A Dissection of the Surface Temperature Biases in the Community Earth System Model

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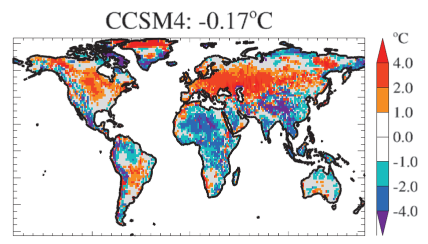
Introduction

Surface Temperature Biases in Climate Models

Possible contributors to the Biases

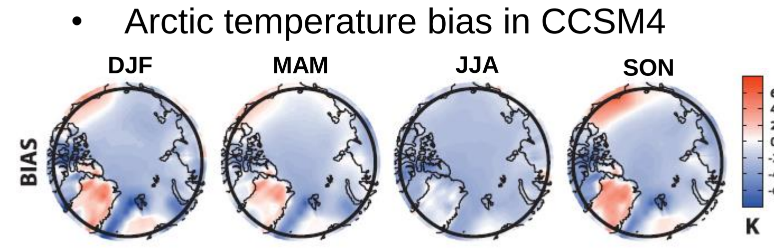
- Albedo feedback
- Water vapor feedback
- Cloud feedback
- Sensible/latent heat fluxes
- Surface dynamics
- Atmospheric dynamics

- Land temperature bias in CCSM4



(Gent et al, 2011)

- Arctic temperature bias in CCSM4



(De Boer et al, 2012)

The present study aims to …

Quantify the relative contributions of seven radiative (physical: albedo, water vapor, and cloud) and non-radiative (dynamical: sensible/latent heat flux, surface dynamics, and atmospheric dynamics).

Data

- **Observation : ERA-Interim (1979-present)**
- **Model : CESM1 historical run (1850-2005)**
- **Used Variables**
  - Solar insolation, surface pressure, surface temperature, surface latent/sensible heat flux, surface downward/upward SW, air temperature, specific humidity, cloud amount, and cloud liquid/ice water
- **Analysis period: Annual mean of 1979-2005**

Methods

CFRAM Formulation

- The total energy balance at M atmospheric layers and one surface (M+1)[th] layer

$$\vec{R} = \vec{S} + \vec{Q}^{non\text{-}radiative}$$

$\vec{Q}^{non\text{-}radiative}$ ← Energy due to non-radiative dynamical processes; $\vec{S}$: SW radiation flux; $\vec{R}$: LW radiation flux

- The difference between two climate states

$$\Delta\frac{\partial \vec{E}}{\partial t} = \Delta\vec{S} - \Delta\vec{R} + \Delta\vec{Q}^{non\text{-}radiative}$$

Change in energy storage → negligible

α : albedo
w : water vapor
c : cloud
SH : Sensible heat flux
LH : Latent heat flux
sfc_dyn : surrface dynamics
atmos_dyn : Atmospheric dynamics

$$\Delta\vec{Q}^{non\text{-}radiative} \approx \Delta\vec{Q}^{(SH)} + \Delta\vec{Q}^{(LH)} + \Delta\vec{Q}^{(sfc\_dyn)} + \Delta\vec{Q}^{(atmos\_dyn)}$$

$$\Delta\vec{S} \approx \Delta\vec{S}^{(\alpha)} + \Delta\vec{S}^{(w)} + \Delta\vec{S}^{(c)}$$

$$\Delta\vec{R} \approx \Delta\vec{R}^{(w)} + \Delta\vec{R}^{(c)} + \frac{\partial \vec{R}}{\partial \vec{T}}\Delta\vec{T}$$

Planck feedback matrix

$$\left(\frac{\partial \vec{R}}{\partial \vec{T}}\right) = \begin{pmatrix} \frac{\partial R_1}{\partial T_1} & \cdots & \frac{\partial R_1}{\partial T_{M+1}} \\ \vdots & \ddots & \vdots \\ \frac{\partial R_{M+1}}{\partial T_1} & \cdots & \frac{\partial R_{M+1}}{\partial T_{M+1}} \end{pmatrix}$$

