Using Temperature, Humidity, and Emissivity Observations to Confront and Uproot the Persistent Cold-Pole Biases in Earth System Models

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First Forum Workshop

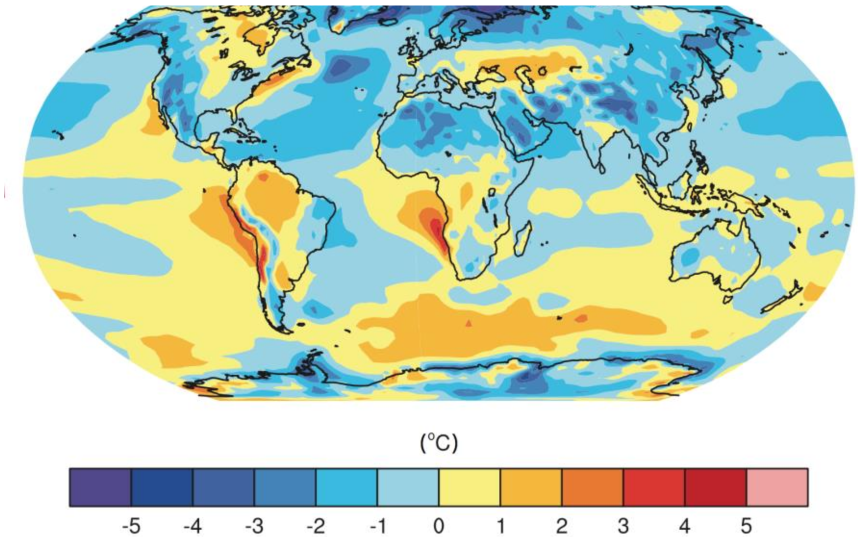
October 24, 2018

Outline

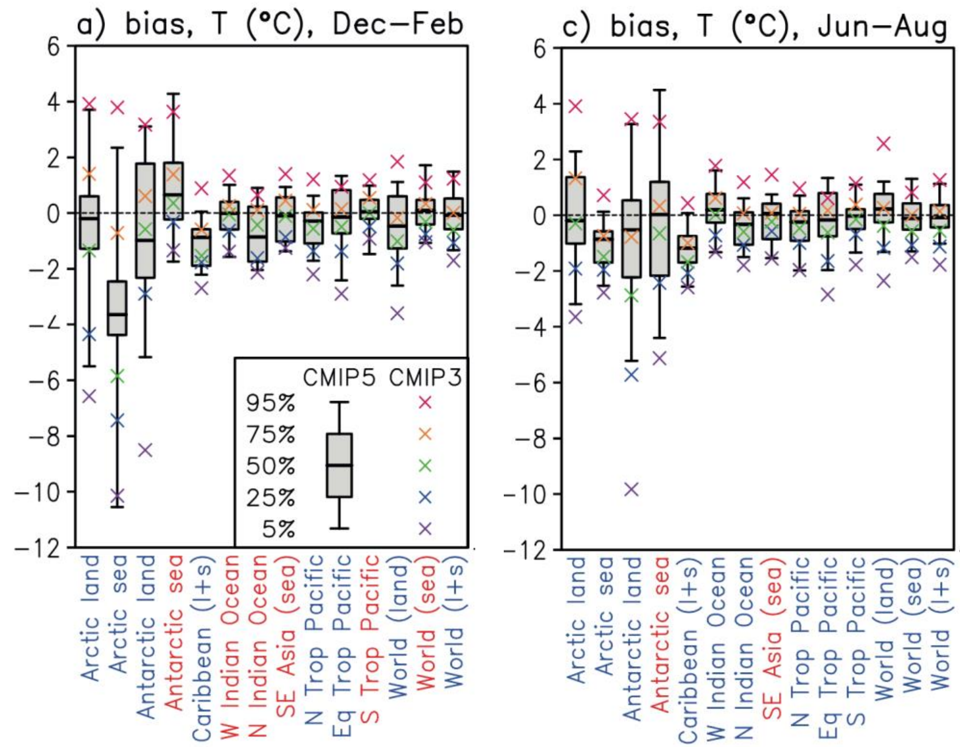
- Overview of Persistent Cold Pole Biases in Climate Models.
- Updating Climate Model Infrared Radiation.
- Climate Model Response to Updated Infrared Radiation.
- Using FORUM Observations to Uproot Model Biases.
- Lessons Learned from Limited Far-IR Observations.
- Discussion.

The Problem: Persistent Multi-model Arctic Cold Biases

CMIP5 Multi Model Mean T_S Bias



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



Flato et al, 2013, IPCC AR5

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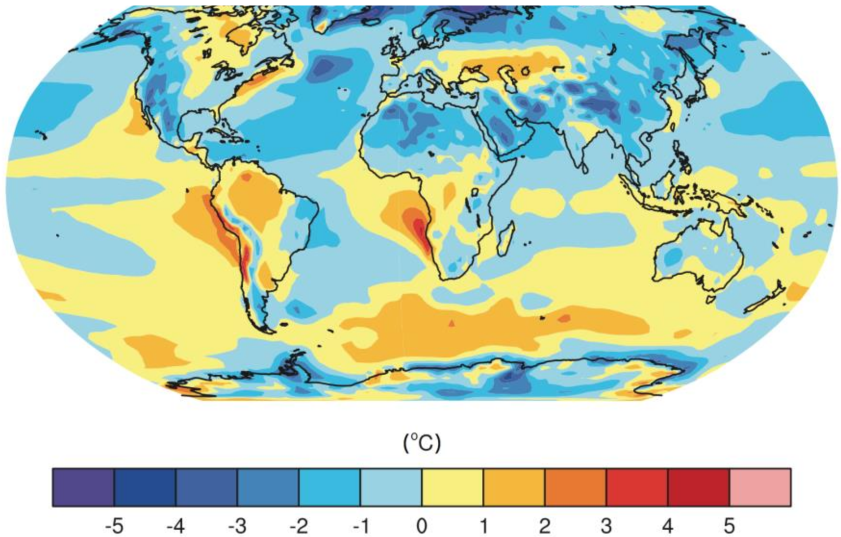

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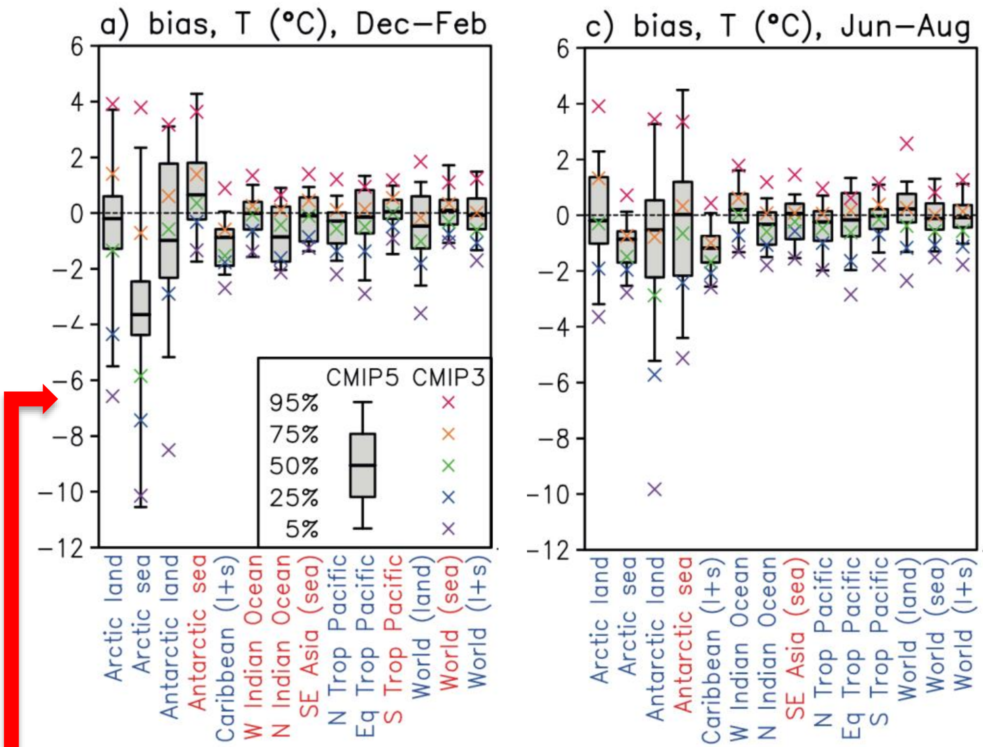

CESM

Flato et al, 2013, IPCC AR5

The Problem: Persistent Multi-model Arctic Cold Biases

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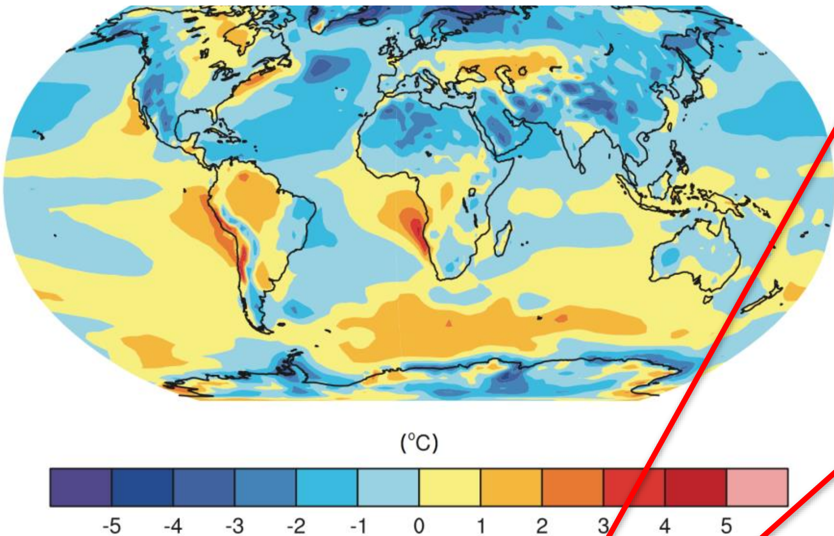

