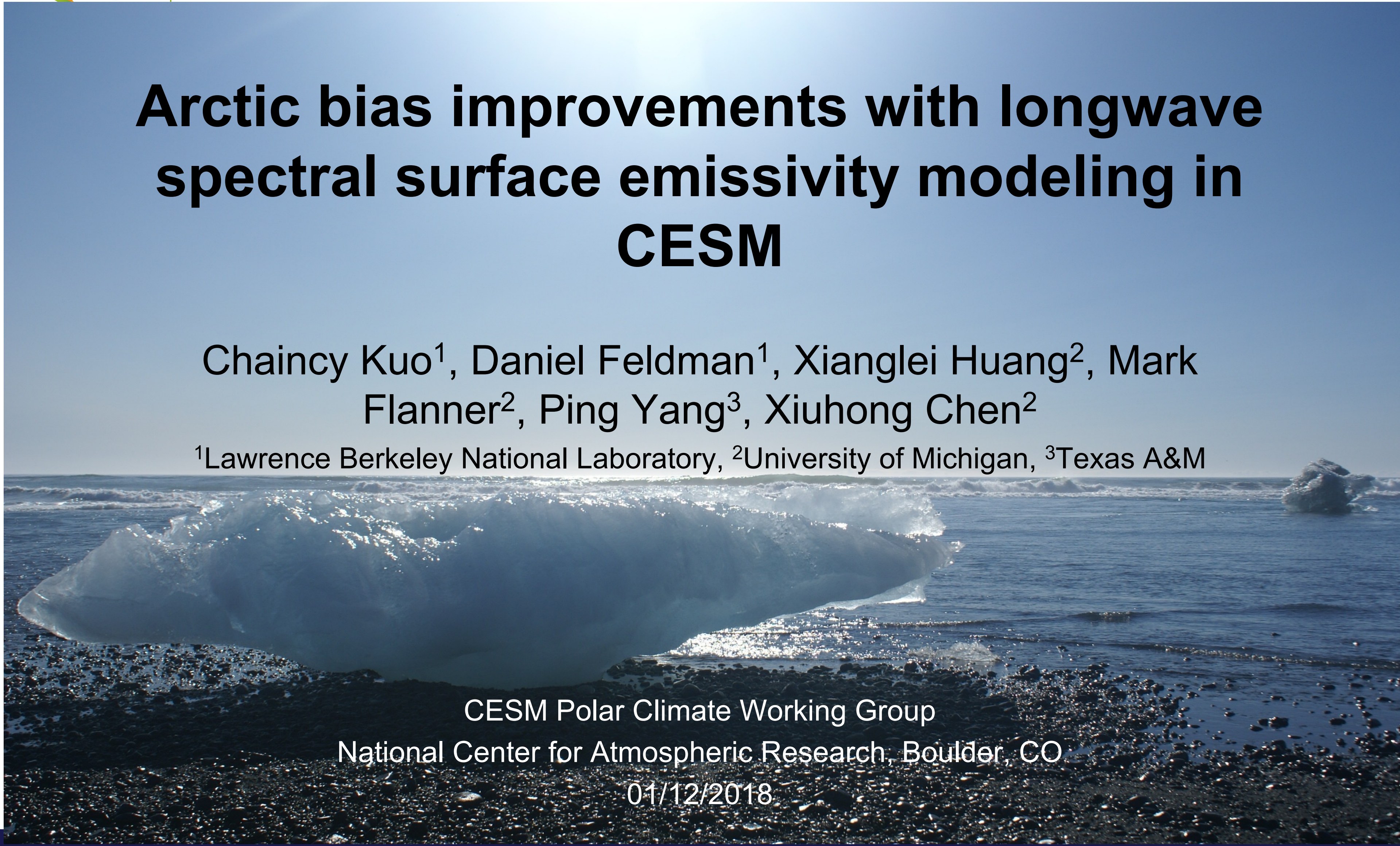

Arctic bias improvements with longwave spectral surface emissivity modeling in CESM

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CESM Polar Climate Working Group
National Center for Atmospheric Research, Boulder, CO
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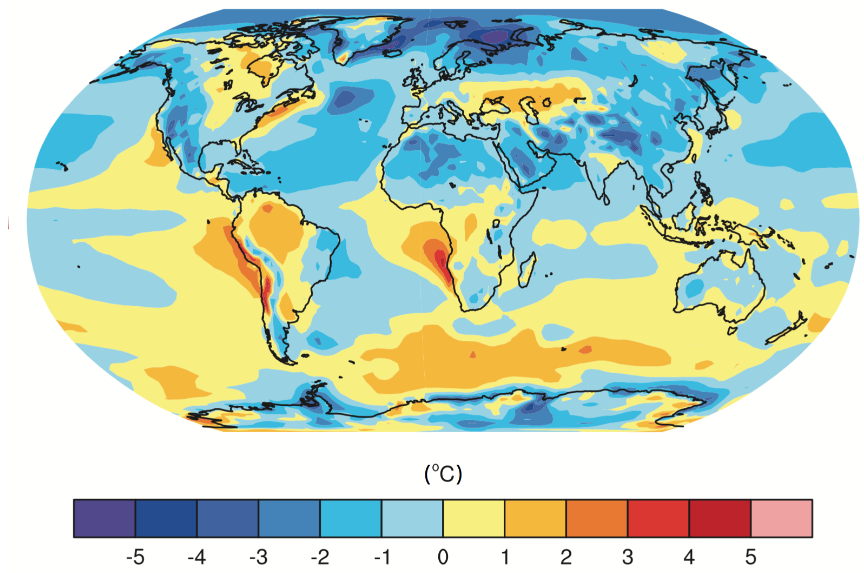
Outline/Motivation

- **Motivation**
  - Modeling the polar climate and its response to global warming has underestimated high latitude warming.
  - Surface emissivity=1.0 in atmospheric component of 24 CMIP5 models.
  - Some models assume grey-body in surface components
    - Inconsistent treatment of between atmospheric and surface components (eg. CESM)
- **Objective**
  - Implement realistic spectral surface emissivity in CESM atmospheric component
  - Secure physical consistency between atmospheric and surface components
  - Test model realism with hindcast
    - Are these modifications justified?
  - Quantify surface emissivity feedback