- Rearranging the terms …

$$\Delta\vec{T} = \left(\frac{\partial \vec{R}}{\partial \vec{T}}\right)^{-1}\left\{\Delta\vec{S}^{(\alpha)} + \Delta(\vec{S}-\vec{R})^{(w)} + \Delta(\vec{S}-\vec{R})^{(c)} + \Delta(\vec{S}-\vec{R})^{(SH)} + \Delta(\vec{S}-\vec{R})^{(LH)} + \Delta\vec{Q}^{(sfc\_dyn)} + \Delta\vec{Q}^{(atmos\_dyn)}\right\}$$

Albedo; Water vapor; Cloud; Sensible heat flux; Latent heat flux; Surface dynamics; Atmospheric dynamics

Decomposition Procedure

Define Surface Temperature Bias

Model: CESM1 Surface Temperature
Observation: ERA-Interim Surface Temperature
→ Bias in CESM1 = Model – Observation

Annual-mean

Input for Radiative transfer model

Surface	Multi-layer
Solar insolation	Air temperature
surface pressure	Specific humidity
surface temperature	Cloud amount
surface latent/sensible heat flux	Cloud liquid water
surface downward/upward SW	Cloud ice water

Fu-Liou radiative transfer model (Fu and Liou, 1992; 1993)

Energy perturbation terms

$\Delta\vec{S}^{(\alpha)}$ $\Delta(\vec{S}-\vec{R})^{(w)}$ $\Delta(\vec{S}-\vec{R})^{(c)}$

$\Delta(\vec{S}-\vec{R})^{(SH)}$ $\Delta(\vec{S}-\vec{R})^{(LH)}$ $\Delta\vec{Q}^{(sfc\_dyn)}$ $\Delta\vec{Q}^{(atmos\_dyn)}$

CFRAM (Lu and Cai, 2009)

Partial temperature changes

$\Delta\vec{T}^{albedo}$ $\Delta\vec{T}^{water\ vapor}$ $\Delta\vec{T}^{cloud}$

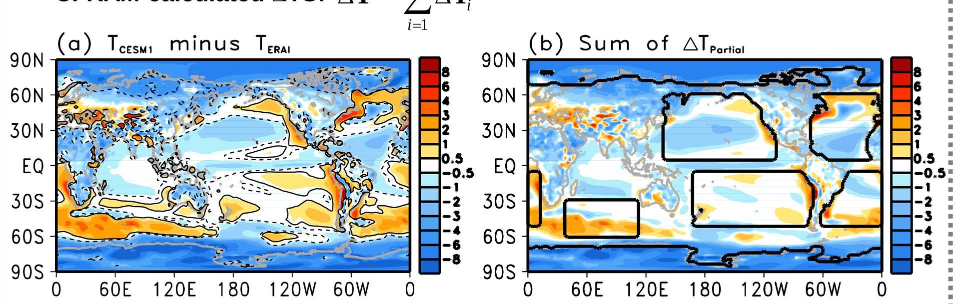
$\Delta\vec{T}^{SH}$ $\Delta\vec{T}^{LH}$ $\Delta\vec{T}^{sfc\_dyn}$ $\Delta\vec{T}^{atmos\_dyn}$

