Shortwave and longwave contributions to global warming under increased CO$_2$

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Energy imbalance and temperature change

**Unperturbed**
- ASR = OLR
  - Atmospheric Emission Level
  - Atmospheric Temperature

**Solar Perturbation**
- ASR = OLR

**Greenhouse Perturbation**
- ASR = OLR
- CO₂ CO₂
Top of Atmosphere Radiative response to greenhouse and shortwave forcing

A. Canonical response to instantaneous greenhouse forcing

B. Canonical response to instantaneous solar forcing

OLR returns to unperturbed value in 20 years
How to reconcile this – response to greenhouse forcing with a shortwave feedback

**LW feedback only**

Greenhouse forcing

\[ F_{\text{LW}} = 4 \text{ W m}^{-2} \]

\[ \Delta T = \frac{F_{\text{LW}}}{-\lambda_{\text{LW}}} = 2 \text{ K} \]

\[ \Delta OLR = 0 \]

Forcing = response

\[ F_{\text{LW}} = -\lambda_{\text{LW}} \Delta T \]

if \( \lambda_{\text{LW}} = -2 \text{ W m}^{-2} \text{ K}^{-1} \)

\[ \Delta T = F_{\text{LW}} / -\lambda_{\text{LW}} = 2 \text{ K} \]
Time evolution of OLR response to greenhouse forcing with SW feedback

OLR must go from \(-\text{FLW}\) at time 0 to FLW in the equilibrium response

\[ \rightarrow \text{OLR returns to unperturbed value when half of the equilibrium temperature change occurs} \]

The energy imbalance equation:

Has the solution: \( T_s \)

With the characteristic timescale (\( \tau \))

\[ \tau = \frac{-1}{\frac{1}{\lambda} + \frac{3}{2}} \]

= 30 years (for 150 meter deep ocean)
Inter-model spread in TOA response

The TOA response to greenhouse forcing differs a lot between GCMs:

- OLR returns to unperturbed values ($T_{\text{CROSS}}$) within 5 years for some GCMs and not at all for others (bi-modal)
- On average, $T_{\text{CROSS}} = 19$ years
Linear Feedback model

\[ C(t) \frac{dT_S}{dt} = F_{SW} + F_{LW} + (\lambda_{LW} + \lambda_{SW}) T_S(t). \]

- \( C \) = heat capacity of climate system. Time dependent – meters of ocean
- \( T_S \) = Global mean surface temperature change
- \( F_{SW} \) and \( F_{LW} \) are the SW and LW radiative forcing (including fast cloud response to radiative forcing – W m\(^{-2}\))
- \( \lambda_{LW} \) and \( \lambda_{SW} \) are the LW and SW feedback parameters. W m\(^{-2}\) K\(^{-1}\)
- Given above parameters and \( T_S \), we can predict the TOA response

\[ OLR(t) = -F_{LW} - \lambda_{LW} T_S(t) \]
\[ ASR(t) = F_{SW} + \lambda_{SW} T_S(t). \]
Backing out Forcing and feedbacks from instantaneous 4XCO2 increase runs

- Feedbacks parameters ($\lambda_{LW}$ and $\lambda_{SW}$) are the slope of $-\text{OLR}$ and ASR vs. $T_S$ (W m$^{-2}$ K$^{-1}$)
- Forcing ($F_{SW}$ and $F_{LW}$) is the intercept (W m$^{-2}$). Includes rapid cloud response to CO$_2$ (Gregory and Webb)
The TOA response in each model (and ensemble average) – solid lines– is well replicated by the linear feedback model.

