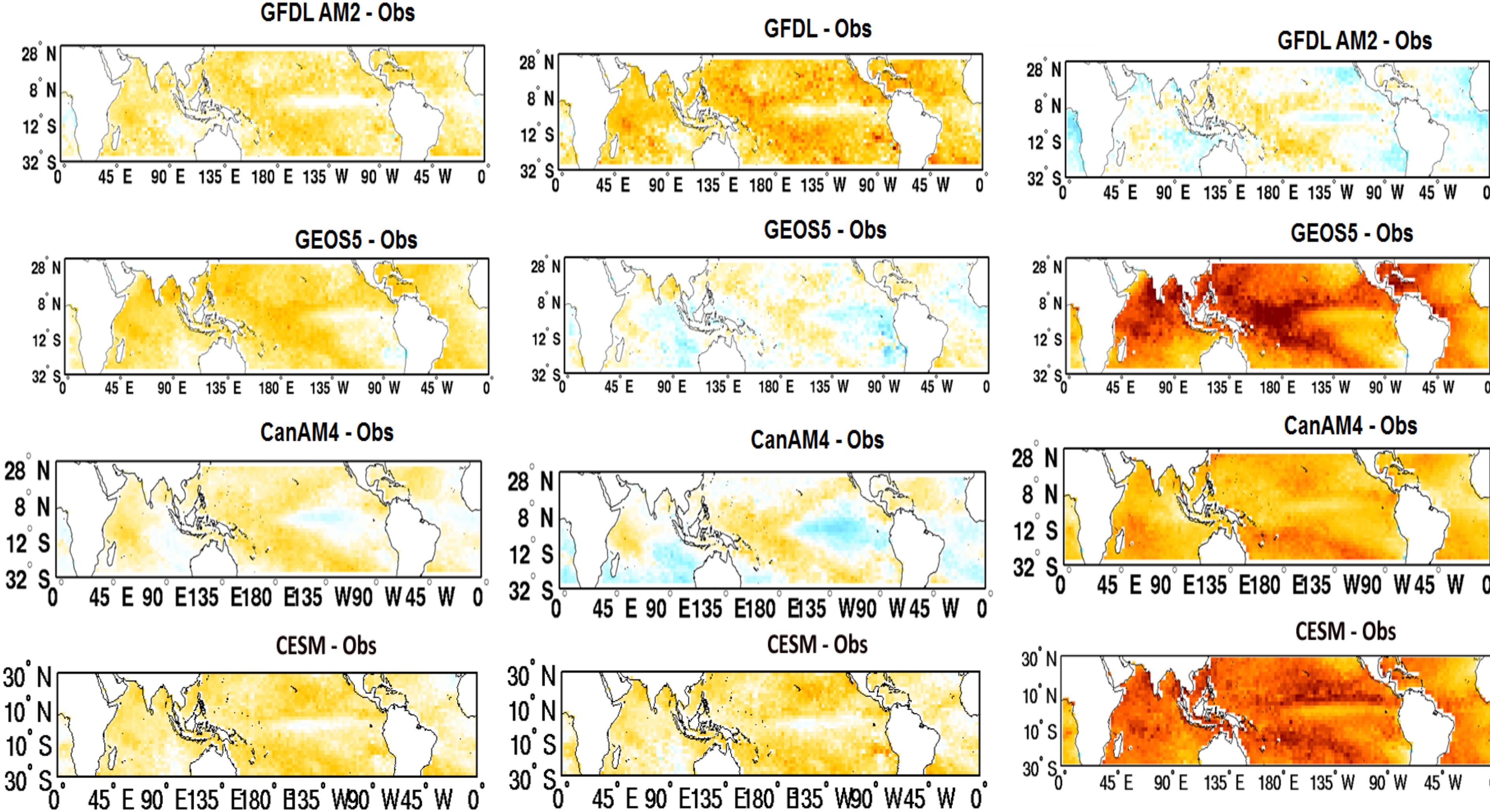


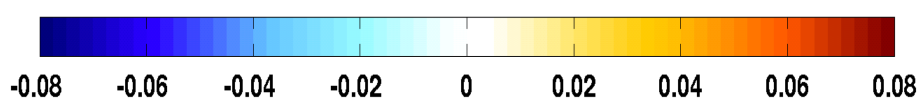
Let me illustrate with two examples

Example 1

Greenhouse efficiency $$g_{\Delta v} = \frac{\int_{\Delta v} B_v(T_s)dv - F_{\Delta v}(TOA)}{\int_{\Delta v} B_v(T_s)dv}$$

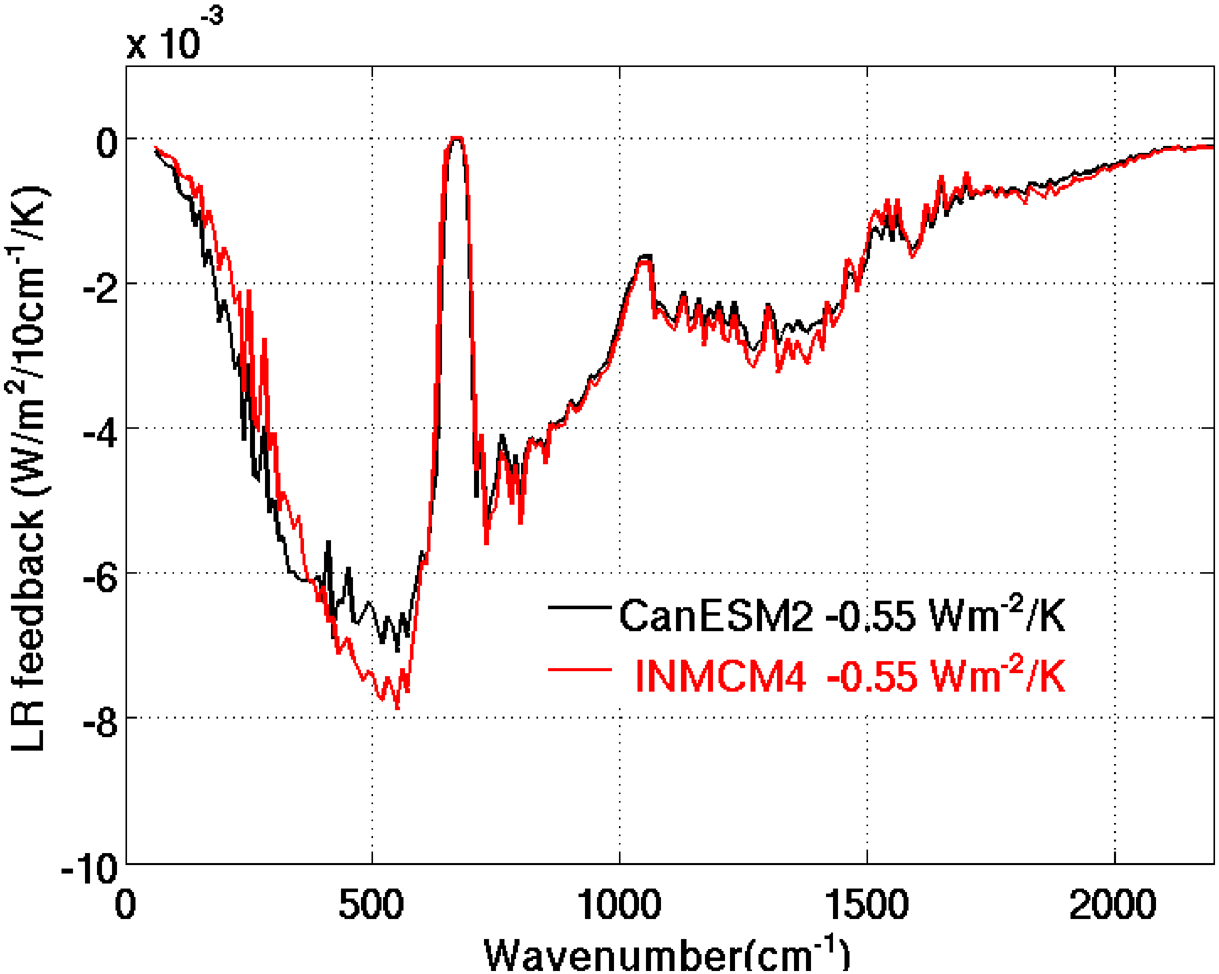
LW broadband | H_2O far-IR and v_2 bands | Window band





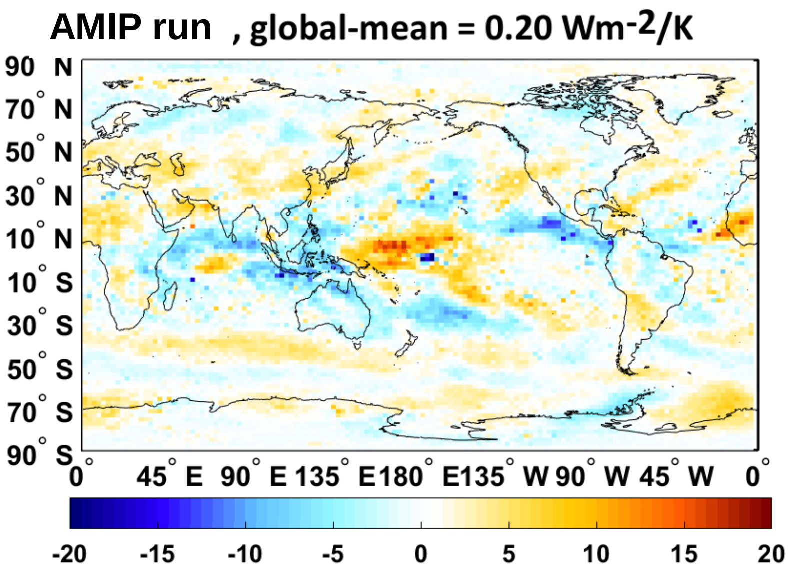
(updated from Huang et al., 2008)

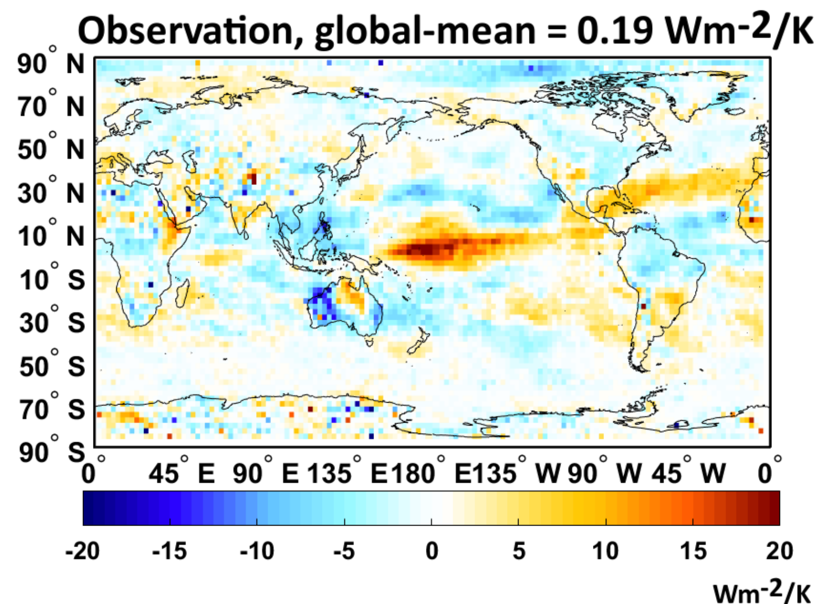
Example 2: Spectral decomposition of broadband lapse-rate feedback



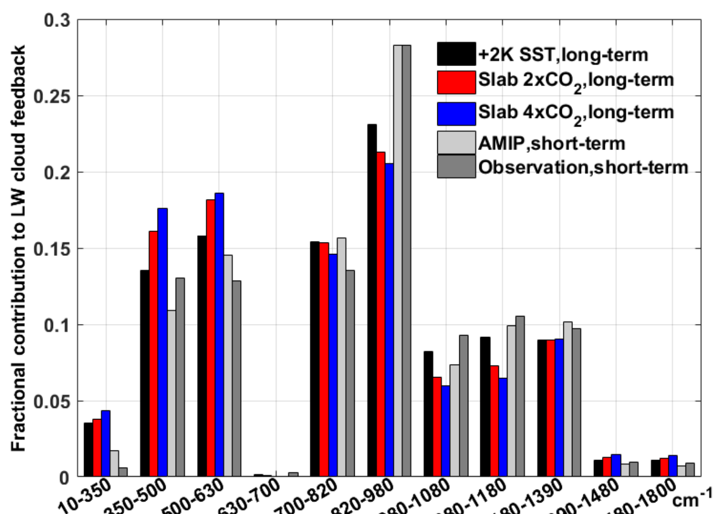
(Huang et al, 2014, GRL)

