Estimating climate sensitivity using a two-zone energy balance model and satellite observations

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Daily average carbon dioxide at South Pole

mole fraction (ppm)

year

2014  2015  2016  2017

394   396   398   400   402

NOAA
Climate sensitivity is the equilibrium (steady-state) change in the annual global-mean surface temperature (GMST) following a doubling of the atmospheric equivalent CO₂ concentration.

In IPCC (2013), the effective radiative forcing for a doubled CO₂ concentration is given as 3.7 W m⁻². This value will be adopted here; thus,

\[ \Delta Q = 3.7 \text{ W m}^{-2} \]
## Climate sensitivity estimates

<table>
<thead>
<tr>
<th>Source</th>
<th>Range</th>
<th>Best Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charney Report (1979)</td>
<td>1.5 – 4.5°C</td>
<td>3.0°C</td>
</tr>
<tr>
<td>IPCC AR4 (2007)</td>
<td>2.0 – 4.5°C</td>
<td>3.0°C</td>
</tr>
<tr>
<td>IPCC AR5 (2013)</td>
<td>1.5 – 4.5°C</td>
<td>None given</td>
</tr>
</tbody>
</table>
Estimating climate sensitivity using GCMs
Water vapour feedback (amplification of CO$_2$-induced warming by the resulting increase in atmospheric water vapour) is the primary source of global warming in GCMs.

What about the real climate system?
Estimating climate sensitivity using simple energy balance models and satellite observations
Radiative Response Coefficient \((b)\):

\[
b \equiv \frac{dFlux}{dT}
\]

Estimates of \(b\) can be obtained by linearly regressing fluctuations in upward (LW+SW) radiative flux at TOA, from observations or from non-equilibrium GCM output, against fluctuations in surface temperature.
The Zero-Dimensional Energy Balance Model (ZDM)
The Zero-Dimensional Model (ZDM)

Globally-averaged radiative response: \( \dot{b} T' \)

Globally-averaged external forcing: \( Q' \)

Globally-averaged surface temperature perturbation: \( T' \)

(Mixed Layer Ocean)
If we take $b$ as given by satellite observations, the ZDM expression for climate sensitivity is given by Eq. (4):

$$T_{ZDM} = \frac{Q}{b}$$
Two-zone(tropical/extratropical) Energy Balance Models

Model A (Lindzen and Choi, 2011)

The Two-Zone Models (A and B)

- $b_1T_1'$
- $Q_1'$
- $b_2T_2'$
- $Q_2'$

Zone 1 (Tropics)

Zone 2 (Extratropics)

$DHT'$

$T_1'$

$T_2'$
Energy Equations for Model B

Primes refer to small perturbations about a basic equilibrium climate state (all quantities are running annual means evolving slowly on long time scales):

\[ c_0 \frac{dT_1}{dt} = Q_1 \quad b_1 T_1 \quad d \quad T_1 \quad T_2 \]

\[ c_0 \frac{dT_2}{dt} = Q_2 \quad b_2 T_2 + d \quad T_1 \quad T_2 \]
**Sensitivity Analysis**

The sensitivity of Model B is found by imposing a step-function forcing

\[ Q_1, Q_2 = Q, Q \ 1(t) \]

where \( Q = 3.7 \ \text{Wm}^{-2} \)

and taking the equilibrium solution at \( t = \) .
Using $T$ to denote global mean increments at equilibrium, e.g., $T = \frac{T_1 + T_2}{2}$, it is found that

$$\bar{T}_B = 1 + X \; T_A$$

where

$$T_A = \frac{Q}{b_1 + b_2}$$

$$X = \frac{1}{S_2^2} \; \frac{b_1}{2} \; \frac{b_2}{2}$$

It is seen that $X = 0$ and $T_B = T_A$ under two circumstances:

$$b_1 \; b_2$$

Under general circumstances, $X$ can be large and $T_B$ and $T_A$ can be quite different.
Parameter Values