Partial Temperature Biases

Difference of TS between CESM1 and ERAI vs. Total TS changes

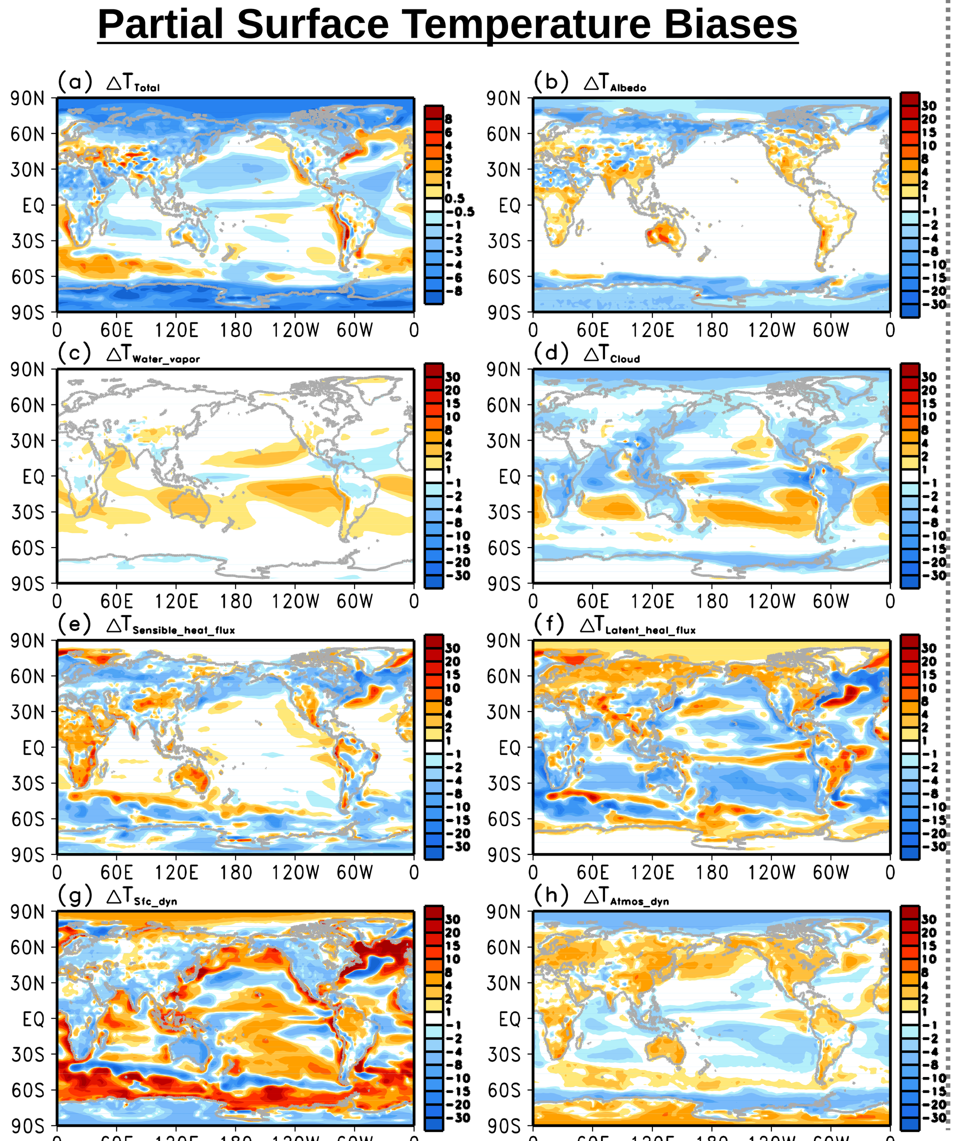
Difference of TS in original data: $\Delta\vec{T} = \vec{T}(CESM1) - \vec{T}(ERAI)$