“short-term” cloud radiative feedback: CESM vs. observation (2003-2013)





Longterm vs. “short-term” cloud radiative feedback



	Total fractional contribution from 10-630 cm^{-1} (far-IR)	Total fractional contribution from 820-1180 cm^{-1} (window)
+2K SST	0.33	0.40
Slab 2xCO_2	0.38	0.35
Slab 4xCO_2	0.40	0.33
AMIP	0.27	0.45
Observation	0.26	0.48

CESM

A-Train

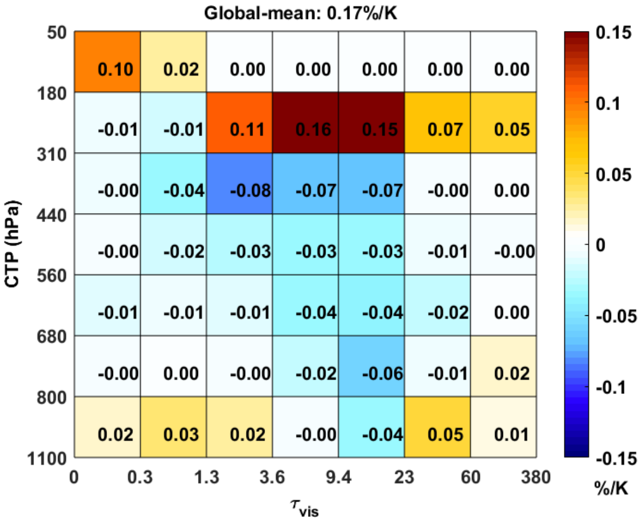
(Huang et al., under revision)

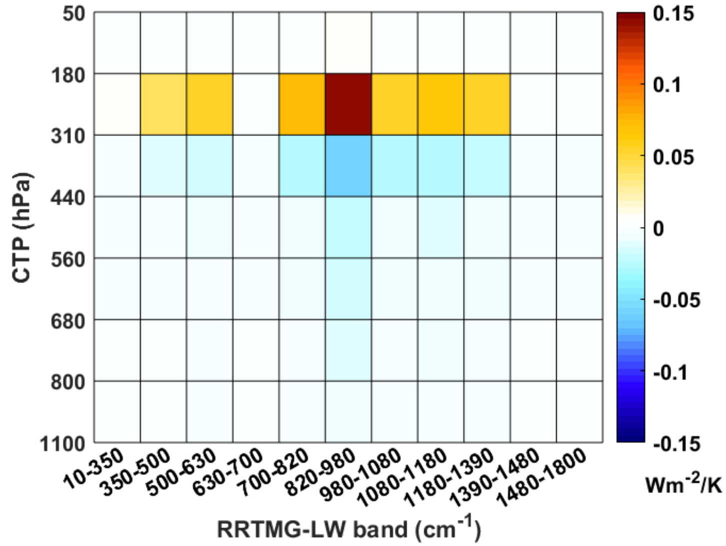
Why the far-IR vs. Window band different for long-term and short-term?

Cloud fraction change

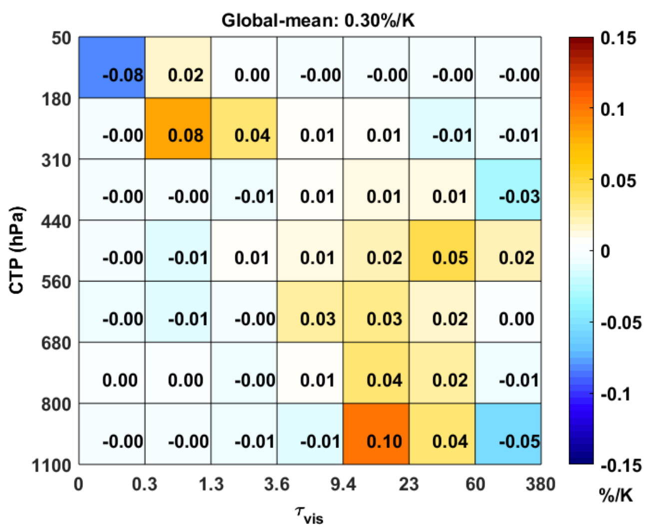
Cloud feedback

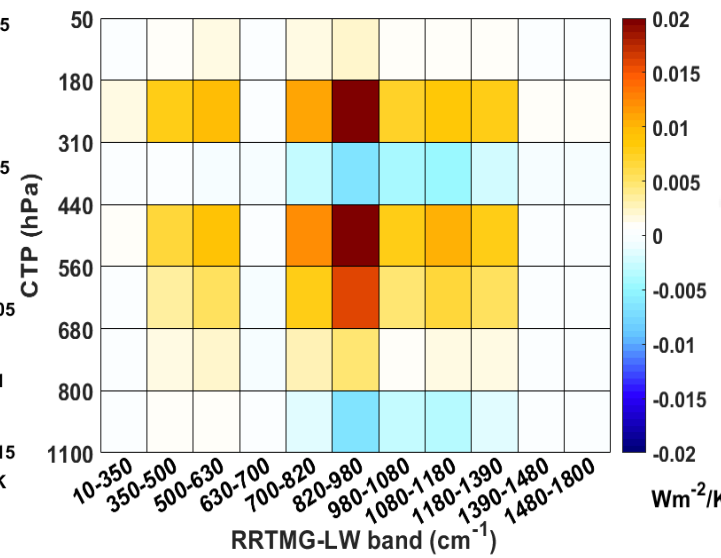
Slab $2xCO_2$





AMIP, short-term





FORUM can do

Synergy with PREFIRE

Early this year, PREFIRE was selected by NASA as the 4th EV-I mission, launch was scheduled for 2021-2022.

SCIENCE TEAM		
Tristan L'Ecuyer	Principal Investigator, University of Wisconsin, Madison	Internationally recognized in satellite based climate science; responsible for mission success
Brian Drouin	Deputy Principal Investigator / Project Scientist, JPL	Experienced spectrometer builder, algorithm data provider
Aronne Merelli	SSEC/UW, Madison	Cloud/Water vapor retrievals
Jennifer Kay	University of Colorado	Global modeling
Xianglei Huang	University of Michigan	Surface spectral emissivity; radiance to broadband conversion
Brian Kahn	Jet Propulsion Laboratory	Cloud/Water vapor retrievals
Nicole-Jeanne Schlegel	Jet Propulsion Laboratory	Ice sheet modeling

TECHNICAL TEAM	
Jet Propulsion Laboratory (JPL)	Decades of experience in space-project management and instrument development
University of Wisconsin, Madison (UW)	Experience with Data Center and Data Processing and Ground Operations
Space Science and Engineering Center (SSEC) at UW	Earth Climate data processing center
Space Dynamics Laboratory (SDL) (Utah State University)	Small satellite builder and missions operations; one of the nodes on the MC3 network

63 channels in total, ~30 channels in the far-IR, ~15km IFOV, 1-yr baseline mission

Polar Radiant Energy in the Far InfraRed Experiment (PREFIRE)

Revealing fluctuations in Earth's thermostat by capturing the full spectrum of Arctic radiant energy

Principal Investigator: Tristan L'Ecuyer, UW-Madison

Project Scientist: Brian Drouin, JPL/CalTech

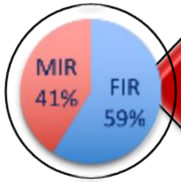
PREFIRE Hypotheses

1. Time-varying errors in far-infrared emissivities and atmospheric greenhouse effects (GHE) bias estimates of energy exchanges between the surface and the atmosphere in the Arctic.
2. These errors are responsible for a large fraction of the spread in projected rates of Arctic warming, sea ice loss, ice sheet melt, and sea level rise.

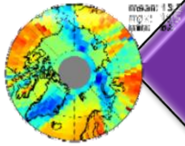
PREFIRE will document, for the first time, variability in spectral fluxes from 5-45 μm on hourly to seasonal timescales.

Two 3U CubeSats in distinct 470–650 km altitude, near-polar (82°-98° inclination) orbitseach carrying a miniaturized IR spectrometer, **covering 5- 45 μm at 0.84 μm spectral resolution, operating for one seasonal cycle (a year).**

The Arctic is Earth's thermostat. It regulates the climate by venting excess energy received in the tropics.



Nearly 60% of Arctic emission occurs at wavelengths > 15 μm (FIR) that have never been systematically measured.

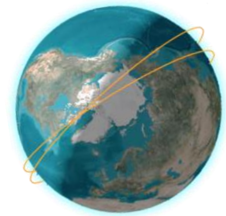


PREFIRE improves Arctic climate predictions by anchoring spectral FIR emission and atmospheric GHE

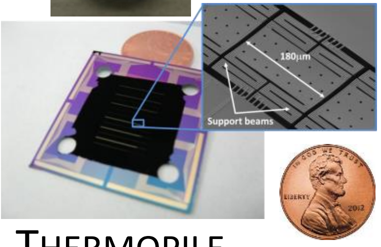
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON · SSEC · NASA · Jet Propulsion Laboratory California Institute of Technology · Space Dynamics Laboratory Utah State University Research Foundation · University of Colorado Boulder · UNIVERSITY OF MICHIGAN

Why Are PREFIRE Measurements Now Possible?

- Two 3-U CubeSats in asynchronous polar orbits
  - Solar panels configured to minimize thermal variations
  - High data rate – Arctic prioritized with Antarctica as a secondary target
- Thermal IR Spectrometer (TIRS)
  - Ambient temperature FIR spectral imager
  - Thermopile focal plane
  - Offner architecture: 0.97 kg and fits within 1U
  - Shaped groove grating (Silicon with gold plating)



GRATING



THERMOPILE

Thermopile array	Spectral resolution	Spatial coverage	Mass	Data rate	Power peak/avg
64 × 16 pixels	0.84 µm from 0–45 µm	16 cross-track pixels with 1.2° footprints	0.97 kg	35 kbps	6.74 / 1.74 W

Conclusions and discussions

- Surface-atmosphere longwave coupling in the climate models can be further improved. New spectral observations are needed.

In general, my thoughts about FORUM mission

- Most compelling arguments (besides spectroscopy/retrievals)
  - The last uncharted spectral territory in our understanding of radiation budget
  - With IASI together, provide observational results for testing climate models in a more stringent way, spectral OLR test
    - Is it a necessary condition for a model to be "eligible" for projecting climate? Very Likely.

Conclusions and discussions (cont)

- Challenges
  - Cope with partial cloudy scenes
  - Validations of far-IR surface emissivity retrievals
  - 4-year lifetime is short for climate-change studies, in general.
    - But it is sufficient to depict the spectral dimension of the mean climate states.
    - A step-stone for long-term spectral monitoring
      - High-latitude change is rapid and variability is small
    - PREFIRE can be informative for future FORUM data analysis.

THANK YOU!