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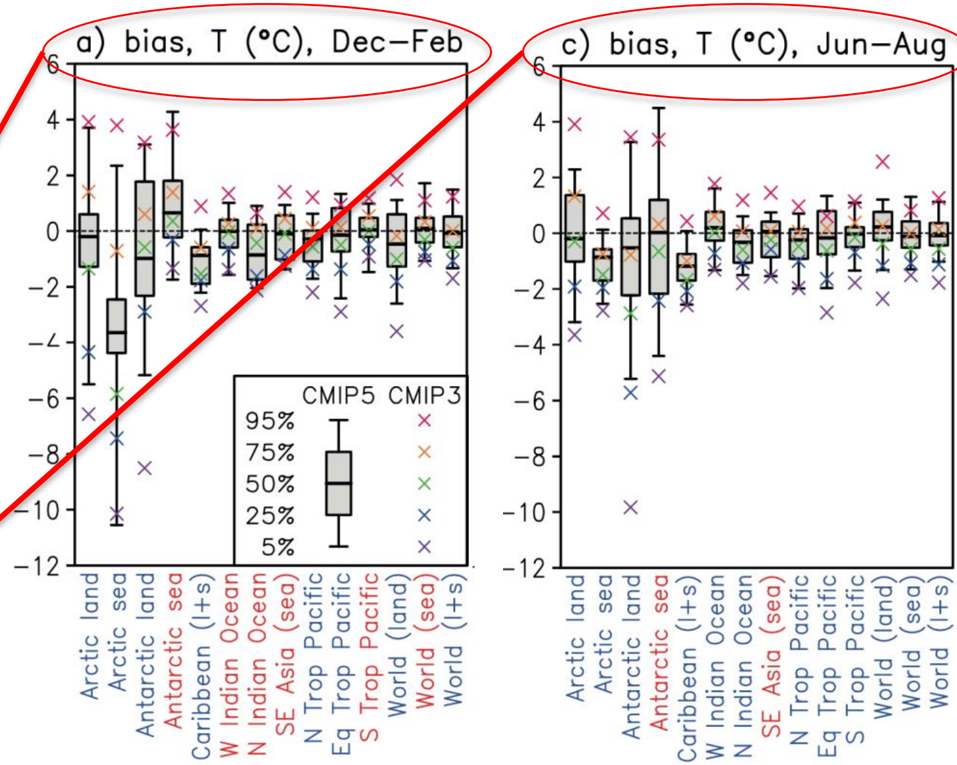
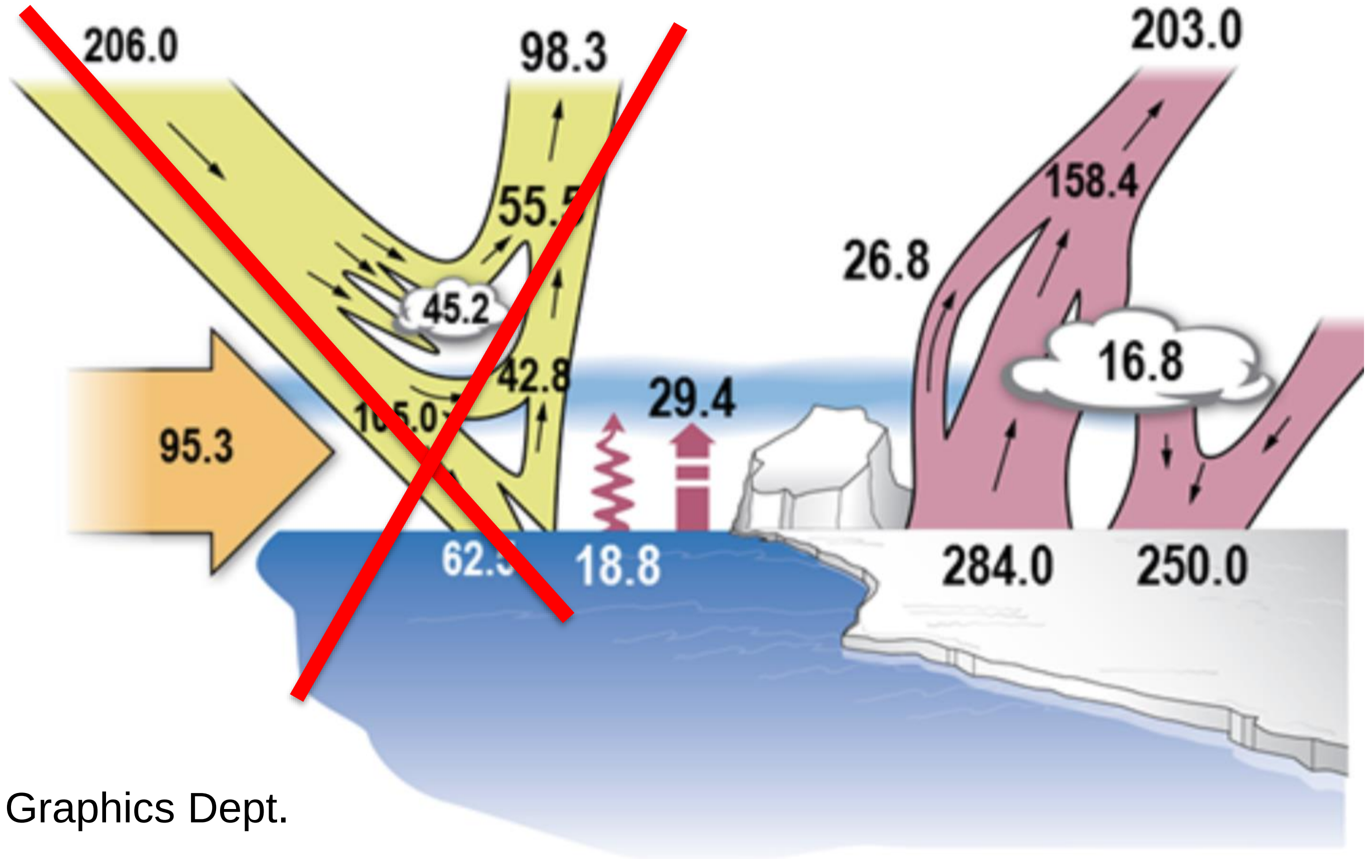


Probably not directly related to albedo !

Flato et al, 2013, IPCC AR5

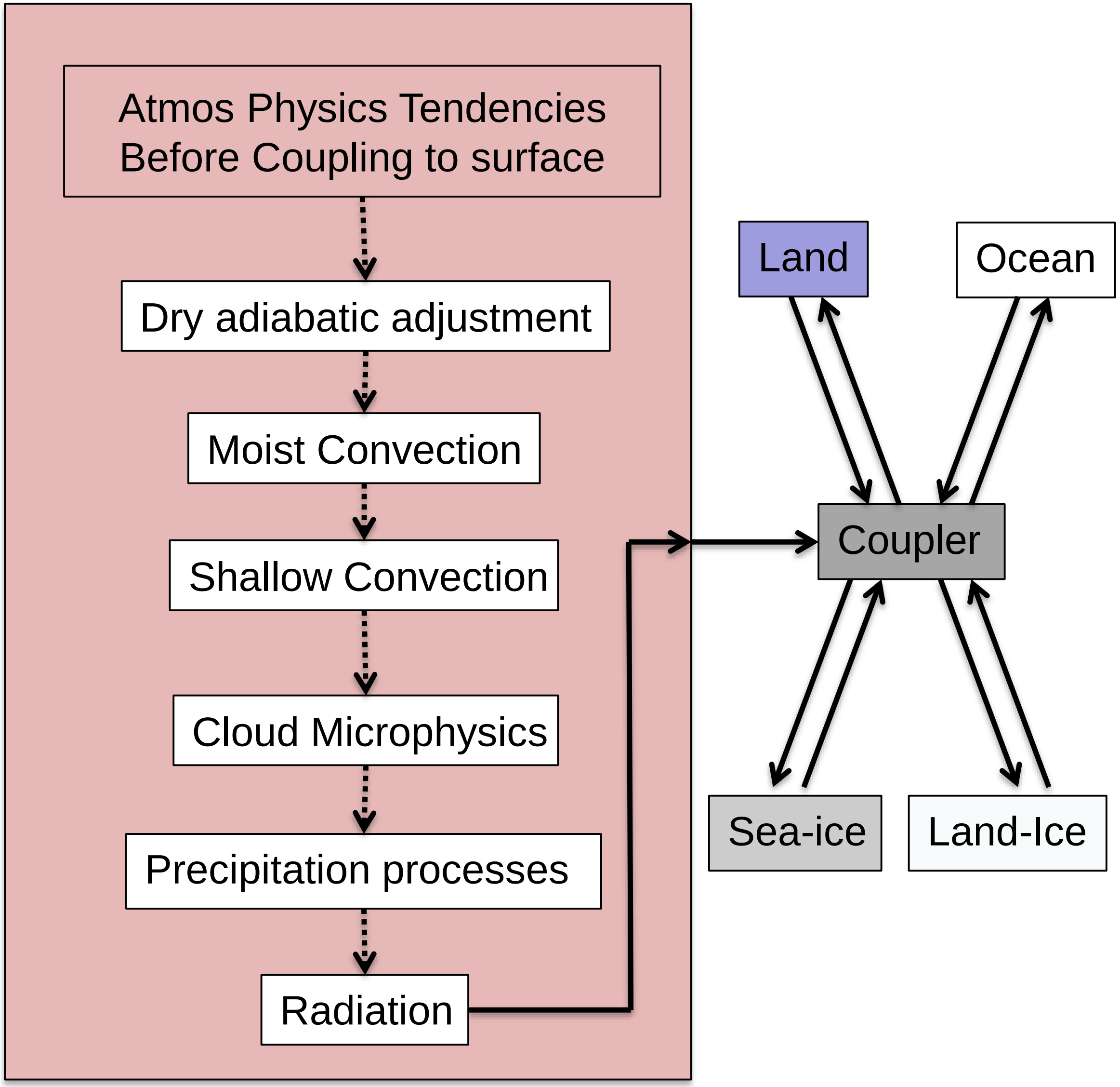
Clues to the Source of the Problem



JPL Graphics Dept.

- ***The polar radiative energy budget is governed by heat transport, incoming shortwave and outgoing longwave radiation.***
- ***During winter, the lack of incoming shortwave radiation simplifies the problem: polar heat transport and radiation drive boundary layer temperature and frozen surface extent.***

Model Representation of Physical Processes

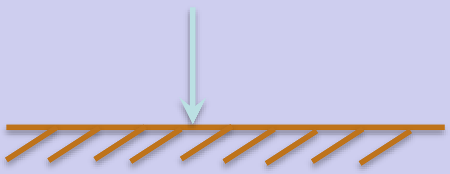


- ***As we seek to uproot cold pole biases in models, it is critical we understand how physical processes are represented in the models.***