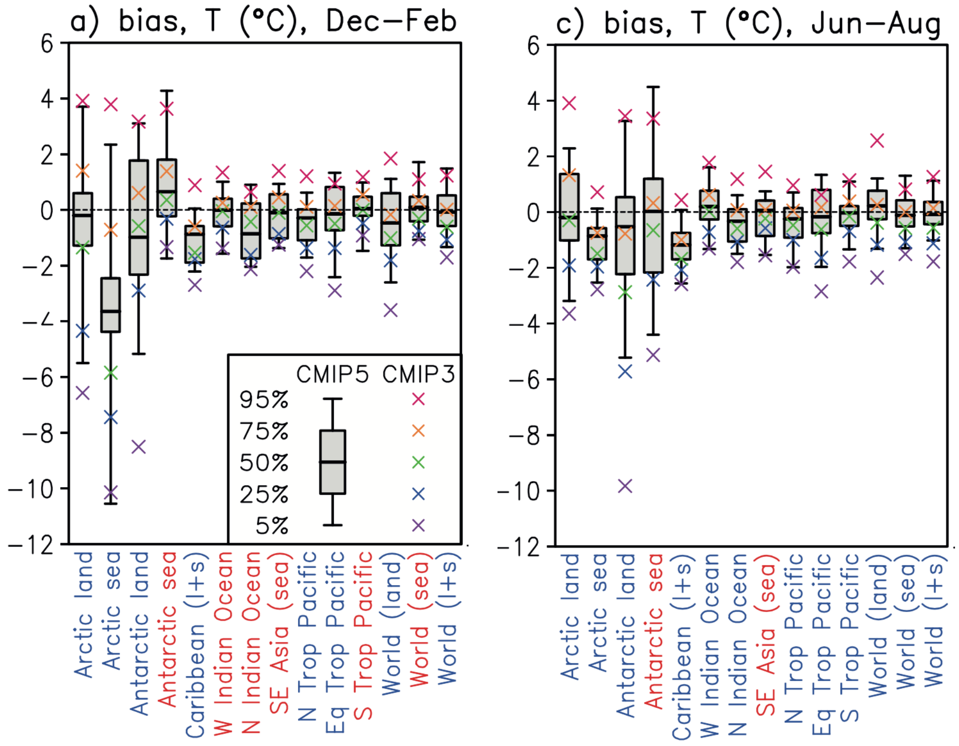
Multi-model Arctic Cold Bias

Reported in IPCC AR5

CMIP5 Multi Model Mean T_S Bias



Surface air temperature bias 1980-2005 against ERA-Interim (Dee et al, 2011)

