Investigating effective radiative forcing with Eocene and preindustrial climate background

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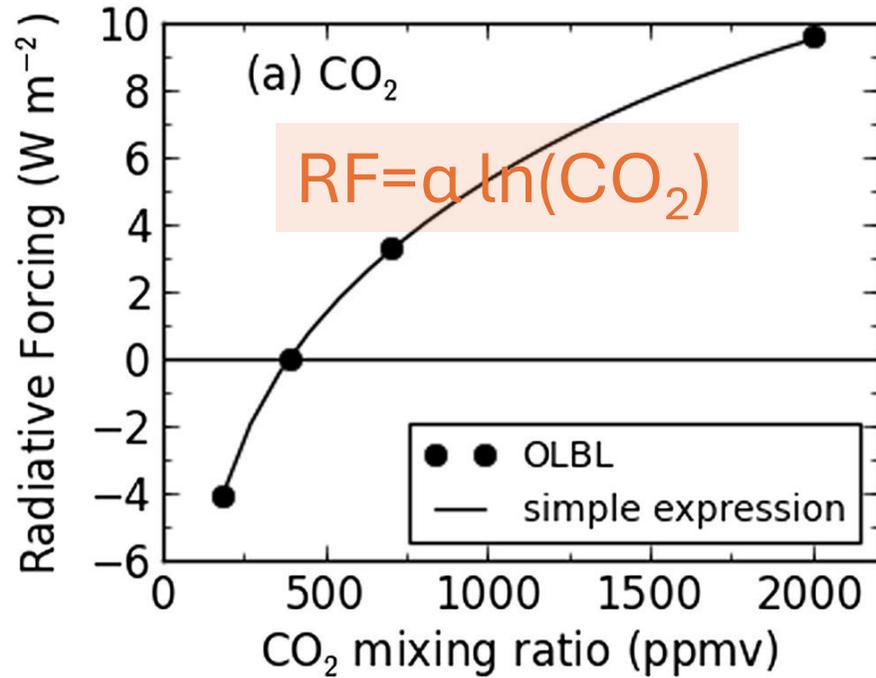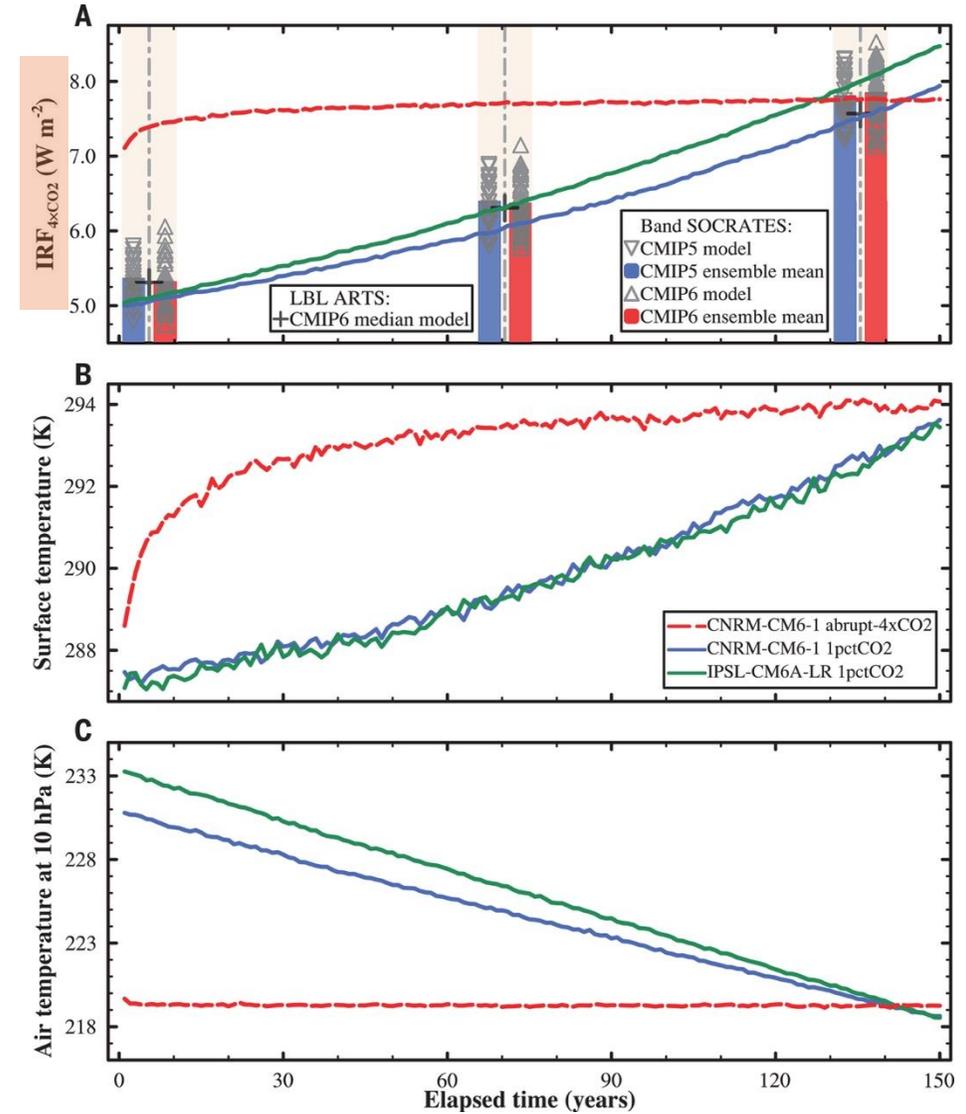# Objective

