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

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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
The Problem: Persistent Multi-model Arctic Cold Biases

CMIP5 Multi Model Mean $T_S$ Bias

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CESM

Flato et al, 2013, IPCC AR5
The Problem: Persistent Multi-model Arctic Cold Biases

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

Probably not directly related to albedo!

Flato et al, 2013, IPCC AR5
Clues to the Source of the Problem

- 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.
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

- \( F_{\text{down}} \) from Atmospheric model

- Soil Temperature Model
  Adjusts surface temperature, \( T_S \)

- \( F_{\text{up}} = \approx \langle \varepsilon(v) \rangle \sigma T_s^4 \)
  Latent heat and sensible heat
  Back to Atmospheric model
Continuation of atmospheric tendencies

Atmos Physics Tendencies Before Coupling to surface

- Dry adiabatic adjustment
- Moist Convection
- Shallow Convection
- Cloud Microphysics
- Precipitation processes
- Radiation

Atmos Physics Tendencies After Coupling to surface

- Vertical diffusion
  - Momentum
  - Moisture
  - Trace constituents
  - Static energy

Coupler

Land

Ocean

Sea-ice

Land-Ice
Infrared Radiation: Model vs. Real World

- **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.**

From Chen et al, GRL, 2014
Drier Atmospheres are Far More Transparent

- 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.

From Feldman et al, PNAS, 2014
Realistic Infrared Surface Emissivity

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

<table>
<thead>
<tr>
<th>1850CNTL (1850-2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global Mean Variable</strong></td>
</tr>
<tr>
<td>TS</td>
</tr>
<tr>
<td>TS (CESM-LME)</td>
</tr>
<tr>
<td>SST</td>
</tr>
<tr>
<td>$F_{\text{atm}}^{\uparrow} - F_{\text{land}}^{\uparrow}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Forcing Scenario</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1850CNTL</td>
<td>1850 atmosphere, no forcing</td>
<td>1850-2005</td>
</tr>
<tr>
<td>HISTCO2</td>
<td>Start 1850 atmosphere, Historical CO₂</td>
<td>1850-2005</td>
</tr>
<tr>
<td>RCP2.6</td>
<td>RCP2.6 scenario</td>
<td>2005-2100</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>RCP8.5 scenario</td>
<td>2005-2100</td>
</tr>
</tbody>
</table>
**Summary of Models**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\varepsilon(\nu)$</th>
<th>Resolution</th>
<th>Run type</th>
</tr>
</thead>
<tbody>
<tr>
<td>CESM.$\varepsilon(\nu)$</td>
<td>Y</td>
<td>2 deg</td>
<td>Fully coupled</td>
</tr>
<tr>
<td>CESM.LME</td>
<td>N</td>
<td>2 deg</td>
<td>Fully coupled</td>
</tr>
<tr>
<td>CAL_VR7_MG2_EMISS</td>
<td>Y</td>
<td>AMR 7 km</td>
<td>AMIP</td>
</tr>
<tr>
<td>CAL_VR7_MG2</td>
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</tbody>
</table>

- 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

\[ \Delta T_{\epsilon(\nu)} = -1.1 \pm 1.2 \text{ K} \]
\[ \Delta T_{\text{LME}} = -7.2 \pm 0.9 \text{ K} \]
\[ \Delta T_{\epsilon(\nu)} = 0.0 \pm 0.4 \text{ K} \]
\[ \Delta T_{\text{LME}} = -1.1 \pm 0.4 \text{ K} \]

Kuo et al, 2017, JGR-Atmospheres
Realistic Surface Emissivity Matters for Polar Climate

**DJF**

\[
\Delta T_{\varepsilon(v)} = -1.1 \pm 1.2 \text{ K}
\]

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**JJA**

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Kuo et al, 2017, JGR-Atmospheres

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**Figure a)** CESM-$\epsilon(\nu)$, HISTCO2 Model Validation in Arctic

**Figure c)** DJF Model $T_s$ residuals to ERA-Interim data

**Figure d)** JJA Model $T_s$ residuals to ERA-Interim data

**Legend**

- Skin Temp: ERA-Interim, 1979-2005, 69°-90° N
- TS: CESM-$\epsilon(\nu)$, HISTCO2, 69°-90° N
- 〈TS〉: CESM-LME, Hist. 20th century forcing, 69°-90° N

**DJF average surf. temp increased by 6 ° K !!**
CESM1 Wintertime Cold Bias Resolved by $\varepsilon(v)$
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
The changes in Arctic model temperature arising from the use of realistic surface emissivity are largely confined to the boundary layer.
The boundary layer temperature changes of sea-ice are statistically-significant.
The boundary layer changes in humidity are large but not statistically significant.
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

- 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.

<Surface Albedo Feedback>
≈ +0.3 W/m²/K

Flato et al, 2013, Sanderson, 2010

Kuo et al, 2017, JGR-Atmospheres
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.
What are the Observational Signals of These Effects?

- The difference in TOA spectra over the Arctic Ocean, as calculated from the modified and unmodified versions of CESM, are large and greater than 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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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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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.
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- Thanks for your attention!