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, *Geophs. Res. Letts.*, doi:10.1002/2014GL061216, 41(18), 6530-6537, 2014.
2. 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.
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4. Huang, X. L., X.H. Chen, G. L. Potter, L. Oreopoulos, J. N.S. Cole, D.M. Lee, N. G. Loeb, A global climatology of outgoing longwave spectral cloud radiative effect and associated effective cloud properties, J. Climate, 27, 7475-7492, doi:10.1175/JCLI-D-13-00663.1, 2014.
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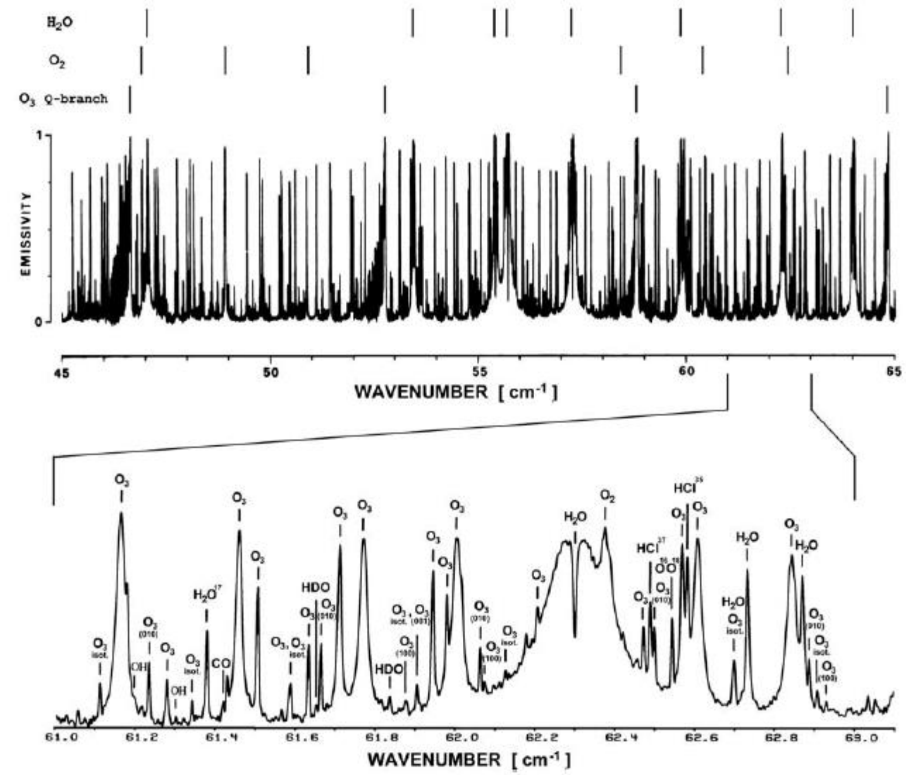
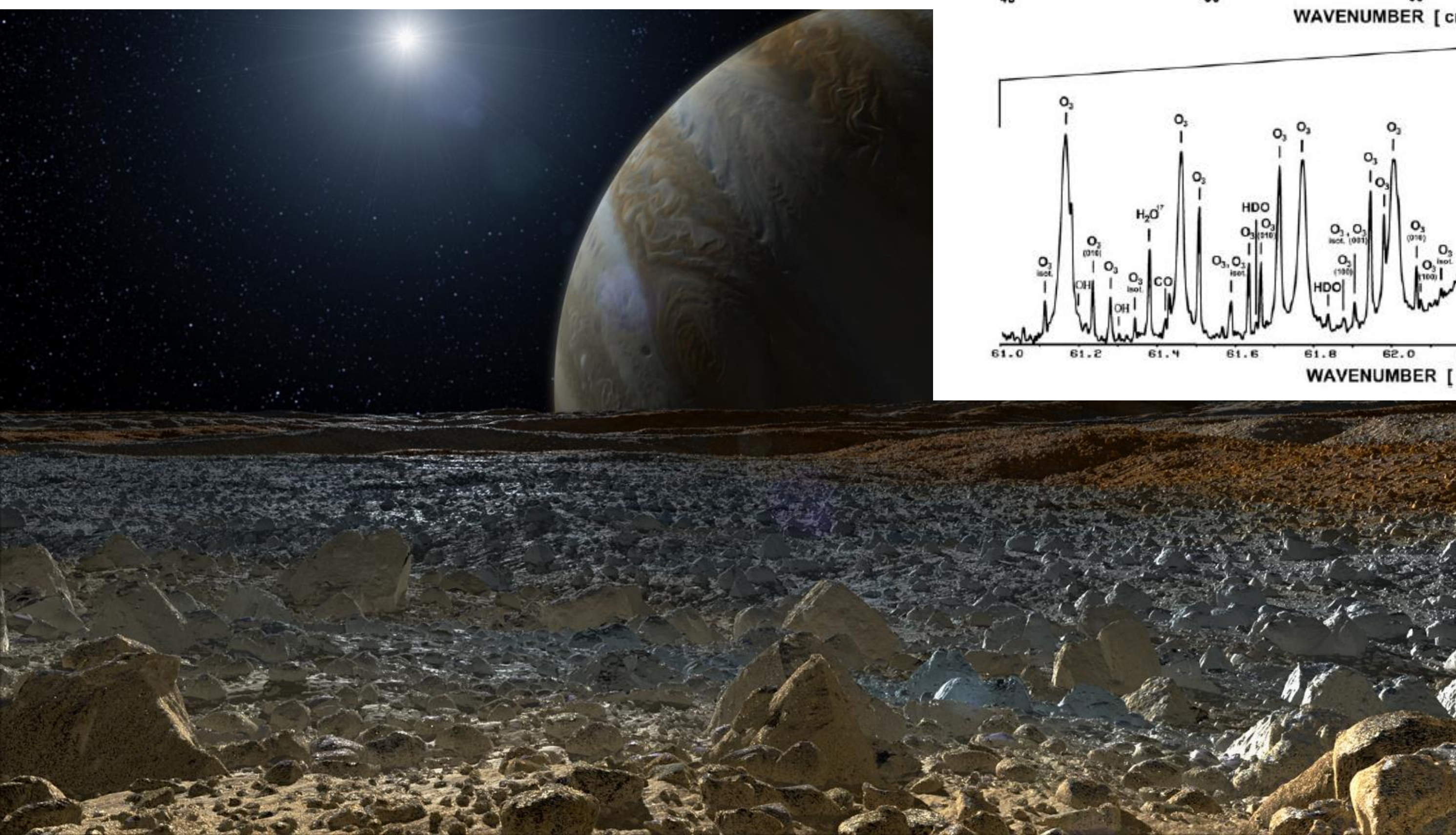
6. Chen, X.H., X.L. Huang, N. G. Loeb, H. L. Wei, Comparisons of clear-sky outgoing far-IR flux inferred from satellite observations and computed from three most recent reanalysis products, J. Climate, 26(2), 478-494, doi:10.1175/JCLI-D-12-00212.1, 2013.

To what extent improving our far-IR understanding about the Earth can help our exploration of ICY WORLDS?



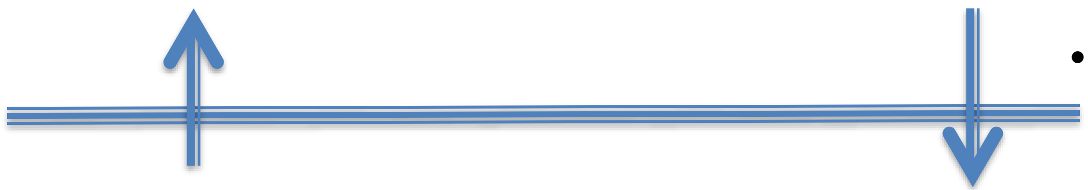
Icy world flagship mission
Europa clipper (JPL estimated $5B project)

(From JPL Astrobiology websites)



(Harries et al.2018; Carli et al., 1984)

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



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

Emission **Reflection**

An example: CLM in the CESM

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

Atmosphere module

- Lower B.C. for radiation scheme is $F^{\uparrow}_{LW\_SFC}(\Delta\nu)$
- But input to radiation scheme is not lower B.C., but $\mathbf{T_{skin}}$
- **Always assume blackbody (except GISS model)**

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

Surface modules

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

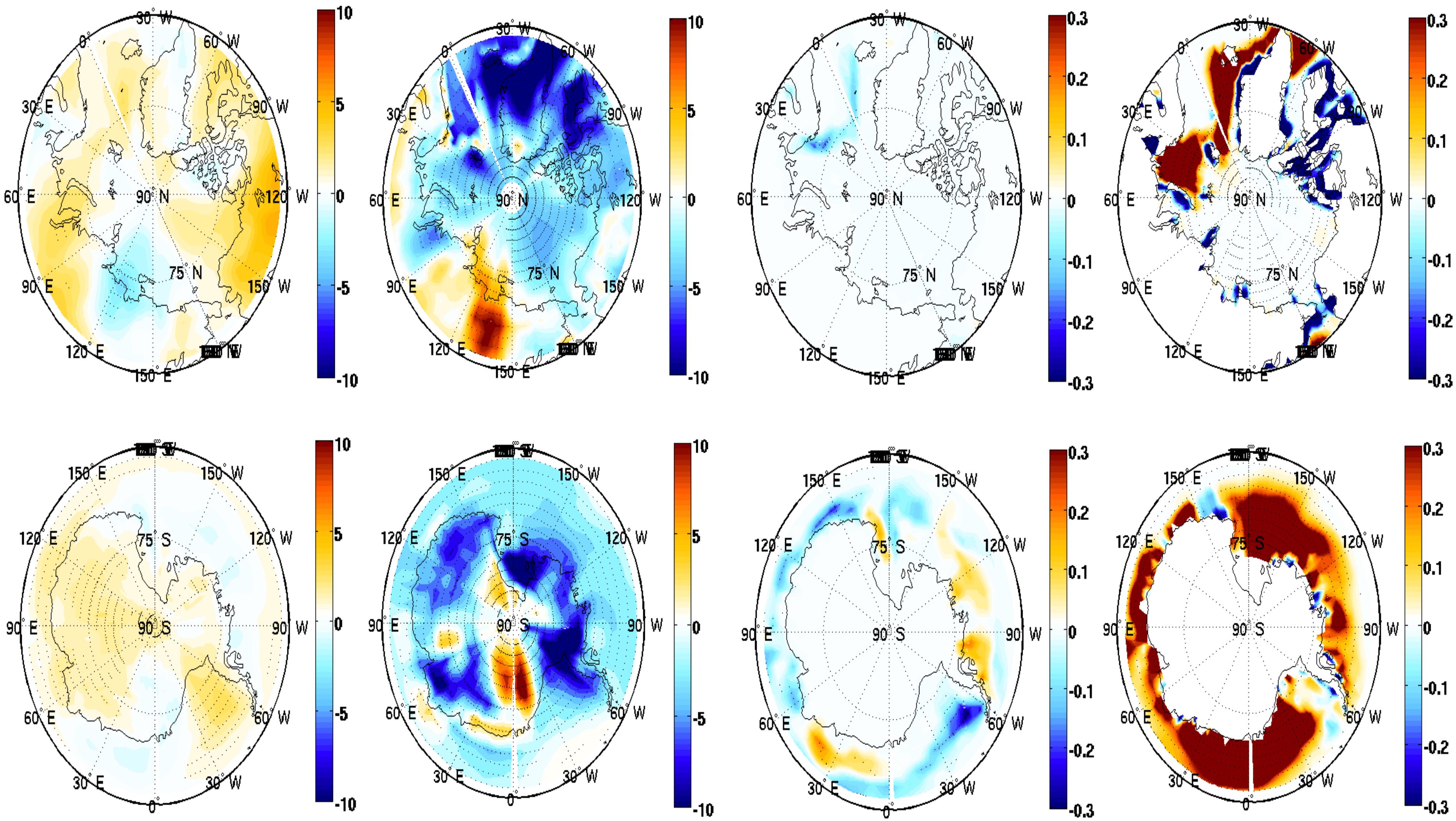
Issues: 1. Broadband flux is passed through correctly. But inconsistent in the spectral decomposition.

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

For February month

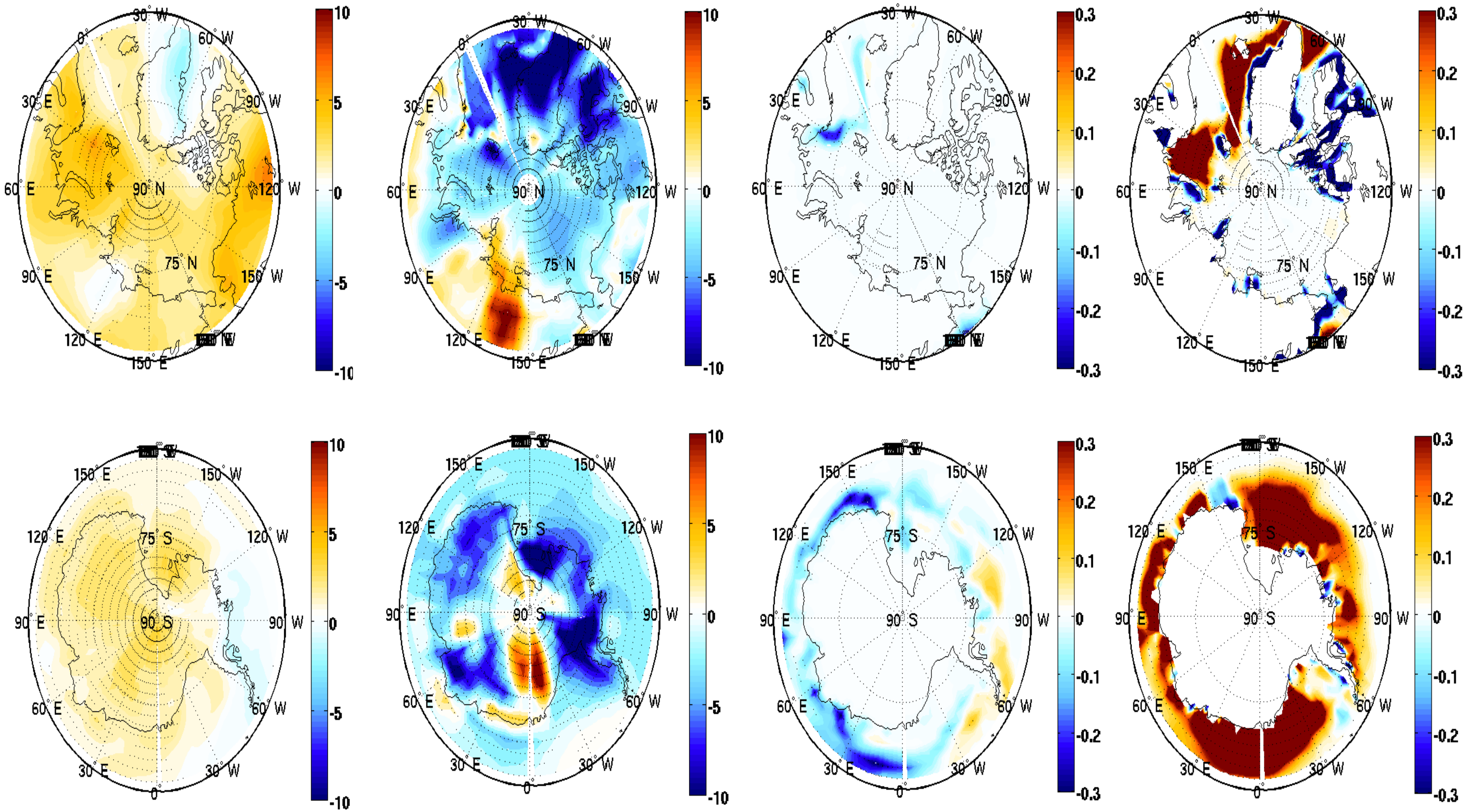
Modified run: MC6 + scat; control run: MC6 only

Tair difference (modi. – control)	Tair difference (control – obs.)	f_{ice} difference (modi. – control)	f_{ice} difference (control – obs.)