Example: Surface Fluxes in the Land Component

Land Component

- F^{down} from Atmospheric model

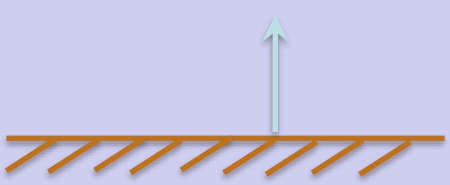


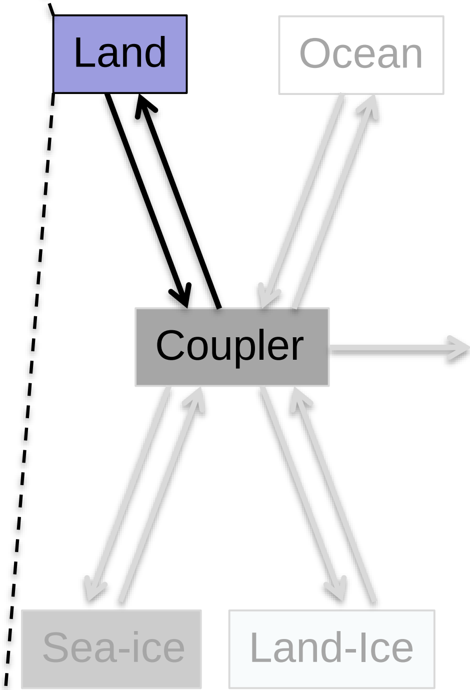
- Soil Temperature Model

Adjusts surface temperature, T_S

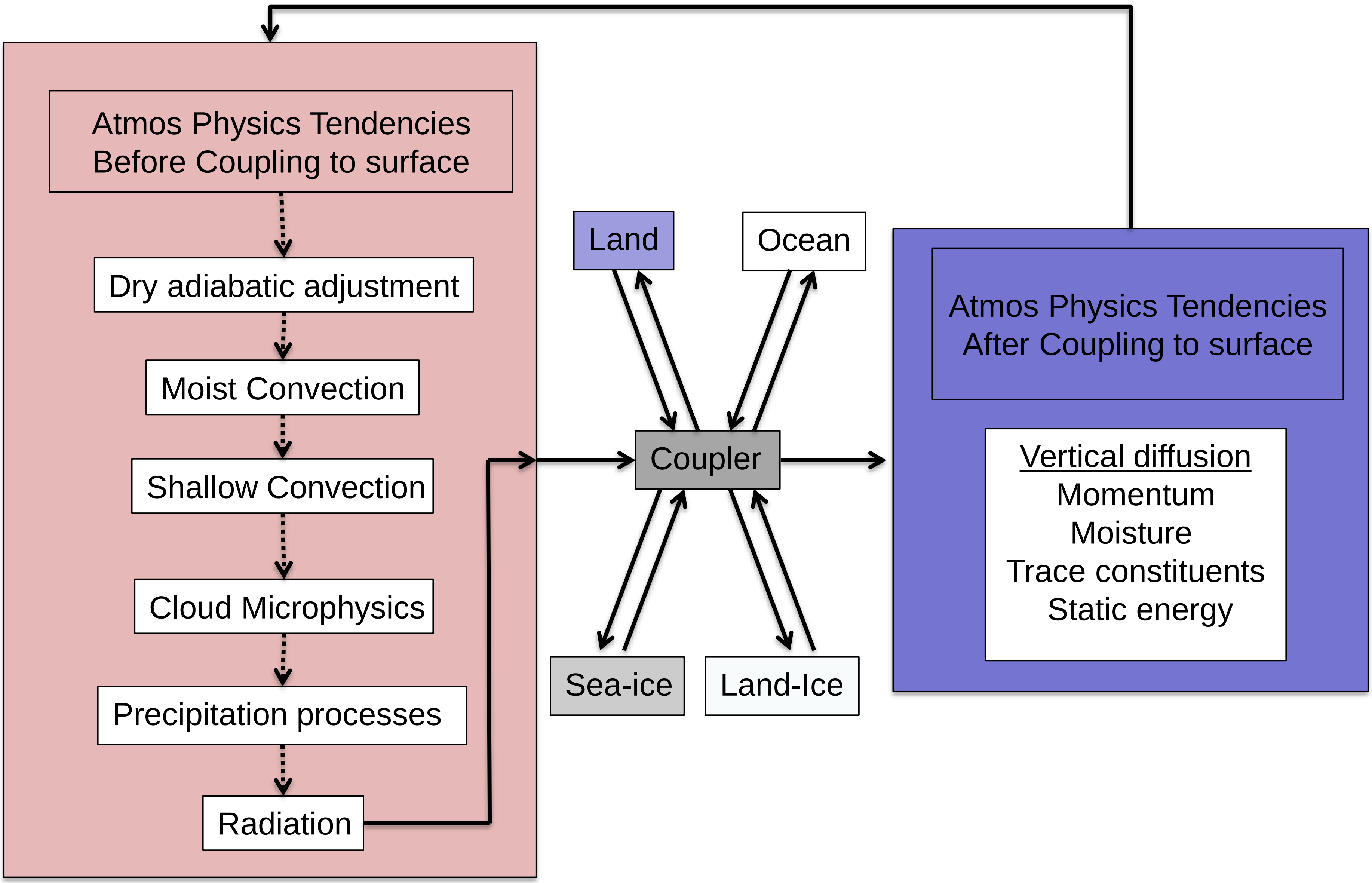
- $F^{up} = \approx \langle \varepsilon(\nu) \rangle \sigma T_s^4$

Latent heat and sensible heat
Back to Atmospheric model

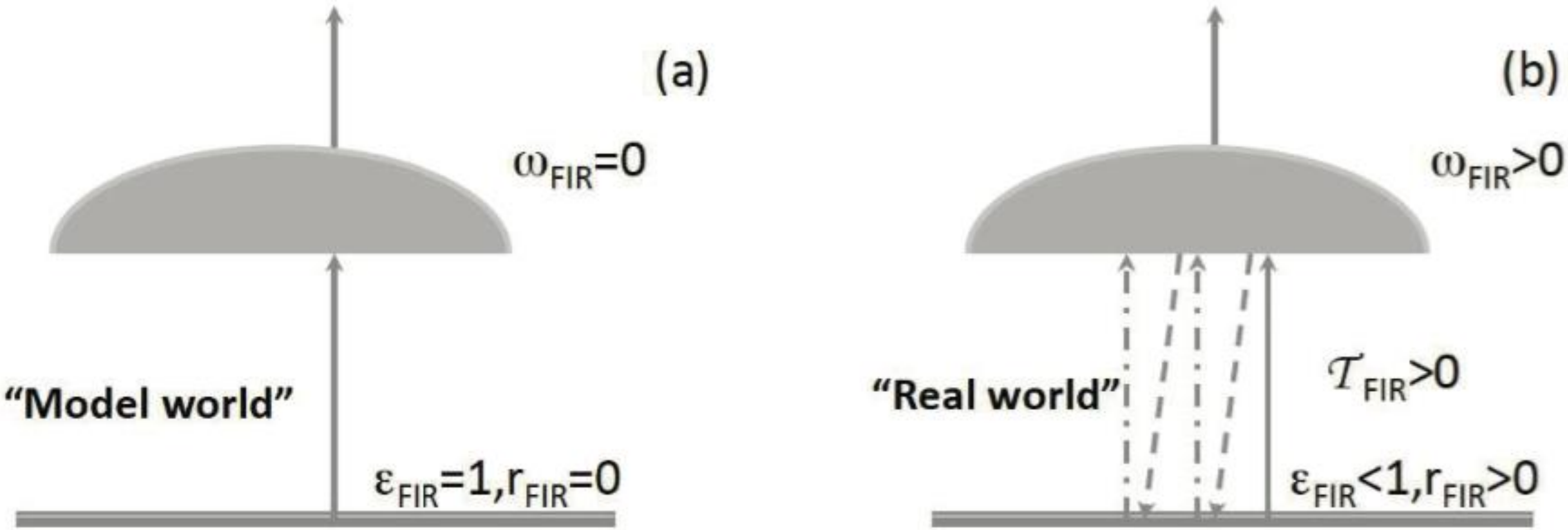




Continuation of atmospheric tendencies



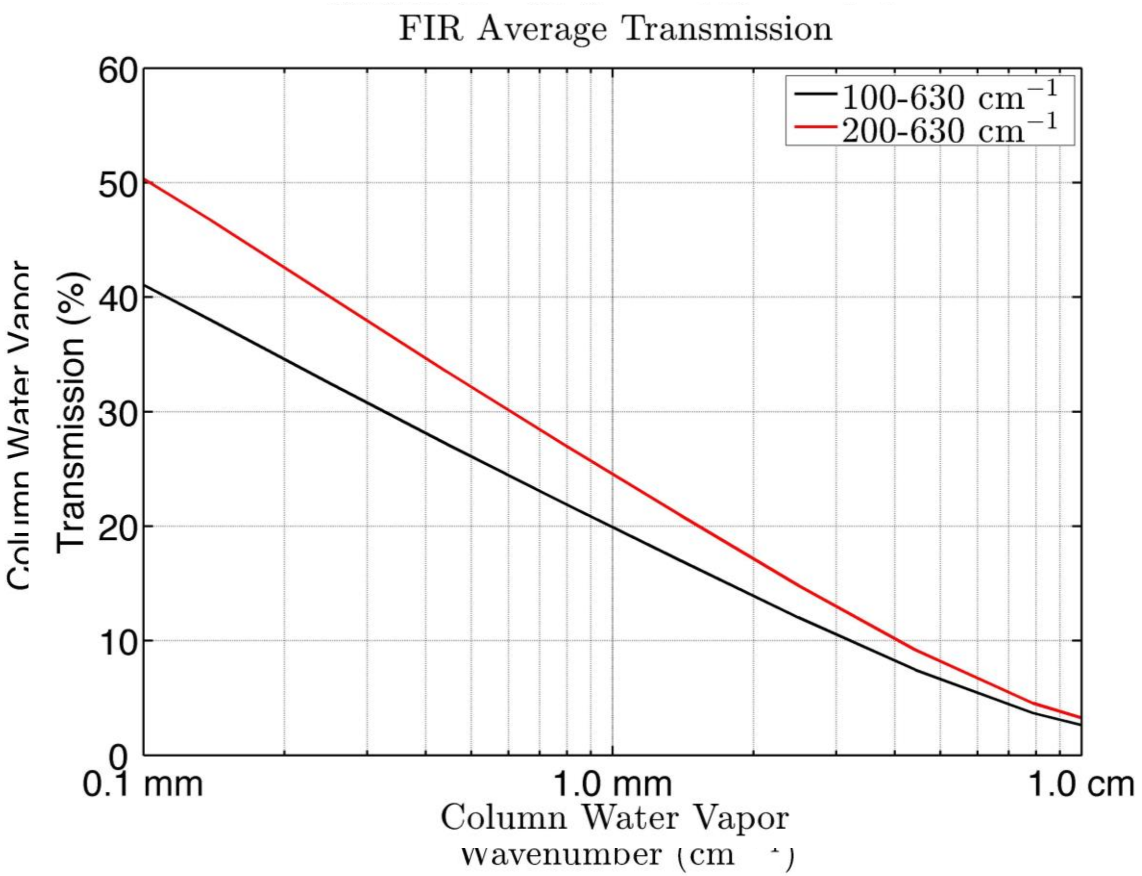
Infrared Radiation: Model vs. Real World



From Chen et al, GRL, 2014

- ***There is a discrepancy between how infrared radiation is handled in models vs. real-world processes.***
- ***Surfaces are not perfect emitters (their emissivity < 1), and, under dry conditions, clouds and the surface can interact radiatively.***
- ***A survey of models indicates that these processes are not well-represented in the CMIP5 models, and may be important at high-latitudes where it is drier.***

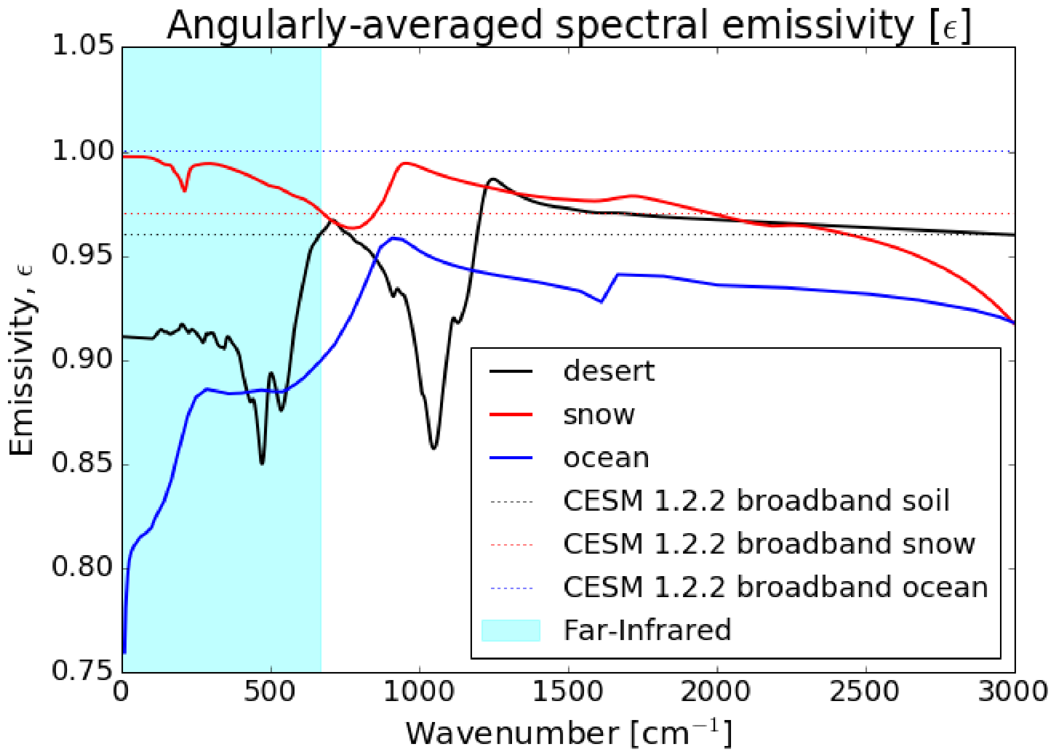
Drier Atmospheres are Far More Transparent



From Feldman et al, PNAS, 2014

- ***At high latitudes, the atmosphere begins to become quite transparent, even at far-infrared wavelengths, which are quite opaque at lower latitudes.***
- ***Therefore, interactions between the surface, boundary layer, and free troposphere cannot be ignored.***