Common Assumption: Whether radiative forcing (RF) scales linearly with ln(C/C_0) and is independent of the climatological base state.

|	Full Name	Definition
IRF	Instantaneous Radiative Forcing	The change in TOA net radiative flux immediately after a perturbation, before any atmospheric adjustment occurs.
RF (SARF)	Stratosphere-Adjusted Radiative Forcing	The radiative flux change after allowing stratospheric temperatures to adjust to radiative equilibrium. RF = IRF + Stratosphere adjustment
ERF	Effective Radiative Forcing	The change in net top-of-atmosphere radiative flux after rapid adjustments, excluding radiative feedbacks driven by changes in global-mean surface temperature. ERF = IRF + Stratosphere adjustment + Other rapid adjustments

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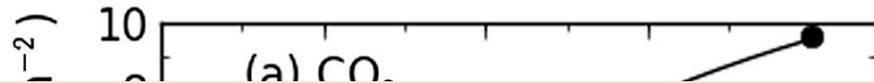# Objective

$$RF = \alpha \ln(CO_2)$$
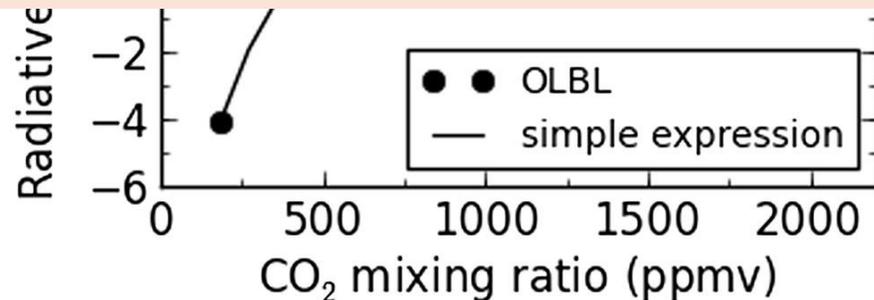
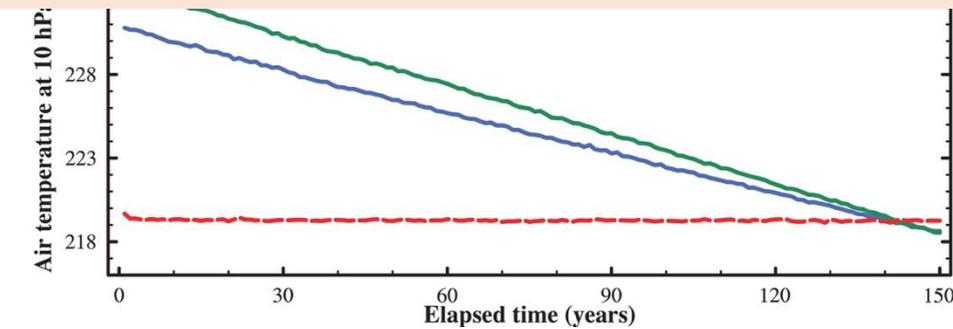(Etminan et al., 2016, GRL)

(He et al., 2023, Science)

