The Earth’s energy budget and climate sensitivity

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recent thoughts

Energy conservation for the Earth

Energy in = Energy out + Energy stored

Use observations and calculations without a climate model

Energy conservation has no natural cycles.

1) Major energy terms
   (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

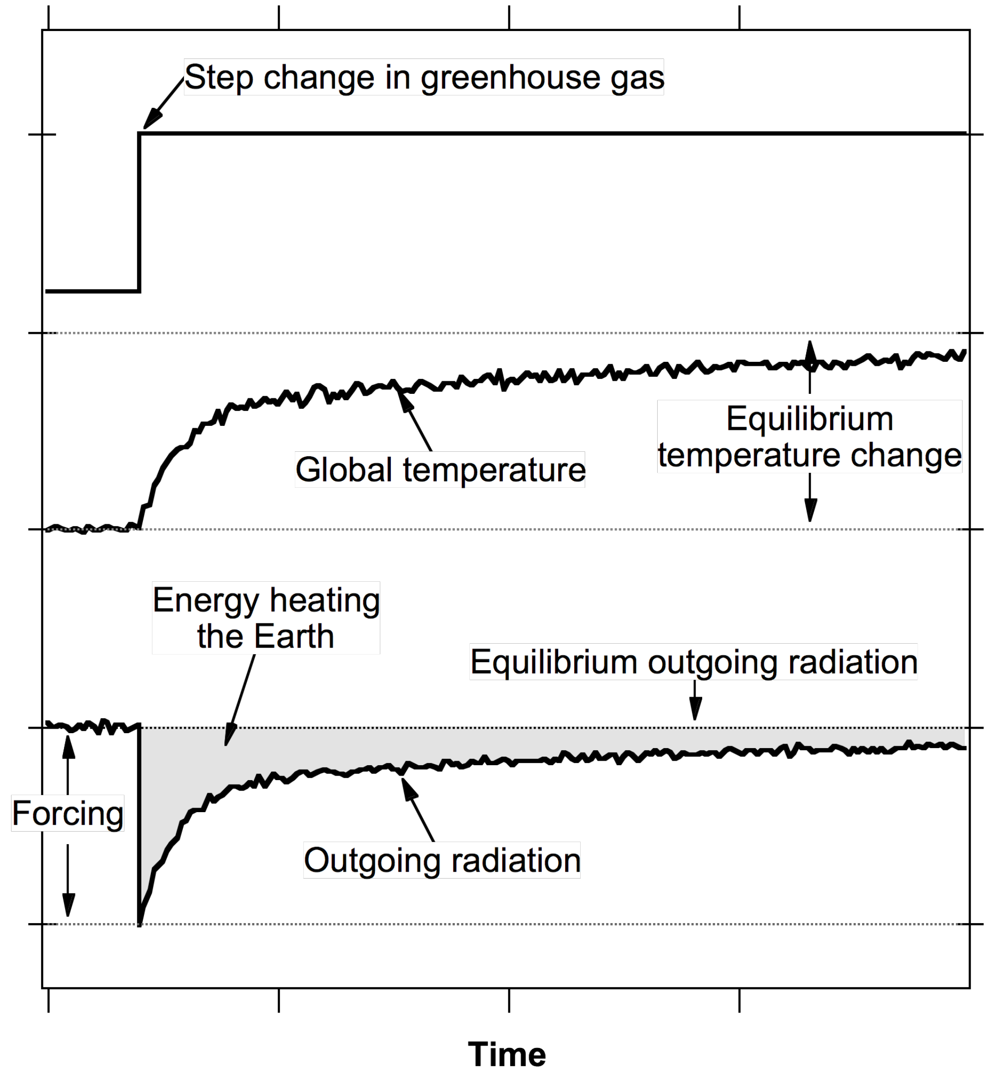
Energy stored = radiative imbalance = forcing – response