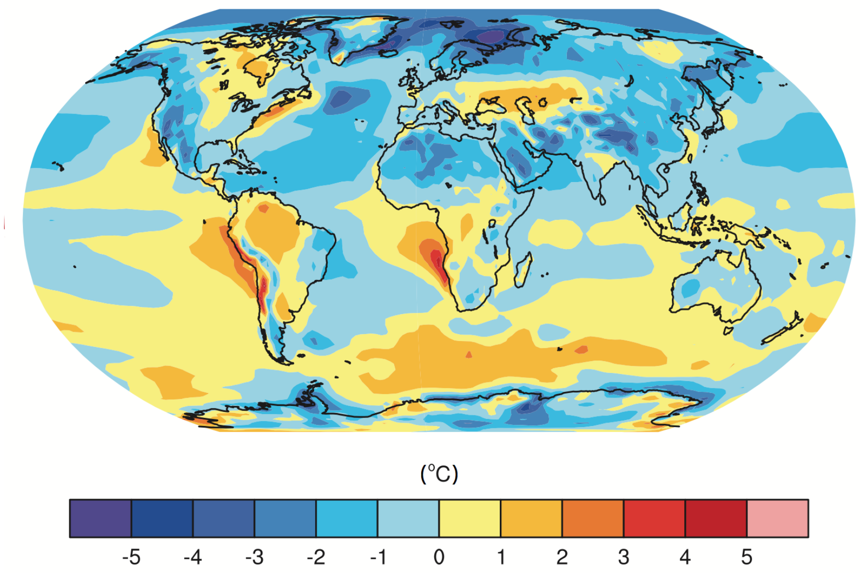


Flato et a, 2013, IPCC AR5

Multi-model Arctic Cold Bias

Reported in IPCC AR5

CMIP5 Multi Model Mean T_S Bias



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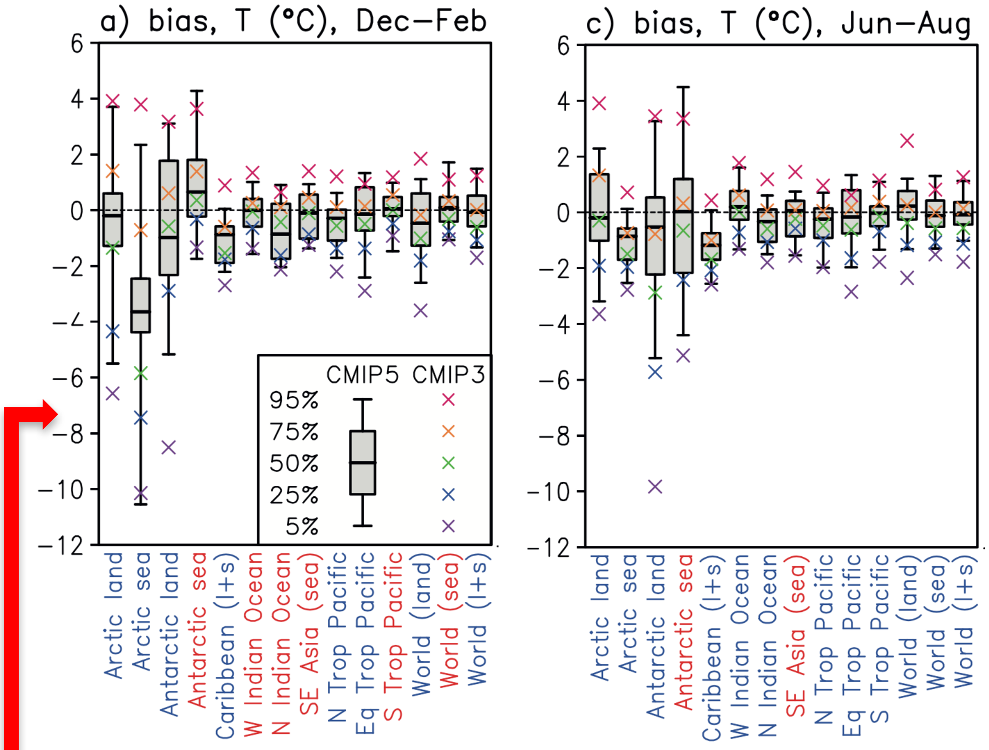
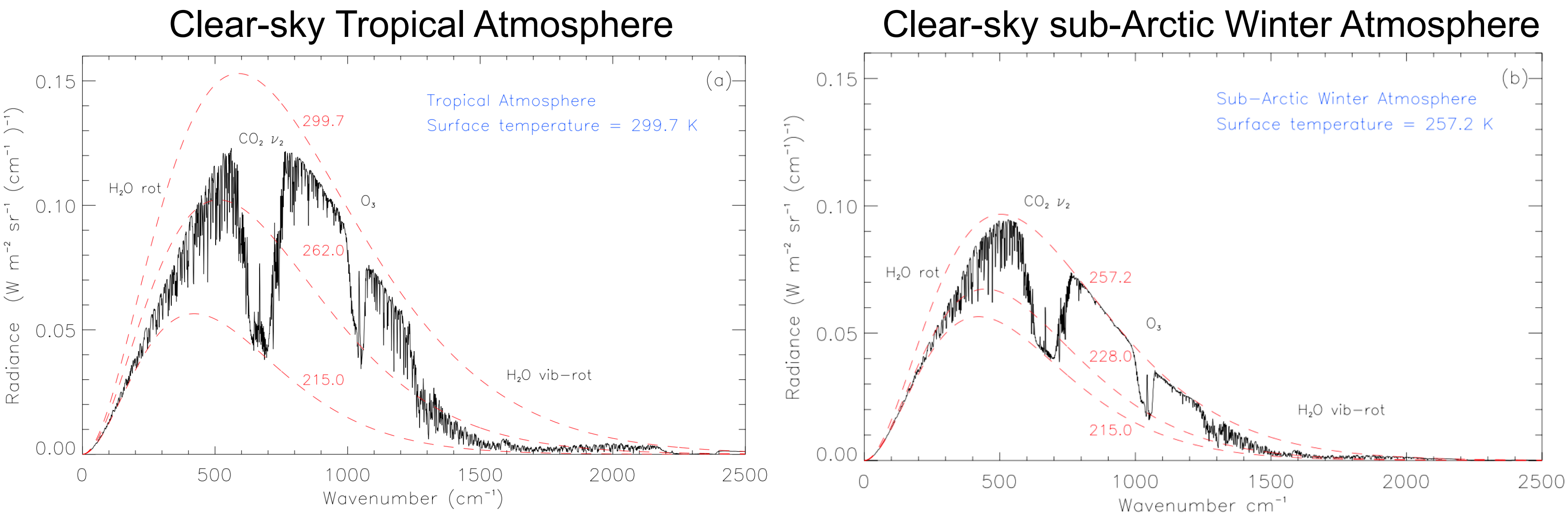


CESM

Flato et a, 2013, IPCC AR5

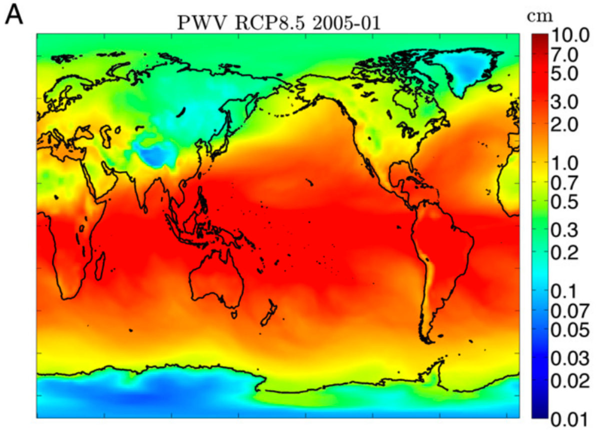
High latitude atmosphere more transparent to Infrared



Clear-sky Tropical Atmosphere

Clear-sky sub-Arctic Winter Atmosphere

Harries et al, 2008, Rev of Geophys



Feldman et al,2014,PNAS

Spectral Emissivity

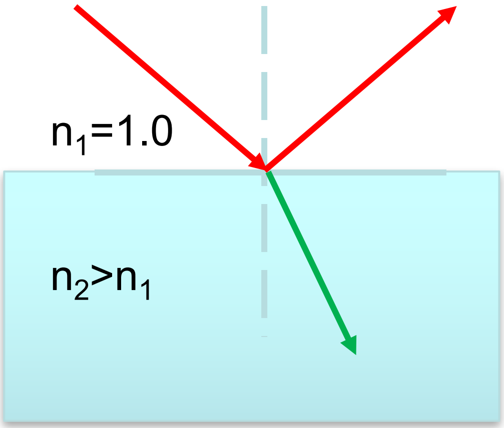
$$\varepsilon(\nu) = \frac{P_a(\nu, T)}{P(\nu, T)}$$

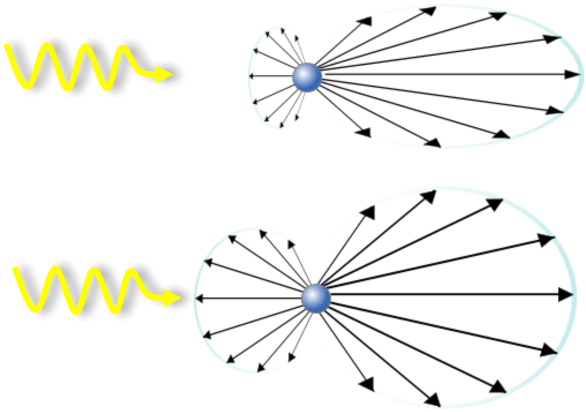
$P_a(\nu, T)$ is the actual power emitted by a body

$P(\nu, T)$ is the power emitted by a black-body

ν is wavenumber
T is equilibrium temperature of the body

Emissivity dependence on geometry





$\varepsilon(\nu) = Q_A(\nu)$ from Mie theory

Fresnel Equations

R(ν)+T(ν)=1

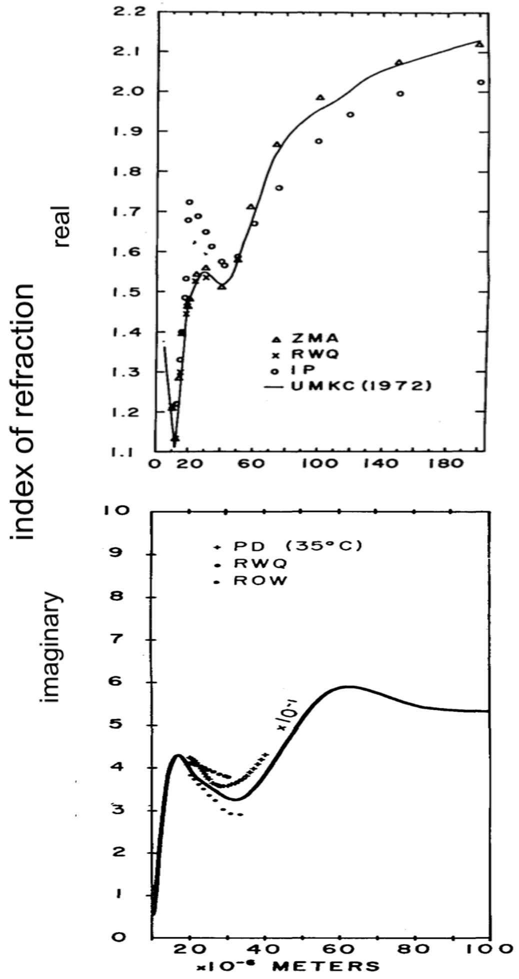
ε (ν)=1-R (ν) (ang. avg)