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Objective
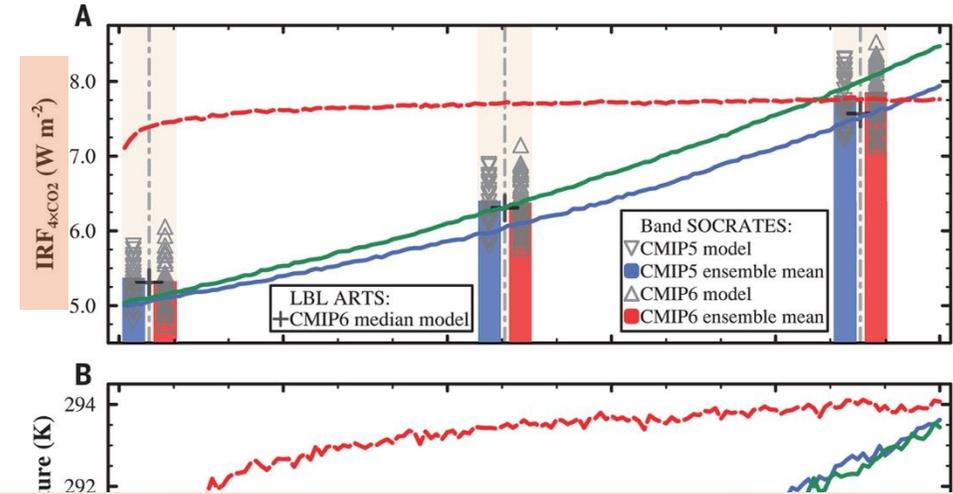
1. ERF also linearly scales with $\ln(C/C_0)$?
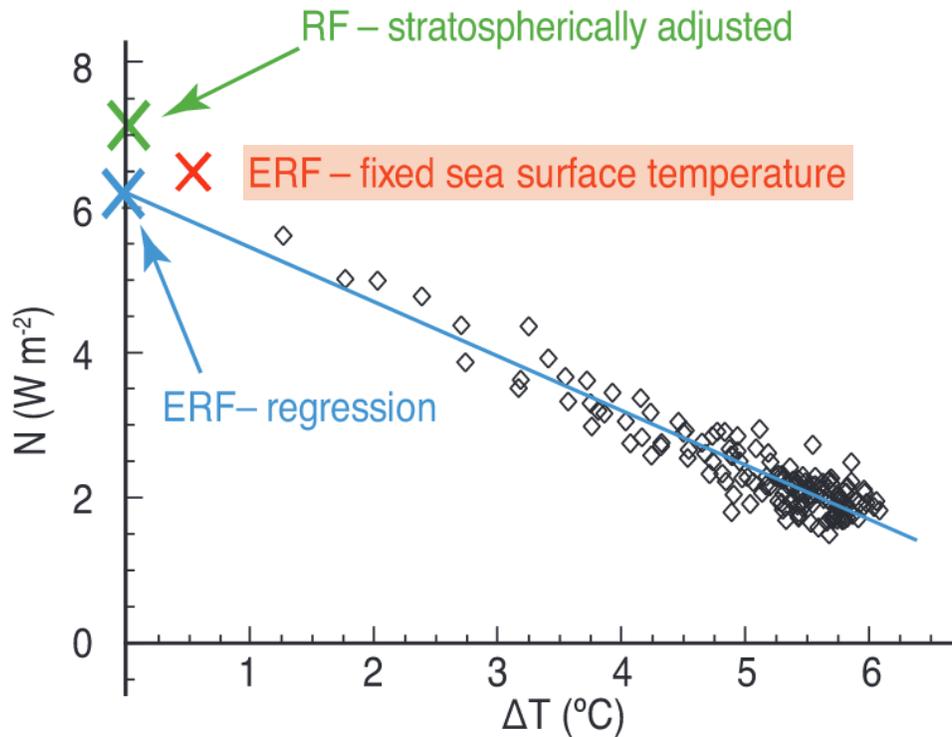2. ERF independent of the climate background?

(Etminan et al., 2016, GRL)

(He et al., 2023, Science)

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Experiment (Fixed-SST)

RF – stratospherically adjusted

ERF – fixed sea surface temperature

ERF– regression

(Sherwood et al., 2015, Bull. Amer. Meteorol. Soc.)

Experiment design:

Model: iCESM1.3.1
Resolution: ne30_ne30
Compset:
1850_CAM50_CLM40%SP_CICE%PRES_DOCN%DOM_RTM
_SGLC_SWAV