Realistic Infrared Surface Emissivity



From Kuo et al, JGR, 2017

- ***Surface emissivity can be calculated based on surficial geometry and the measured indices of refraction of surficial material. It can also be retrieved from spectrally-resolved remote sensing measurements.***

- ***There may be significant, spectrally-dependent differences in the emissivity of certain surface types, and we can implement those differences in models.***

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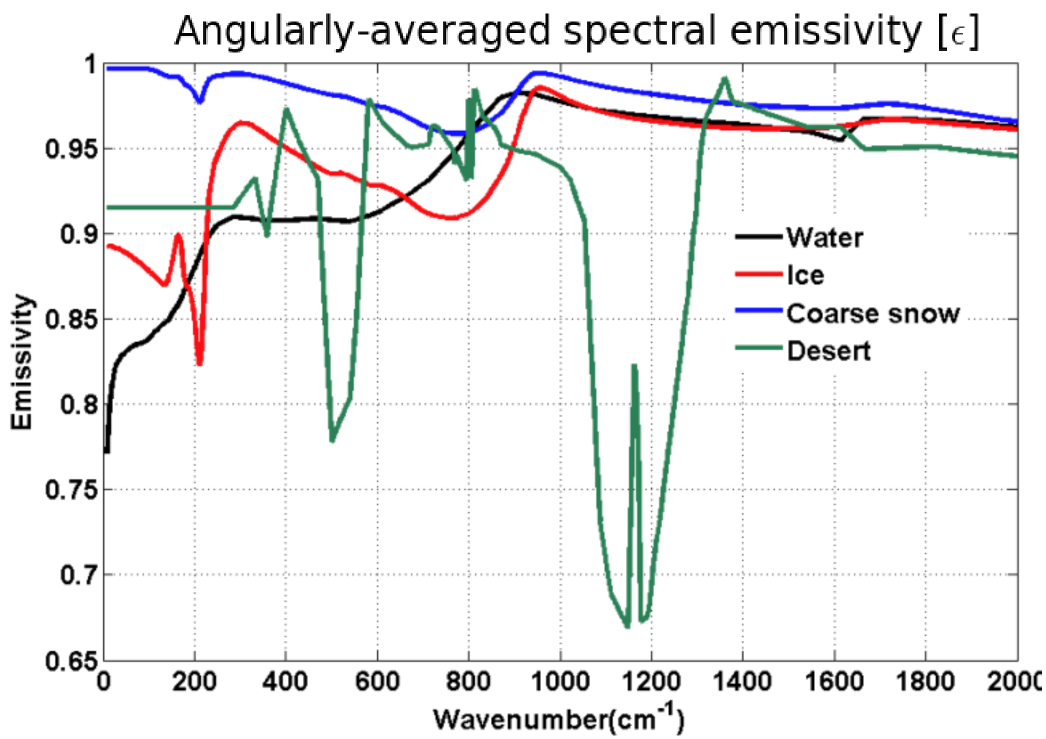

From Huang et al, JC, 2018

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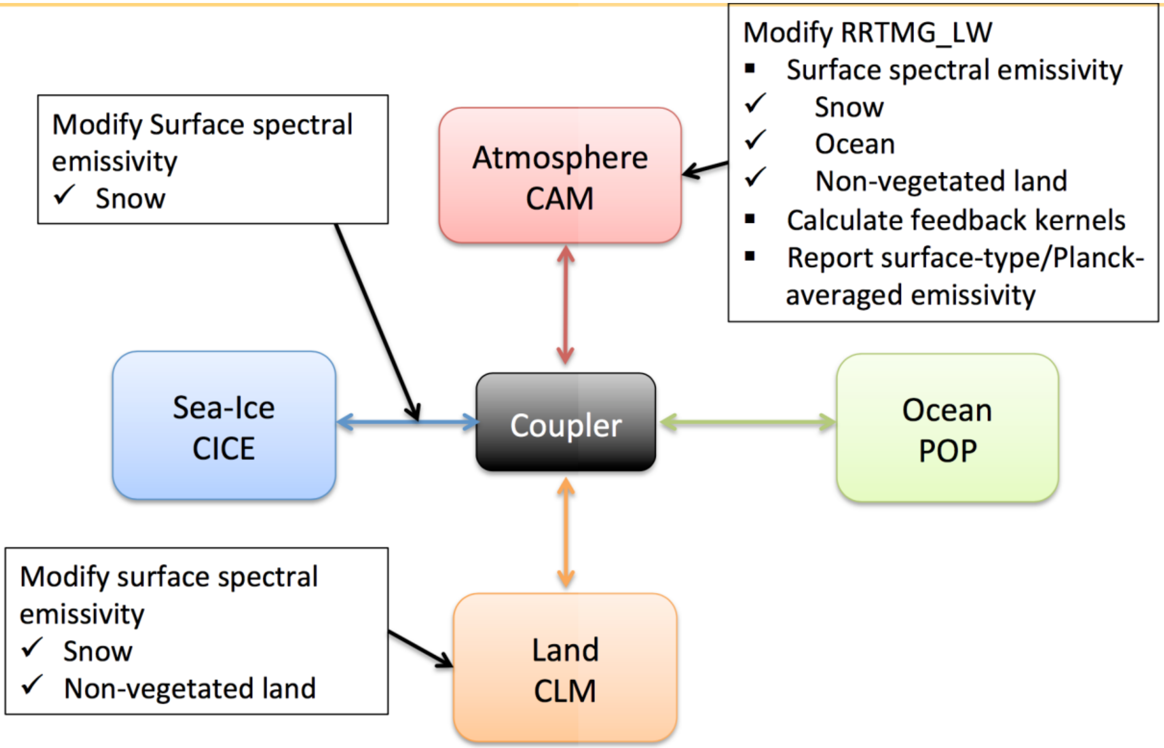
Coupled Earth System Model Modifications



- ***Many modifications are needed to incorporate realistic surface emissivity into a fully-coupled Earth System Model, such as CESM.***
- ***Efforts are underway to modify UKESM so that it too has realistic surface emissivity.***

CESM-ε(ν) control model is stable

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

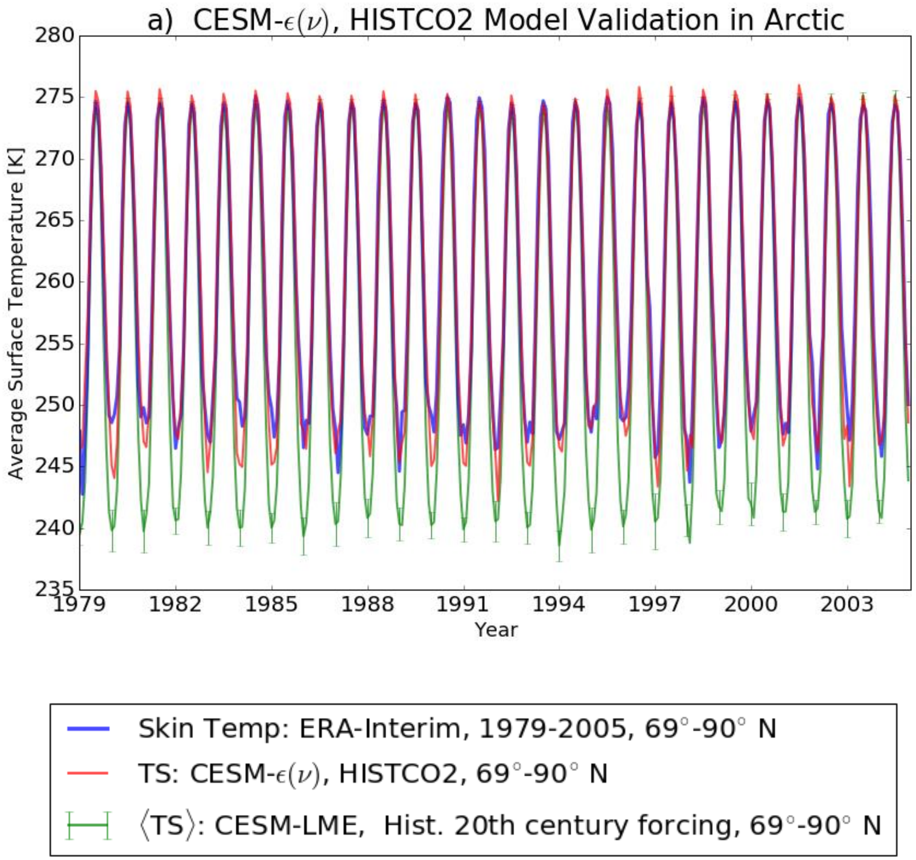
Summary of Models

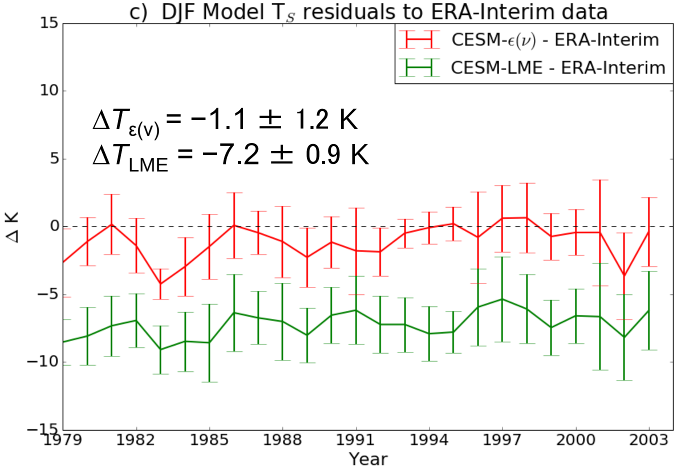
Model	$\varepsilon(\nu)$	Resolution	Run type
CESM.$\varepsilon(\nu)$	Y	2 deg	Fully coupled
CESM.LME	N	2 deg	Fully coupled
CAL_VR7_MG2_EMISS	Y	AMR 7 km	AMIP
CAL_VR7_MG2	N	AMR 7 km	AMIP

- ***We have produced several different integrations of the CESM to determine the source(s) and process(es) contributing to that model's polar biases.***

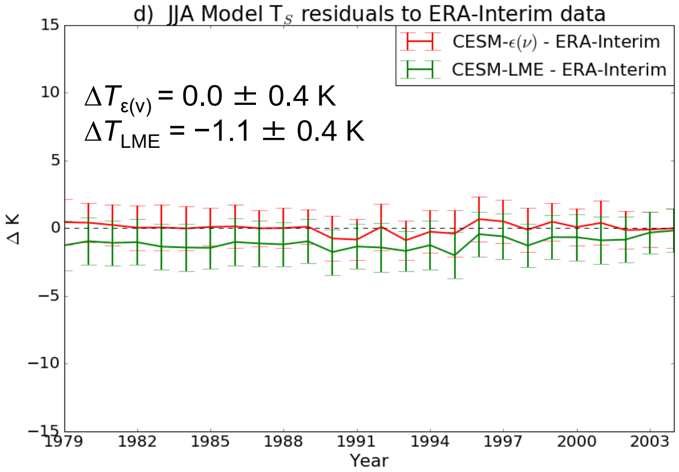
- ***The LME is an unmodified version of the model, while the VR7_MG2 does not have realistic surface emissivity.***