Modified run: MC6 + scat + emis; control run: MC6

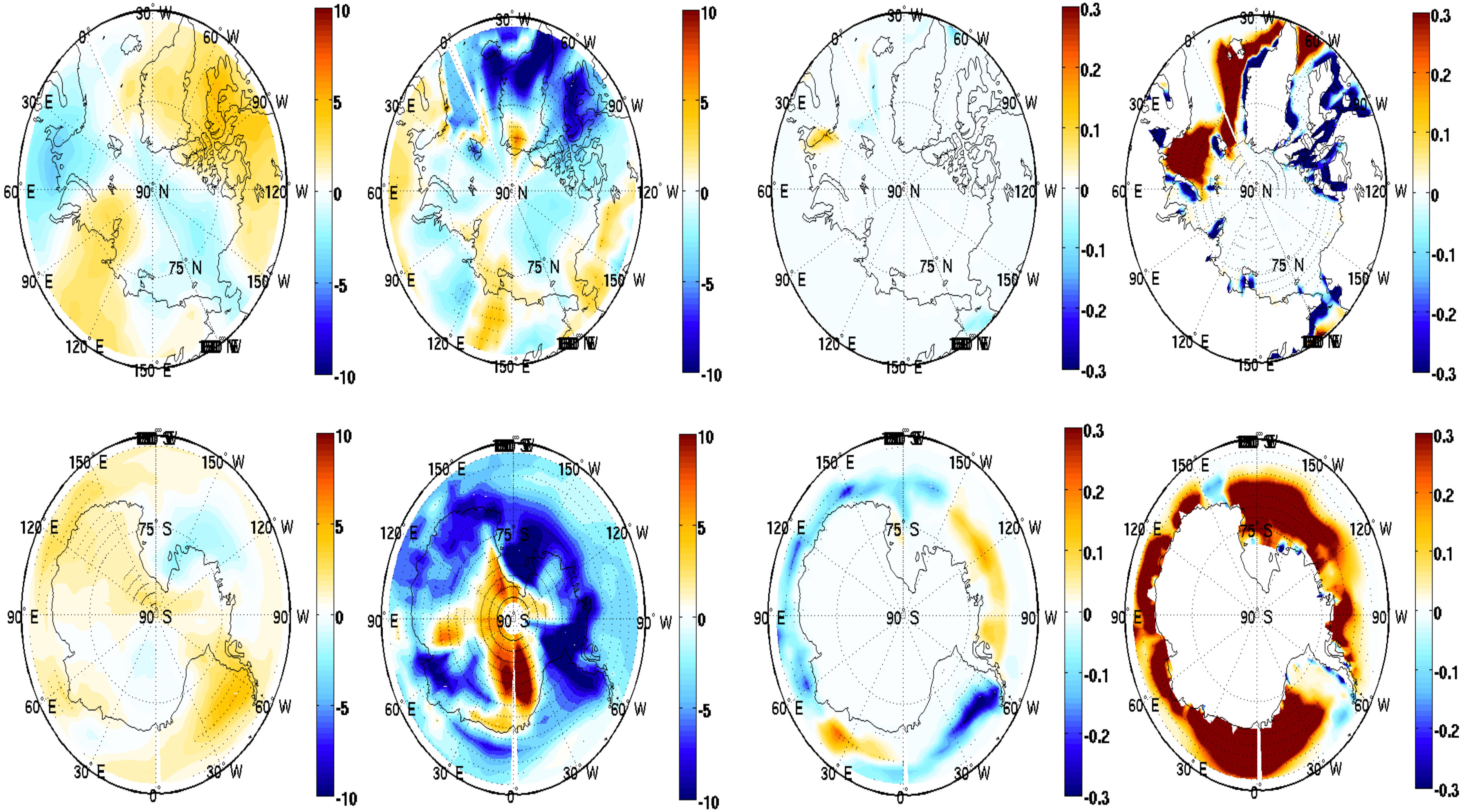
Tair difference (modi – control)	Tair difference (control – obs.)	f_{ice} difference (modi. – control)	f_{ice} difference (control – obs.)



For March month

Modified run: MC6 + scat; control run: MC6 only

Tair difference (modi. – control)	Tair difference (control – obs.)	f_{ice} difference (modi. – control)	f_{ice} difference (control – obs.)



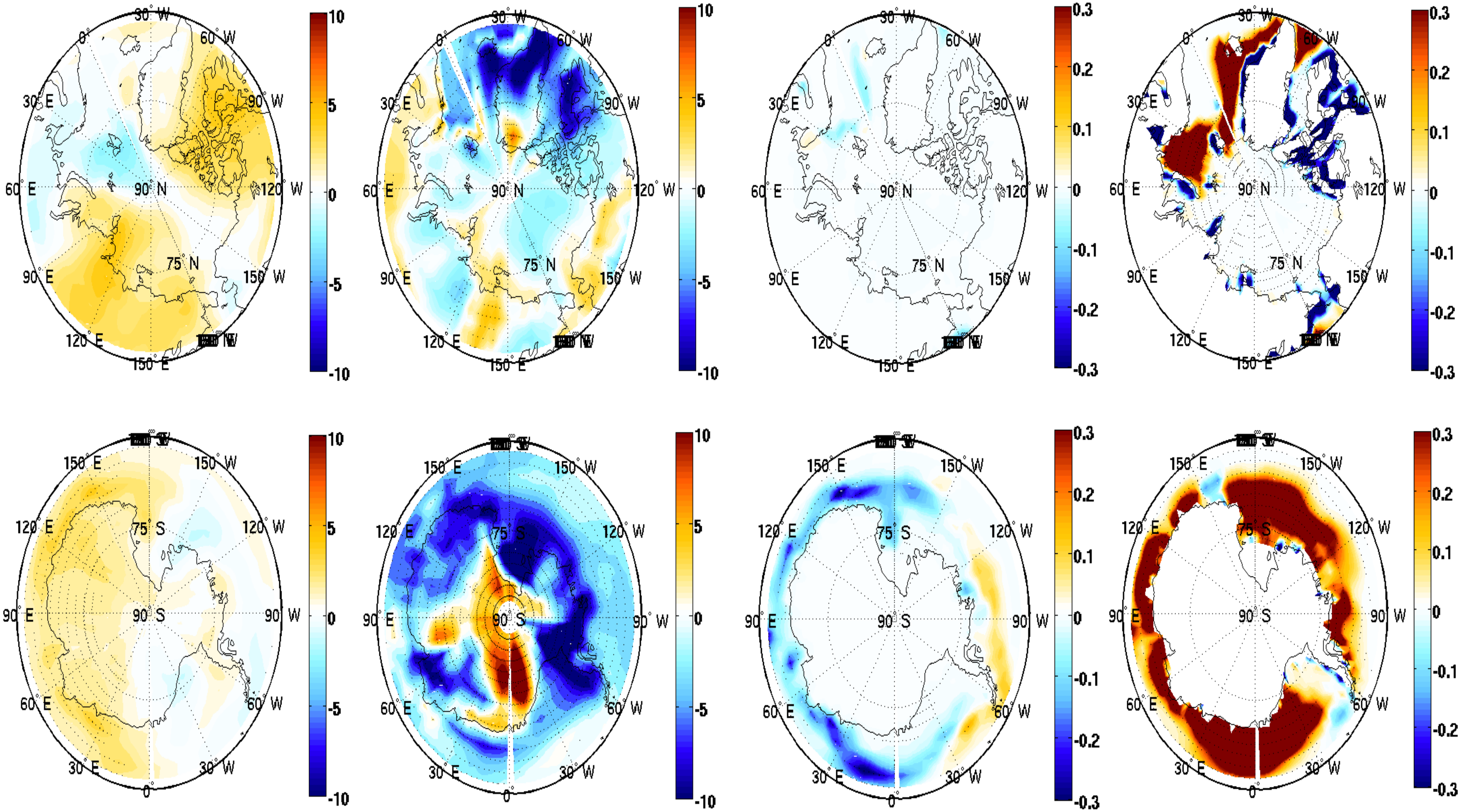
Modified run: MC6 + scat + emis; control run: MC6

Tair difference (modi – control)

Tair difference (control – obs.)

f_{ice} difference (modi. – control)

f_{ice} difference (control – obs.)



PREFIRE Team

Who is doing the work and how?

PREFIRE utilizes university partnerships for data analysis, spacecraft, and ground systems along with advances in planetary detector technology, SDL flight-proven spacecraft, and JPL instrumentation.

SCIENCE TEAM		
Tristan L'Ecuyer	Principal Investigator, University of Wisconsin, Madison	Internationally recognized in satellite based climate science; responsible for mission success
Brian Drouin	Deputy Principal Investigator / Project Scientist, JPL	Experienced spectrometer builder, algorithm data provider
Aronne Merelli	SSEC/UW, Madison	Cloud/Water vapor retrievals
Jennifer Kay	University of Colorado	Global modeling
Xianglei Huang	University of Michigan	Surface spectral emissivity; radiance to broadband conversion
Brian Kahn	Jet Propulsion Laboratory	Cloud/Water vapor retrievals
Nicole-Jeanne Schlegel	Jet Propulsion Laboratory	Ice sheet modeling

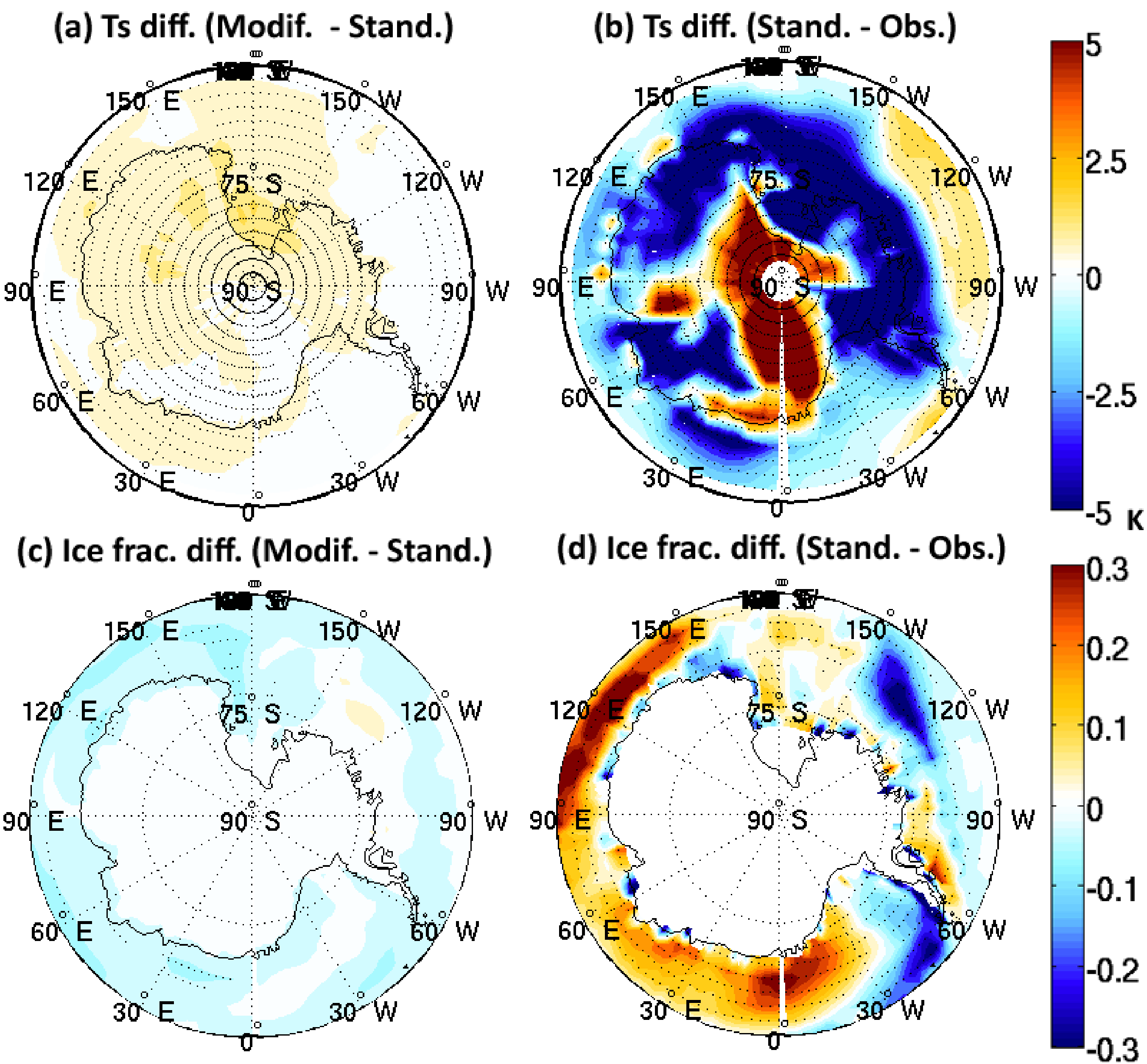
TECHNICAL TEAM	
Jet Propulsion Laboratory (JPL)	Decades of experience in space-project management and instrument development
University of Wisconsin, Madison (UW)	Experience with Data Center and Data Processing and Ground Operations
Space Science and Engineering Center (SSEC) at UW	Earth Climate data processing center
Space Dynamics Laboratory (SDL) (Utah State University)	Small satellite builder and missions operations; one of the nodes on the MC3 network