- What parameters (forcing, feedbacks, heat capacity) set the mean radiative response and its variations across models?
Ensemble average OLR recovery timescale

Ensemble average forcing and feedbacks
- $\lambda_{LW} = -1.7 \text{ W m}^{-2} \text{ K}^{-1}$
- $\lambda_{SW} = +0.6 \text{ W m}^{-2} \text{ K}^{-1}$
- $F_{LW} = +6.1 \text{ W m}^{-2}$

Equilibrium temperature change
$$T_{EQ}$$

ASR in new equilibrium = $T_{EQ} \lambda_{SW} = 4 \text{ W m}^{-2}$

- To come to equilibrium, OLR must go from $-F_{LW} = -6.1 \text{ W m}^{-2}$
to $T_{EQ} \lambda_{LW} = +4 \text{ W m}^{-2}$
- OLR must change by 10 W m$^{-2}$ to come to equilibrium
  $\Rightarrow$ OLR crosses zero about 60% of the way the equilibrium
Climate model differences in OLR response time

Time series of TOA Radiation change in 4XCO₂ Runs

“FAST” response example- GFDL CM3 model

CMIP5 Ensemble Average Response

“SLOW” response example- GFDL ESM2M model
Sensitivity of $\tau_{\text{CROSS}}$ to feedback parameters

If $F_{SW} = 0$ (simplification):

$$\tau_{\text{CROSS}} = \tau \ln(-\lambda_{LW} / \lambda_{SW})$$

$\tau_{\text{cross}}$ is determined by the OLR value demanded in the new equilibrium

→ Set by relative magnitudes of $\lambda_{LW}$ and $\lambda_{SW}$

→ HAS STEEP GRADIENTS IN VICINITY OF $\lambda_{SW} = 0$
Cause of SW positive feedbacks:

- Water vapor feedback = +0.3±0.1 W m\(^{-2}\) K\(^{-1}\)
- Surface albedo feedback = +0.26 ±0.08 W m\(^{-2}\) K\(^{-1}\)

Bony et al. (2006)
Observations of the co-variability of global mean surface temperature and ASR/OLR give statistically significant estimates of $\lambda_{SW}$ and $\lambda_{LW}$:

- $\lambda_{SW} = 0.8 \pm 0.4$ W m$^{-2}$ K$^{-1}$
- $\lambda_{LW} = -2.0 \pm 0.3$ W m$^{-2}$ K$^{-1}$

<table>
<thead>
<tr>
<th>Temperature Data</th>
<th>$\lambda_{SW}$</th>
<th>$\lambda_{LW}$</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEP Reanalysis TAS</td>
<td>0.7 ± 0.4</td>
<td>-1.7 ± 0.2</td>
<td>-1.0 ± 0.3</td>
</tr>
<tr>
<td>GIS TEMP</td>
<td>0.8 ± 0.4</td>
<td>-2.2 ± 0.3</td>
<td>-1.4 ± 0.4</td>
</tr>
<tr>
<td>CW HadCRUT4</td>
<td>0.9 ± 0.5</td>
<td>-2.0 ± 0.4</td>
<td>-1.1 ± 0.4</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.8 ± 0.4</strong></td>
<td><strong>-2.0 ± 0.3</strong></td>
<td><strong>-1.2 ± 0.4</strong></td>
</tr>
</tbody>
</table>
Implications for OLR recovery timescale

- Observational constraints suggest that $\tau_{\text{cross}}$ is of order decades in response to LW forcing only.

- Assumes an (CMIP5 ensemble average) radiative relaxation timescale ($\tau$) of 27 years.

$\tau_{\text{CROSS}} = \tau \ln(-\lambda_{\text{LW}} / \lambda_{\text{SW}})$
Can we get climate feedbacks from interannual variability of CERES (and surface temperature)?
Radiation causes surface temperature anomalies as well as responds to it—potential to confuse the non-feedback forcing with the feedback.
Conclusions

CO2 initiates global warming by decreasing OLR but the TOA energy imbalance is dominated by increased absorbed solar radiation in most climate models – associated with surface albedo and SW water vapor feedbacks.

CERES data also suggest a positive shortwave feedback \( \rightarrow \) global warming will most likely result in enhanced ASR and we should not expect to see reduced OLR from the forcing.