Scattered field dependence on

- Size of particle vs. wavelength
- Bulk asymmetry of field scaled by multiple scattering

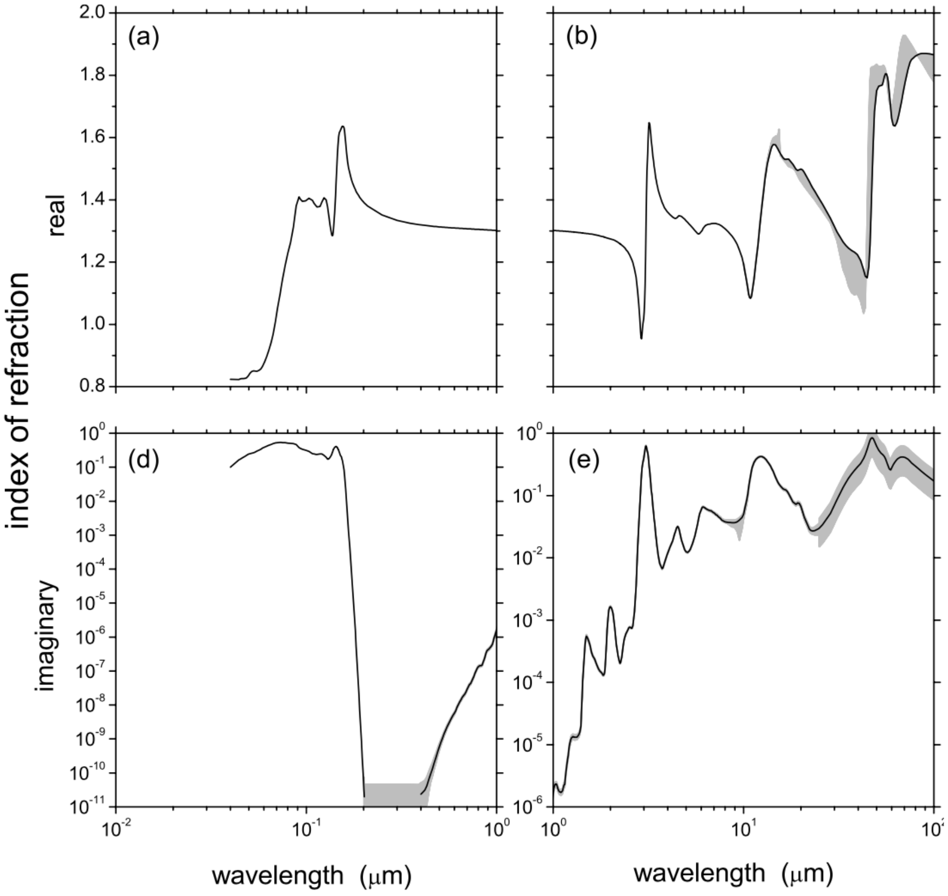
Far Infrared photons strongly attenuated by unfrozen and frozen water