Modify the CESM to include both surface emissivity and cloud scattering

- Developed a global surface emissivity data set suitable for NWP and climate model usages
  - Huang et al., 2016, JAS
  - Can be used as prescribed or as prognostic fields
- Ice cloud optics based on Yang et al. (2013)
- Modified the RRTMG_LW to enable hemispheric mean two-stream scattering calculation (Toon et al., 1989)
- Slab-ocean run and fully-coupled run for 30 years
- First change surface emissivity only, then include cloud scattering

Impact on Simulated Climatology

Southern Hemisphere (fully-coupled run, 30-year mean difference)



- Prognostic emissivity over ocean
- Prescribed over land
- Similar for NH polar region

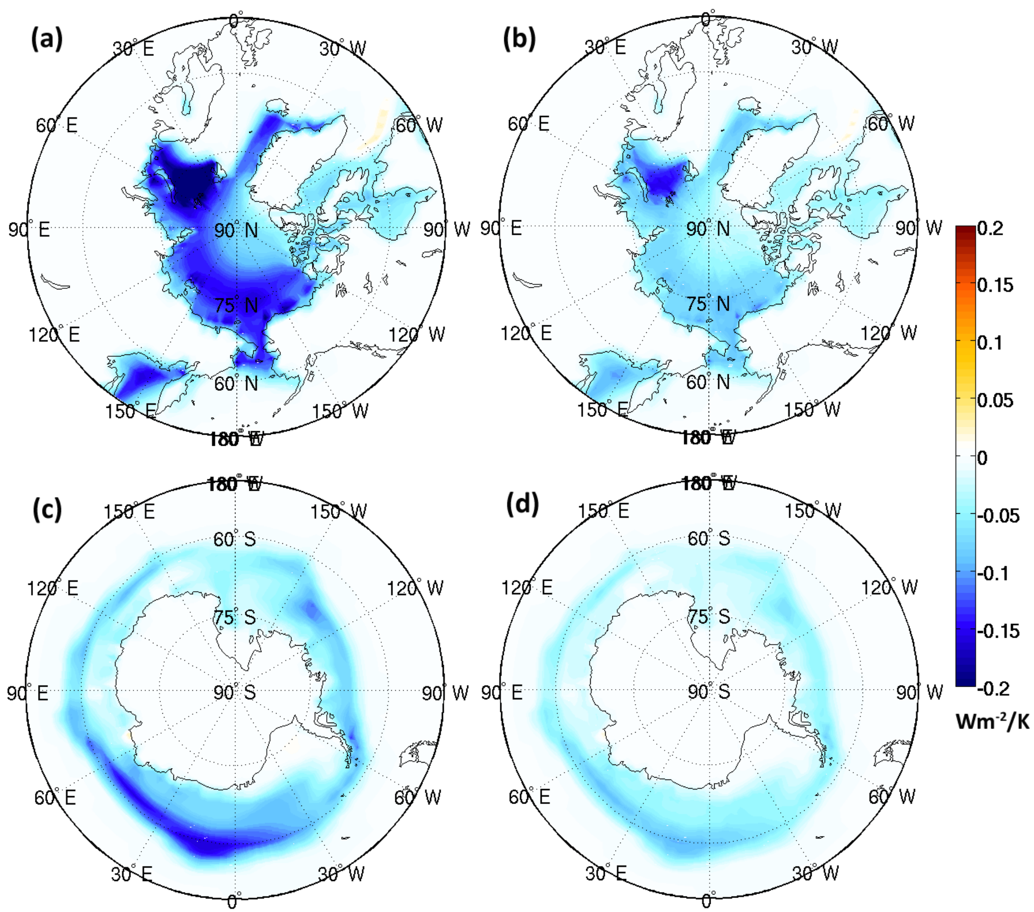
(Huang et al., 2018)

Impact on Simulated Climate Change

Sea ice emissivity feedback: 2-sided PRP methods for equilibrium $2xCO_2$ simulation

Clear-sky: -0.007 Wm^{-2}/K
All-sky: -0.003 Wm^{-2}/K

If coarse snow emissivity is used as sea ice emissivity, the feedback strength is 0.003 Wm^{-2}/K (clr-sky) and 0.002 Wm^{-2}/K (all-sky)



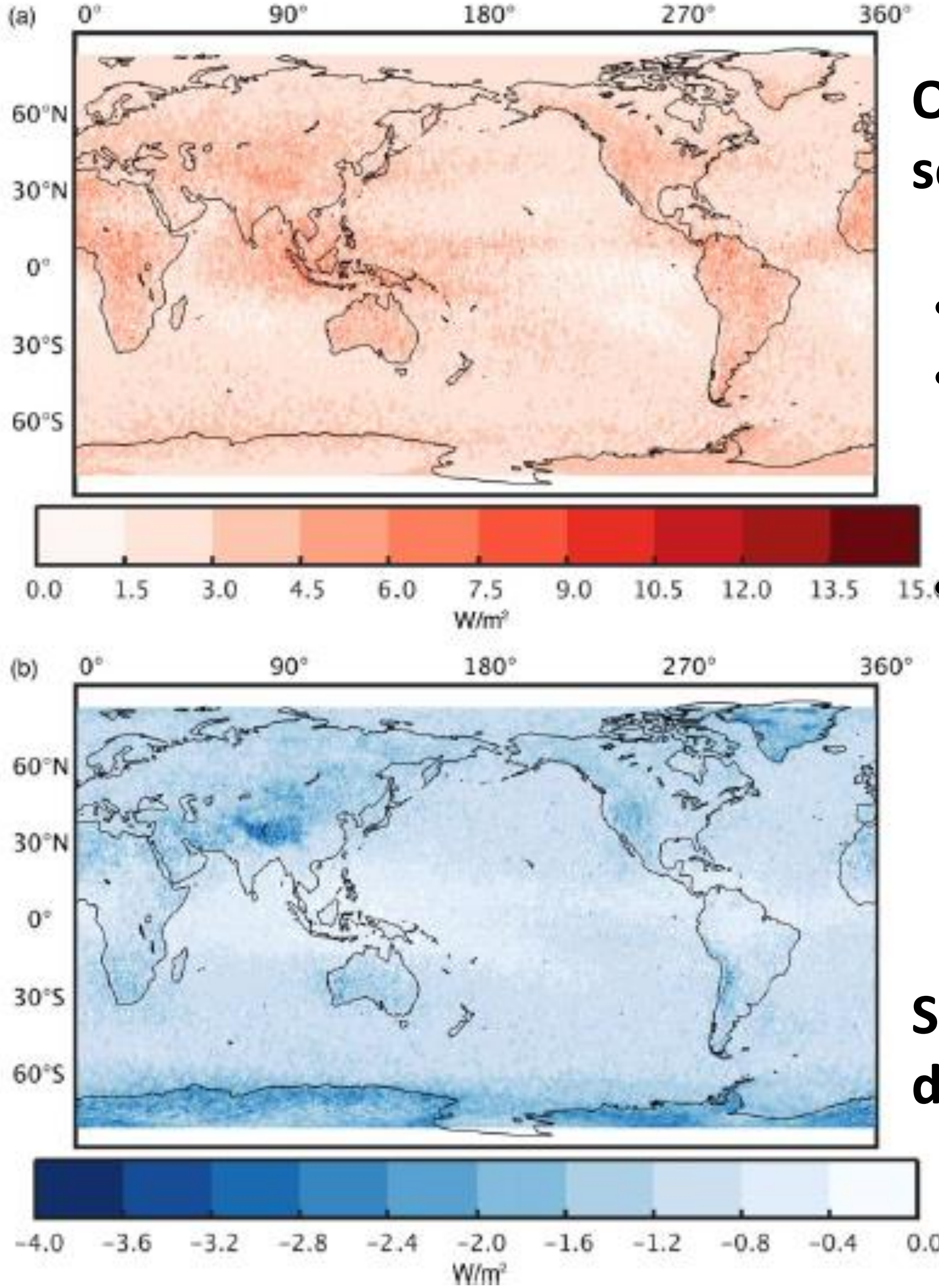
Clear-sky

All-sky

For comparison: sea ice shortwave albedo feedback 0.3 Wm^{-2}/K

(Huang et al., 2018)

PRP = partial radiative perturbation



OLR difference (no scattering – scattering)

- Offline DISORT calculation
- Using CCCM profiles (Cloudsat/CALIPSO/CERES/MODIS) in 2010
- Flux difference due to ignoring the cloud LW scattering

Surface downward LW flux difference

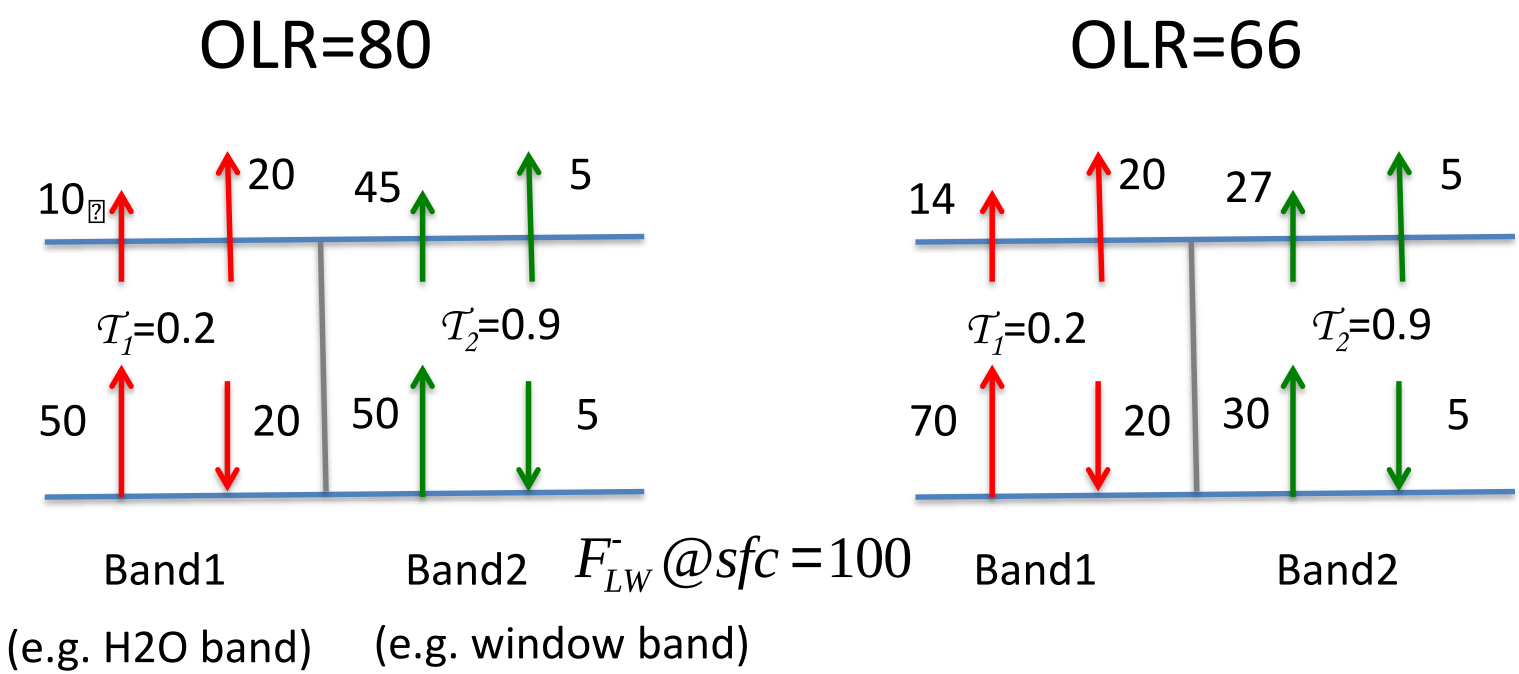
(Kuo et al, 2017, JAMES)

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)



In order to include scattering in RRTMG_LW, a two-stream radiation solver based on Toon et al. (1989) has been incorporated. This solver uses a hemispheric mean two-stream approximation for the phase function and for the angular dependence. Note that in Chia-Pang's JAMES paper, they used a 16-stream DISORT radiation solver for calculating scattering, which is different from the solver in our simulations.