Can interannual variability in CERES tell us anything about climate feedbacks?
Are the radiative feedbacks that operate on inter-annual timescales equivalent to equilibrium feedbacks?
Water Vapor as a SW Absorber

- Figure: Robert Rhode Global Warming Art Project

- Radiation Transmitted by the Atmosphere
  - Downgoing Solar Radiation: 70-75% Transmitted
  - Upgoing Thermal Radiation: 15-30% Transmitted
  - Spectral Intensity: 0.2 - 70
  - Wavelength (μm): 0.2 - 70

- 2xCO₂ Change in SW Absorption Profile in GFDL 2.1
  - Pressure level (hPa): 0 - 1000
  - Change in Seasonal amplitude of SW absorption (W m⁻² per 1000 hPa): 0 - 200
Heat capacity: $4XCO_2$

- Heat capacity increases with time as energy penetrates into the ocean.
- In first couple decades, energy is within the first couple 100 m of ocean and system $e$-folds to radiative equilibrium in about a decade.
How fast does the system approach equilibrium?

Ensemble average forcing and feedbacks
- $C = 250 \text{ m (30 W m}^{-2}\text{year K}^{-1})$
  - the ensemble average for first century after forcing
- $\lambda_{\text{LW}} = -1.7 \text{ W m}^{-2}\text{K}^{-1}$
- $\lambda_{\text{SW}} = +0.6 \text{ W m}^{-2}\text{K}^{-1}$

The energy imbalance equation:

Has the solution:

$$T_S = \frac{-1}{\lambda} (1 - e^{-\lambda / \tau})$$

With the characteristic timescale ($\tau$)

$$\tau = \frac{C}{\lambda} = \frac{250}{-1.7} = 27 \text{ years}$$

Key point:
OLR returns to unperturbed value in
of order the radiative relaxation timescale of
the system $\rightarrow$ decades
What parameter controls inter-GCM spread in TOA response?

- Using all GCM specific parameters gets the inter-model spread in $\tau_{\text{cross}}$

- Varying just $\lambda_{\text{SW}}$ and $F_{\text{SW}}$ between GCMS captures inter-model spread in $\tau_{\text{cross}}$

- $\lambda_{\text{LW}}$, $F_{\text{LW}}$, and heat capacity differences between GCMs less important for determining the radiative response

- Varying just $\lambda_{\text{SW}}$ gives bi-modal distribution of $\tau_{\text{cross}}$ with exception of two models ($F_{\text{SW}}$ plays a role here)
$T_{\text{cross}}$ dependence on feedback parameters

Ensemble average forcing and feedbacks

- $\lambda_{\text{LW}} = -1.7 \text{ W m}^{-2} \text{ K}^{-1}$
- $\lambda_{\text{SW}} = +0.6 \text{ W m}^{-2} \text{ K}^{-1}$
- $F_{\text{LW}} = +6.1 \text{ W m}^{-2}$

equilibrium temperature change

$T_{\text{EQ}}$

Feedback gain: Amplification of response due to

$G_{\text{FEED}}$

$T_{S}$

$\text{OLR}$

initial  final  transition

$\text{OLR} = 0$ at $\tau = T_{\text{cross}}$

How far from equilibrium $\text{OLR} = 0$
How fast does the system approach equilibrium?

Ensemble average forcing and feedbacks
- \( C = 250 \text{ m (30 W m}^{-2}\text{ year K}^{-1}) \) for the ensemble average for first century after forcing
- \( \lambda_{\text{LW}} = -1.7 \text{ W m}^{-2}\text{ K}^{-1} \)
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The energy imbalance equation:
Has the solution:
\[
T_S(t) = -\frac{\lambda}{\lambda_C}(1 - e^{-\frac{t}{\tau}}) = \frac{1 - e^{-\frac{t}{\tau}}}{1.1^2} = 27 \text{ years}
\]

Key point: OLR returns to unperturbed value in of order the radiative relaxation timescale of the system \( \rightarrow \) decades
What parameter controls inter-GCM spread in TOA response?

- Using all GCM specific parameters gets the inter-model spread in $\tau_{\text{cross}}$.

- Varying just $\lambda_{\text{SW}}$ and $F_{\text{SW}}$ between GCMS captures inter-model spread in $\tau_{\text{cross}}$.

- $\lambda_{\text{LW}}, F_{\text{LW}}$, and heat capacity differences between GCMs less important for determining the radiative response.