Water indices of refraction



Hale & Querry, 1973, Applied Optics

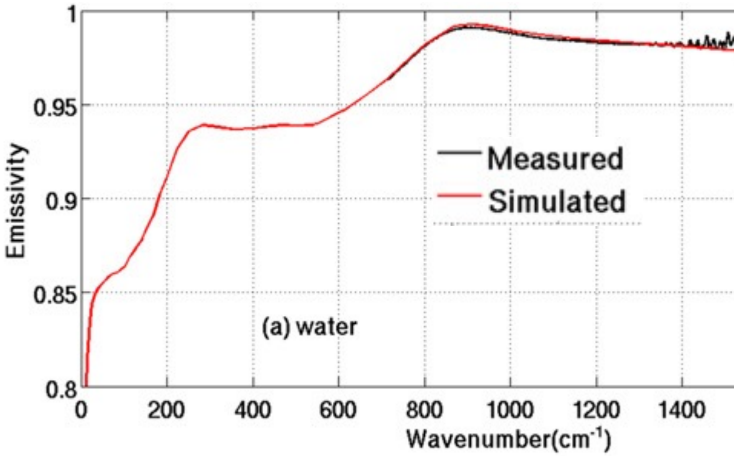
Ice indices of refraction



Warren & Brandt, 2008

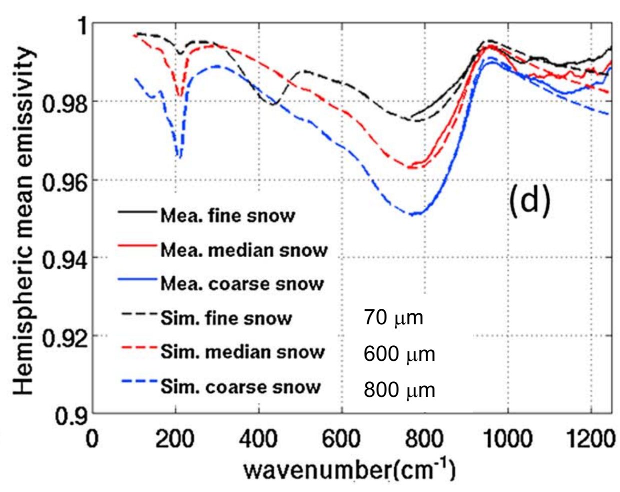
Spectral Emissivity

Water Emissivity



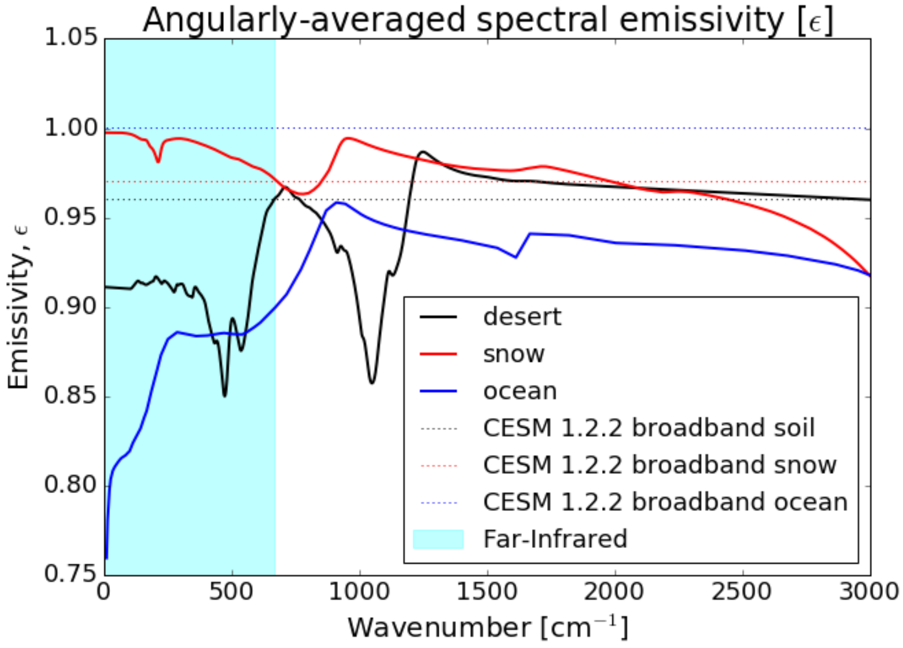
Huang XL et al, 2016, JAS

Snow Emissivity



Chen et al, 2014, GRL

Emissivity implemented in CESM-ε(ν)



CESM: Surface emissivity & radiative surface temperature in atmospheric component (CAM) not consistent with surface components

Surface upwelling longwave flux

$$F^{\uparrow}_{surf} = \varepsilon\sigma T^{4}_{s\,surf} \qquad \varepsilon < 1$$

$$F^{\uparrow}_{atm} = \sigma T^{4}_{s\,atm} \qquad \varepsilon = 1$$

Atmospheric model (CAM 5.3)

$$F^{\uparrow}_{atm} = F^{\uparrow}_{surf}$$

$$T_{s,atm} = \sqrt[4]{\frac{F^{\uparrow}_{surf}}{\sigma}} \qquad \varepsilon = 1$$

Consequences

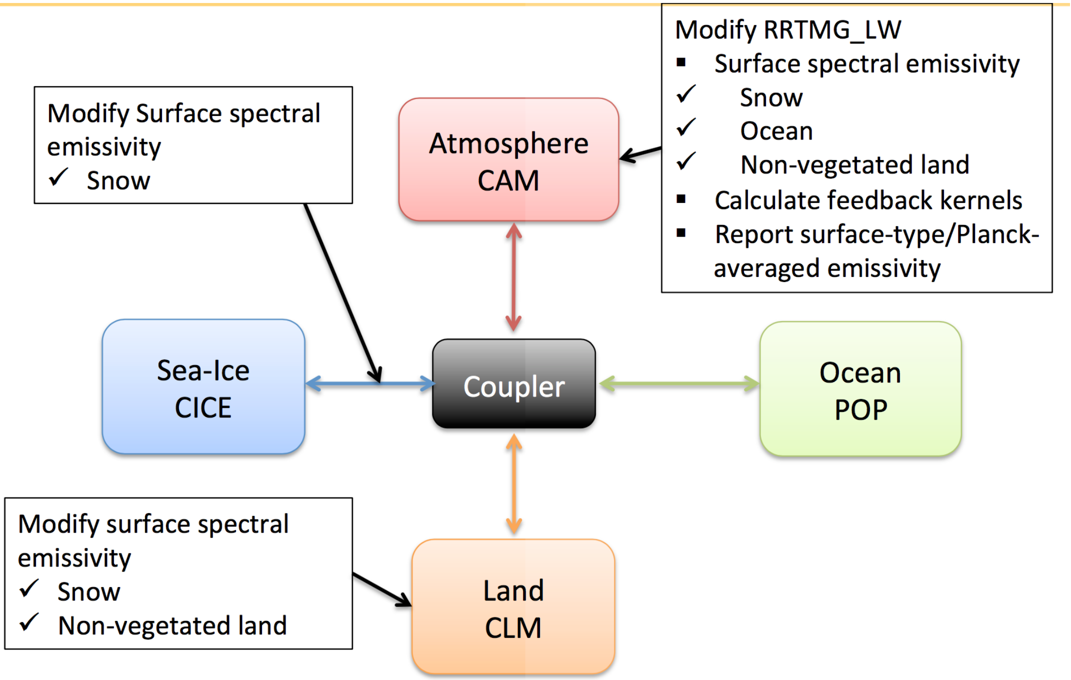
- $T_{s,atm} \leq T_{s,surf}$
- Planck function shape shifted→ redistributed spectral fluxes
- Planetary boundary layer cooling rate errors up to 20% (Cheng et al., 2016, JQSRT)

CESM-ε(ν) Experimental Setup

$$F^{\uparrow}_{atm\;model} = \pi \int_0^\infty \varepsilon(\nu) B(\nu, T_{surf}) d\nu$$

$$F^{\uparrow}_{surf\;model} = \bar{\varepsilon}\sigma_{SB}T^4_{surf}$$

where is the Planck-weighted emissivity $\bar{\varepsilon} = \frac{\int_0^\infty \varepsilon(\nu)B(\nu,T)d\nu}{\int_0^\infty B(\nu,T)d\nu}$



Modify Surface spectral emissivity
- ✓ Snow

Modify RRTMG_LW
- Surface spectral emissivity
  - ✓ Snow
  - ✓ Ocean
  - ✓ Non-vegetated land
- Calculate feedback kernels
- Report surface-type/Planck-averaged emissivity