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

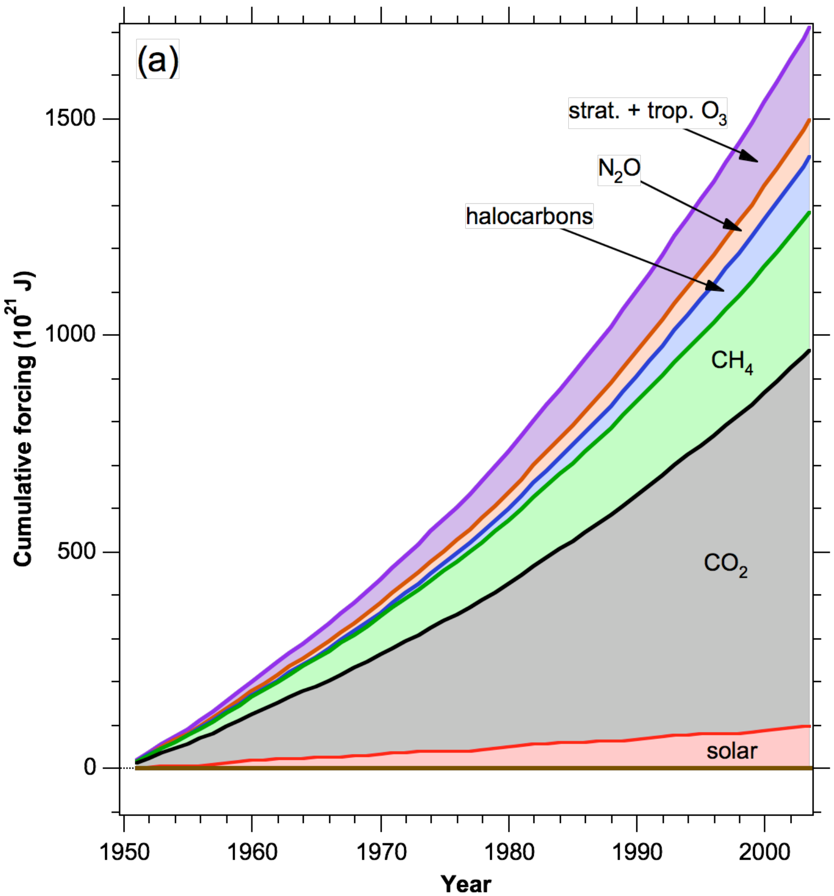
Closely related to climate sensitivity

at equilibrium $\Delta T \approx F/\lambda$

Qualitative response



Positive forcings



Measurements of gases

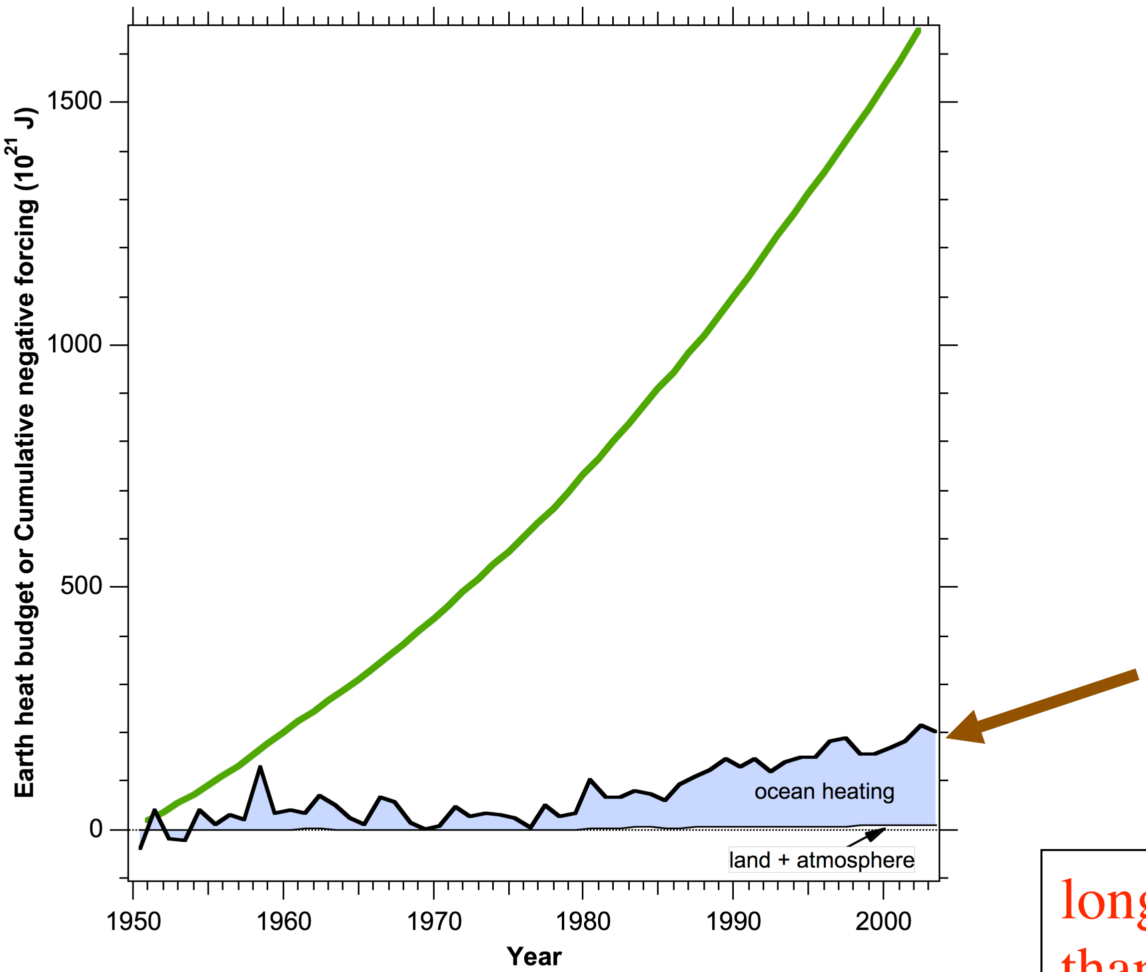
Radiative transfer model

± 5% (except O_3)

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

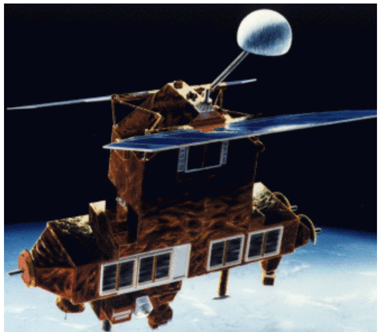
Domingues et al. (2008)

Ishii et al. (2009)

Levitus et al. (2009)

longer record, better accuracy than satellite data for ΔN

Radiation to space from a warming Earth



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

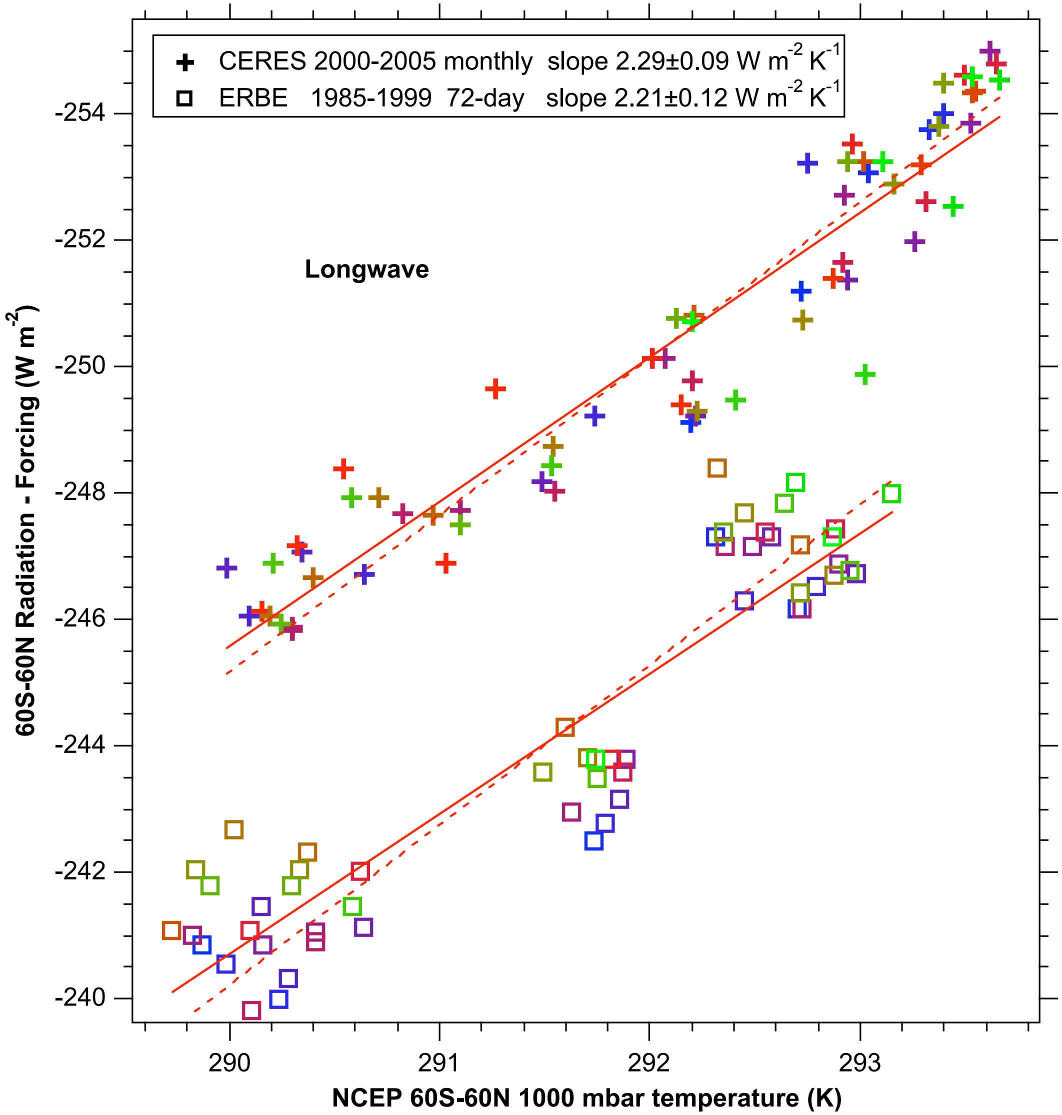
$$\Delta E = \Delta N \approx F - \lambda \Delta T$$

We have continuous $T_{surface}$.