The ice optics is based on Yang et al. (2013), which utilizes the MODIS-observed ice cloud particles statistics in conjunction with state-of-the-art scattering computation capabilities. Moreover, these optical coefficients have unprecedented advances in terms of scattering calculations: three-dimensional random orientations for eleven ice crystal habits and three surface roughness conditions for each crystal habit are taken into account, all of which affect the scattering abilities of ice particles (Yang et al., 2005; Yi et al., 2013).

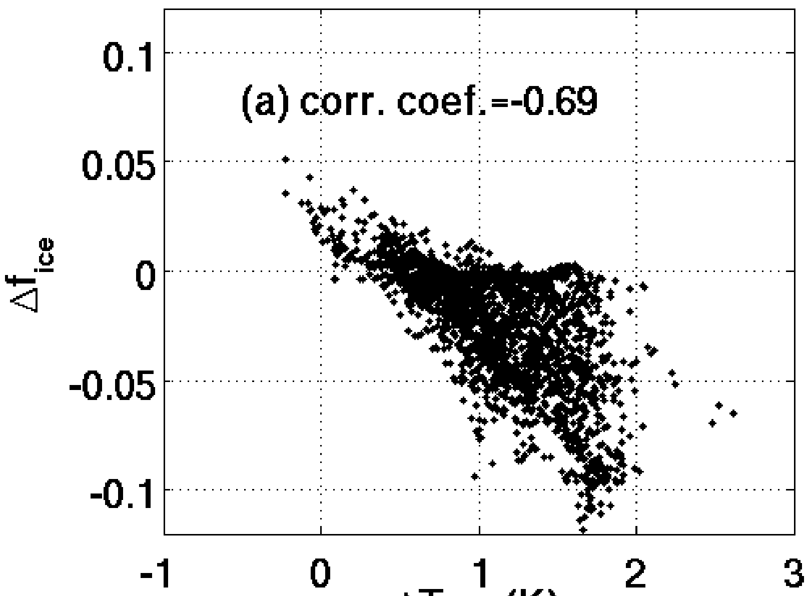
Reference:

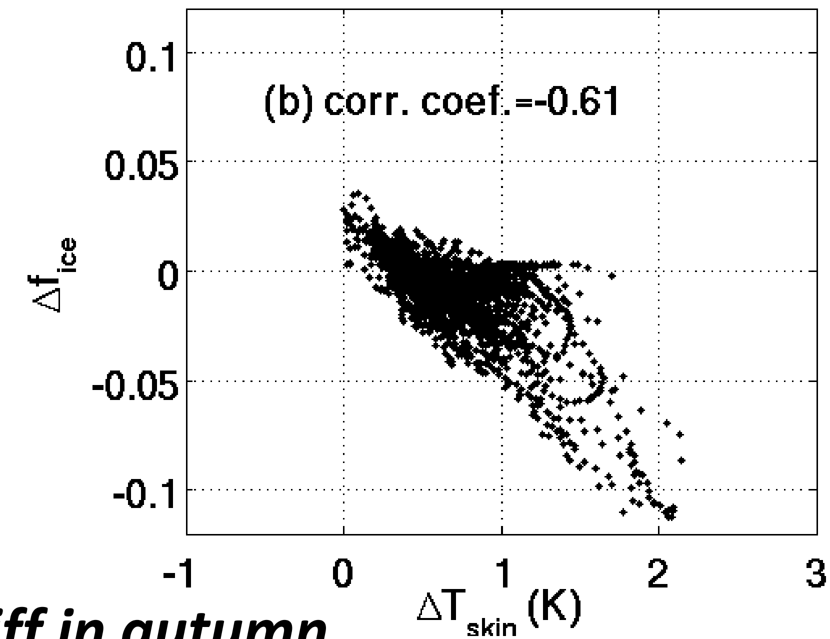
Toon, O. B., McKay, C. P., Ackerman, T. P., & Santhanam, K. (1989). Journal of Geophysical Research, 94(89), 287–301. http://doi.org/10.1029/JD094iD13p16287

Yang, P., Bi, L., Baum, B. a., Liou, K.-N., Kattawar, G. W., Mishchenko, M. I., & Cole, B. (2013). Spectrally Consistent Scattering, Absorption, and Polarization Properties of Atmospheric Ice Crystals at Wavelengths from 0.2 to 100 μ m. Journal of the Atmospheric Sciences, 70(1), 330–347. http://doi.org/10.1175/JAS-D-12-039.1

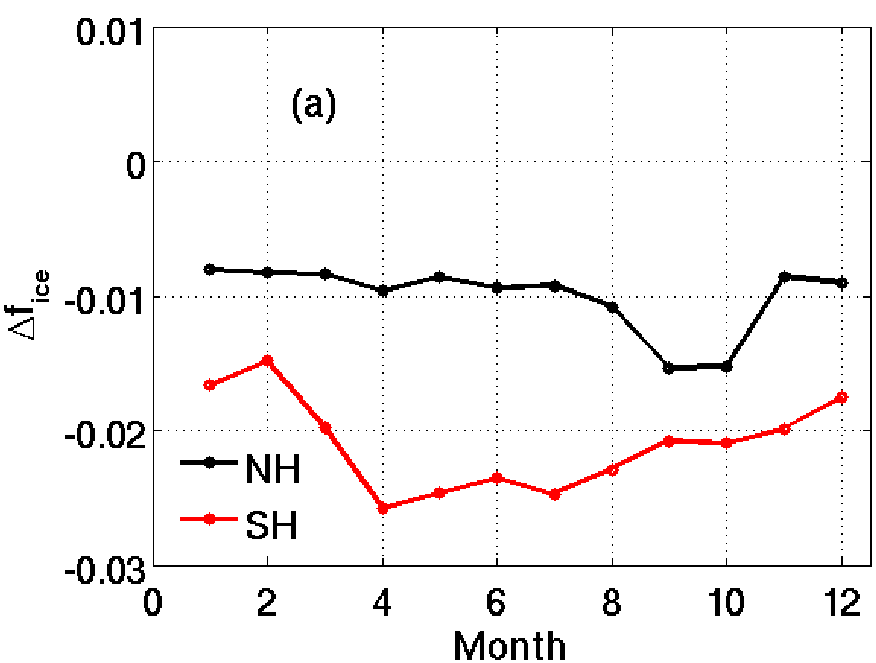
Slab-ocean run

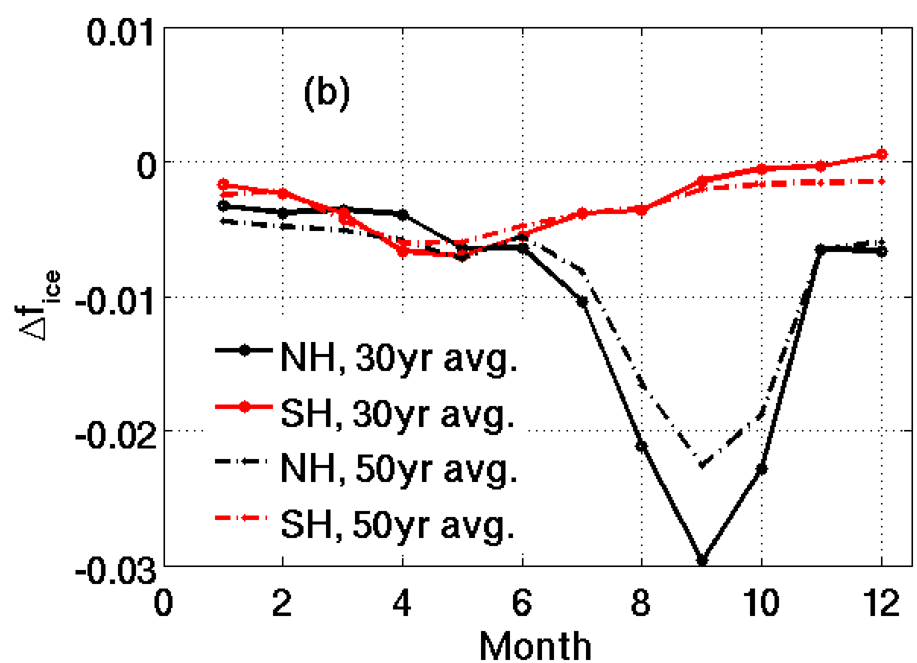
Fully coupled run



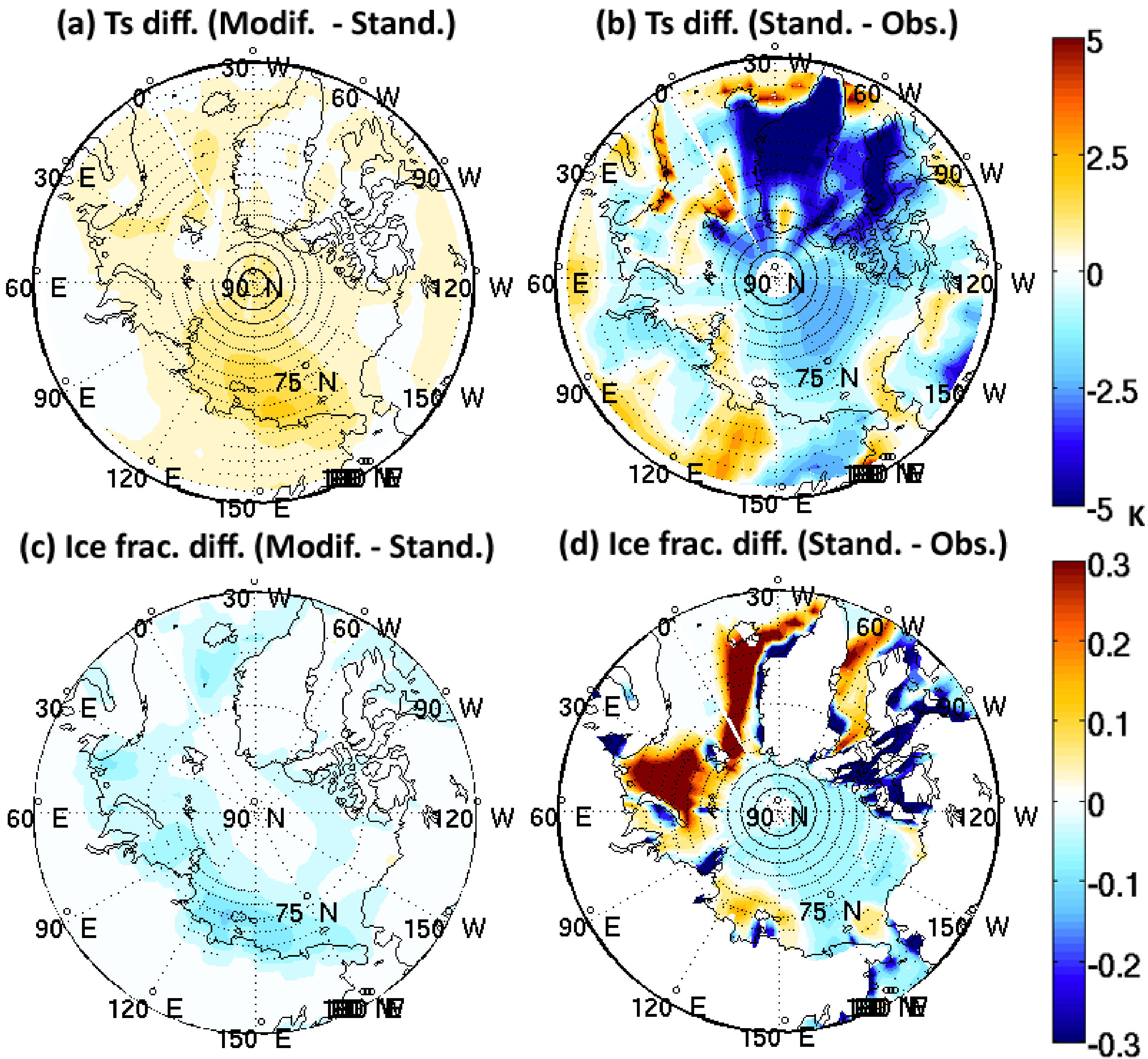


Max diff in autumn





Northern Hemisphere (fully-coupled run, 30-year mean difference)