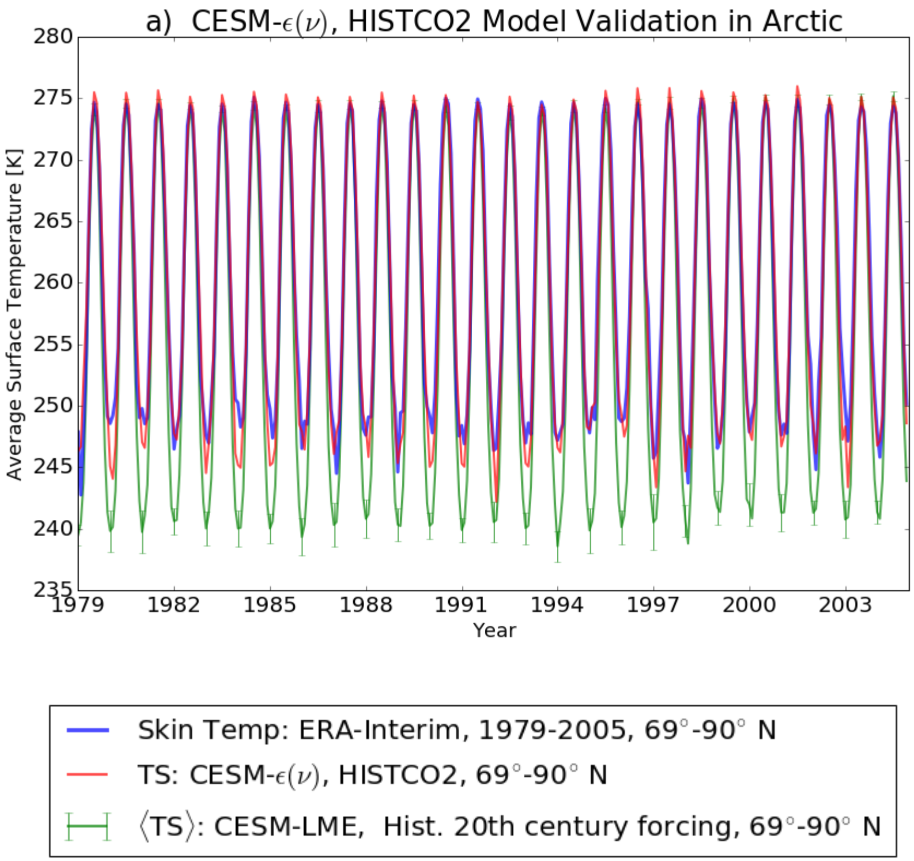
Modify surface spectral emissivity
- ✓ Snow
- ✓ Non-vegetated land

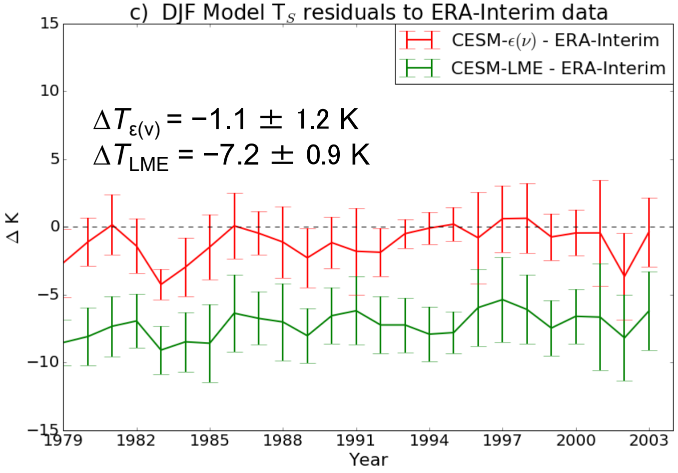
CESM-$\varepsilon(\nu)$ control model is stable

1850CNTL (1850-2005)		
Global Mean Variable	Global Mean Value	155-year Trend
TS	287.12 ± 0.11 K	$+1.6 \times 10^{-4}$ K/year
TS (CESM-LME)	287.16 ± 0.43 K	$+1.2 \times 10^{-4}$ K/year
SST	285.71 ± 0.06 K	$+0.9 \pm 1.1 \times 10^{-4}$ K/year
$F^{\uparrow}_{atm} - F^{\uparrow}_{land}$	**$1.3 \pm 0.1 \times 10^{-2}$ W/m^2**	**$-5.3 \pm 19.1 \times 10^{-6}$ W/m^2/year**

Case Name	**Forcing Scenario**	**Years**
1850CNTL	1850 atmosphere, no forcing	1850-2005
HISTCO2	Start 1850 atmosphere, Historical CO_2	1850-2005
RCP2.6	RCP2.6 scenario	2005-2100
RCP8.5	RCP8.5 scenario	2005-2100

