The Earth’s energy budget and climate sensitivity

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recent thoughts
Energy conservation for the Earth

\[ \text{Energy in} = \text{Energy out} + \text{Energy stored} \]

Use observations and calculations without a climate model

*Energy conservation has no natural cycles.*

1) Major energy terms 
   \((\text{satellite data important})\)

2) Time history of energy storage 1950-2005

3) Using energy balance as a tutorial on radiative forcing

4) Stick my neck out on satellite needs
Major components of the energy budget

Look at *perturbations from a non-volcanic, preindustrial Earth* (like radiative forcing)

- Radiative forcing by gases and aerosols
- Radiative response to changing temperature
  *A warmer Earth loses more heat to space.*
- Energy gained or lost by the Earth (oceans $>>$ land)
Energy balance equation

Energy stored = radiative imbalance = forcing – response

\[ \Delta E = \Delta N \approx F - \lambda \Delta T \]

Closely related to climate sensitivity

at equilibrium \( \Delta T \approx F/\lambda \)
Qualitative response

Step change in greenhouse gas

Global temperature
Equilibrium temperature change

Energy heating the Earth
Equilibrium outgoing radiation

Forcing
Outgoing radiation

Time
Positive forcings

Measurements of gases
Radiative transfer model
± 5% (except O₃)

return to this later

55e21 J boils the Great Lakes
All the coal ever burned about 15e21 J from combustion
Energy retained by the Earth

Compilations of ocean temperature profiles
- Domingues et al. (2008)
- Ishii et al. (2009)
- Levitus et al. (2009)

longer record, better accuracy than satellite data for $\Delta N$
Radiation to space from a warming Earth

Outgoing radiation measured by
ERBE on ERBS: 1985-1999
CERES on TERRA: 2000-2005
… incomplete data

\[ \Delta E = \Delta N \approx F - \lambda \Delta T \]

We have continuous \( T_{\text{surface}} \).

response \( \approx -\lambda \Delta T_{\text{surface}} \)

Assumption: \( \lambda \) derived from ERBE & CERES applies to other years.
Outgoing infrared from Earth

\[ \Delta N - F \approx -\lambda \Delta T \]

**Assumption:** unknown forcings are constant.

ERBE and CERES:
- identical slopes
- calibration, sampling offsets

\[ \lambda \approx 2.25 \text{ W m}^{-2} \text{ K}^{-1} \]
\[ \text{blackbody} \approx 3.2 \text{ W m}^{-2} \text{ K}^{-1} \]

water vapor feedback
Averaging satellite data

Monthly / 72-day

+ Wide range of $T_{\text{surface}}$
  => more accurate slopes
– Additional assumption:
  Earth’s response to seasonal temperature changes is similar to decadal response.

or

Annual

+ No seasonal assumptions

- Small range of $T_{\text{surface}}$
  => less accurate slopes
- Greater demands on satellite stability.

![Graph showing correlation between Global Radiation - Forcing and NCEP Global 1000 mbar temperature.](image-url)
Detail: annual cycle in Earth’s orbit

Using just outgoing shortwave doesn’t work:

Base case

Earth further from sun

*less reflected sunlight*

**negative** forcing

Darker Earth

*less reflected sunlight*

**positive** forcing
Reflected sunlight from Earth

Albedo * (average solar) climate feedback is via albedo

ERBE and CERES: identical slopes calibration, sampling offsets

Negative slope => positive feedback

Structured residual:
Comparison of $\lambda$
Reference temperature

\[ \text{response} \approx -\lambda \Delta T_{\text{surface}} \]

What is reference for \( \Delta T \)?

The equilibrium temperature of Earth with:
- no anthropogenic forcings
- no major volcanoes

Too cold:
  late 19\textsuperscript{th} century

Too warm:
  1950s

\[ \text{0.2 K apart} \]

A \textit{much} more accurate absolute reference than ERBE or CERES by themselves!
\[ \pm 0.1 \text{ K} \times \lambda \approx \pm 0.13 \text{ W m}^{-2} \text{ vs. perhaps } 3 \text{ W m}^{-2} \]
What has balanced greenhouse heating since ~1970:

-1.1±0.4 W m\(^{-2}\)

Aerosol direct + indirect:
IPCC AR4 GCMs:
-1.2 W m\(^{-2}\)

Rules out very large negative indirect effects.
Quantitative agreement for volcanic perturbations

Independent data sources, no scaling.
• Residual forcing flat 1970-1990, larger than 1950s.
• Matches emissions history.
• The residual forcing is indeed due to aerosols.
Time history: a puzzle

- Residual increases in late 1990s.
- Either a big increase in aerosol forcing or an underestimate of ocean heat uptake.
- No increase in global aerosol optical depth.
- Steady sea level rise.
- Others have noted discrepancy of ocean heat data and sea level after about 1995.
Outstanding issue

What happened to ocean heat in the late 1990s?
Climate sensitivity

$\lambda_{\text{longwave}}$ for recent past known to $\sim3\%$ or $\sim30\%$ (!)

$\lambda_{\text{shortwave}}$ for recent past, *including seasons*, known to $<25\%$

Can we use this to improve global climate models?
Revisit energy balance equation

radiative imbalance = forcing – response

\[ \Delta N \approx F - \lambda \Delta T \]

at equilibrium \( \Delta T \approx F/\lambda \)

What is missing from this equation?
Revisit energy balance equation

\[ \Delta N \approx F - \lambda \Delta T \]

1) \( \Delta T \) at surface
   why not \( \lambda_{\text{surface}} \Delta T_{\text{surface}} + \lambda_{500} \Delta T_{500} + \ldots \) ?