Values of the tropical radiative response coefficient \((b_1)\) are given by

(i) Satellite observations;
(ii) GCMs run in AMIP mode (fixed SST);
(iii) GCMs run in CMIP mode (SST calculated using a coupled ocean model)

Values taken from

Lindzen and Choi (2011)
Mauritsen and Stevens (2015)
<table>
<thead>
<tr>
<th></th>
<th>((\text{Slope})_{\text{obs}})</th>
<th>((\text{Slope})_{\text{AMIP}})</th>
<th>((\text{Slope})_{\text{CMIP}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC11, LW</td>
<td>5.3 ± 1.3</td>
<td>1.8 ([-0.8, 4.4])</td>
<td>3.0 ([0.6, 5.8])</td>
</tr>
<tr>
<td>LC11, SW</td>
<td>1.9 ± 2.6</td>
<td>([-2.9, -3.8, -0.1])</td>
<td>1.2 ([-3.3, 3.9])</td>
</tr>
<tr>
<td>LC11, LW + SW</td>
<td>6.9 ± 1.8</td>
<td>([-1.1, -4.7, 1.0])</td>
<td>4.2 ([0.5, 8.1])</td>
</tr>
<tr>
<td>MS15, LW</td>
<td>4.1 ± 0.8</td>
<td>2.7 ([0.8, 5.4])</td>
<td>2.2 ([0.2, 4.2])</td>
</tr>
<tr>
<td>MS15, SW</td>
<td>(-0.9 ± 0.9)</td>
<td>([-1.4, -4.3, 1.8])</td>
<td>([-1.2, -4.6, 0.8])</td>
</tr>
<tr>
<td>MS15, LW + SW</td>
<td>3.2 ± 1.0</td>
<td>1.3 ([-1.1, 4.7])</td>
<td>1.0 ([-1.1, 3.0])</td>
</tr>
</tbody>
</table>

\(^a\)The uncertainty interval in the first column of figures is ±1 standard error; values in curly brackets in the other columns are the outer limits of the quantity in question. The slopes of *Lindzen and Choi* [2011; LC11] are evaluated using data for the oceanic part of the latitude band \(20^\circ\text{S}–20^\circ\text{N}\), while those of *Mauritsen and Stevens* [2015; MS15] are evaluated using data for the entire latitude band \(20^\circ\text{S}–20^\circ\text{N}\).
Estimating $b_2$

It is difficult to estimate $b_2$ observationally from satellites because of the predominance of noise in surface temperatures over land.

Lindzen and Choi (2011) assumed that $b_2$ is given by the Planck value corresponding to the extratropical emission temperature (249 K), based on the low specific humidity and approximately unvarying 50% cloud cover in this region; this gives $b_2 = 3.5 \text{ W m}^{-2} \text{ K}^{-1}$.

Pierrehumbert [1995, Figure 2] has used a GCM radiation code to evaluate the clear-sky OLR as a function of low-level air temperature for various relative humidities. Choosing a low-level temperature characteristic of the extratropics (280 K) and the 75% RH curve, his calculations gives $b_2 \approx 2.1 \text{ W m}^{-2} \text{ K}^{-1}$.

Langen and Alexeev [2005], in aquaplanet experiments using two GCMs without an iris effect, found an extratropical LW response coefficient of approximately $2 \text{ W m}^{-2} \text{ K}^{-1}$.