- **Prognostic emissivity over ocean**
- **Prescribed over land**

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 $0.05^o \times 0.05^o$ spatial resolutions to decide surface type defined in our study
- Averaged onto $0.5^o \times 0.5^o$ grid
- Validation: compare with IASI mid-IR retrievals of spectral emissivity at $0.5^o \times 0.5^o$ grid and at RRTMG_LW bands
- Far-IR as calculated

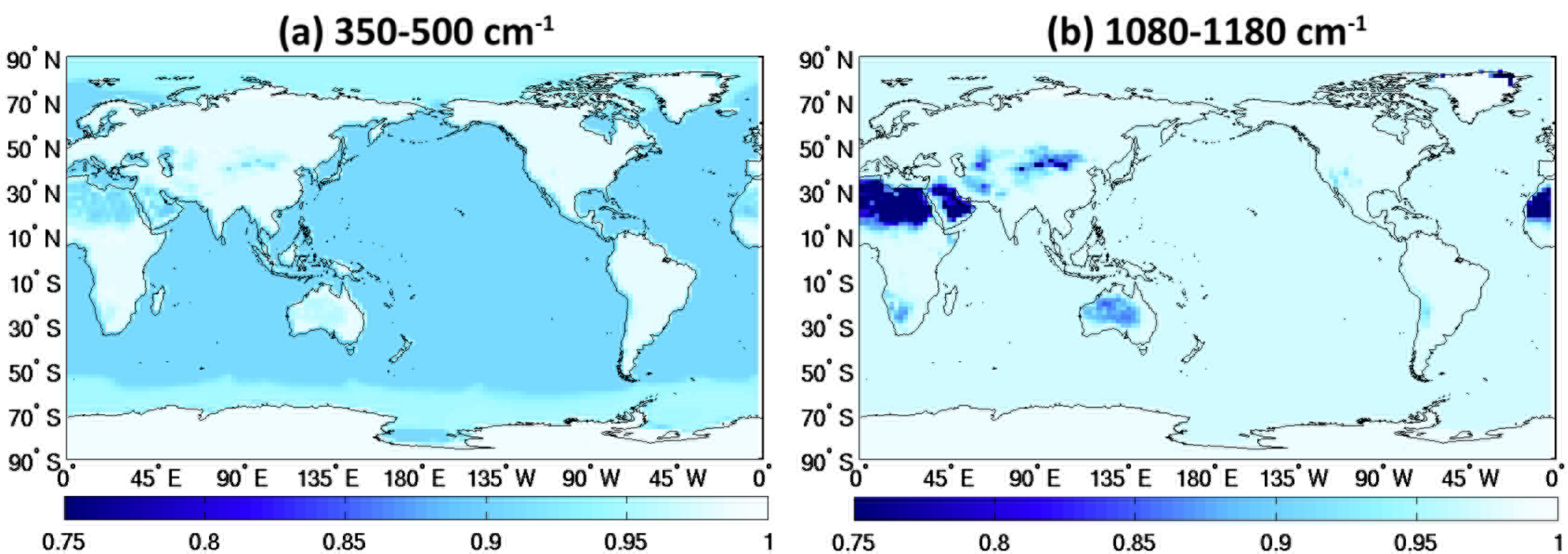
Usage

- 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)

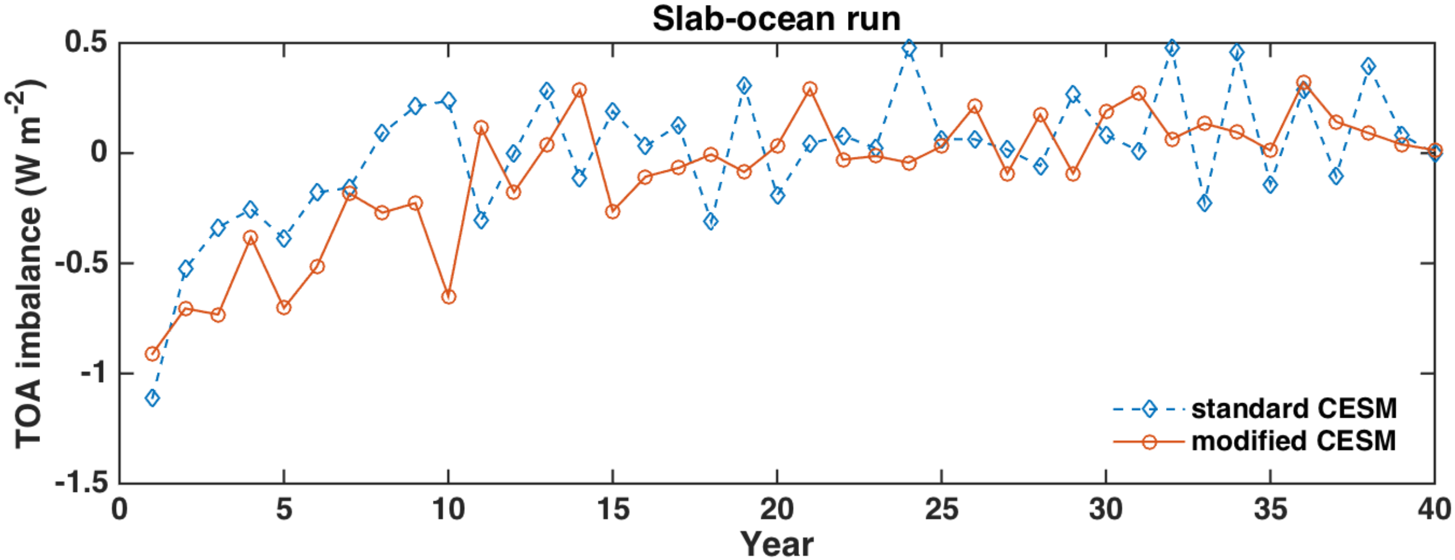
Surface emissivity dataset: http://www-personal.umich.edu/~xianglei/emissivity.html

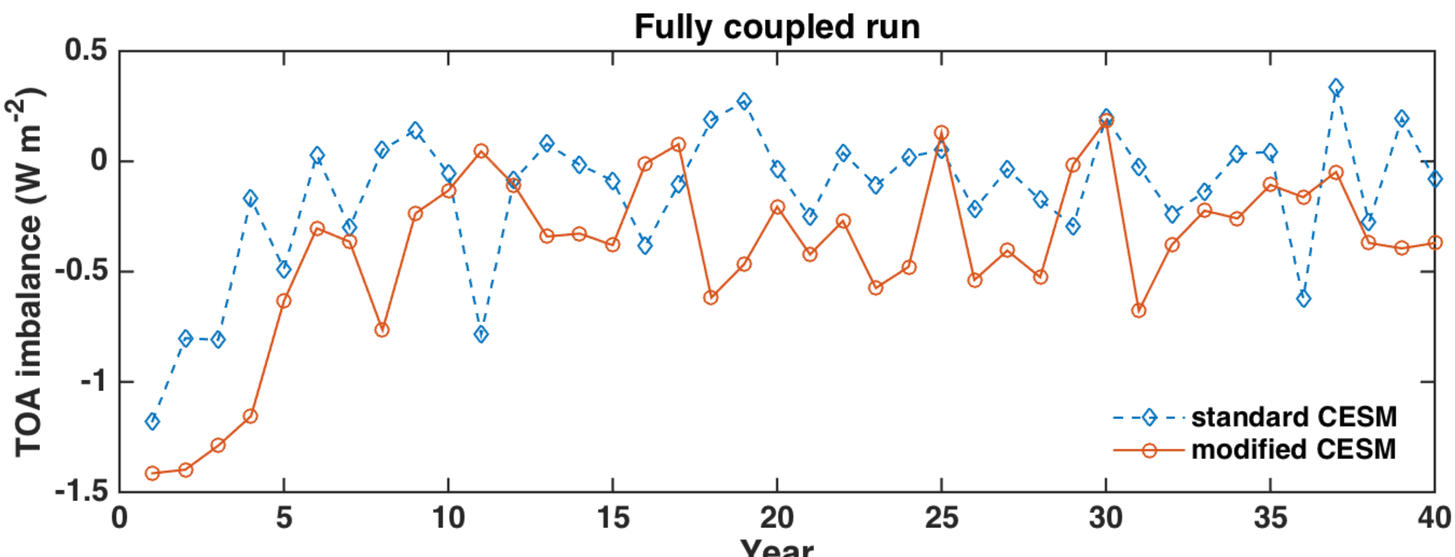
Simulation set-up (Modified CESM)