Realistic Surface Emissivity Matters for Polar Climate





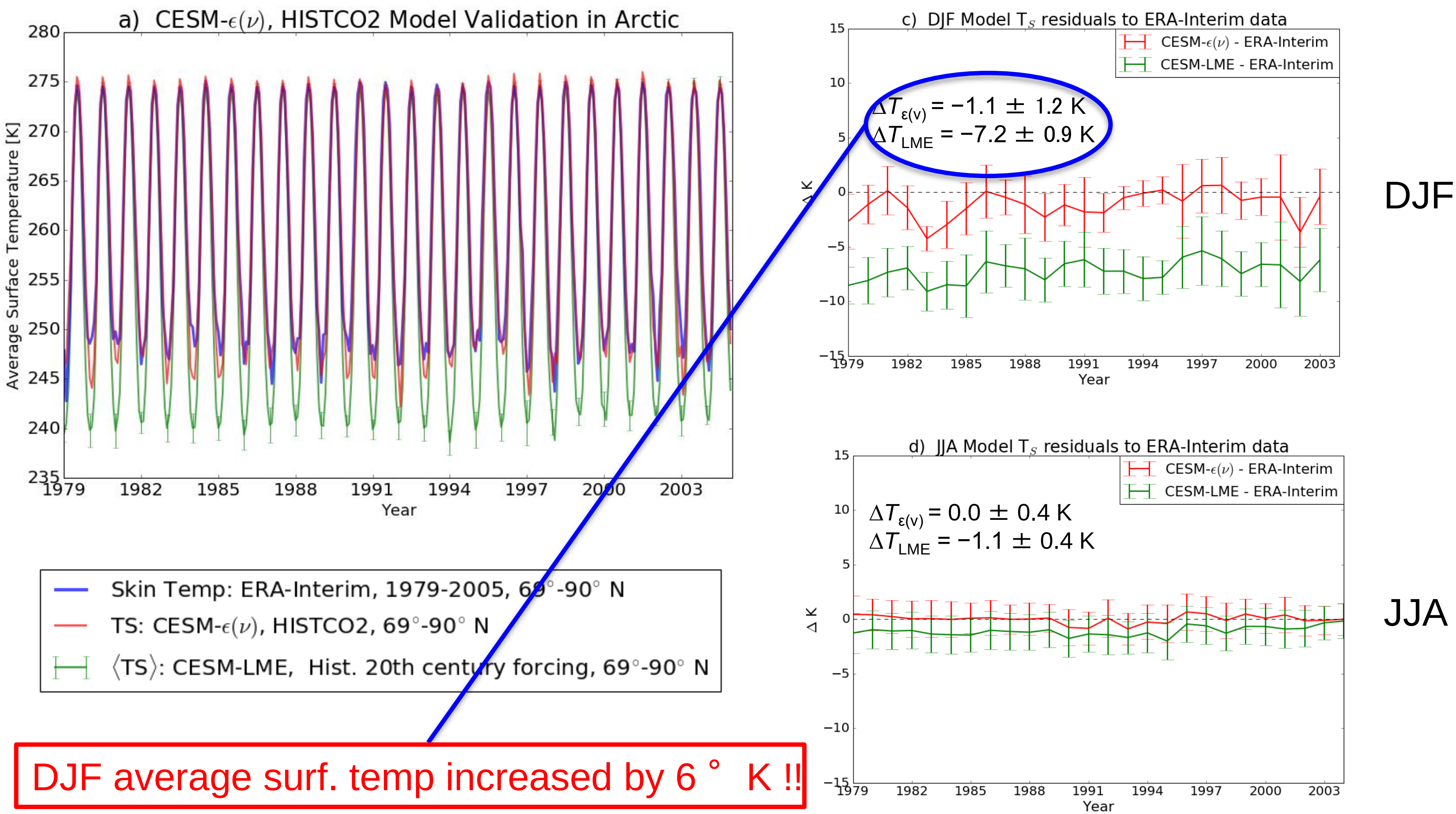
DJF



JJA

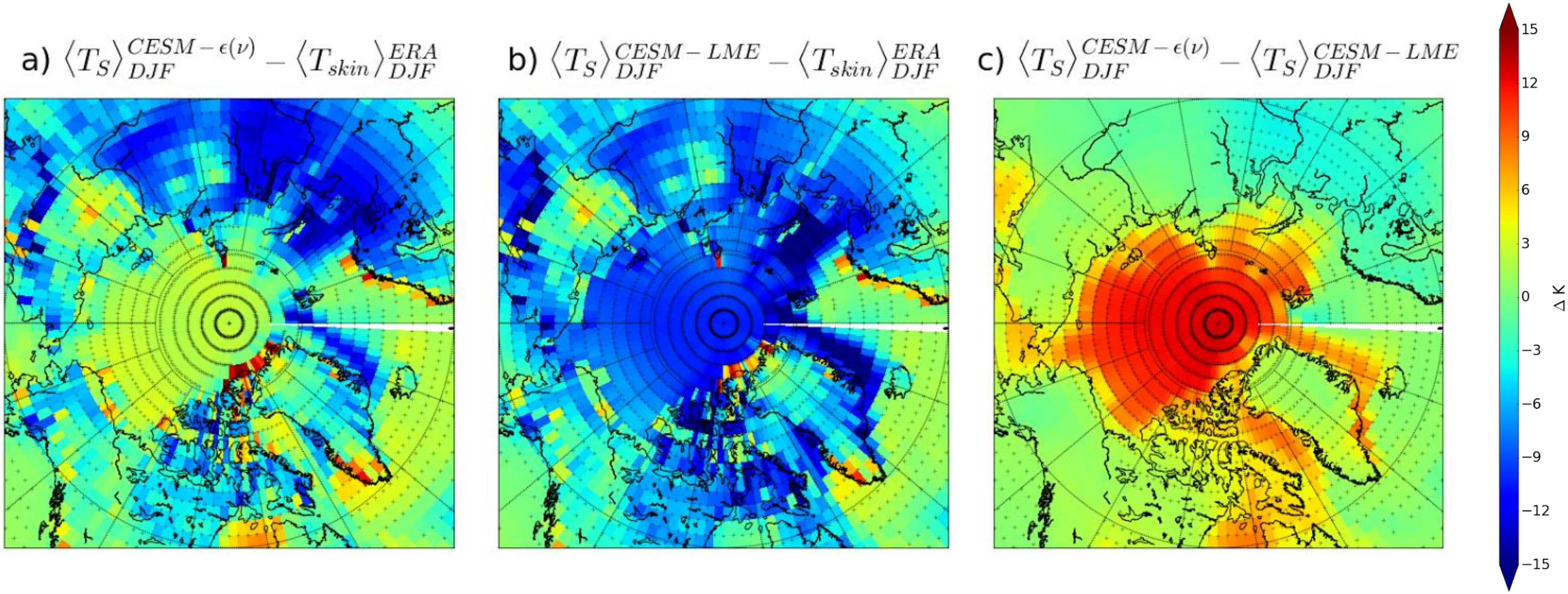
Kuo et al, 2017, JGR-Atmospheres

Realistic Surface Emissivity Matters for Polar Climate



Kuo et al, 2017, JGR-Atmospheres

CESM1 Wintertime Cold Bias Resolved by ε(ν) 1997-2005

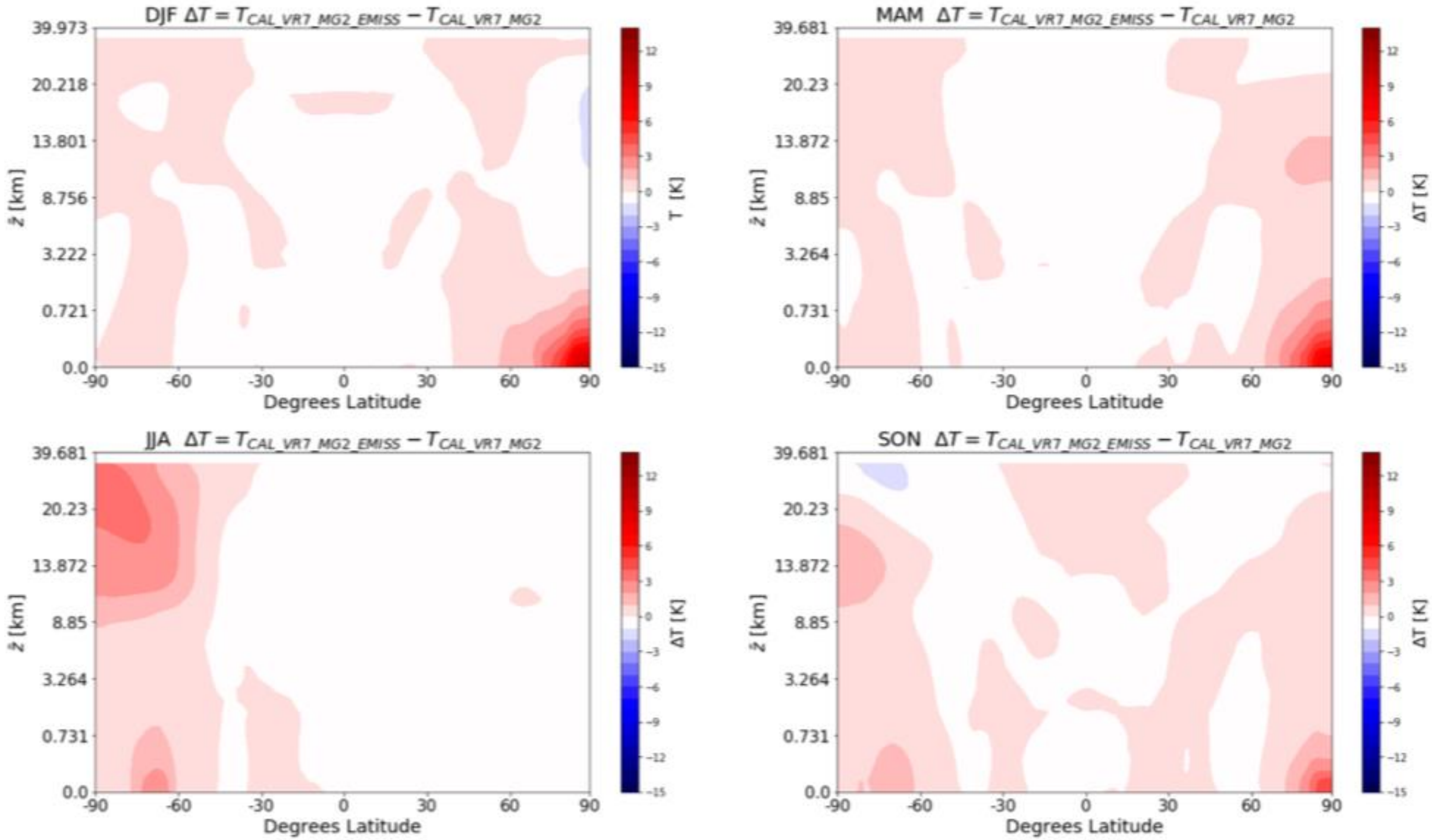


- ***CESM Large Millenial Ensemble shows biases relative to ERA in DJF.***
- ***The model with realistic emissivity has polar temperature biases resolved in DJF.***