CFRAM-calculated ΔTS: $\Delta\vec{T} = \sum_{i=1}^{7}\Delta\vec{T}_i$



$$\vec{T}(CESM1) - \vec{T}(ERAI) \approx \sum_{i=1}^{7}\vec{T}_i$$

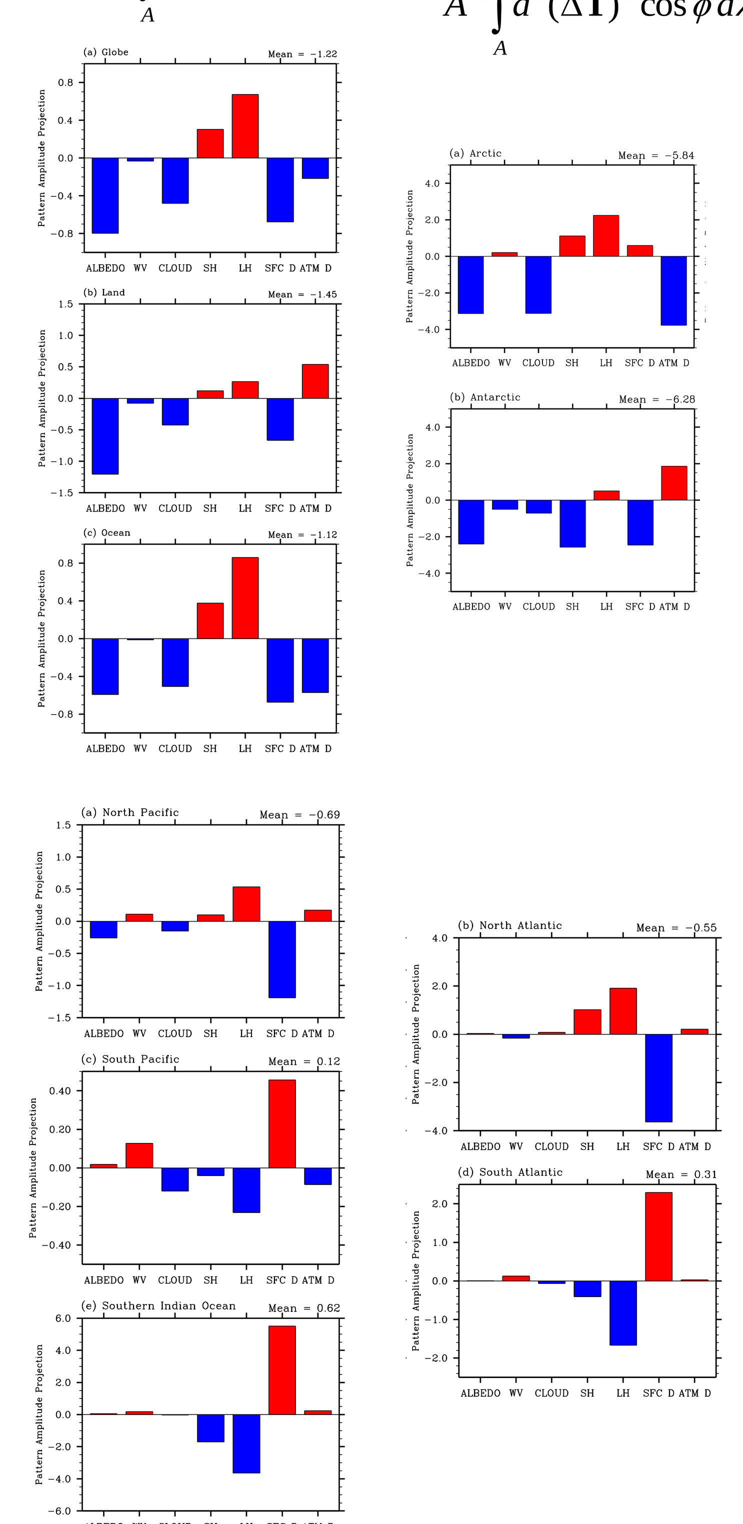
Partial Surface Temperature Biases



Quantification of the relative contributions

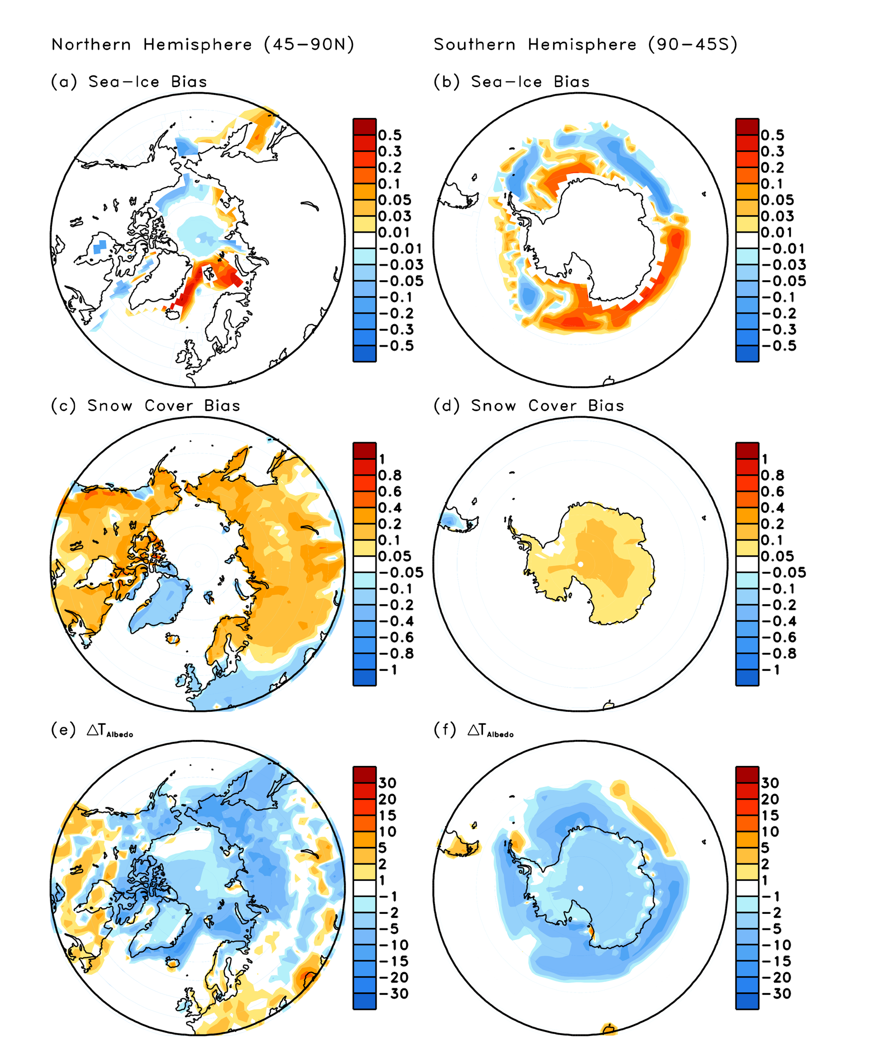
- Pattern Amplitude Projection (PAP) coefficients

$$\overline{\mathrm{PAP}}_i = A^{-1}\int_A a^2\Delta\vec{T}\cos\phi\, d\lambda\, d\phi \cdot \frac{A^{-1}\int_A a^2\Delta\vec{T}_i\Delta\vec{T}\cos\phi\, d\lambda\, d\phi}{A^{-1}\int_A a^2(\Delta\vec{T})^2\cos\phi\, d\lambda\, d\phi}$$

