Climate Sensitivity: Linear Perspectives
Isaac Held, Jerusalem, Jan 2009
How can the response of such a complex system be “linear”?

Infrared radiation escaping to space -
- 50km model under development at GFDL
Response of global mean temperature to increasing CO2 seems simple, as one might expect from the simplest linear energy balance models.
But we are not interested in global mean temperature, but rather things like the response in local precipitation.

Percentage change in precipitation by end of 21st century: PCMDI-AR4 archive

White areas => less than two thirds of the models agree on the sign of the change.
Precipitation and evaporation
“Aqua_planet” climate model
(no seasons, no land surface)

Instantaneous precip (lat,lon)

Time means
Aqua planet (P – E) response to doubling of CO$_2$
Saturation vapor pressure

\[ e_s = e^{\exp \left( -\frac{L}{R_v T} \right)} \]

\[ \frac{1}{e_s} \frac{de_s}{dT} = \frac{L}{R_v T^2} \]

\[ \frac{\delta e_s}{e_s} \approx \frac{L}{R_v T^2} \delta T \approx 0.07 \delta T \]

\[ \Rightarrow \text{7% increase per 1K warming} \]
\[ \text{20% increase for 3K} \]
GCMs match observed trend and interannual variations of tropical mean (ocean only) column water vapor when given the observed ocean temperatures as boundary condition.

Courtesy of Brian Soden
Local vertically integrated atmospheric moisture budget:

\[ P - E = -\nabla \cdot F = -\nabla \cdot (\rho v q) \]

precipitation \rightarrow \text{vertically integrated moisture flux} \rightarrow \text{vapor mixing ratio}

\[
\frac{\delta F}{F} \approx \frac{\delta q}{q} \approx 0.07 \delta T
\]
But response of global mean temperature is correlated (across GCMs) with the response of the poleward moisture flux responsible for the pattern of subtropical decrease and subpolar increase in precipitation.

**PCMDI/CMIP3**

% increase in poleward moisture flux in midlatitudes

![Graph showing the relationship between global mean temperature and poleward moisture flux.](image)
One can see effects of poleward shift of midlatitude circulation
And increase(!) in strength of Hadley cell
PCMDI - AR4 Archive

Arctic land, ANN

Temperature Change

% Precipitation change

Temperature change

TS(mn,mx) = 3.0165, 7.2289
PR(mn,mx) = 14.597, 37.977
One often sees the statement that
“Global mean is useful because averaging reduces noise”

But one can reduce noise a lot more
by projecting temperature change onto a pattern that looks like
this (pattern predicted in response to increase in CO2)
or this (observed linear trend)

Or one can find the pattern that maximizes
the ratio of decadal scale to interannual variability – Schneider and Held 2001
“The global mean surface temperature has an especially simple relationship with the global mean TOA energy balance.”

Seasonal OLR vs Surface T at different latitudes

Seasonal OLR vs 500mb T at different latitudes

\[ F(\theta) = \int \beta(\theta, \xi) \delta T(\xi) d\xi \]

\[ < F > = \int F(\theta) d\theta = \int B(\xi) T(\xi) d\xi; \quad B(\xi) = \int \beta(\theta, \xi) d\theta \]

if \( \delta T(\theta) = f(\theta) < T > \) then \( < F > = \tilde{B} < T > \)

\[ \tilde{B} = \int B(\xi) f(\xi) d\xi \]

Relation between global means depends on spatial structure
**Efficacy** (Hansen et al, 2005):

Different sources of radiative forcing that provide the same net global flux at the top-of-atmosphere can give different global mean surface temperature responses

Forcing for doubling CO$_2$ roughly 3.7 W/m$^2$

If global mean response to doubling CO$_2$ is $T_{2X}$

$$E = \text{efficacy} = (\langle T \rangle / T_{2X})(3.7/F)$$

One explanation for efficacy:
Responses to different forcings have different spatial structures
Tropically dominated responses $\Rightarrow$ $E < 1$

Polar dominated responses $\Rightarrow$ $E > 1$
Why focus on top of atmosphere energy budget rather than surface?

Because surface is strongly coupled to atmosphere by non-radiative fluxes (particularly evaporation)

Classic example: adding absorbing aerosol does not change $T$, but reduces evaporation
If net solar flux does not change, outgoing IR does not change either (in equilibrium), -- with increased CO2, atmosphere is more opaque to infrared photons => average level of emission to space moves upwards, maintaining same T => warming of surface, given the lapse rate

Final response depends on how other absorbers/reflectors (esp. clouds, water vapor, surface snow and ice) change in response to warming due to CO2, and on how the mean lapse rate changes
Equilibrium climate sensitivity:
Double the CO$_2$ and wait for the system to equilibrate

But what is the “system”?
glaciers? “natural” vegetation?
Why not specify emissions rather than concentrations?