$response \approx -\lambda \Delta T_{surface}$

Assumption: λ 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

$\lambda \approx 2.25$ W m^{-2} K^{-1}

blackbody ≈ 3.2 W m^{-2} K^{-1}

water vapor feedback

Averaging satellite data

Monthly / 72-day

+ Wide range of $T_{surface}$
  => more accurate slopes

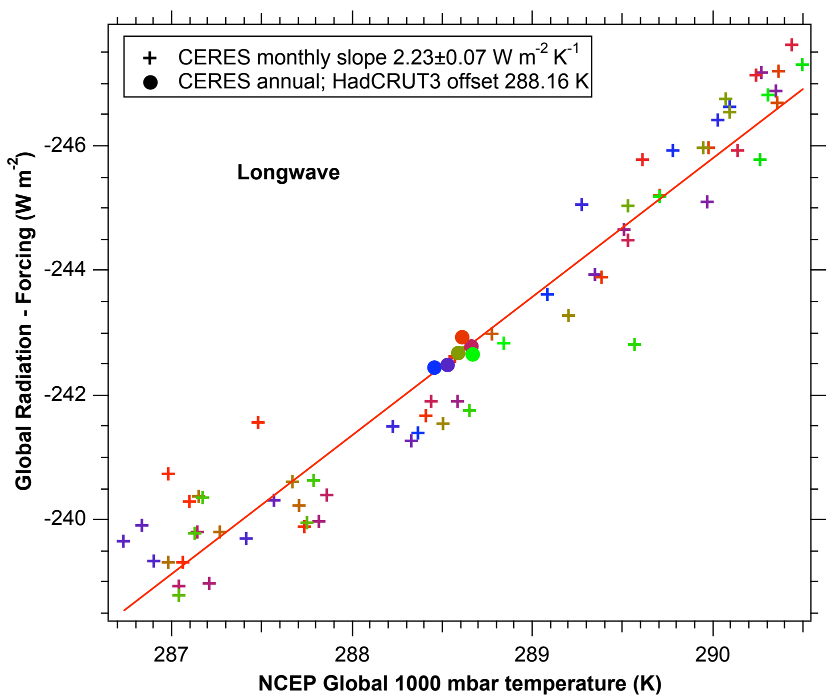
– Additional assumption:
Earth's response to seasonal temperature changes is similar to decadal response.

or

Annual

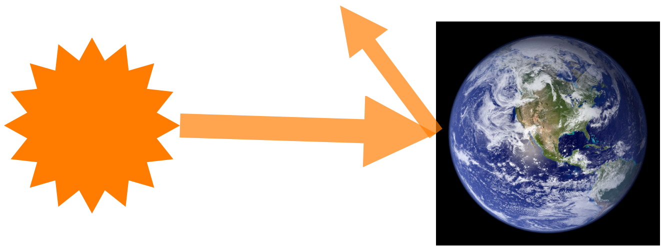
+ No seasonal assumptions

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



Detail: annual cycle in Earth's orbit

Using just outgoing shortwave doesn't work:

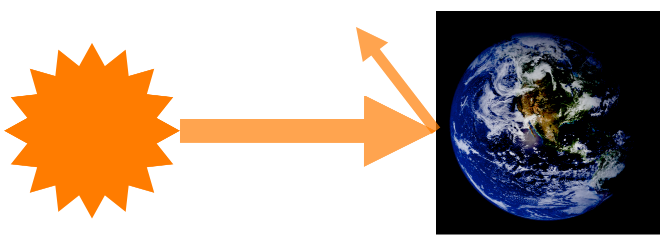


base case

Earth further from sun

less reflected sunlight

negative forcing

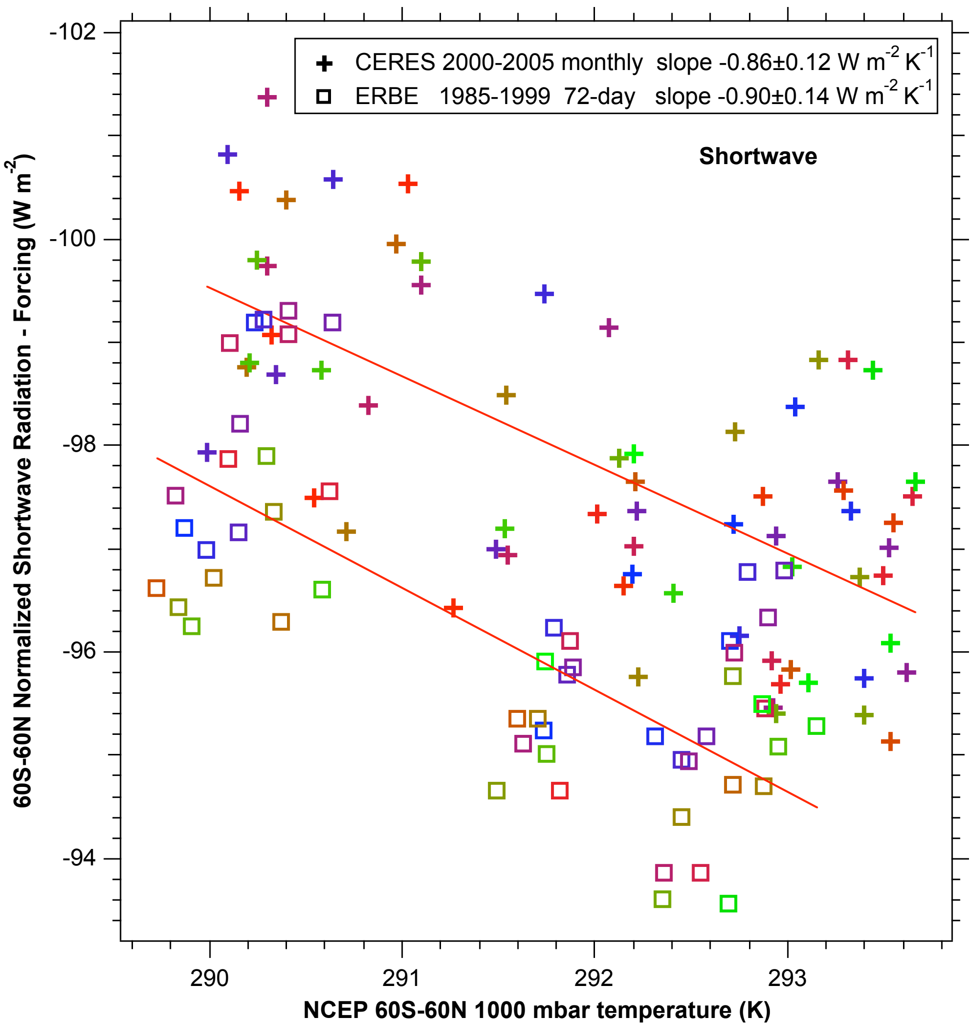


darker Earth

less reflected sunlight

positive forcing

Reflected sunlight from Earth



Albedo * (average solar)

climate feedback is via albedo

ERBE and CERES:

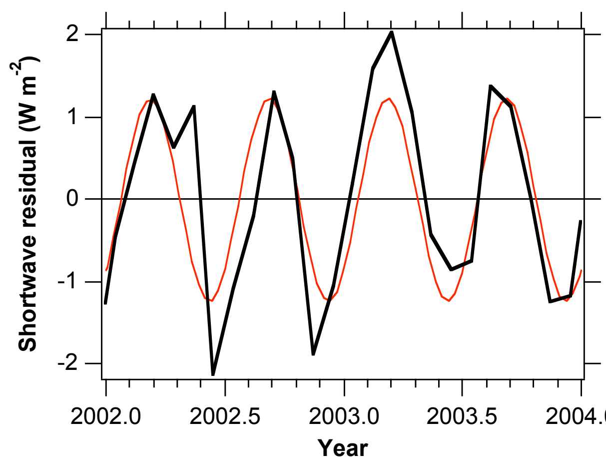
identical slopes

calibration, sampling offsets

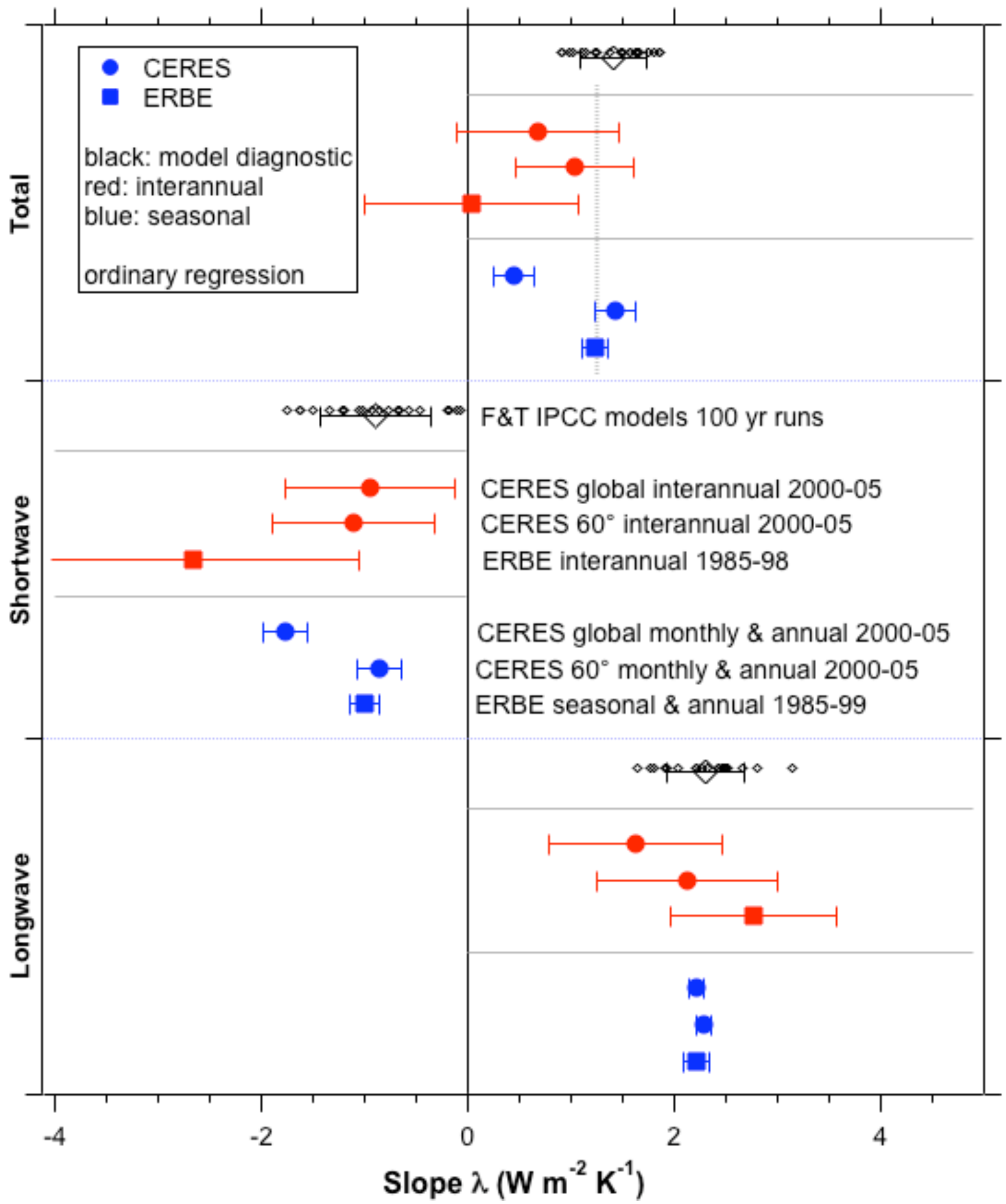
Negative slope

=> positive feedback

Structured residual:



Comparison of λ



Reference temperature

$$response \approx -\lambda \Delta T_{surface}$$

What is reference for ΔT?