Model Validation with Observation

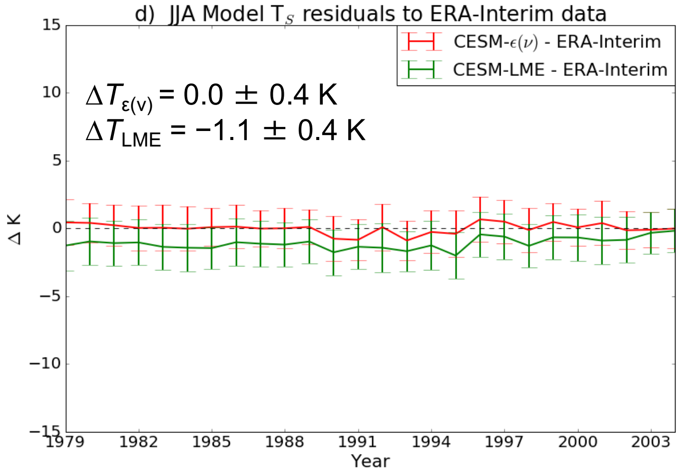




$\Delta T_{\epsilon(v)} = -1.1 \pm 1.2$ K

$\Delta T_{\mathrm{LME}} = -7.2 \pm 0.9$ K

DJF



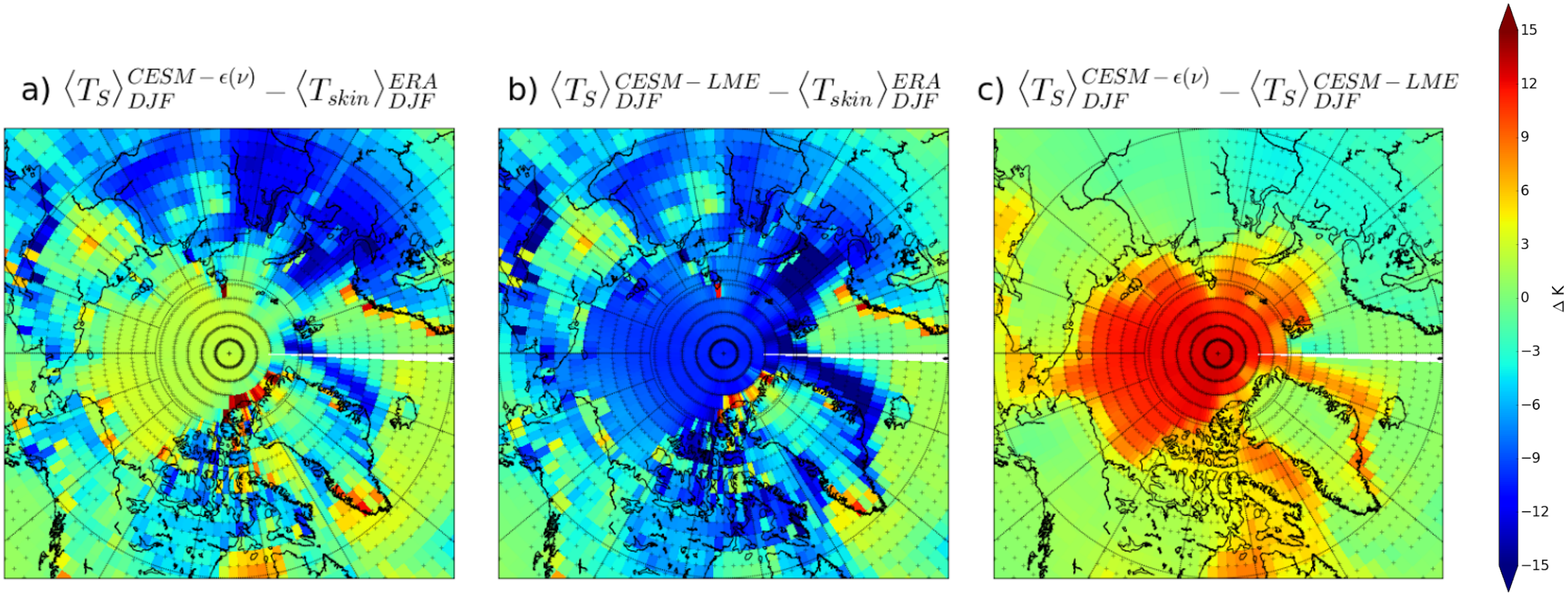
$\Delta T_{\epsilon(v)} = 0.0 \pm 0.4$ K

$\Delta T_{\mathrm{LME}} = -1.1 \pm 0.4$ K

JJA

C. Kuo et al, *2018*, JGR-Atmospheres

CESM1 Wintertime Cold Bias Resolved by $\varepsilon(\nu)$
1997-2005



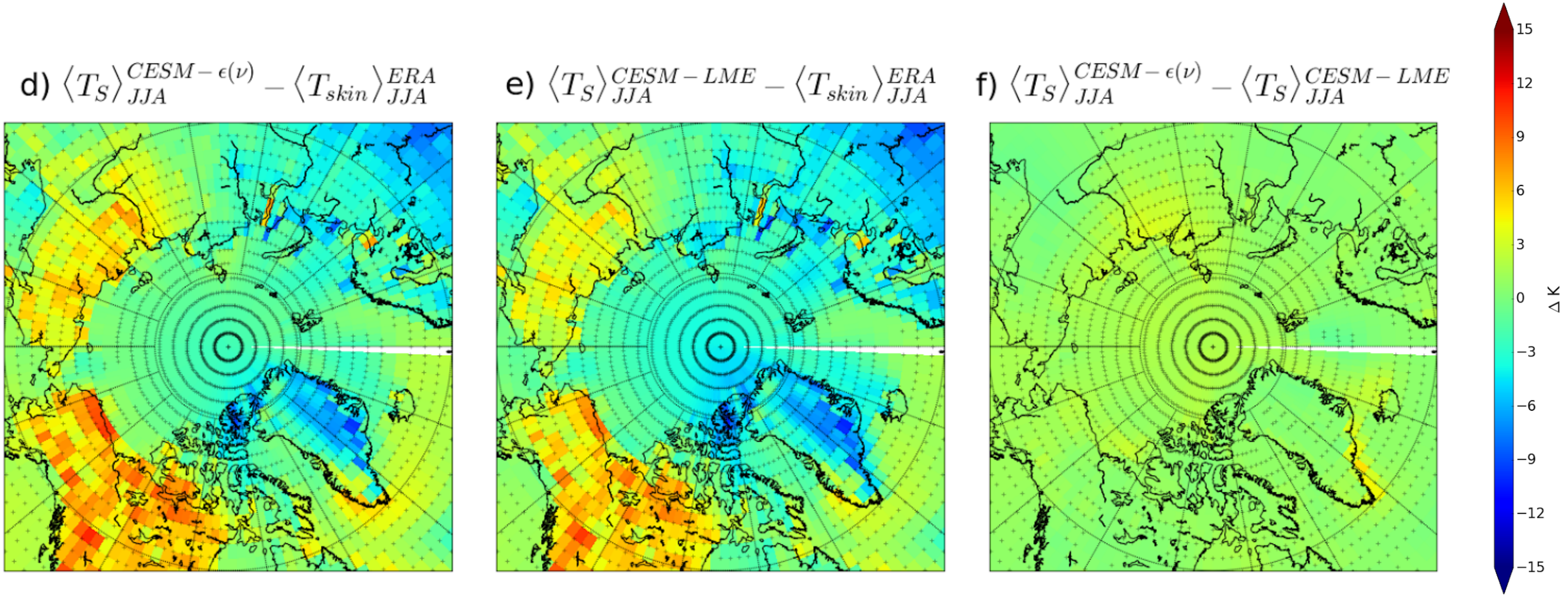
a) $\langle T_S \rangle_{DJF}^{CESM-\epsilon(\nu)} - \langle T_{skin} \rangle_{DJF}^{ERA}$

b) $\langle T_S \rangle_{DJF}^{CESM-LME} - \langle T_{skin} \rangle_{DJF}^{ERA}$

c) $\langle T_S \rangle_{DJF}^{CESM-\epsilon(\nu)} - \langle T_S \rangle_{DJF}^{CESM-LME}$

C. Kuo et al, *2018*, JGR-Atmospheres

Summertime surface temperatures
1997-2005



d) $\langle T_S \rangle^{CESM-\epsilon(\nu)}_{JJA} - \langle T_{skin} \rangle^{ERA}_{JJA}$

e) $\langle T_S \rangle^{CESM-LME}_{JJA} - \langle T_{skin} \rangle^{ERA}_{JJA}$

f) $\langle T_S \rangle^{CESM-\epsilon(\nu)}_{JJA} - \langle T_S \rangle^{CESM-LME}_{JJA}$