Guided by these results, $b_2$ is allowed to vary in the range $(2.0, 3.5) \text{ W m}^{-2} \text{ K}^{-1}$.
Figure 1. EfCS provided by Model A ($\Delta T_A$) and Model B ($\Delta T_B$) as functions of the tropical radiative response coefficient ($b_1$) with the extratropical radiative response coefficient ($b_2$) set at 3.5 W m$^{-2}$ K$^{-1}$ and the DHT coefficient ($d$) set at (0, 2, 4) W m$^{-2}$ K$^{-1}$. Forcing: $\Delta Q = 3.7$ W m$^{-2}$. See text for further details.
<table>
<thead>
<tr>
<th>((b_1, b_2, d))</th>
<th>(\Delta T_B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((4.1, 3.5, 2.0))</td>
<td>0.977</td>
</tr>
<tr>
<td>((4.1, 3.5, 4.0))</td>
<td>0.976</td>
</tr>
<tr>
<td>((5.3, 3.5, 2.0))</td>
<td>0.860</td>
</tr>
<tr>
<td>((5.3, 3.5, 4.0))</td>
<td>0.854</td>
</tr>
<tr>
<td>((4.1, 2.0, 2.0))</td>
<td>1.279</td>
</tr>
<tr>
<td>((4.1, 2.0, 4.0))</td>
<td>1.254</td>
</tr>
<tr>
<td>((5.3, 2.0, 2.0))</td>
<td>1.123</td>
</tr>
<tr>
<td>((5.3, 2.0, 4.0))</td>
<td>1.083</td>
</tr>
</tbody>
</table>

\(^{a}\)Units of \((b_1, b_2, d)\): W m\(^{-2}\) K\(^{-1}\). Units of \(\Delta T_B\): °C. Forcing: \(\Delta Q = 3.7\) W m\(^{-2}\). See text for further details.
Findings from the Recent Scientific Literature

- Bates (2016)
- Lewis and Curry (updated w/Stevens, 2015 data)
- Lewis and Curry (2014)
- Skeie et al. (2014)
- Loehle (2014)
- Spencer & Braswell (2013)
- Otto et al. (2013)
- Masters (2013)
- Lewis (2013)
- Hargreaves et al. (2012), Bayesian, dust
- Hargreaves et al. (2012), Regression, dust
- Hargreaves et al. (2012), Bayesian
- Hargreaves et al (2012), Regression
- Ring et al. (2012)
- van Hateren (2012), low solar variability
- van Hateren (2012), variable sun
- Aldrin et al. (2012)
- Lindzen and Choi (2011)
- Schmittner et al. (2011), Land+Ocean
- Annan and Hargreaves (2011), Cauchy
- Annan and Hargreaves (2011), Expert
Is a climate sensitivity estimate of 1°C compatible with the observed evolution of the GMST over the period of the global instrumental record?
Global average temperature anomaly (1850-2015)

- Met Office Hadley Centre and Climatic Research Unit
- NOAA National Centers for Environmental Information
- NASA Goddard Institute for Space Studies

Difference from 1961-1990 average (°C)

Year
Annual Global Temperature (Land, Ocean, and Combined)

Global temperature anomaly (deg C)
Land temperature anomaly (deg C)
Ocean temperature anomaly (deg C)

NCDC / NESDIS / NOAA
1. Valentia Observatory

Mean annual temperature (°C)

1860    1880    1900    1920    1940    1960    1980    2000
RSS GLOBAL TLT TEMPERATURE ANOMALIES

Degree Centigrade

Years:
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
- 2012
- 2014
- 2016
How Much of the Marked Warming of 2015-2016 is due to Greenhouse Gas Increase and How Much is Due to Natural Variability?
(a) The Role of ENSO
(b) The Current warming is much more asymmetric than is expected from the approximately symmetric CO$_2$ increase.
Surface air temperature anomaly for 2016 relative to the average for 1981-2010
Cederlöf et al. (2016): The mid-tropospheric trend is similar over land and ocean. It agrees closely with the ocean surface trend. A land surface trend substantially in excess of the mid-tropospheric trend, as above, is suggestive of a problem with the land surface temperatures. Cederlöf et al. strongly suggest using tropospheric temperature trends from reanalyses in climate sensitivity studies.
Conclusions

1) A two-zone (tropical/extratropical) energy balance model of the climate system that includes inter-zone energy transport has been constructed and its properties examined.

2) Satellite observations indicate that in the tropics the real climate system is radiatively more stable (i.e., emits more energy to space for a given surface temperature increase) than is indicated by the GCMs.

3) Inserting the observed value of the tropical radiative response coefficient and the best estimates of the other parameters into the two-zone model gives a climate sensitivity of ~ 1°C.

4) This value of climate sensitivity is not inconsistent with the observed global temperature record.
References


The End