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

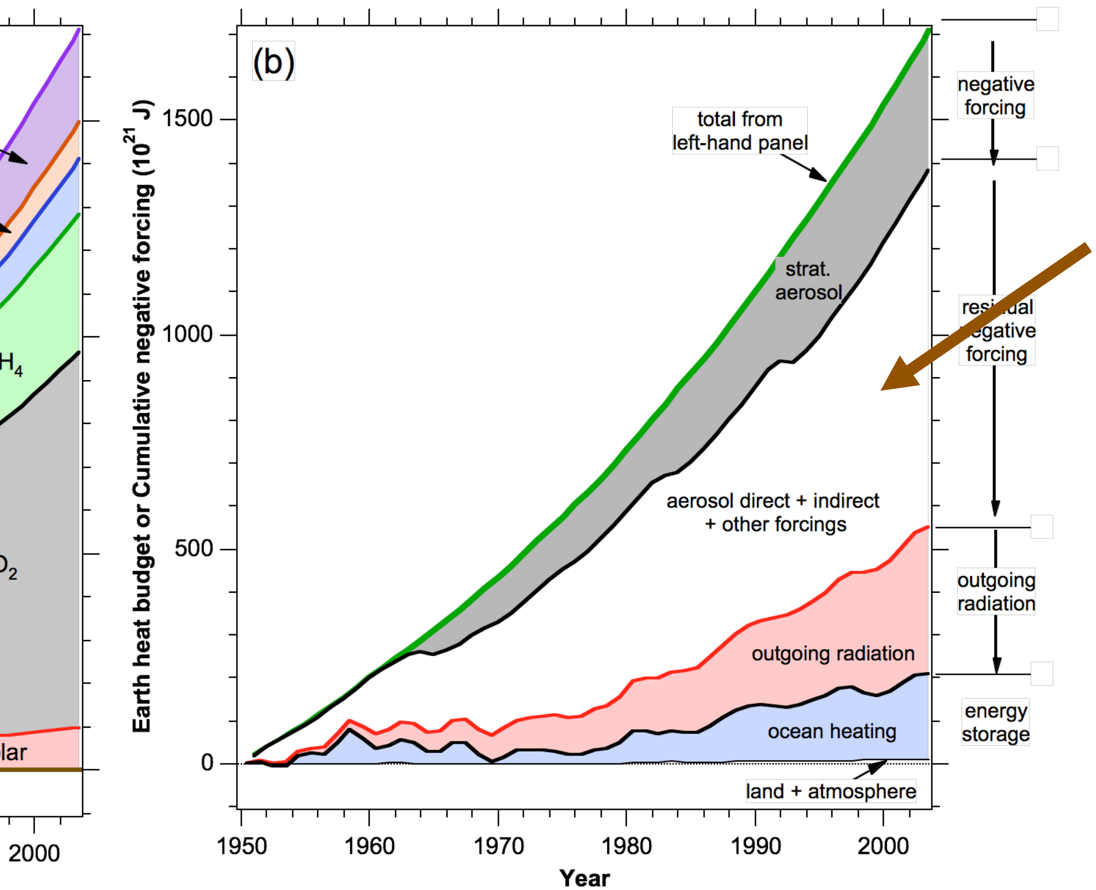
Too cold:
late 19th century

Too warm:
1950s

} 0.2 K apart

A *much* more accurate absolute reference than ERBE or CERES by themselves!
± 0.1 K * $\lambda \approx \pm 0.13$ W m^{-2} vs. perhaps 3 W m^{-2}

What has balanced greenhouse heating

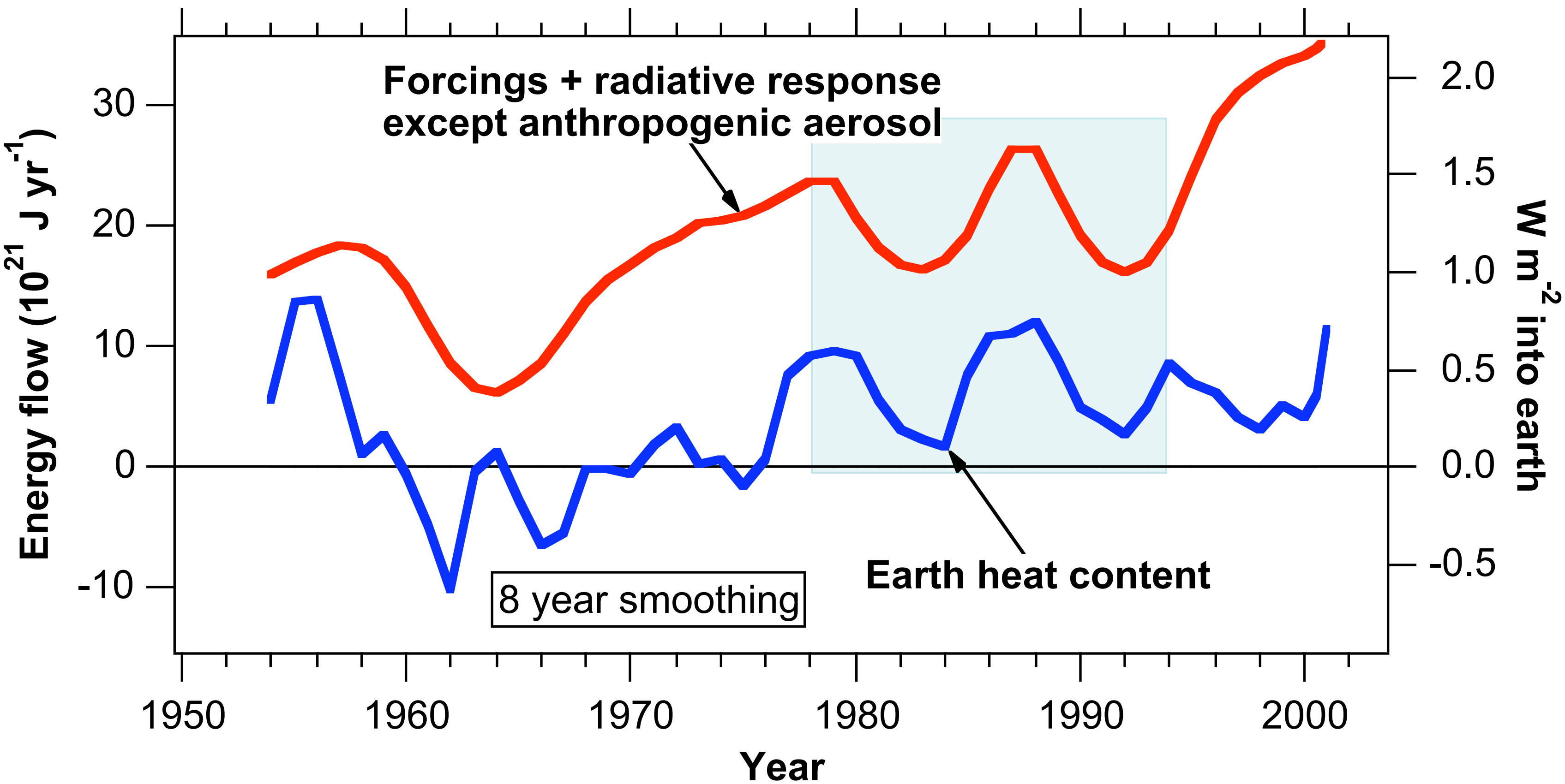


Since ~1970
-1.1±0.4 W m^{-2}

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

Rules out very large negative indirect effects.