Transient climate sensitivity:
Increase CO$_2$ 1%/yr and examine climate at the time of doubling

Typical setup – increase till doubling – then hold constant

After CO2 stabilized, warming of near surface can be thought of as due to reduction in heat uptake
“Observational constraints” on climate sensitivity (equilibrium or transient)

Model \((a,b,c,\ldots)\)

- Simulates some observed phenomenon:
  - comparison with simulation constrains \(a,b,c,\ldots\)
- Predicts climate sensitivity;
  - depends on \(a,b,c,\ldots\)

Model can be GCM – in which case constraint can be rather indirect
(constraining processes of special relevance to climate sensitivity)
Or it can be simple model in which climate sensitivity
is determined by 1 or 2 parameters.
A great example of an observational constraint: looking across GCMs, strength of snow albedo feedback very well correlated with magnitude of mean seasonal cycle of surface albedos over land
=> observations of seasonal cycle constrain strength of feedback

Can we do this for cloud feedbacks?
The simplest linear model

\[ C \frac{dT}{dt} = F - \beta T \equiv N \]

\[ T_{EQ} = \frac{F}{\beta} \]

The left-hand side of this equation (the ocean model) is easy to criticize, but what about the right hand side?
The simplest linear model

\[ C \frac{dT}{dt} = F - \beta T \equiv N \]

\[ T_{EQ} = \frac{F}{\beta} \]

\[ \frac{N}{F} = 1 - \frac{T}{T_{EQ}} \]

If correct, evolution should be along the diagonal

\[ N/F \]

\[ T/T_{EQ} \]
\[
C \frac{dT}{dt} = F - \beta T \equiv N
\]
\[
T_{EQ} = \frac{F}{\beta}
\]
\[
\frac{N}{F} = 1 - \frac{T}{T_{EQ}}
\]

Evolution in a particular GCM (GFDL’s CM2.1) for 1/\% till doubling + stabilization
\[ C \frac{dT}{dt} = F - \beta T \equiv N \]
\[ T_{\text{EQ}} = \frac{F}{\beta} \]
\[ N / F = 1 - T / T_{\text{EQ}} \]

\[ \beta T = F - N \]

replaced by
\[ \beta T = F - E_N N \]

Transient sensitivity affected by efficacy as well as magnitude of heat uptake

The efficacy of heat uptake >1 since it primarily affects subpolar latitudes
Are some of our difficulties in relating different observational constraints on sensitivity due to inadequate simple models/concepts?

Lots of papers, and IPCC, use concept of “Effective climate sensitivity” to estimate equilibrium sensitivity -- can’t integrate models long enough to get to accurate new equilibrium,

Linearly extrapolating from zero, through time of doubling, to estimate equilibrium sensitivity

Result is time-dependent
Not well correlated across models – equilibrium response brings into play feedbacks/dynamics in subpolar oceans that are suppressed in transient response
Response of global mean temperature in CM2.1 to instantaneous doubling of CO2

Equilibrium sensitivity \( >3K \)

Transient response \( \sim 1.6K \)

\[ T = (1.6K) e^{-t/(4 \text{ yrs})} \]

Fast response

Slow response evident only after \( \sim 100 \text{ yrs} \) and seems irrelevant for transient sensitivity
In equilibrium:

\[ F = \alpha \delta T = \gamma \delta T - \beta \delta T \]
\[ F + \beta \delta T = \gamma \delta T \]

\[ \delta T = \frac{F}{\alpha} = \frac{F}{\gamma - \beta} = \frac{F}{\gamma \left( \frac{1}{1 - f} \right)} \]
The global mean feedback analysis for CM2.1 (in A1B scenario over 21st century) shows that base in isolation would give a sensitivity of ~1.2K. Feedbacks convert this to ~3K.
Assorted estimates of equilibrium sensitivity
Gaussian distribution of $f \Rightarrow$ skewed distribution of $1/(1-f)$
Cloud feedback as residual

Lapse rate cancels water vapor in part and reduces spread

Cloud feedback by adjusting cloud forcing for masking effects
Cloud feedback is different from change in cloud forcing

\[
\overline{R} = (1 - f)(\alpha + \beta w_1)
\]

\[
\delta \overline{R} = \delta_c \overline{R} + \delta_w \overline{R}
\]

Cloud feedback \( \delta_c \overline{R} = - (\alpha + \beta w_1) \delta f \)

Water vapor feedback \( \delta_w \overline{R} = (1 - f) \beta \delta w_1 \)

Cloud forcing

\[
C_{RF} = -f (\alpha + \beta w_2)
\]

\[
\delta C_{RF} = -(\alpha + \beta w_2) \delta f - f \beta \delta w_2
\]
Another problem