CO_2 Forcing:
$1\times CO_2$, $3\times CO_2$, $6\times CO_2$, $9\times CO_2$

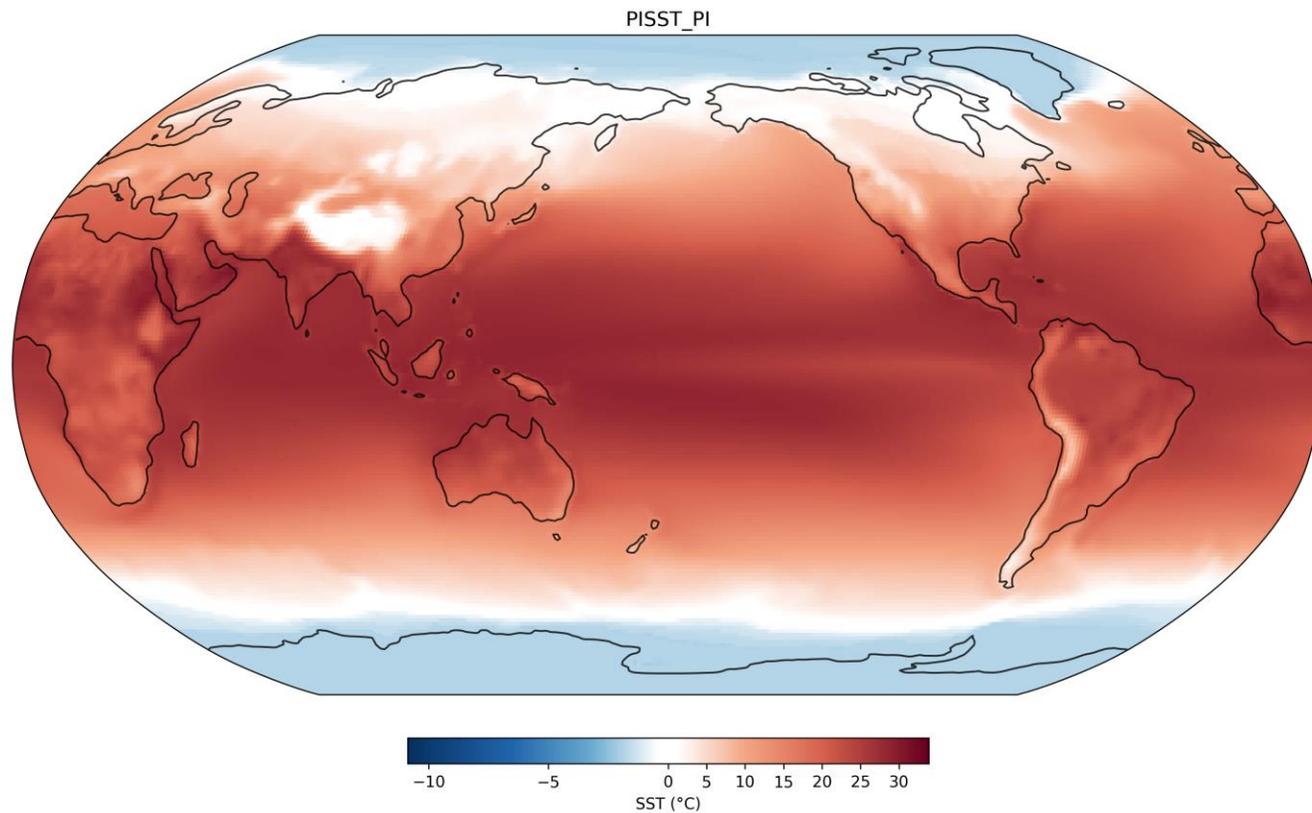**Climatological Background States:**
Pre-Industrial, Eocene

Simulation Length:
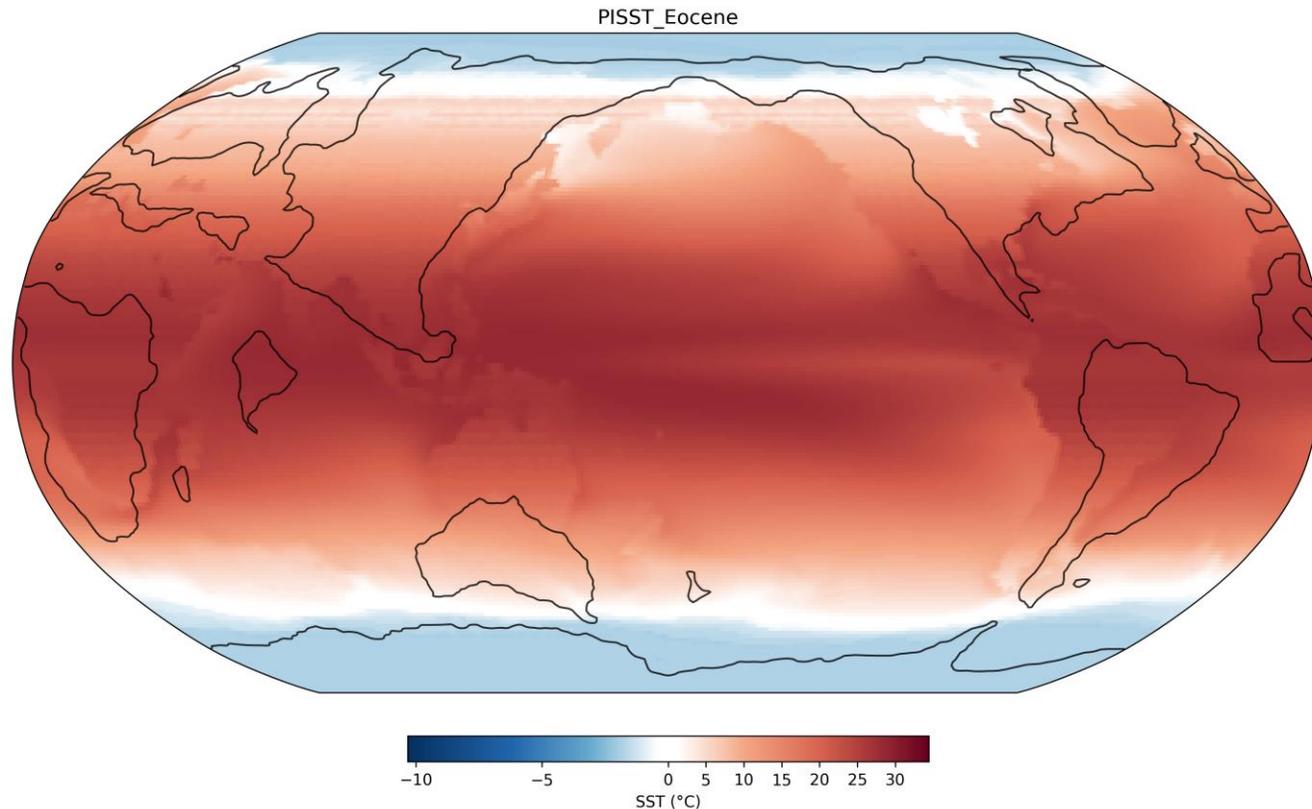Total runtime: 30 years
Analysis period: last 20 years