Kuo et al, 2017, JGR-Atmospheres

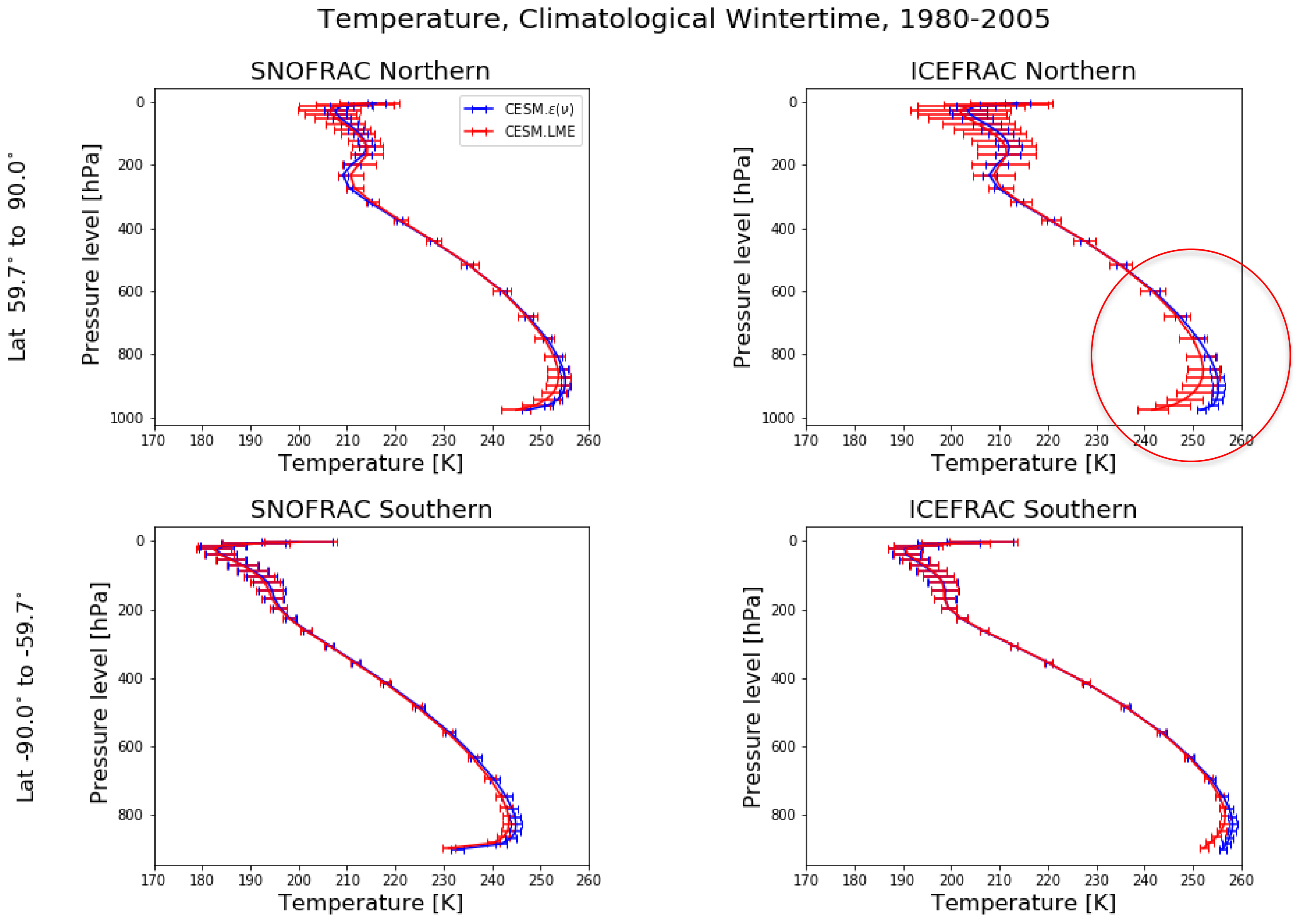
Including Emissivity Changes Temperature and Moisture

Climatological T, 1999-2015



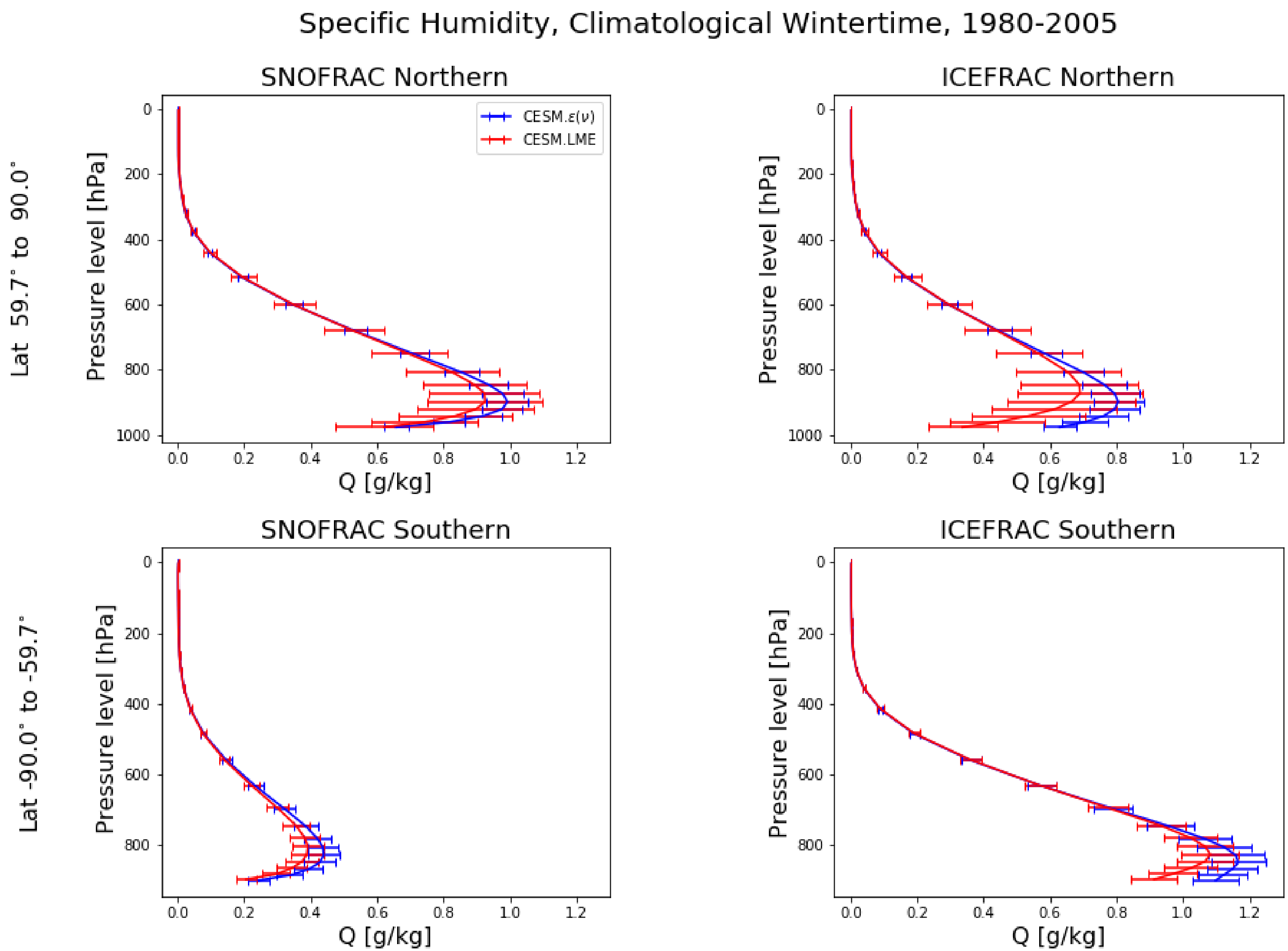
- ***The changes in Arctic model temperature arising from the use of realistic surface emissivity are largely confined to the boundary layer.***

Realistic Emissivity Changes Boundary Layer Temperature



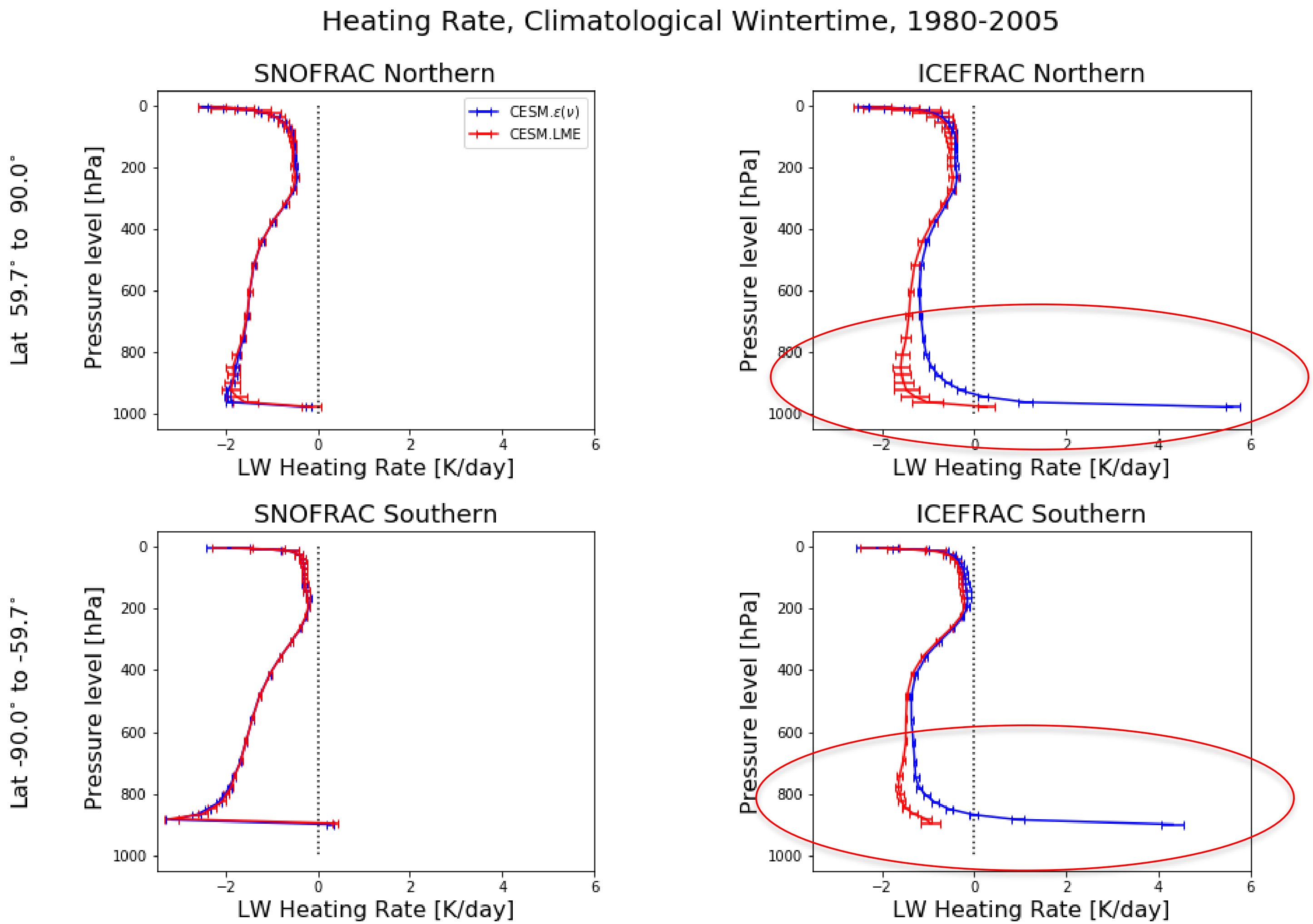
- ***The boundary layer temperature changes of sea-ice are statistically-significant.***