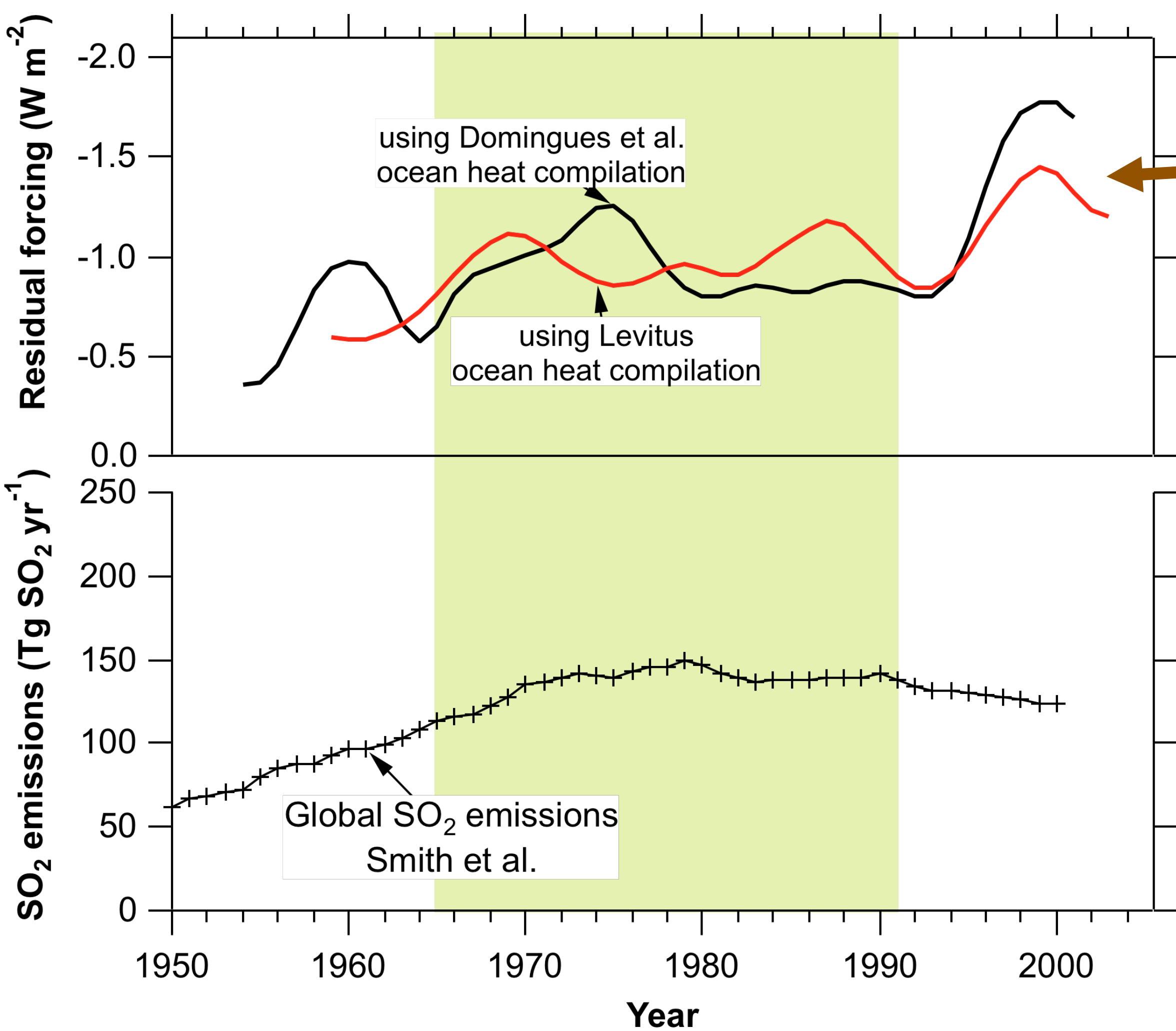
Time history

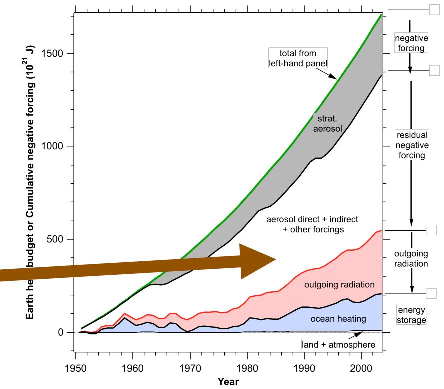


Quantitative agreement for volcanic perturbations

Independent data sources, no scaling.

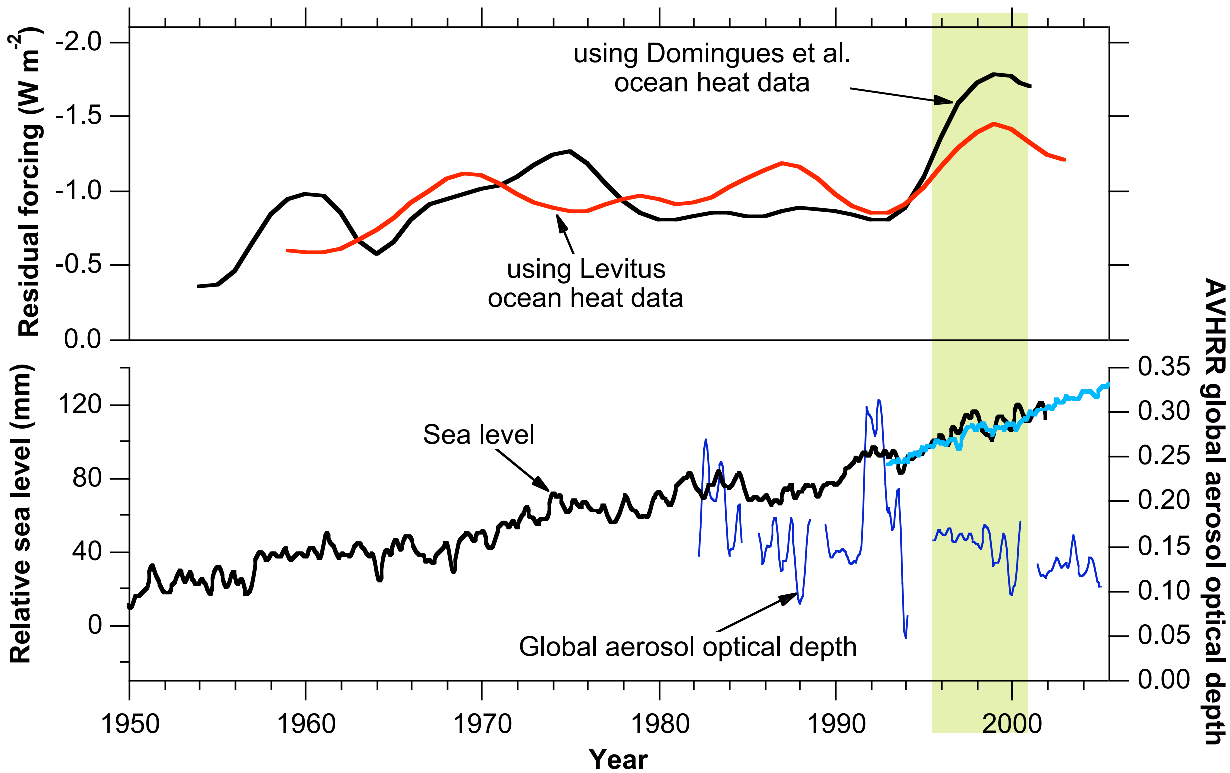
Time history





- Residual forcing flat 1970-1990, larger than 1950s.
- Matches emissions history.
- The residual forcing is indeed due to aerosols.