$A = \text{control} \quad B = \text{perturbation} \quad \delta \sim B - A$

1) Simple substitution

but taking clouds from $A$ and water vapor from $B$ decorrelates them

$$R(w_B, c_A) = (1 - f_A)\left[\alpha + \beta(f_B w_{2B} + (1 - f_B)w_{1B})\right]$$

$$\delta_w R = R(w_B, c_A) - R(w_A, c_A) = \beta(1 - f)\delta w_1 + \beta(1 - f)f(w_2 - w_1)$$

Soden et al, J.Clim, 2008 describe alternative ways of
Alleviating this problem

Right answer

Not a perturbation quantity
Annual, zonal mean water vapor kernel, normalized to correspond to % change in RH

Mostly comes from upper tropical troposphere, so negatively correlated with lapse rate feedback

Difference between total and clear sky kernels used to adjust for masking effects and compute cloud feedback from change in cloud forcing
LW feedbacks positive (FAT hypothesis? => Dennis’s lecture)
SW feedbacks positive/negative, and correlated with total

Net cloud feedback from 1%/yr CMIP3/AR4 simulations

Courtesy of B. Soden simulations
$Wm^{-2}K^{-1}$

- Base: 3.0
- Lapse Rate: 1.0
- Snow/Ice: -1.0
- Water Vapor: -2.0
- Net "Feedback": 3.0

Net total:

$Wm^{-2}K^{-1}$
Choice of “base” = “no feedback” is arbitrary!
What if we choose constant relative humidity rather than constant specific humidity as the base.
Fixed rh uniform T base

$Wm^{-2}K^{-1}$

fixed rh lapse rate

rh

Snow/ice clouds Net “feedback”

total
Clouds look like they have increased in importance (since water vapor change due to temperature change resulting from cloud change is now charged to the "cloud" account).
Observational constraints

- 20\textsuperscript{th} century warming
- 1000yr record
- Ice ages – LGM
- Deep time
- Volcanoes
- Solar cycle
- Internal Fluctuations
- Seasonal cycle etc
Pliocene – could our models be this wrong on the latitudinal structure?

21st century Warming IPCC

Pliocene reconstruction

Fig. 2. Surface air temperature anomalies of (top) the late 21st century and (bottom) the mid-Pliocene.
“We conclude that a climate sensitivity greater than 1.5 °C has probably been a robust feature of the Earth’s climate system over the past 420 million years …”
Royer, Berner, Park; Nature 2007

CO₂ thought to be major driver of deep-time temperature variations
Ice Age Temperature Changes

Carbon Dioxide Variations

The Industrial Revolution Has Caused A Dramatic Rise in CO₂
Global mean cooling due to Pinatubo volcanic eruption

Relaxation time after abrupt cooling contains information on climate sensitivity.
Pinatubo simulation

Low sensitivity model

High sensitivity model

Yokohata, et al, 2005
Observed total solar irradiance variations in 11yr solar cycle (~ 0.2% peak-to-peak)

1 Willson & Mordvinov, GRL, 2003   RC Willson, earth_obs_fig26 11/23/2008
Tung et al =>
0.2K peak to peak
(other studies yield only 0.1K)

Seems to imply large transient sensitivity

Only gives 0.05 peak to peak

1.8K (transient) sensitivity

4 yr damping time
Models can produce very good fits by including aerosol effects, but models with stronger aerosol forcing and higher climate sensitivity are also viable (and vice-versa).
“It is likely that increases in greenhouse gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place.” (AR4 WG1 SPM).
Observed warming

approx. response to LLGGs over 20th century, CMIP–3 models

estimated by dividing transient climate sensitivity (AR4 Ch.8) by 1.5

number of models

degrees C

Observed warming

CM2.1

median

47
Kiehl, 2008: In AR4, forcing over 20th century and equilibrium climate sensitivity negatively correlated

How would this look for transient climate sensitivity?
Do interhemispheric differences in warming provide a simple test of aerosol forcing changes over time?

http://data.giss.nasa.gov/gistemp/
temperature anomalies (10yr running means) averaged around latitude circles over 20th century:

-- Observations (big)
-- 5 realizations of a model simulation (small)

Internal variability can create Interhemispheric gradients

Forcing computed from differencing TOA fluxes in two runs of a model (B-A)
B = fixed SSTs with varying forcing agents; A fixed SSTs and fixed forcing agents
Temperature change averaged over 5 realizations of coupled model
Fit with

\[ C \frac{dT}{dt} = F - \alpha T; \quad \alpha = 1.6 \text{ Wm}^{-2}/K; \quad \frac{C}{\alpha} = 4 \text{ years} \]
Forcing (with no damping) fits the trend well, if you use transient climate sensitivity, which takes into account magnitude/efficacy of heat uptake.
Spenser-Braswell, 2008

\[ c \frac{\partial T}{\partial t} = S + N - \alpha T \]

(Assuming no forcing)