Experiment (PISST-PI)

PISST_PI

SST (°C)

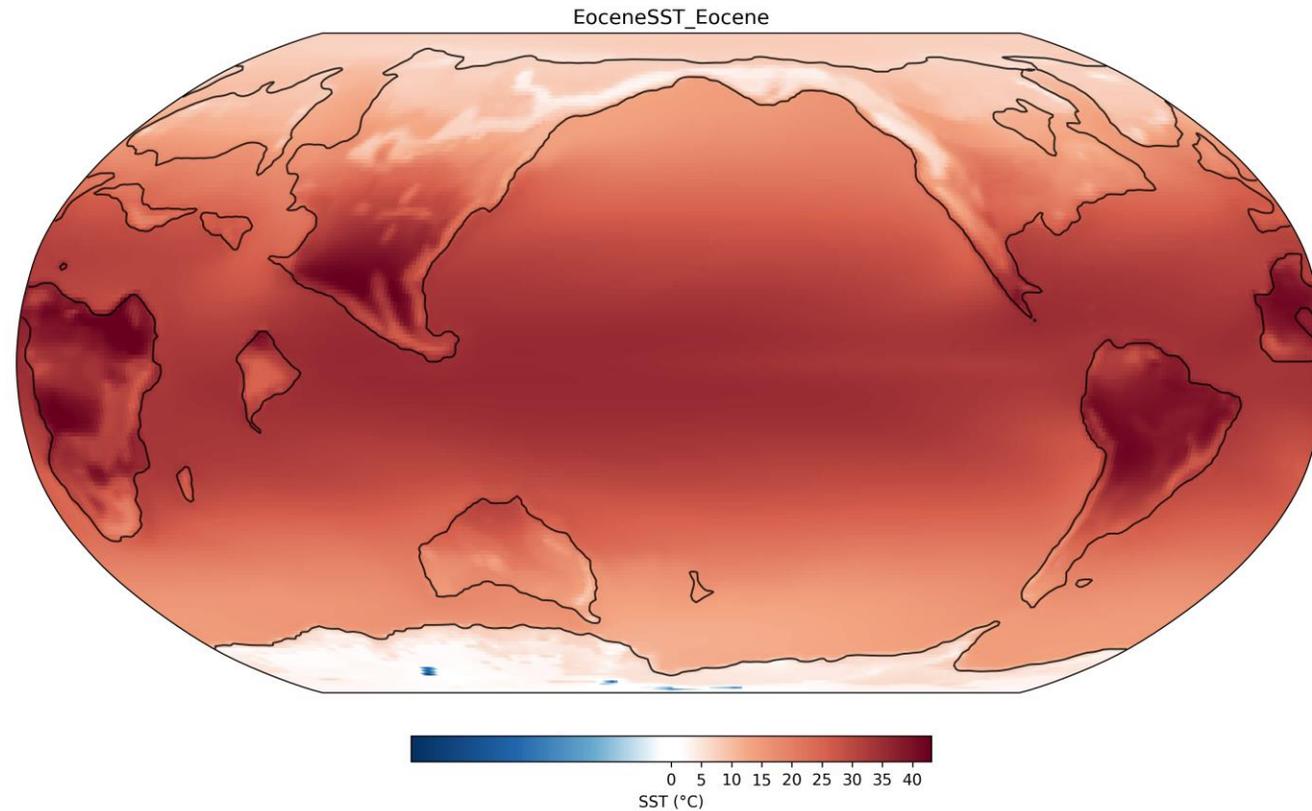- **Make PISST file:**
  Calculate the 100-year mean SST and ice fraction from a previous PI simulation
- **CO_2 Forcing:**
  $1\times CO_2$, $3\times CO_2$, $6\times CO_2$, $9\times CO_2$
- **Other boundary condition:**
  Pre-Industrial