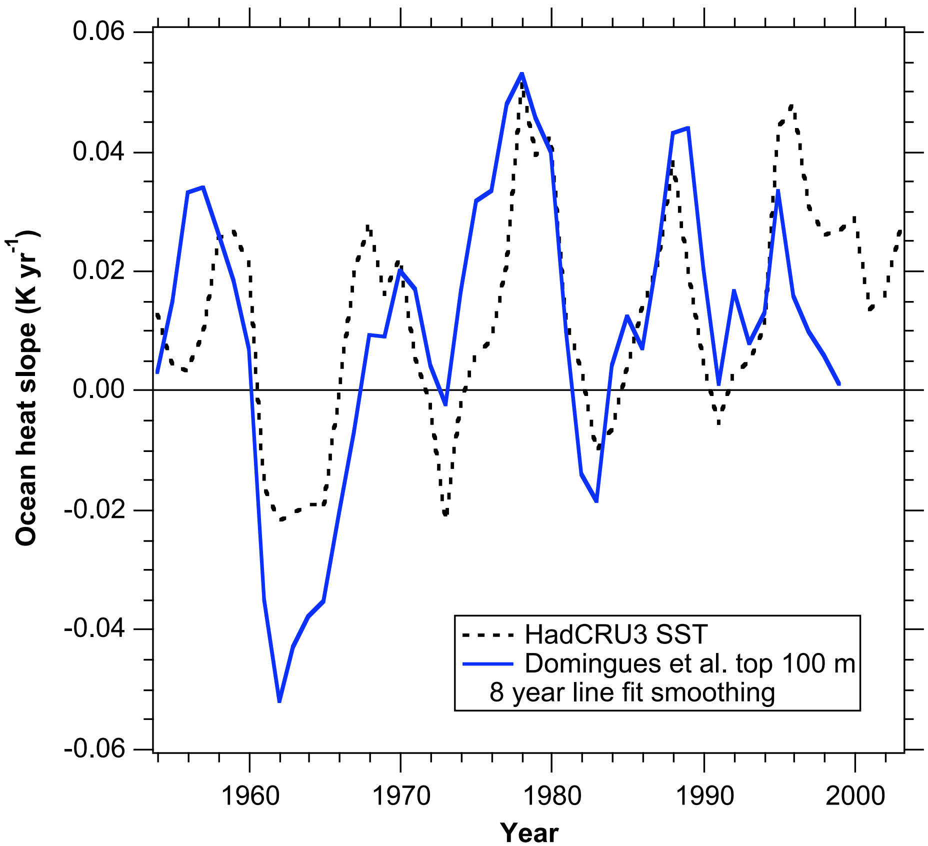
Time history: a puzzle



- 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.

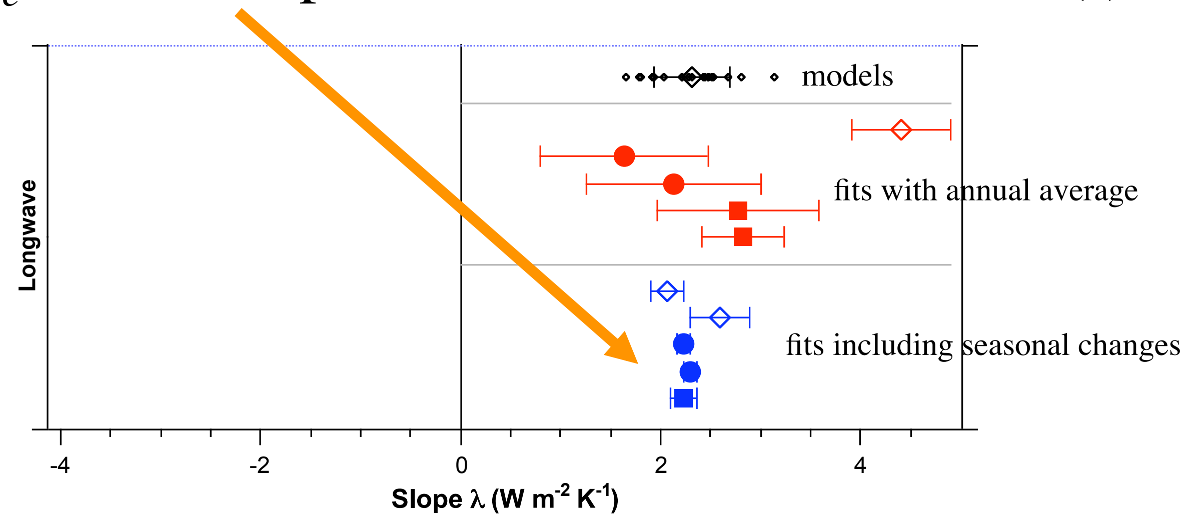
Outstanding issue

What happened to ocean heat in the late 1990s?



Climate sensitivity

$\lambda_{longwave}$ for recent past known to ~3% or ~30% (!)



$\lambda_{shortwave}$ 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

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

$$\text{at equilibrium } \Delta T \approx F/\lambda$$

What is missing from this equation?

Revisit energy balance equation

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

1) ΔT at <u>surface</u>

why not $\lambda_{surface}\Delta T_{surface} + \lambda_{500}\Delta T_{500} + \ldots$?

- *surface temperature is important and measurable*
- *we take care of other altitudes by either:*
    - *adjusting λ (lapse rate feedback)*
    - *adjusting F (stratospheric adjustment)*

Revisit energy balance equation

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

1) *ΔT at <u>surface</u>*
2) *<u>Global average</u> ΔT*

   why not $\lambda_{avg}\Delta T_{avg} + \lambda_{eq\text{-}pole}\Delta T_{eq\text{-}pole} + \ldots$?

- *we take care of other patterns by either:*
  - *adjusting* λ *(if proportional to* ΔT_{avg}*)*
  - *adjusting F (if not proportional)*

Revisit energy balance equation

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

1) *ΔT at surface*
2) *Global average ΔT*
3) *Global average F*

- F has spatial patterns!

=> efficacy

Revisit energy balance equation

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

1) *ΔT at <u>surface</u>*
2) *Global <u>average</u> ΔT*
3) *<u>Global average</u> 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

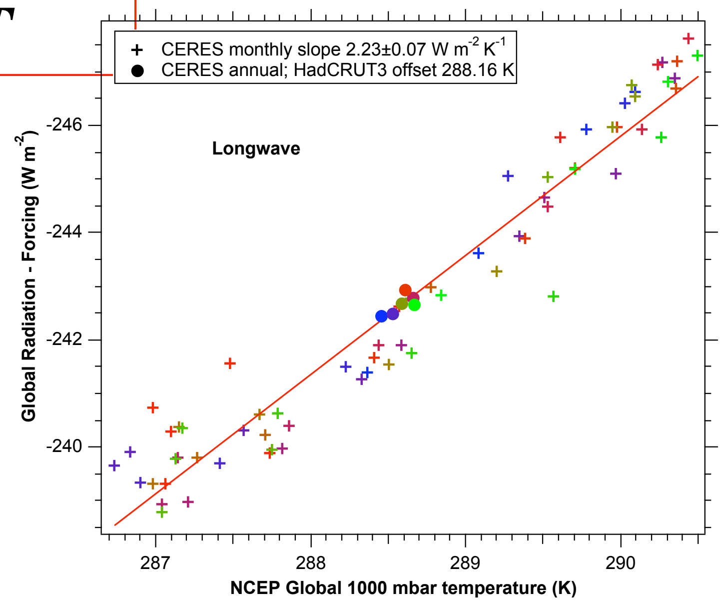
   (Williams et al., 2008)