Suppose \( N \) is TOA noise, but correlated with \( T \) because it forces \( T \)

Regressing flux with \( T \)

\[ - \frac{\langle (N - \alpha T)T \rangle}{\langle T^2 \rangle} = \alpha' \]

If \( S \) and \( N \) are uncorrelated and have the same spectrum one can show that

\[ \alpha' = \alpha \frac{\langle N^2 \rangle}{\langle N^2 \rangle + \langle S^2 \rangle} < \alpha \]
Following an idea of K. Swanson, take a set of realizations of the 20th century from one model, and correlate global mean TOA with surface temperature across the ensemble.
Shortwave regression across ensemble, following K. Swanson 2008

Is this a sign of non-linearity? What is this?
Shortwave regression across ensemble, following K. Swanson 2008

Estimate of noise in this statistic from 2000yr control run

$Wm^{-2}K^{-1}$

All-forcing 20th century

A1B scenario

90%
Shortwave regression across ensemble, following K. Swanson 2008

Well-mixed greenhouse gases only

$Wm^{-2}K^{-1}$
Shortwave regression across ensemble, following K. Swanson 2008

Independent set of 10 A1B runs

Wm$^{-2}$K$^{-1}$
Longwave regression across ensemble, following K. Swanson 2008

$Wm^{-2}K^{-1}$

All-forcing
20th century
Longwave regression across ensemble, following K. Swanson 2008

$Wm^{-2}K^{-1}$

All-forcing
20th century

A1B scenario
Longwave regression across ensemble, following K. Swanson 2008

$Wm^{-2}K^{-1}$
Longwave regression across ensemble, following K. Swanson 2008

\[ Wm^{-2}K^{-1} \]

Well-mixed greenhouse gases only
Longwave regression across ensemble, following K. Swanson 2008

But we can fit the models 20th century simulations without time-dependence in OLR-temperature relationship!

May be telling us that ENSO is changing, but with no obvious connection to global sensitivity
A framework for inferring sensitivity from internal variability:
(why wait for a volcano when the climate is always relaxing back from being perturbed naturally)

**Fluctuation-dissipation**
*(Fluctuation-response)*

\[
\frac{dx}{dt} = Lx + N + F \quad N = \text{white noise} \\
<x> = L^{-1}F \\
C(t) = <x_i(t)x_j(0)>; \quad L^{-1} = \int_0^\infty C(t)C^{-1}(0)dt
\]

*Exact for this multi-variate linear system, but also works for some nonlinear systems – ie statistical mechanics*
GCM response to localized equatorial heating

response obtained from fluctuation-dissipation relation

upper tropospheric streamfunction

Gritsun and Branstator, 2007
Final Thoughts:

1) The uncertainty in forcing over the 20th century is what primarily limits our ability to use 20th century warming to determine transient sensitivity empirically => constraining aerosol forcing the key

2) The difficulty in simulating clouds prevents us from developing a satisfying reductive theory/model of climate sensitivity (Can we constrain cloud feedbacks analogously to how Hall and Qu constrain albedo feedbacks?)

3) Is some of the spread in estimates of sensitivity based on different methods due to inappropriate simple models/concepts (e.g., ignoring the efficacy of heat uptake)?

4) Can one use observations of internal variability (temporal correlations or relationships between TOA fluxes and other fields) to constrain sensitivity
Supplementary figures
Atmospheric CO$_2$ at Mauna Loa Observatory

1974-2008 NOAA/ESRL

(C. Keeling)
Carbon dioxide

Nitrous oxide

CFCs: (1975) V. Ramanathan

Ice cores + direct measurements provide a beautiful record of the history of atmospheric carbon dioxide.
Carbon dioxide

methane

Nitrous oxide

CFCs

other

http://www.esrl.noaa.gov/gmd/aggi/
Was the 20th century warming

1) primarily forced by increasing greenhouse gases?

or,

2) primarily forced by something else?

or,

3) primarily an internal fluctuation of the climate?

Claim: Our climate theories STRONGLY support 1)

A central problem for the IPCC has been to evaluate this claim and communicate our level of confidence appropriately
Energy is going into ocean

More energy is entering the atmosphere from space than is going out

Almost all parts of the Earth’s surface have warmed over the past 100 years

IPCC 4th Assessment Report.

www.globalwarmingart.com
IPCC AR4 WG1 Summary for Policymakers
Clouds (especially in the tropics) are influenced by small scales in the atmospheric circulation.
Change in Low Cloud Amount (%/K) GFDL and NCAR/CAM models

GFDL AM2-WL (2xCO₂ - CTRL)

NCAR CAM2 (Year70 @1%CO₂/yr - CTRL)

Courtesy of Brian Soden
Total Column Water Vapor Anomalies (1987-2004)

We have high confidence in the model projections of increased water vapor.

Held and Soden J.Clim. 2006