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



TOA imbalance: no additional tuning needed

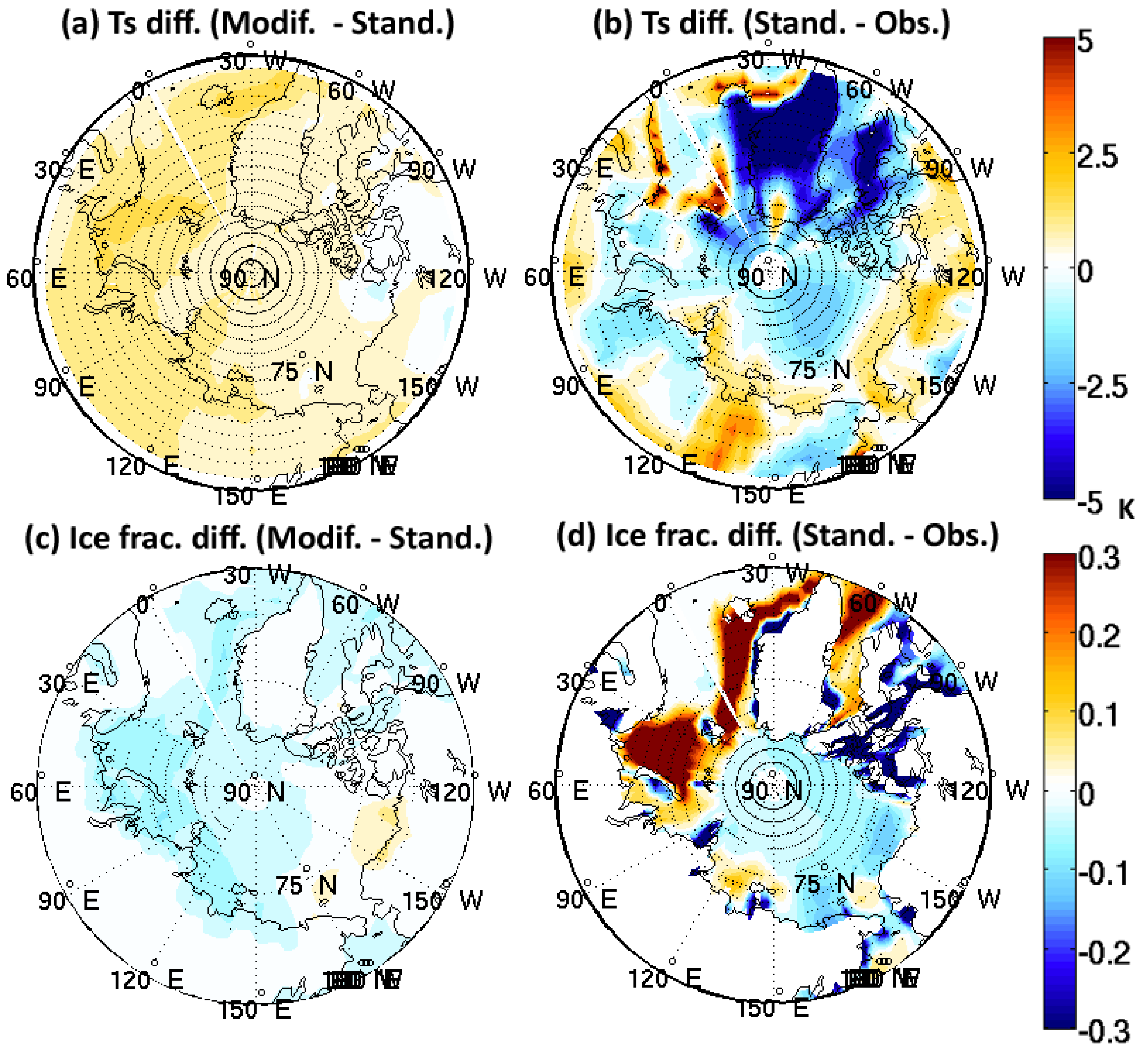


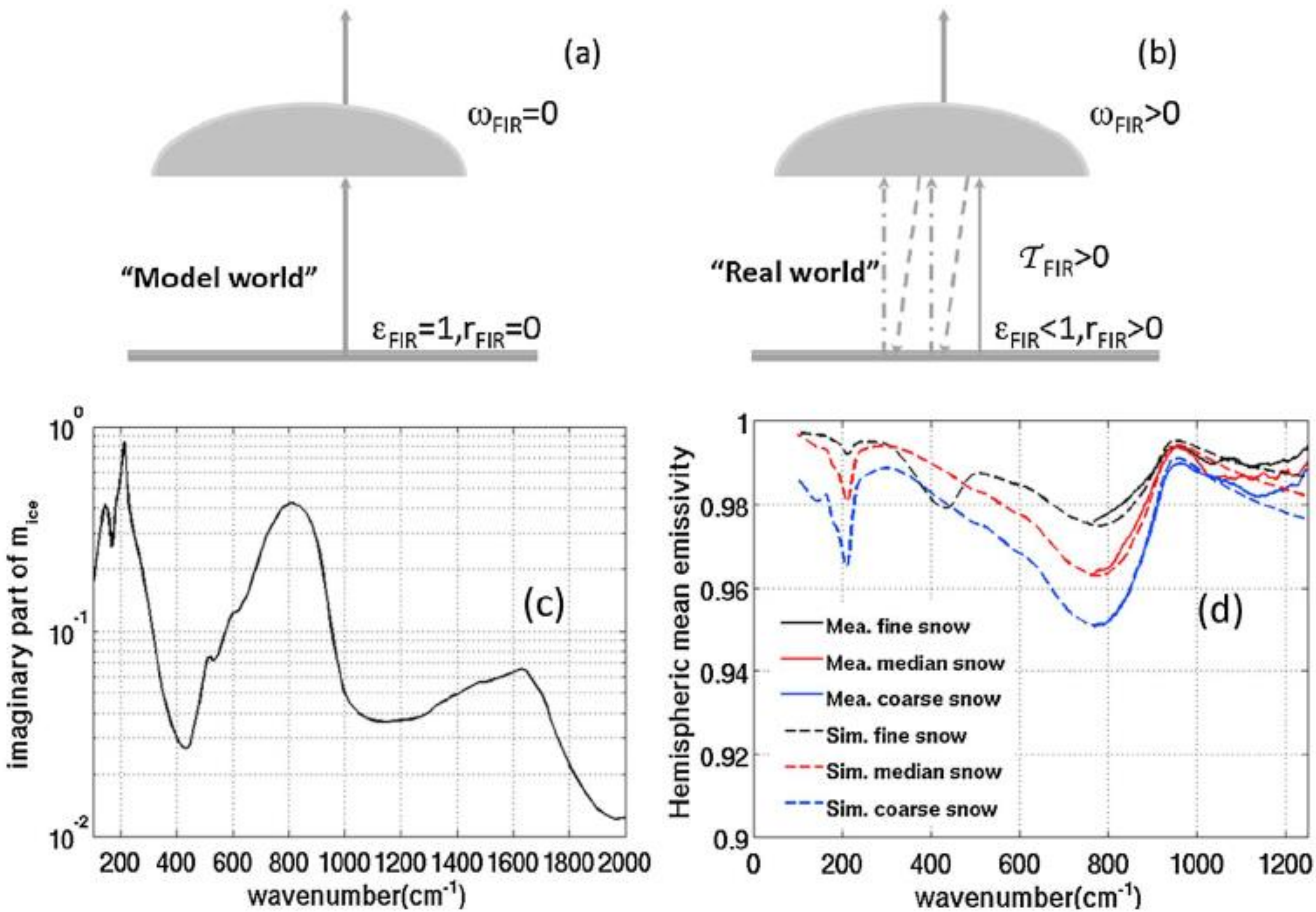


Modified CESM: spectral surface emissivity included

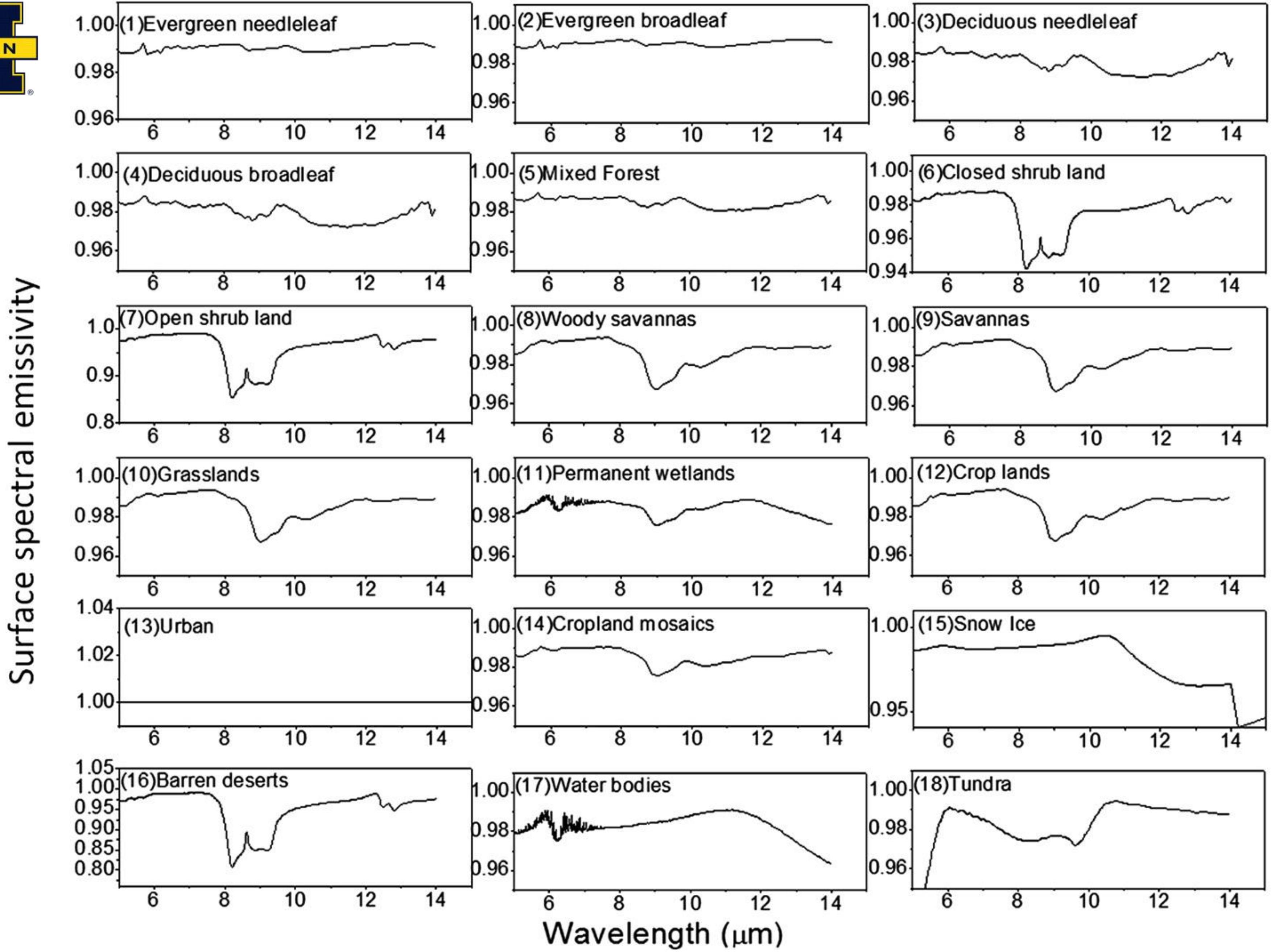
Standard CESM: blackbody

Northern Hemisphere (slab ocean run, 30-year mean difference)





(Chen et al., 2014)



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

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

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

Emission **Reflection**

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

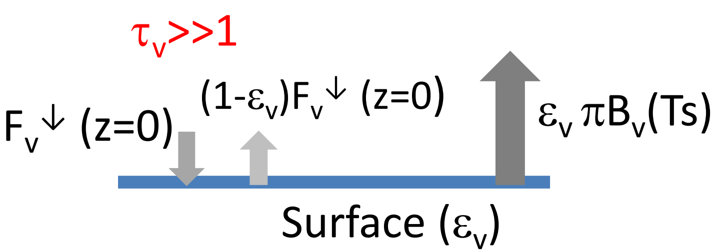
Issues:

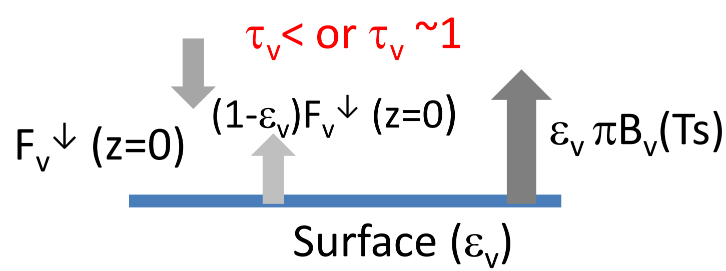
- **Spectral variation of surface emissivity ignored**
- **Cannot simply change ε in RRTMG_LW to realistic values and still using the same T_{skin}**

Surface emissivity

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

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





$$e_v = A_v$$

$$r_v = 1 - A_v = 1 - e_v$$

Upward flux at surface

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

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

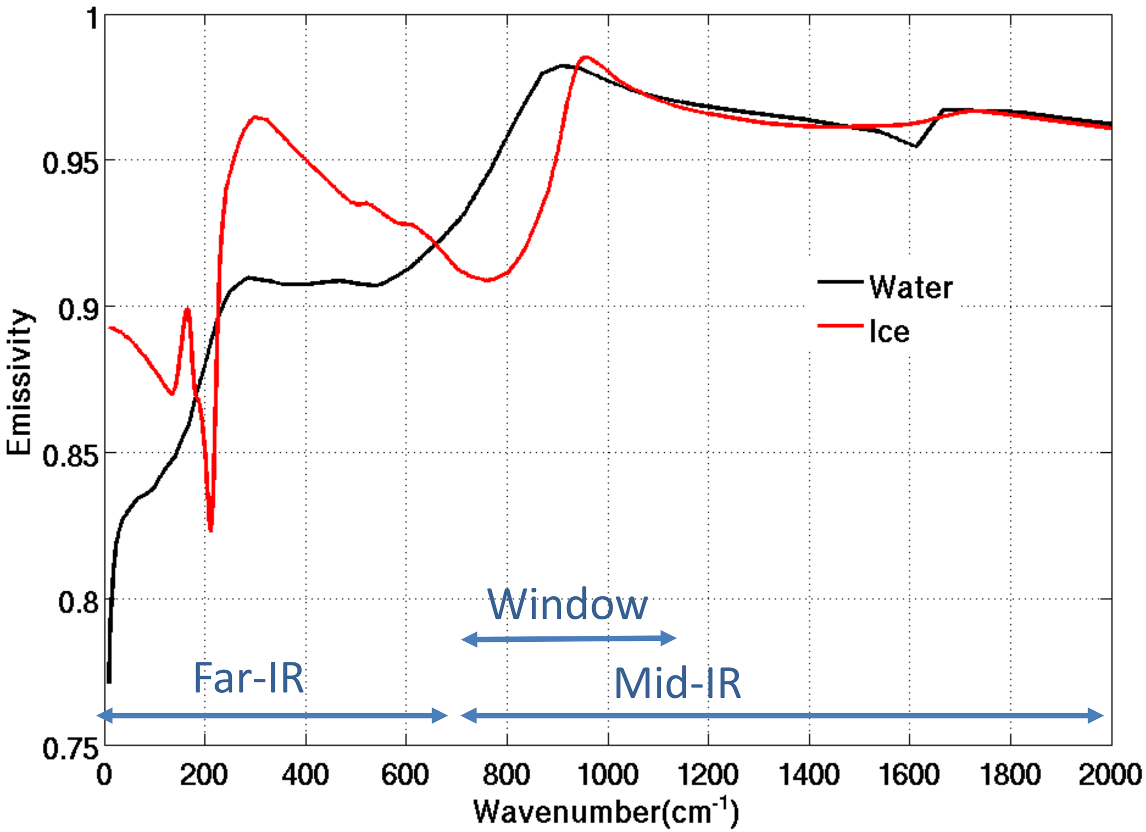
$$F^{\uparrow}(z=0) \approx \pi B_v(T_s)$$

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

Where does this wisdom break down? $F_v^{\downarrow}(z=0) < \pi B_v(T_s)$

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

Possible Impact on simulated climate change



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

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

Emission Reflection Upward LW flux from surface