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Experiment (PISST-Eocene)

PISST_Eocene

SST (°C)

- **Make PISST file:**
  Calculate the 100-year mean SST and ice fraction from a previous PI simulation. <u>Here, we used the ocean zonal mean temperature in place of the land temperature at the same latitude.</u>
- **CO_2 Forcing:**
  $1×CO_2$, $3×CO_2$, $6×CO_2$, $9×CO_2$
- **Other boundary condition:**
  Eocene (Zhu et al., 2019, Sci. Adv.; 2020, EPSL; 2024, Annu. Rev. Earth Planet. Sci.)

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Experiment (EoceneSST-Eocene)

EoceneSST_Eocene

SST (°C)

- **Make EoceneSST file:**
  Calculate the 100-year mean SST and ice fraction from a previous Eocene simulation
- **CO_2 Forcing:**
  $1 \times CO_2$, $3 \times CO_2$, $6 \times CO_2$, $9 \times CO_2$
- **Other boundary condition:**
  Eocene (Zhu et al., 2019, Sci. Adv.; 2020, EPSL; 2025, Annu. Rev. Earth Planet. Sci.)

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ERF & Adjustments Calculation

ERF Calculation:

Net radiation at TOA (RESTOM) = Net shortwave radiation at TOA (FSNT) - Outgoing longwave radiation at TOA (FLNT)

ERF = RESTOM_nXCO2 - RESTOM_1XCO2

Adjustments Calculation (Pendergrass et al., 2018, Earth Syst. Sci. Data):

$$\text{adj}_x = k_x * \left(x_{\text{perturbed}} - x_{\text{control}} \right)$$ <u>Stratospheric adjustment is not included.</u>

x: climate variable (e.g., temperature, water vapor), k_x: radiative kernel (W/m^2/unit)

Cloud Adjustment Calculation (Soden et al., 2008, J. Clim.):

$$\delta_c R = \underbrace{dC_{RF}}_{\text{Cloud forcing}} + \underbrace{\left(K_T^0 - K_T \right) dT}_{\text{Temperature effect}} + \underbrace{\left(K_W^0 - K_W \right) dW}_{\text{Water vapor effect}} + \underbrace{\left(K_a^0 - K_a \right) da}_{\text{Albedo effect}} + \underbrace{\left(G^0 - G \right)}_{\text{Reference forcing correction}}$$

K: total-sky radiative kernels, K^0: clear-sky radiative kernels, G: total-sky forcing, G^0: clear-sky forcing

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Results
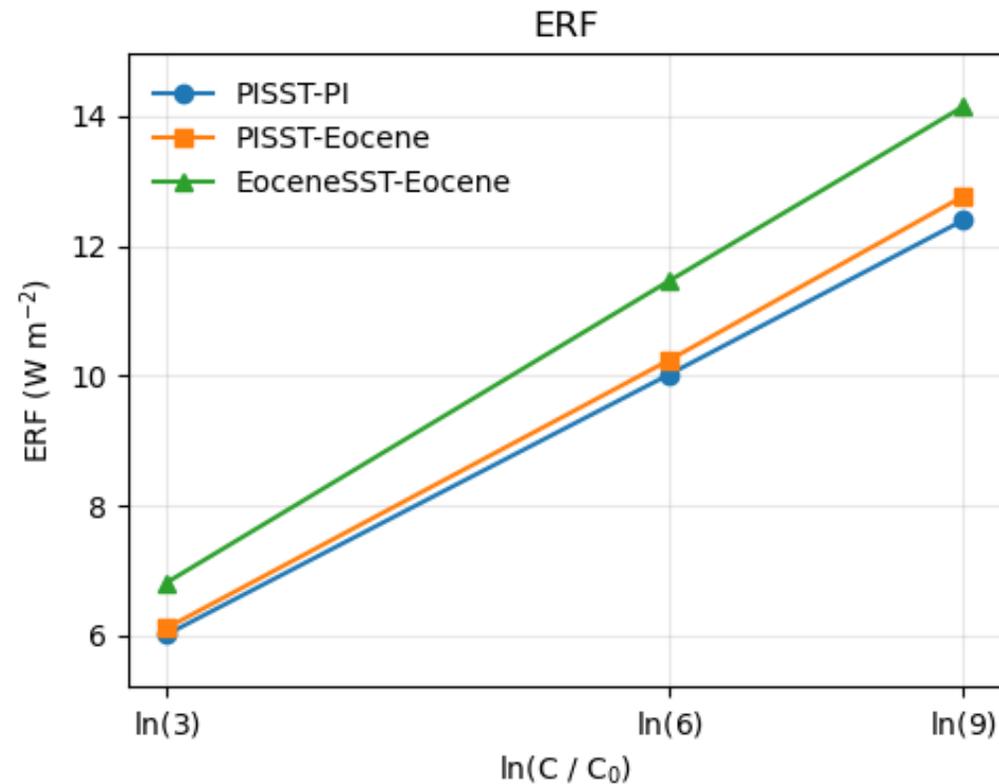
- ERF also linearly scales with $\ln(C/C_0)$

- ERF is dependent of the climate background state
  - Different slopes: The regression slope of ERF versus $\ln(C/C_0)$ differs across experiments.