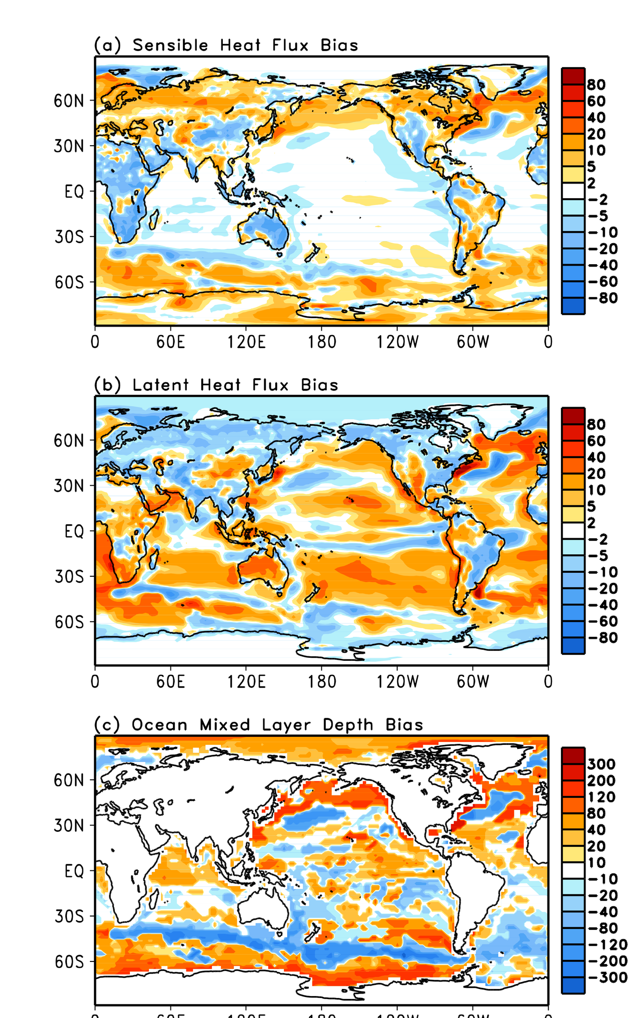


Possible Causes of Partial Temperature Biases

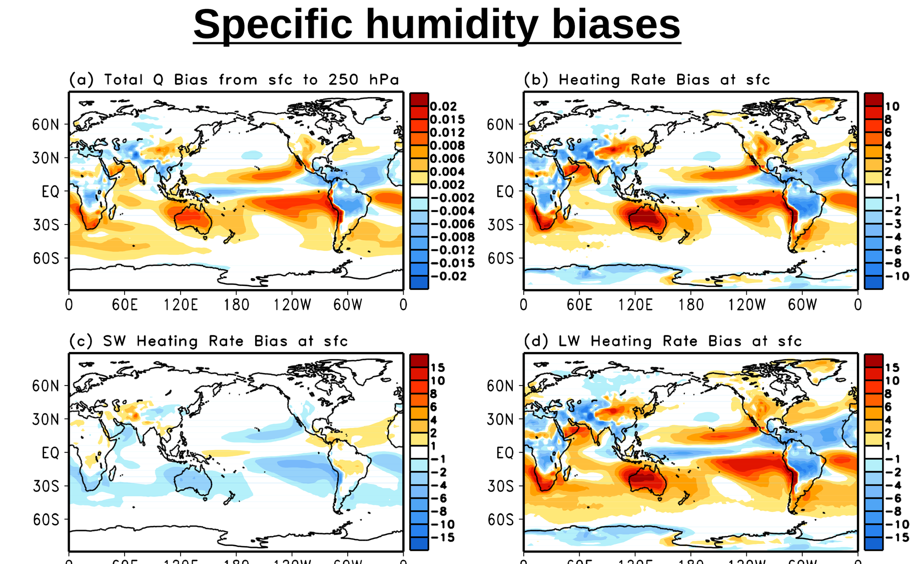
Sea-ice and snow cover biases



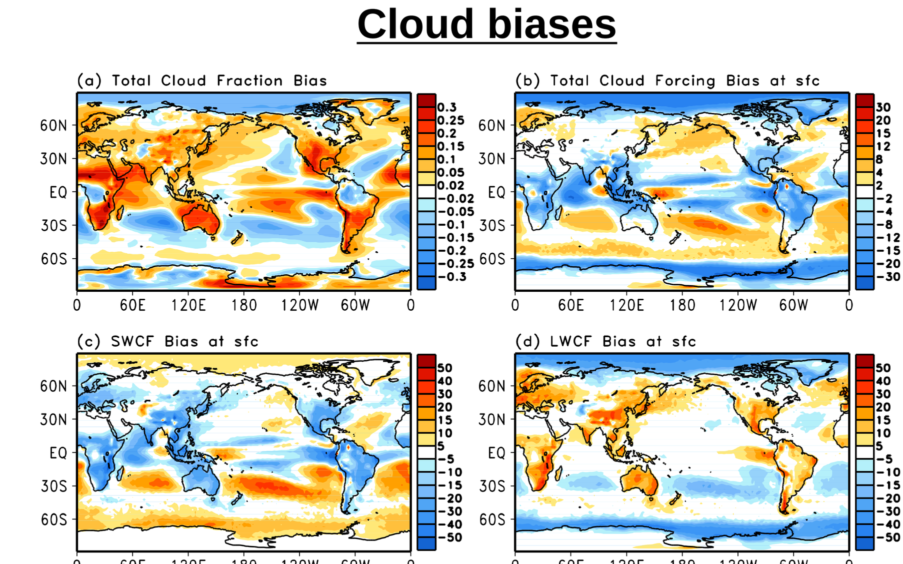
SH/LH and ocean mixed layer depth biases



Specific humidity biases



Cloud biases



Physics vs Dynamics

- **Radiative (physically-induced) energy biases**
  - albedo, water vapor, and cloud
- **Non-radiative (dynamically-induced) energy biases**
  - sensible/latent heat flux, surface dynamics, and atmospheric dynamics