C. Kuo et al, *2018*, JGR-Atmospheres

Emissivity feedback with analytic $\varepsilon(\nu, \vec{r}, t)$ kernel

$$\left.\frac{\partial OLR}{\partial \varepsilon}\right|_{\nu_i}(\vec{r}, t) = \int_{\nu_i}^{\nu_{i+1}} \left[B\left(\nu, \vec{r}, T_s(\vec{r}, t)\right) - F^{\downarrow}(\nu, \vec{r}, t)\right]\theta(\nu, \vec{r}, t)d\nu$$

$B(\nu, \vec{r}, T_s(\vec{r}, t))$	Planck function
$F^{\downarrow}(\nu, \vec{r}, t)$	Longwave downwelling flux
$\Theta(\nu, \vec{r}, t)$	Atmospheric transmission

- Analytic expression allows for online calculation during model integration
- Kernel evolves along with atmospheric state evolution
- Operation of ε kernel on contemporaneous ε perturbation is possible

- Surface emissivity feedback $\mathcal{O}(10^{-3})$ W/m^2/K
- Positivity/negativity? Details in Kuo et al, 2018, JGR-Atm

Far-IR multiple scattering in clouds

- Radiative transfer calculations in flux and heating rate simulations
  - MODIS Collection 6 cloud optics models
  - CALIPSO, CloudSat, CERES & MODIS

- When neglecting LW scattering in clouds,

Region		**Bias (W/m^2)**
Outgoing Longwave	Global	2.6 over
Surface Downward	Global	1.2 under
	Greenland, Antarctic, Tibetan Plateau	3.6 under

- Biases are larger for ice clouds than water clouds

- LW scattering should not be neglected in GCM’s.

Kuo, C.-P., Yang, P., Huang, X., Feldman, D., Flanner, M., Kuo, C., & Mlawer, E. J. (2017). **Impact of multiple scattering on longwave radiative transfer involving clouds**. *JAMES*, 9. https://doi.org/10.1002/ 2017MS001117

Summary

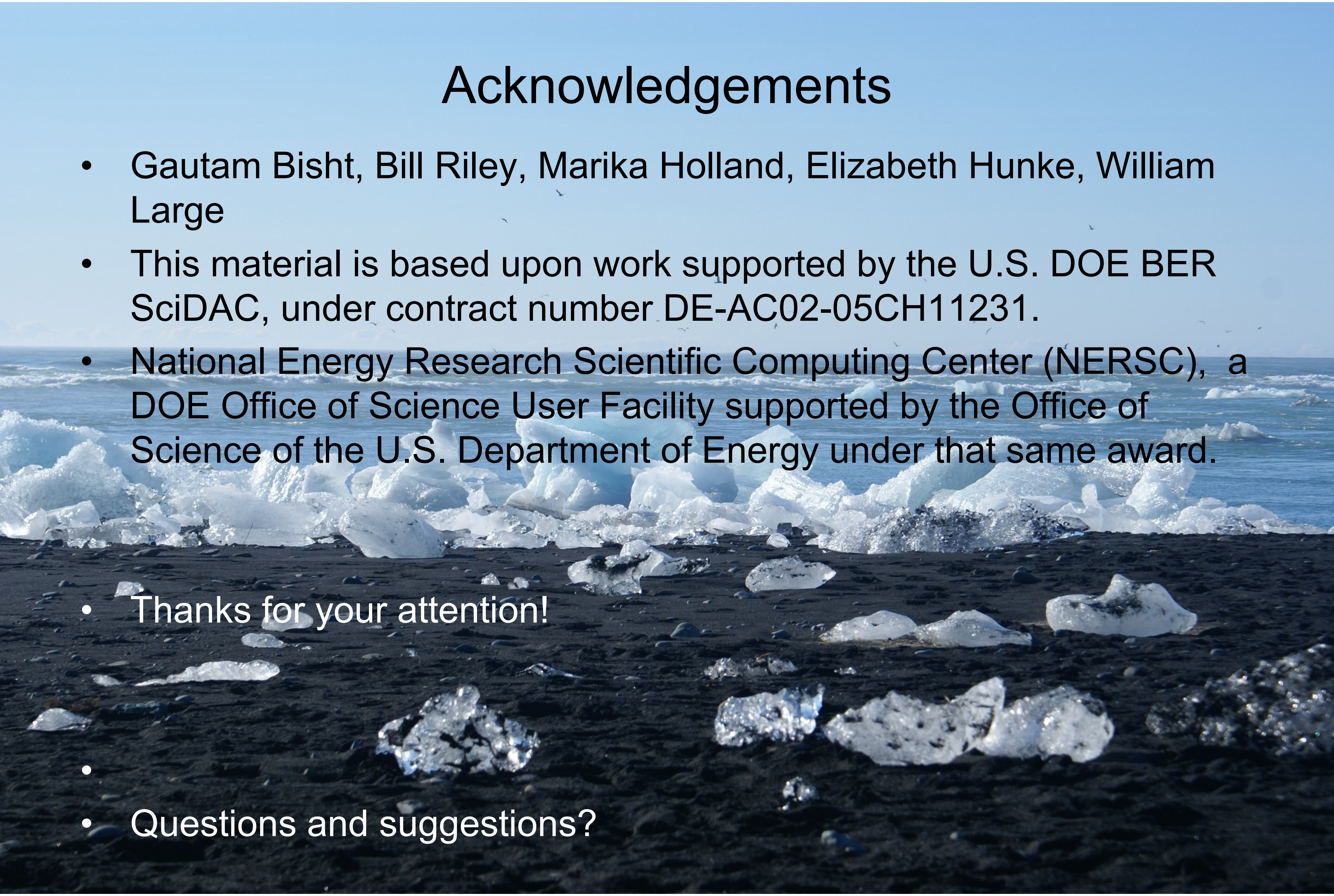
- Realistic surface emissivity and consistent physical representation in both surface and atmospheric components of the CESM coupled-climate model.

- The representation of longwave surface emissivity in CESM impacts its cryospheric response to climate change by +6.1±1.9 K of wintertime Arctic surface temperature in a recent historical period.

- Longwave effects continue in polar wintertime

- Similar analyses to what is presented here for CESM will need to be performed in other climate models to establish if surface-emissivity physics are important for high-latitude bias reduction in the multi-model ensemble.

Kuo, C., Feldman, D. R., Huang, X., Flanner, M., Yang, P., & Chen, X. (2018). **Time-dependent cryospheric longwave surface emissivity feedback in the Community Earth System Model**. *JGR: Atmospheres*, *123*. https://doi.org/10.1002/2017JD027595



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- Thanks for your attention!

- Questions and suggestions?