Realistic Emissivity Changes Boundary Layer Humidity



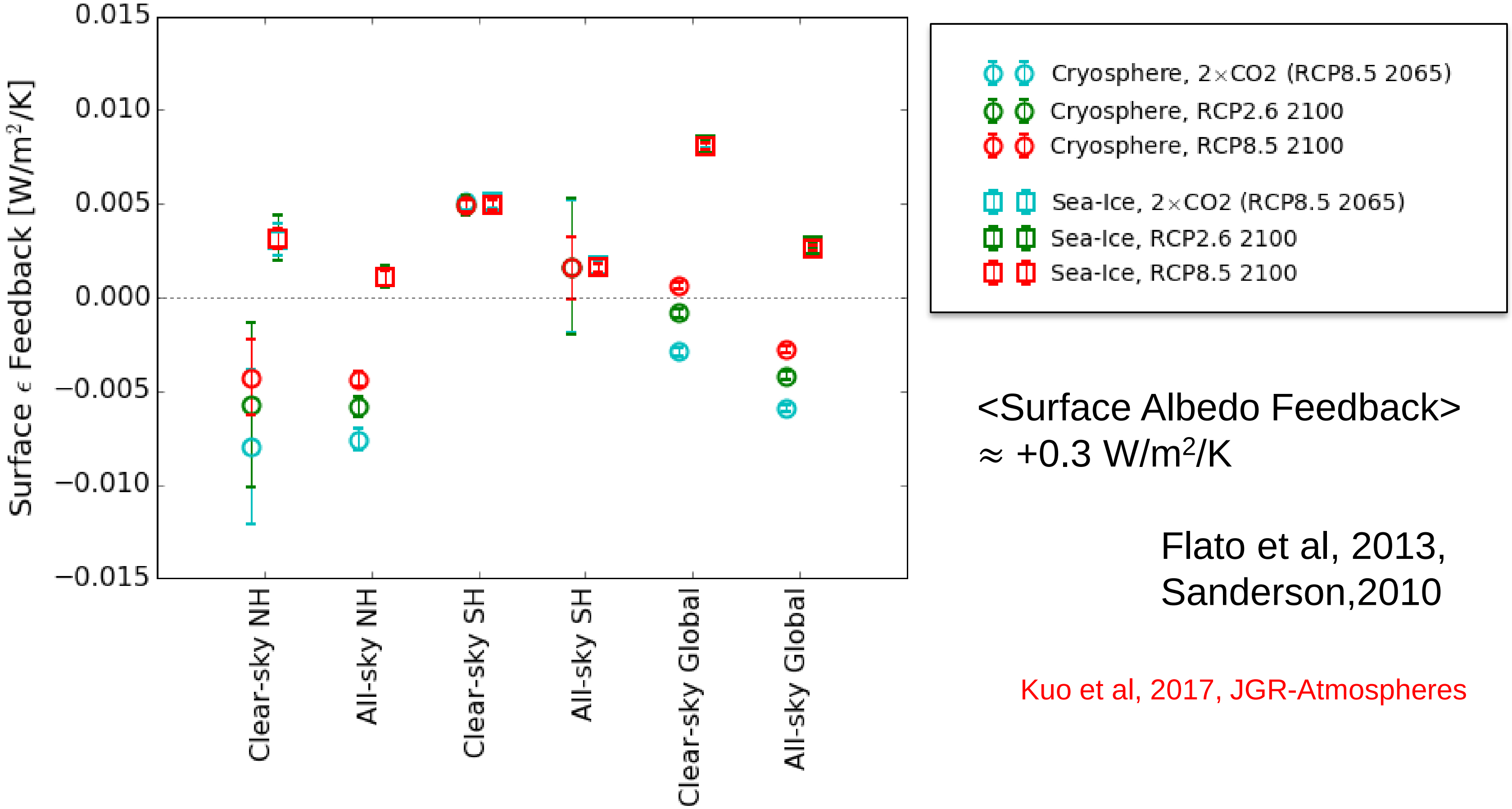
- ***The boundary layer changes in humidity are large but not statistically significant.***

Realistic Emissivity Changes the Sign of Boundary Layer IR Heating



- ***We see the model change sign in the infrared heating rate profile in the boundary layer over sea-ice in both NH and SH. The sign change has major implications for polar climate.***

The Ice-Emissivity Feedback



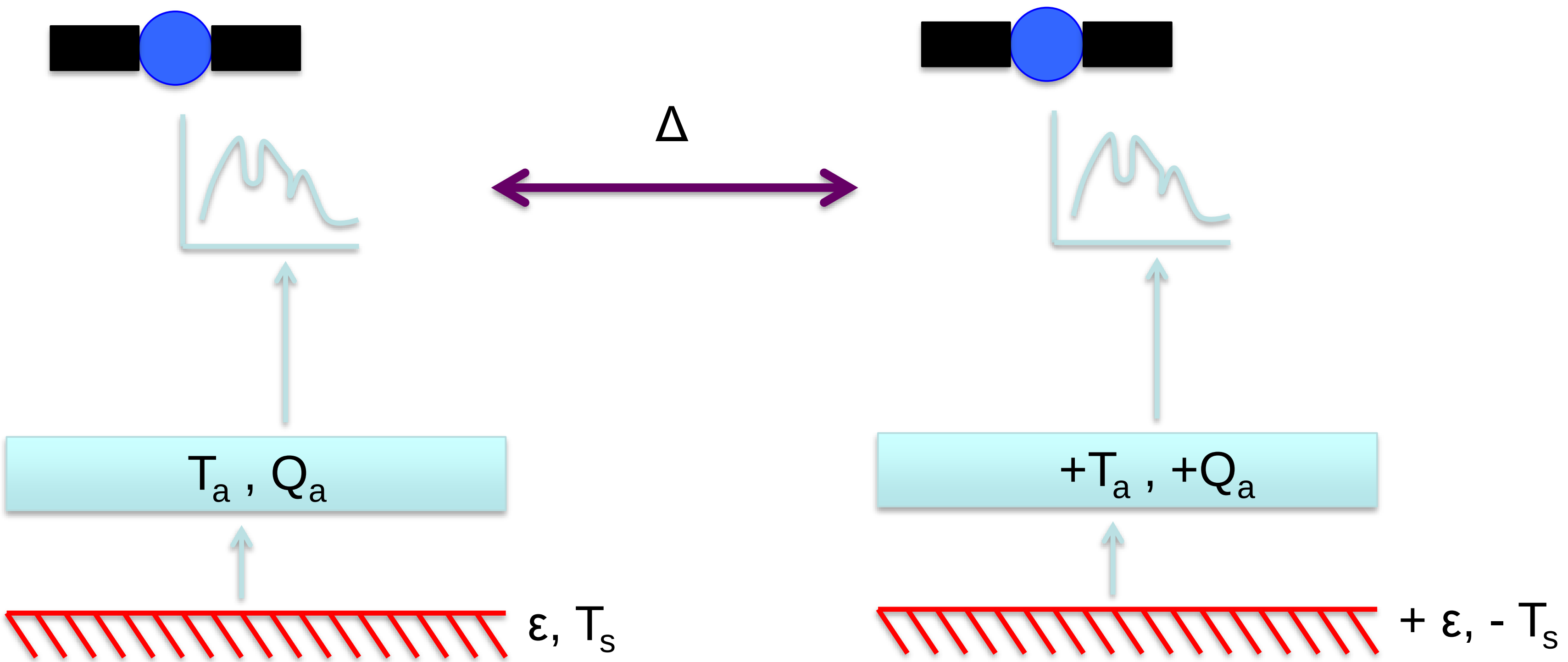
<Surface Albedo Feedback>
≈ +0.3 $W/m^2/K$

Flato et al, 2013,
Sanderson,2010

Kuo et al, 2017, JGR-Atmospheres

- ***We can quantify the feedback for changes in infrared surficial emission accelerate or decelerate polar warming.***
- ***The TOA feedback is small, but it strongly affects the boundary layer.***

What are the Observational Signals of These Effects?



- ***Can an instrument like FORUM provide an observational constraint on the relationship between model surface emissivity and boundary layer infrared radiative heating?***

- ***We can estimate the observational signals associated with the modifications we made to CESM to answer that question.***

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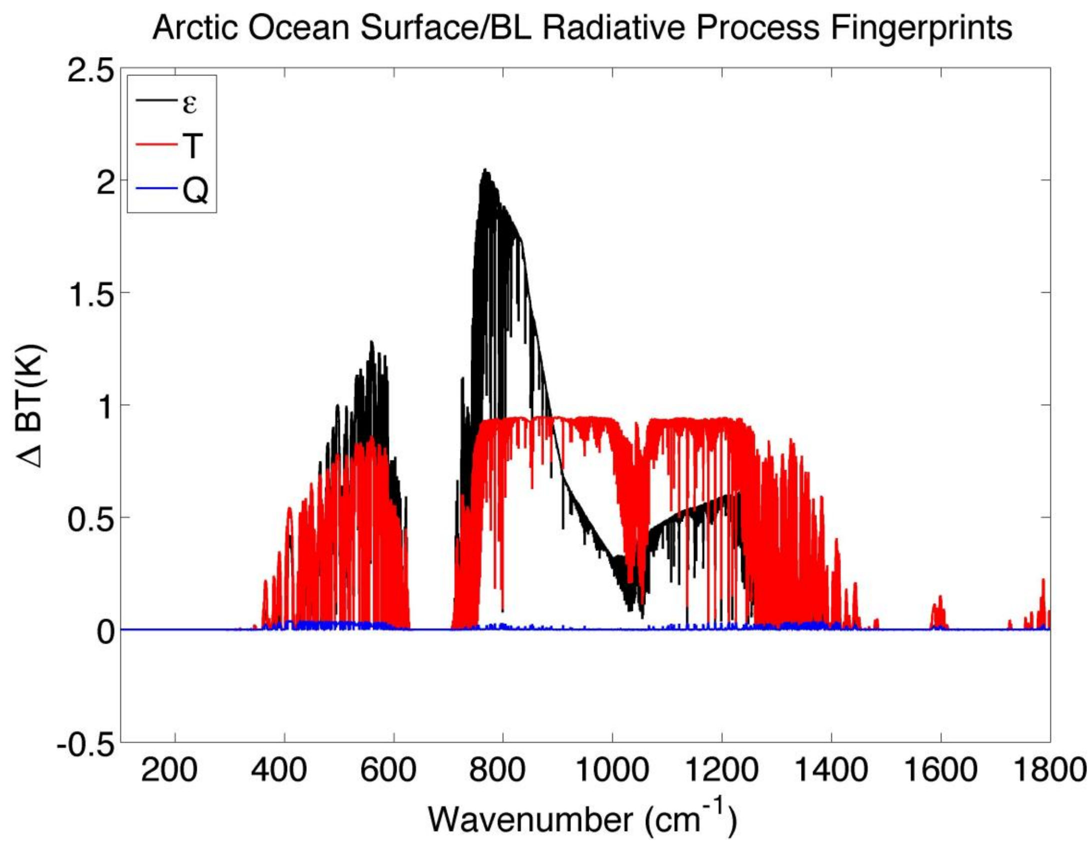


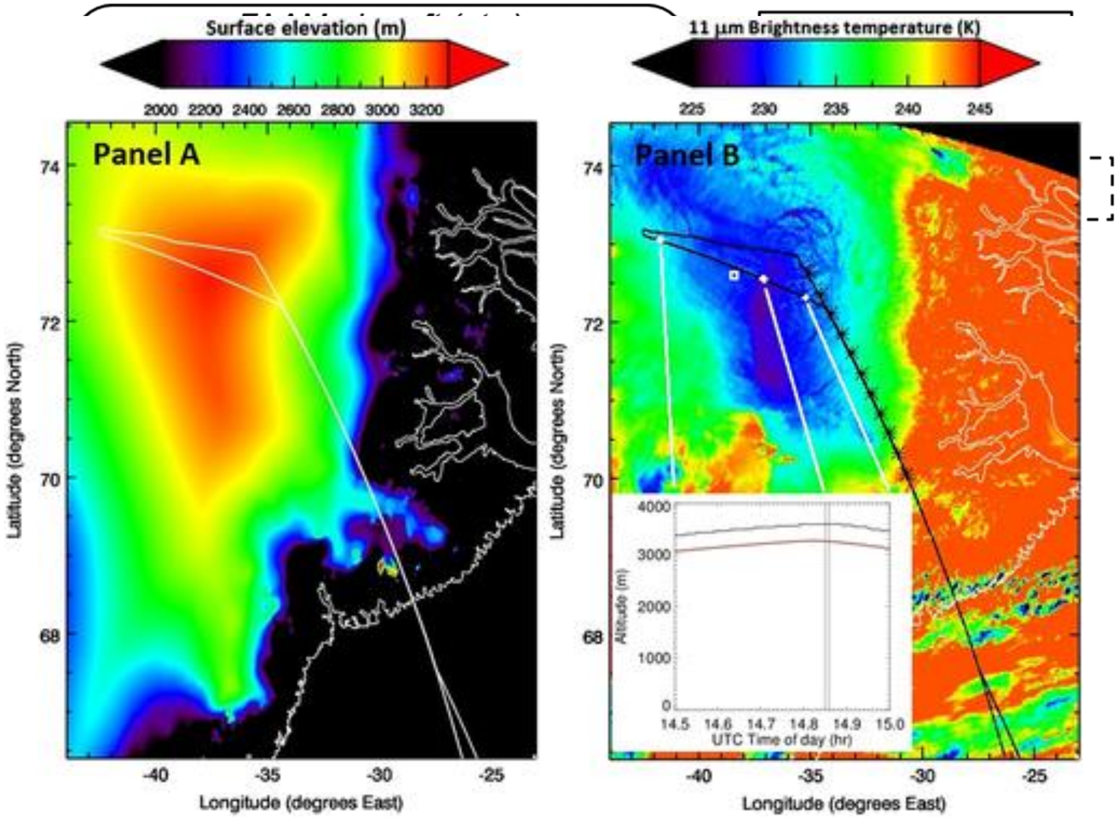
- ***The difference in TOA spectra over the Arctic Ocean, as calculated from the modified and unmodified versions of CESM, are large and > FORUM NeDT.***

- ***We can separate surface emissivity from the model's boundary-layer temperature response.***

What Have We Learned from Actual Observations?

