Constraining the cloud-feedback pattern effect using (mostly) CERES data

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“Equilibrium change in Earth’s global mean surface temperature, in response to a doubling of atmospheric CO$_2$ relative to pre-industrial conditions” (IPCC)
ECS is a good predictor of future warming

Warming by end of century

\[ \Delta T (K) \]

\[ \text{ECS (K)} \]

Observational constraints are weak (as are model-constraints)

Sherwood, Webb et al 2020
Observational constraints are weak (as are model-constraints)

Can we bring better observational constraints?

Sherwood, Webb et al 2020
Global radiative forcing \( F \). In order to approximately account for this lag, we consider the evolution of ice rampings, by about 3

Gregory et al. [1998]. The ocean energy input \( \Delta \bar{F} \) and damping \( \Delta \bar{R} = \lambda \Delta \bar{T} \).

Earth’s Energy Imbalance (EEI)

Energy Budget: \( \Delta N = \Delta F - \lambda \Delta T \)
Energy Budget: $\Delta N = \Delta F - \lambda \Delta T$

Equilibrium Climate Sensitivity

$\Delta Q = 0$

$ECS = \Delta T_{2\times} = \frac{\Delta F_{2\times}}{\lambda}$
ECS: all about the $\lambda$

Energy Budget: $\Delta N = \Delta F - \lambda \Delta T$

Changes since pre-industrial (\(\Delta N\) from ARGO)

Equilibrium Climate Sensitivity
\[
\Delta N = 0 \\
ECS = \Delta T_{2\times} = \frac{\Delta F_{2\times}}{\lambda}
\]
ECS: all about the $\lambda$

Energy Budget: $\Delta N = \Delta F - \lambda \Delta T$

Changes since pre-industrial
($\Delta N$ from ARGO)

Equilibrium Climate Sensitivity

$$ECS_{inf} = \frac{\Delta F_{2x}}{\lambda_{hist}}$$
ECS: all about the $\lambda$

Equilibrium Climate Sensitivity

$$ECS_{inf} = \frac{\Delta F_{2x}}{\lambda_{hist}}$$
Equilibrium Climate Sensitivity

\[ ECS_{inf} = \frac{\Delta F_{2x}}{\lambda_{hist}} \]

Pattern effect correction

Observations (ARGO+)

Model w/ SST\textsubscript{obs}

Models (coupled)
Equilibrium Climate Sensitivity

$$ECS = \frac{\Delta F_{2x}}{\lambda_{hist} - \Delta \lambda}$$

Pattern effect correction

Observations (ARGO+)

Models (coupled)

Model w/ SST_{obs}

Count / PDF

ECS (°C)

ARGO

GCMs

$\Delta \lambda = 0.5 \pm 0.5 \text{W/m}^2/\text{K}$
Pattern effect correction

Equilibrium Climate Sensitivity

\[ ECS = \frac{\Delta F_{2x}}{\lambda_{\text{hist}} - \Delta \lambda} \]

\[ \Delta \lambda = 0.5 \pm 0.5 \text{W/m}^2/\text{K} \]
Equilibrium Climate Sensitivity

\[ ECS = \frac{\Delta F_{2\times}}{\lambda_{hist} - \Delta \lambda} \]

**Pattern effect correction**

*Use CERES to constrain \( \Delta \lambda \)*

**Equilibrium Climate Sensitivity**

\[ \Delta \lambda = 0.5 \pm 0.5 \text{ W/m}^2/\text{K} \]
Pattern effect: feedback depends on warming pattern

\[ \bar{R} = \lambda \bar{T} \]

\[ \lambda_{eq} = \lambda_{hist} \]
Pattern effect: feedback depends on warming pattern

\[ \overline{R} = \lambda \overline{T} \]

\[ \lambda_{eq} = \lambda_{hist} \]

\[ \overline{R} \approx \frac{\lambda}{\overline{\partial R / \partial \overline{T}}} \]
Pattern effect: feedback depends on warming pattern

\[
\frac{\overline{R}}{\overline{T}} \approx \frac{\partial \overline{R}}{\partial \overline{T}}
\]

\[
\frac{\overline{R}}{\overline{T}} \approx \sum_{x,y} \frac{\partial R(x)}{\partial T(y)} \frac{T(y)}{\overline{T}}
\]

- Atmospheric radiative response
- Surface warming pattern
Cloud feedback decomposition

Cloud Radiative kernels (radiation vs cloud fraction)
Cloud amount change (cloud frac vs cloud controlling factors)
Atmospheric Circulation (atmospheric state vs surface temperature)
Warming Pattern
Cloud feedback decomposition

\[ \frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \begin{pmatrix} \frac{\partial R(x)}{\partial f(x, \tau, p)} & \frac{\partial f(x, \tau, p)}{\partial C(x)} & \frac{\partial C(x)}{\partial T(y)} & \frac{T(y)}{\bar{T}} \end{pmatrix} \]

Cloud Radiative kernels (radiation vs cloud fraction)
Cloud amount change  (cloud frac vs cloud controlling factors)
Atmospheric Circulation (atmospheric state vs surface temperature)
Warming Pattern
Tropical Climate Dynamics