- surface temperature is important and measurable
- we take care of other altitudes by either:
  - adjusting \( \lambda \) (lapse rate feedback)
  - adjusting \( F \) (stratospheric adjustment)
Revisit energy balance equation

\[ \Delta N \approx F - \lambda \Delta T \]

1) \( \Delta T \) at surface
2) Global average \( \Delta T \)

why not \( \lambda_{\text{avg}} \Delta T_{\text{avg}} + \lambda_{\text{eq-pole}} \Delta T_{\text{eq-pole}} + \cdots \) ?

- we take care of other patterns by either:
  - adjusting \( \lambda \) (if proportional to \( \Delta T_{\text{avg}} \))
  - adjusting \( F \) (if not proportional)
Revisit energy balance equation

\[ \Delta N \approx F - \lambda \Delta T \]

1) \( \Delta T \) at surface
2) Global average \( \Delta T \)
3) Global average \( F \)

- \( F \) has spatial patterns!

=> efficacy
Revisit energy balance equation

\[ \Delta N \approx F - \lambda \Delta T \]

1) \( \Delta T \) at surface
2) Global average \( \Delta T \)
3) Global average \( F \)
4) no term proportional to \( dT/dt \)
   why not?

- explicit term would be small
- possibly large terms via spatial patterns
  e.g. uneven heating of oceans changes synoptic circulations & cloudiness
  \((\text{Williams et al., 2008})\)
- as always, we adjust \( \lambda \) or \( F \)
=> \( \lambda \) and \( F \) are functions of time and \( dF/dt \)
Revisit energy balance equation

\[ \Delta N \approx F - \lambda \Delta T \]

1) \( \Delta T \) at surface
2) Global average \( \Delta T \)
3) Global average \( F \)
4) no term proportional to \( dT/dt \)
5) higher order terms
   why not \( \lambda \Delta T + \lambda_2 \Delta T^2 + \ldots \) ?

We think non-linearity is more likely to come from physical changes than from radiative processes
(methane release, \ldots)
Revisit energy balance equation

\[ \Delta N \approx F + \gamma - \lambda \Delta T \]

1) \( \Delta T \) at surface
2) Global average \( \Delta T \)
3) Global average \( F \)
4) no term proportional to \( dT/dt \)
5) higher order terms
   why not \( \lambda \Delta T + \lambda_2 \Delta T^2 + \ldots \) ?
6) Everything not proportional to \( \Delta T_{\text{surface}} \) put into \( F_{\text{adjusted}} \)

Means that forcings are affected by circulation
Outstanding issues continued

Why would long-term $\lambda$ be different?

- truly slow feedbacks (e.g. glaciers)
- uneven heating of the Earth
  -> cloud patterns!
- all the other things we stuff into $\lambda$

How do we deal with slow processes that don’t fit linear model?

Williams et al., 2008
Outstanding issues continued

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Williams et al., 2008
Energy budget and forcing summary

- Recent energy budget tells us more about the indirect effect than about climate sensitivity.
- Surface temperature gradients mean that empirical (short-term) sensitivity is not the same as equilibrium sensitivity.
- Tight constraints on short-term behavior of longwave may improve models.
- Radiative forcing is not just radiative transfer
Implications for satellite needs

(I recognize there are other uses than the global energy budget.)

\[ \lambda \Delta T = \Delta N - F \]

Significant decadal uncertainties due to
- changing spatial patterns of aerosol effects
- circulation changes: El Nino and others
- can detailed radiation signatures constrain \( F \)?

ROSENLOF AND REID: TROPICAL LOWER STRATOSPHERIC TRENDS

HALOE equatorial water vapor anomaly at 82 hPa

0.1 W m\(^{-2}\)
Implications for satellite needs
(I recognize there are other uses than $\lambda$ slopes and energy budget.)

$$\lambda \Delta T = \Delta N - F$$

Satellites probably can’t compete with ocean heat content over several decades

How best to merge satellite and ocean heat data?
Implications for satellite needs

\[ \lambda \Delta T = \Delta N - F \]

ERBE and CERES provided significant information.

Need global models to understand what data over 5 to 10 years imply about long-term climate.
Implications for satellite needs

\[ \lambda \Delta T = \Delta N - F \]

Need continuous data over a period long enough for \( \Delta T \)

CERES absolute accuracy was sufficient.

Advantages to both sun-synchronous orbits and sampling diurnal cycle (e.g. \( \Delta T \) may be different day and night)

More than one in orbit more important than last bit of performance?
Climate sensitivity

Weak lower limit from positive shortwave feedback

- Longwave
- Shortwave
- Total

ERBE seasonal & annual 1985-99
F&G seasonal 1985-89
CERES 60° monthly & annual 2000-05
Tsushima et al. monthly avgs.
ERBE interannual 1985-98
ERBE annual by averaging each season
CERES 60° interannual 2000-05
F&T IPCC models 100 yr runs
CERES global monthly & annual 2000-05
CERES 60° monthly & annual 2000-05
ERBE seasonal & annual 1985-99
Upper climate sensitivity

- Annual error limits overlap zero => no upper bound on sensitivity

- If $\lambda$ were zero, outgoing would be zero.

It could be absorbed into other terms.
Lower climate sensitivity

- \( \lambda \) for recent past from satellite data < about 3 W m\(^{-2}\) K\(^{-1}\) (my fits, > 2\(\sigma\))

- If \( \lambda \) were > about 3 W m\(^{-2}\) K\(^{-1}\)
aerosol indirect effects would have to be positive
In 1993, ERBE was turned off for about a month.

≤ 0.2% change in absolute calibration

Using annual averages, changes slope vs. $T$ by ± 100%

### Averaging satellite data

**Annual**

+ No seasonal assumptions

- Small range of $T_{surface}$
  $\Rightarrow$ less accurate slopes

- Greater demands on satellite stability.