- Varying just $\lambda_{\text{SW}}$ gives bi-modal distribution of $\tau_{\text{cross}}$ with exception of two models ($F_{\text{SW}}$ plays a role here).
**Feedback gain:** Amplification of response due to

$G_{\text{FEED}}$

$T_{S}$

$\text{OLR}$

Initial, final, transition

$\text{OLR} = 0$ at $\tau = \tau_{\text{cross}}$

How far from equilibrium $\text{OLR} = 0$
Sensitivity of $\tau_{\text{CROSS}}$ to feedback parameters

If $F_{SW} = 0$ (simplification):

$$\tau_{\text{CROSS}} = -\tau \ln(\frac{1}{1 - \frac{\lambda_{LW}}{\lambda_{SW}}})$$

$\tau_{\text{cross}}$ is determined by the OLR value demanded in the new equilibrium

$\rightarrow$ Set by relative magnitudes of $\lambda_{LW}$ and $\lambda_{SW}$

$\rightarrow$ HAS STEEP GRADIENTS IN VICINITY OF $\lambda_{SW} = 0$
What parameter controls inter-GCM spread in TOA response?

- While the relative magnitudes of $\lambda_{SW}$ and $\lambda_{LW}$ explain the vast majority of the spread in $\tau_{\text{cross}}$, there are several model outliers.

- A more complete analysis includes inter-model differences in $F_{SW}$.

  $F_{SW}$ includes both direct radiative forcing by CO2 (small) and the rapid response of clouds to the forcing.
From before, if \( F_{SW} = 0 \) then:

\[
G_{FEED} = \frac{1}{1 + \frac{\lambda_{LW}}{\lambda_{SW}}}
\]

If \( F_{SW} \neq 0 \) then:

\[
G_{FORCE} = 1 + \frac{2}{F_{LW} |\lambda_{LW}|}
\]

Feedback Gain = 2

Forcing Gain = 2

If \( |\lambda_{SW}| = \frac{1}{2} |\lambda_{LW}| \Rightarrow T_{EQ} \) is doubled

The OLR change to get to equilibrium is:

\[
(2*F_{LW}/|\lambda_{LW}|) * |\lambda_{LW}| = 2F_{LW}
\]

\( \Rightarrow \) OLR = 0 occurs half way to equilibrium

\( \Rightarrow T_{CROSS} = T \ln(2) \)

If \( F_{LW} = F_{SW} \Rightarrow T_{EQ} \) is doubled and OLR asymptotes to \(+F_{LW}\)

\( \Rightarrow OLR = 0 \) occurs half way to equilibrium

\( \Rightarrow T_{CROSS} = T \ln(2) \)
SW and LW Feedbacks and Forcing: 4XCO₂

**Feedbacks**

- LW feedback is negative (stabilizing) and has small inter-GCM spread
- SW feedback is mostly positive and has large inter-GCM spread
- Forcing is mostly in LW (greenhouse)
- SW forcing has a significant inter-GCM spread
Sensitivity of $\tau_{CROSS}$ to feedback parameters

- Positive SW forcing and feedbacks favor a short OLR recovery timescale with a symmetric dependence on the "gain" factors.
- Explains the majority (R= 0.88) of inter-model spread.
- Assumes a time and model invariant heat capacity (250m ocean depth equivalent).
LW Feedback parameter from observations

- Surface temperature explains a small fraction of OLR' variance ($R=0.52$)
- Error bars on regression coefficient ($1\sigma$) are small, why?
- Weak 1 month auto-correlation in OLR' – $r_{\text{OLR}}$ (1month) = 0.3 → lots of DOF ($N^*=113$)

Even if none of the OLR' variance was explained, the regression slope is still significant
→ Given the number of realizations, you would seldom realize such a large regression coefficient in a random sample – in the absence of a genuine relationship between $T_S$ and OLR
SW Feedback parameter from observations

- Very weak correlation ($r=0.16$)
- Almost no memory in ASR’ – $r_{\text{OLR}}$ (1month) = 0.1 – mean we have lots of DOF (N*= 143)

The significance of the regression slope is not a consequence of the variance explained but, rather, the non-zero of the slope despite the number of realizations

→ The feedback has emerged from the non-feedback radiative processes in the record