- Warm Pool
- Subtropics

**Arakawa 1975**

**Stevens 2005**
Response to Warm Pool warming

\[
\frac{\bar{R}}{\bar{T}} \approx \sum_{x, y, \tau, p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}}
\]
Response to Warm Pool warming

\[
\frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}}
\]
Response to Warm Pool warming

\[
\frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}}
\]
Response to Warm Pool warming

\[ \overline{R} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial (f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{T} \]

\( \Delta \text{SST} \)

Warm Pool

Weak Temp. Gradient

Subtropics

Trade inversion

EIS

Hadley/Walker

moist adiabat

\( T_{f,W} \)
Response to Warm Pool warming

\[ \frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}} \]

\[ \Delta SST \]
How to constrain cloud feedbacks?

\[
\frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \begin{array}{cccc}
\frac{\partial R(x)}{\partial f(x, \tau, p)} & \frac{\partial f(x, \tau, p)}{\partial (x, \tau, p)} & \frac{\partial C(x)}{\partial T(y)} & \frac{T(y)}{\bar{T}}
\end{array}
\]

Cloud Radiative kernels (radiation vs cloud fraction)
Cloud amount change  (cloud frac vs cloud controlling factors)
Atmospheric Circulation (atmospheric state vs surface temperature)
Warming Pattern
\[ \frac{\bar{R}}{\bar{T}} \approx \sum_{x, y, \tau, p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}} \]

Constraining net feedback

Radiative transfer

GCMs (4xCO2)

MODIS

Klein et al 2017
Constraining net feedback

\[ \frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}} \]

\[ \frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}} \]

CERES \quad \text{GCMs (4xCO2)}

Scott et al 2020
Myers et al 2021
Method 1: T + EIS

\[
\frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}}
\]

\[
\frac{\bar{R}}{\bar{T}} \approx \frac{\partial R}{\partial T} + \frac{\partial R}{\partial EIS} \Delta EIS \frac{\Delta T}{\bar{T}}
\]

Ceppi and Gregory 2018
Method 1: $T + \frac{\Delta EIS}{\bar{T}}$

CESM2 Abrupt 4xCO2

$\Delta EIS \frac{(fast)}{\bar{T}}$

$\Delta EIS \frac{(slow)}{\bar{T}}$
Method 1: $T + EIS$

$$\bar{R} \approx \frac{\partial R}{\partial T} \bar{T} + \frac{\partial R}{\partial EIS} \Delta EIS$$

Constrainable from CERES
Constraining feedback change

\[
\frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}}
\]

\[
\frac{\bar{R}}{\bar{T}} \approx \lambda_{hist} + \sum_{x,y} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{\Delta T(y)}{\bar{T}} \frac{\Delta \lambda}{\bar{T}}
\]

GCMs (4xCO2)
Constraining feedback change

\[
\frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}}
\]

\[
\frac{\bar{R}}{\bar{T}} \approx \lambda_{\text{hist}} + \sum_{x,y} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial \psi} \frac{\Delta \psi}{\bar{T}} \frac{\Delta \lambda}{\bar{T}}
\]

CERES \hspace{1cm} ERA \hspace{1cm} GCMs (4xCO2)
Change in pattern looks like ENSO
Method 2: Emergent constraint

$\lambda^c_{\text{ENSO}} =$ CRE regressed onto nino3.4

Uncertainty Quantification needed
Constraining feedback change vs ENSO

\[ \frac{\bar{R}}{\bar{T}} \approx \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial f(x, \tau, p)} \frac{\partial f(x, \tau, p)}{\partial C(x)} \frac{\partial C(x)}{\partial T(y)} \frac{T(y)}{\bar{T}} \]

\[ \frac{\bar{R}}{\bar{T}} \approx \lambda_{\text{hist}} + \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial \psi} \frac{\Delta \psi}{\Delta \lambda} \]

CERES  ERA  GCMs (4xCO2)
Constraining feedback change with respect to ENSO

\[
\frac{\bar{R}}{T} \approx \lambda_{\text{hist}} + \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial \psi} \frac{\Delta \psi}{T}
\]
Constraining feedback change with respect to ENSO

\[
\frac{\bar{R}}{T} \approx \lambda_{\text{hist}} + \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial \psi} \frac{\Delta \psi}{T}
\]

Scott et al 2020
Constraining feedback change with respect to ENSO

\[
\frac{\bar{R}}{T} \approx \lambda_{\text{hist}} + \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial \psi} \frac{\Delta \psi}{T}
\]

Get from GCMs

Scott et al 2020
Constraining feedback change with respect to ENSO

\[
\frac{\bar{R}}{T} \approx \lambda_\text{hist} + \sum_{x,y,\tau,p} \frac{\partial R(x)}{\partial C(x)} \frac{\partial C(x)}{\partial \psi} \frac{\Delta \psi}{T}
\]

Scott et al 2020
Summary

Equilibrium Climate Sensitivity

$$ECS = \frac{\Delta F_{2\times}}{\lambda_{hist} - \Delta \lambda}$$

Pattern effect can be constrained from CERES
- Reduced dimension - CRE vs dominant CCF
- Emergent Constraints on ENSO feedback
- Detailed analysis of CRE response to ENSO + how does ENSO state changes?