  - For the same $\ln(C/C_0)$, ERF amplification order: EoceneSST-Eocene > PISST-Eocene > PISST-PI
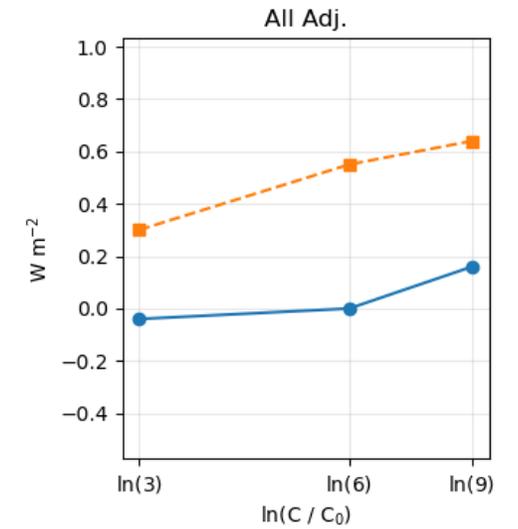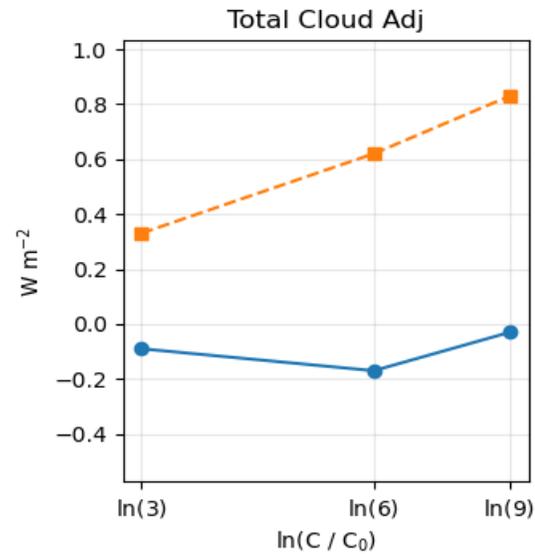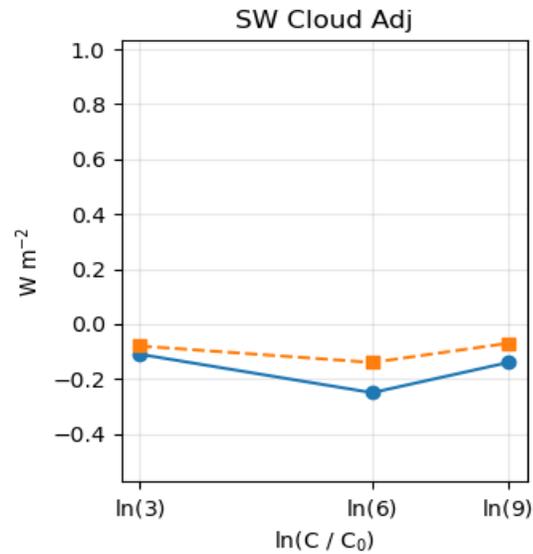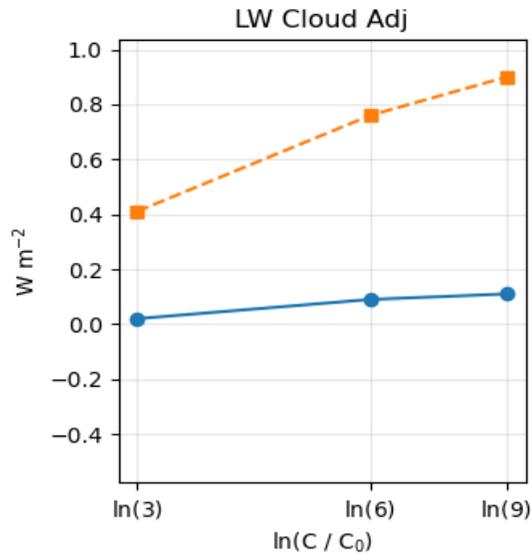
Results
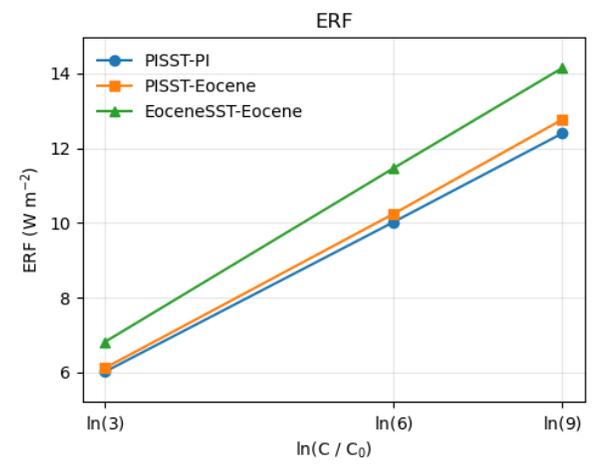
$$\text{Background} - \text{state dependence} = (\text{nxCO}_{2\text{EoceneSST}-\text{Eocene}} - \text{nxCO}_{2\text{PISST}-\text{PI}}), (\text{nxCO}_{2\text{PISST}-\text{Eocene}} - \text{nxCO}_{2\text{PISST}-\text{PI}}), n = 3,6,9$$
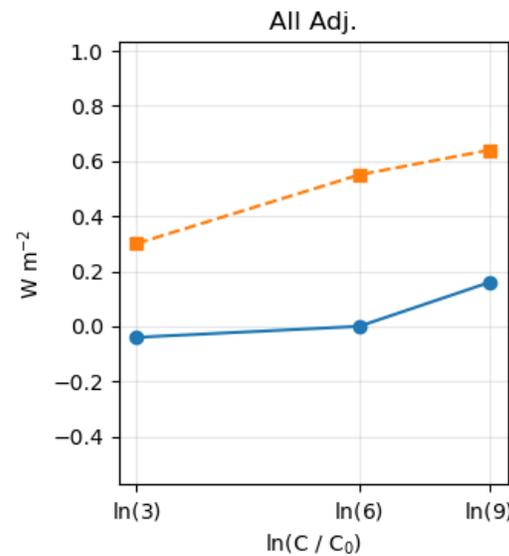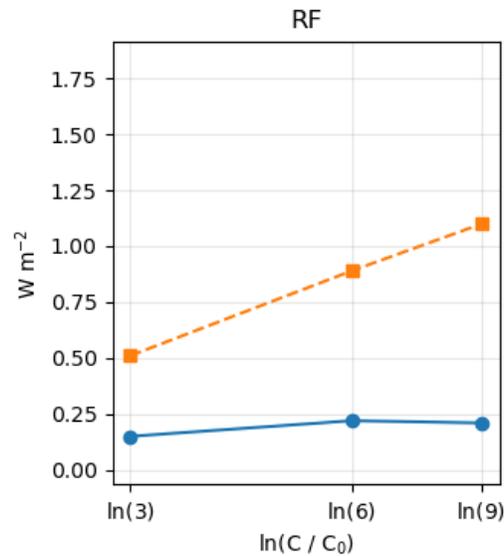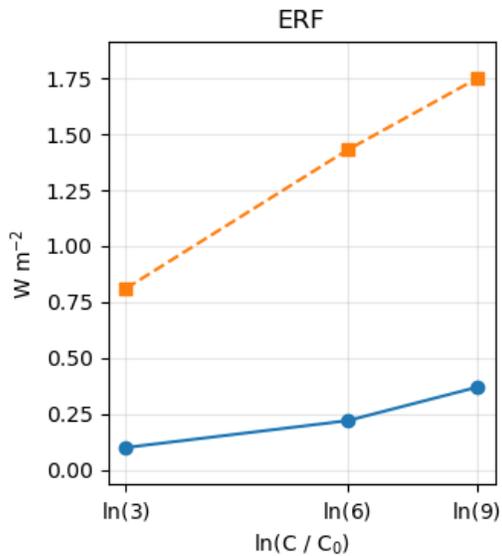
- **ERF vs RF & Background-State Effects**
  - **ERF > RF**, grows with ln(C/C$_0$)→ background amplifies ERF
- **Fast adjustments:** positive & increasing with CO$_2$ in orange, near zero in blue
- Larger ERF differences driven by fast adjustments in warmer background

Results

LW cloud adj: strongly positive, increases (orange)
SW cloud adj: less negative (weaker shortwave cooling)
Mechanism: SST patterns → stability, convection, humidity, winds → cloud type & cloud-top height

Conclusions & Next Steps

In conclusion, ERF scales linearly with $\ln(C/C_0)$ and generally depends on the background climate state, and a warmer background tends to amplify it.

1. IRF Calculation
2. Adjustments Analysis
Changes in Surface Temperature Adj, Troposphere Temperature Adj, and Water Vapor Adj here are very small. Surface Albedo Adj. shows negative changes.

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