- Up to this point, we have presented research that highlights the importance of infrared radiation for controlling cold-pole biases in climate models.
- We have indicated that this could be detectable with a TOA spectrometer such as FORUM.
- But we have not shown any infrared spectroscopic observations.

Surface Emissivity Retrievals



- ***Emissivity can be retrieved by looking at correlated changes infrared window channels.***

- ***Observations with the TAFTS instrument over GIS are qualitatively in agreement with emissivity of ice scenes used in CESM.***

Bellisario et al, 2017, JGR-Atmospheres

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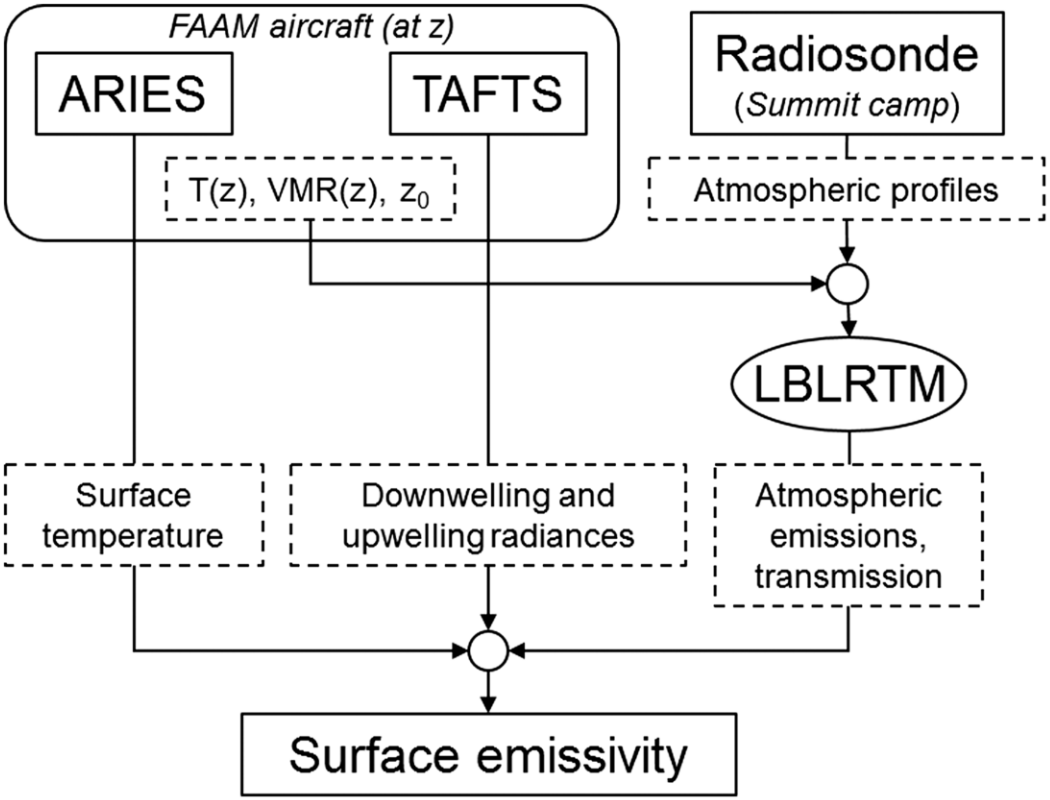

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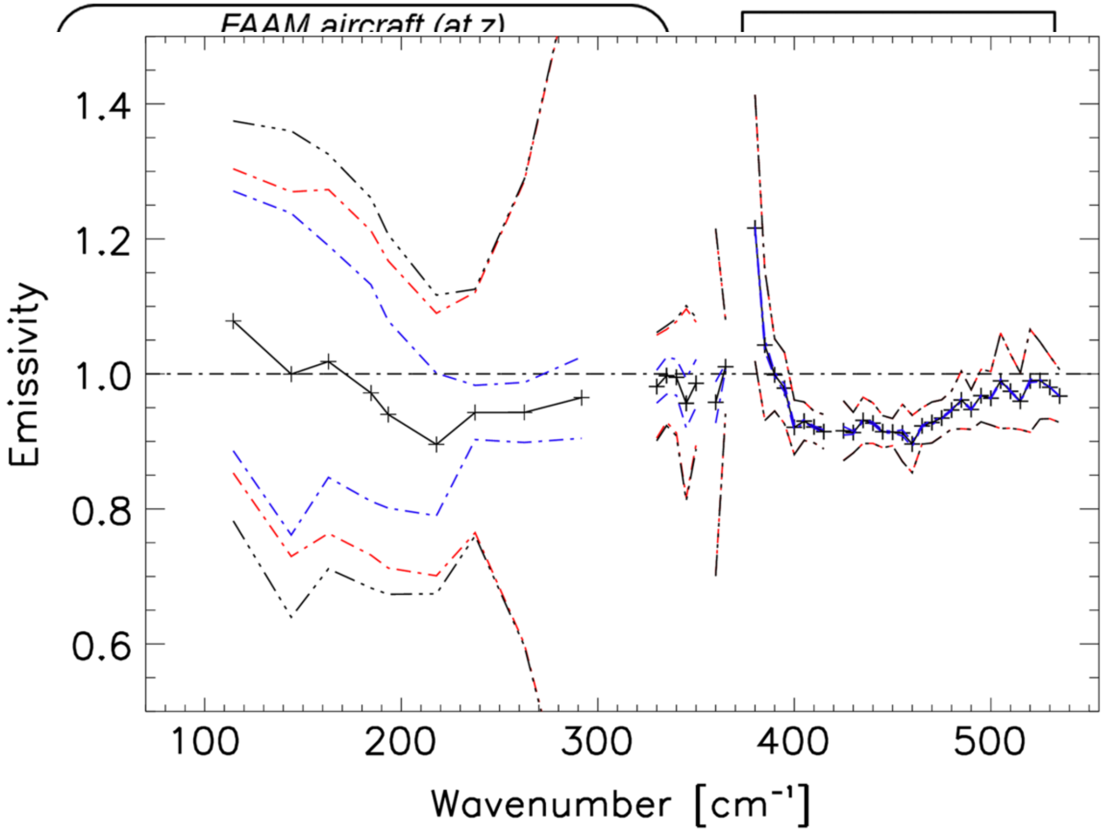

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Surface Emissivity Retrievals at the Surface

- *2003-2004 austral summer measurements at Dome-C, Antarctica from the polar-AERI instrument also provide spectral surface emissivity retrieval opportunities.*

- *Observations generally agree to within measurement uncertainty of ice model.*

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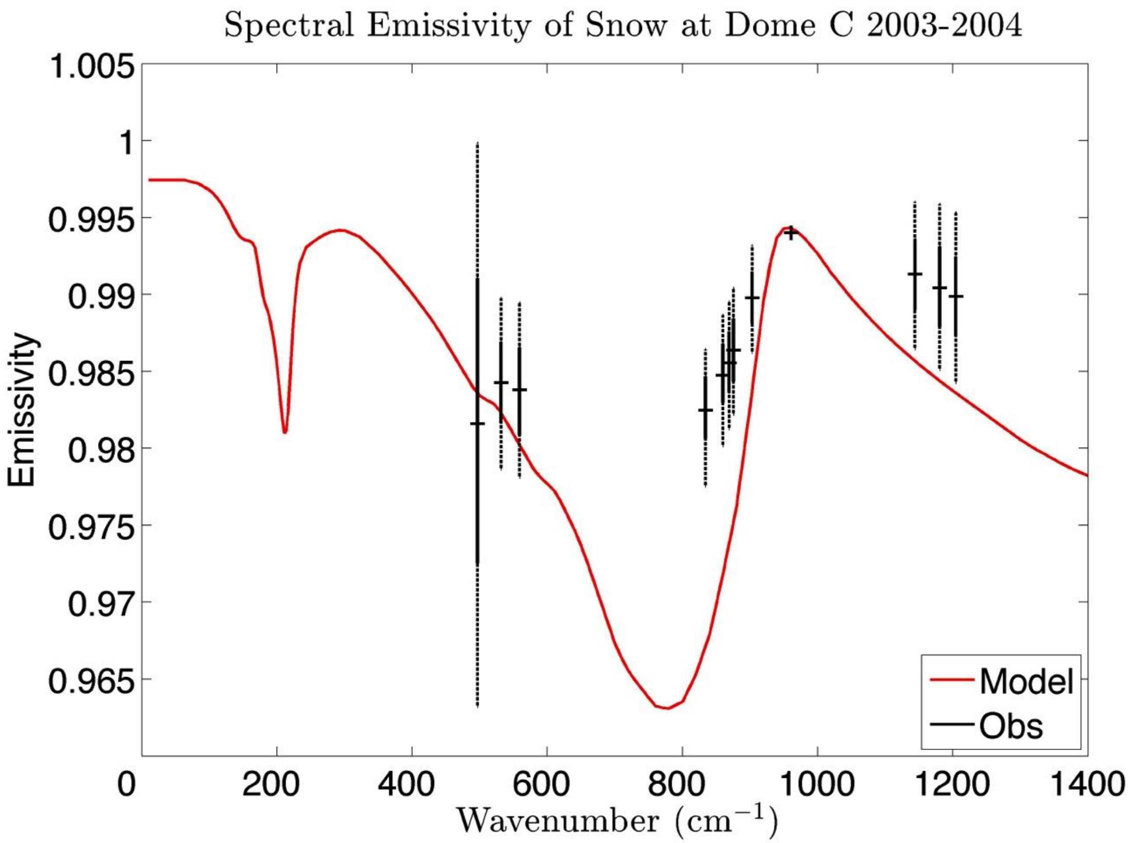

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Summary

- Infrared radiation matters for high-latitude surface temperatures.
- Fixing infrared surface emission largely helps eliminate the wintertime cold-pole bias in CESM.
  - DJF Arctic surface temperature increases by 6 ° K !!
- FORUM observations will be able to differentiate the surface and boundary layer conditions between the different versions of CESM.
  - They can therefore observationally constrain the potential causes of model polar T bias.
- Moving forward, it is critical to determine if the results from CESM are representative of other climate models.
  - OSSEs can show how FORUM observations can uproot biases for an ensemble of models.

Acknowledgements

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- National Energy Research Scientific Computing Center (NERSC), a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under that same award.

- Thanks for your attention!