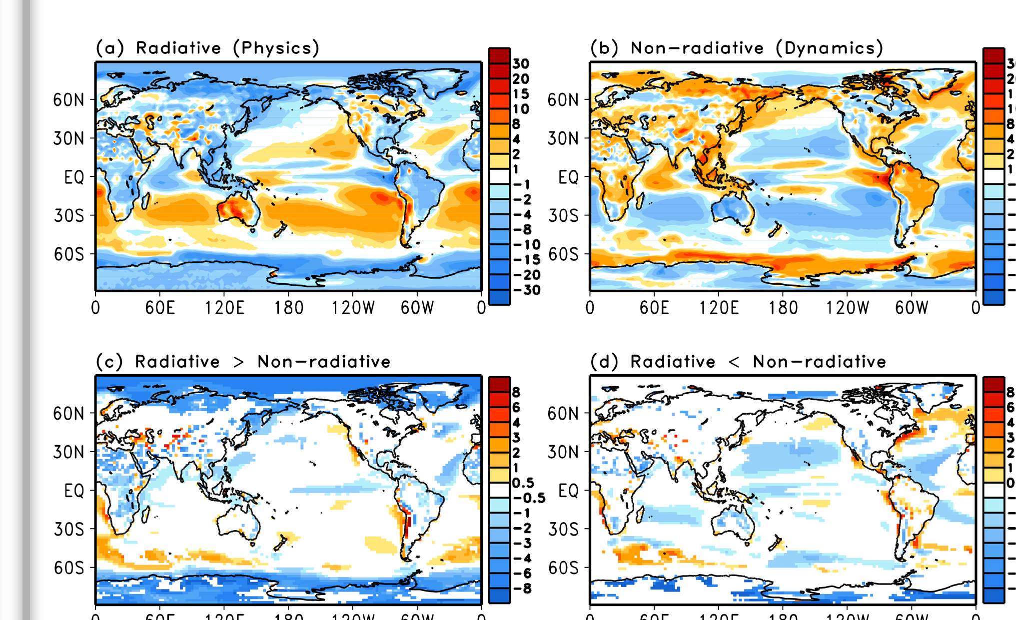


Table 1. The number of total, radiative-origin, and non-radiative-origin grid-points for globe, land, ocean, Arctic, and Antarctica

	Total	Radiative > non-radiative	Radiative < non-radiative
Globe	9,852	6,306 (64.0%)	3,546 (36.0%)
Land	2,969	2,090 (70.4%)	879 (29.6%)
Ocean	6,883	4,216 (61.2%)	2,667 (38.8%)
Arctic	1,194	1,109 (92.9%)	85 (7.1%)
Antarctic	1,203	897 (74.5%)	306 (25.5%)

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