   - as always, we adjust λ or F

   => λ and F are functions of time and dF/dt

Revisit energy balance equation

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



1) *ΔT at surface*
2) *Global average ΔT*
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, …)

Revisit energy balance equation

$$\Delta N \approx F + \gamma - \lambda \Delta T$$

1) *ΔT at surface*
2) *Global average ΔT*
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 $\Delta T_{surface}$ put into $F_{adjusted}$*

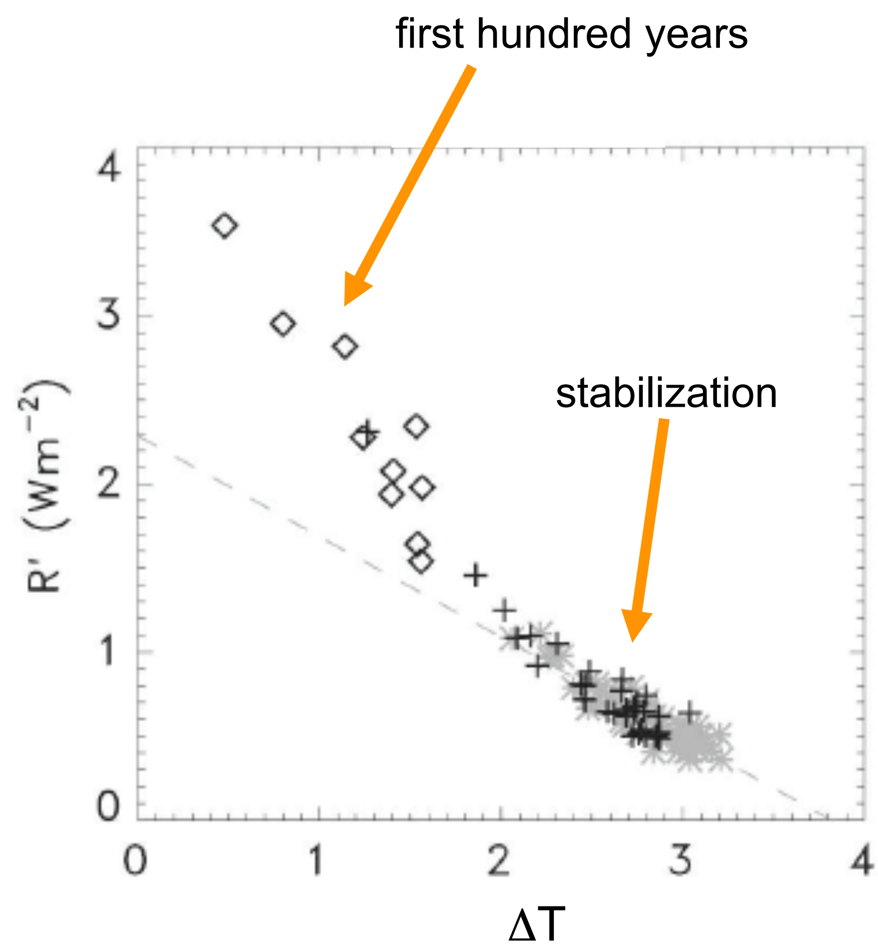
Means that forcings are affected by circulation

Outstanding issues continued

Why would long-term λ be different?

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

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



Williams et al., 2008

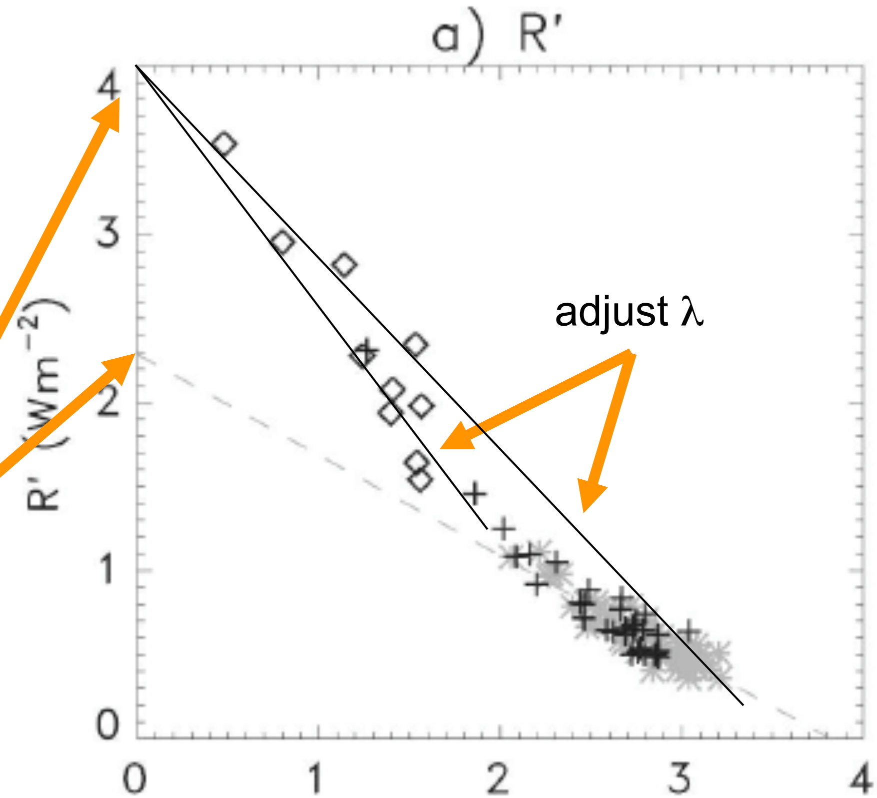
Outstanding issues continued

Why would long-term λ be different?

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

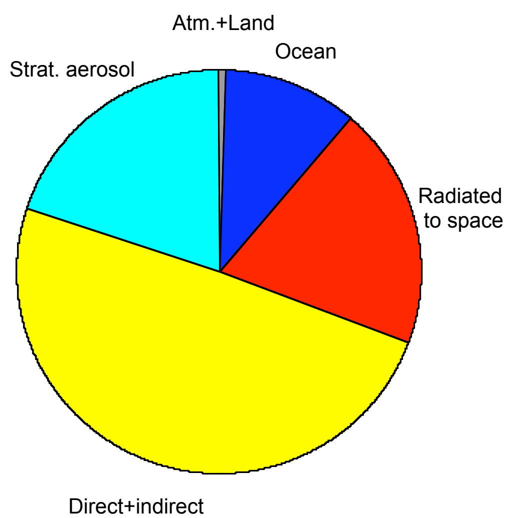
How do we deal with everything that don't fit a linear model?

adjust F



Williams et al., 2008

Energy budget and forcing summary



1950-2002

• 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.

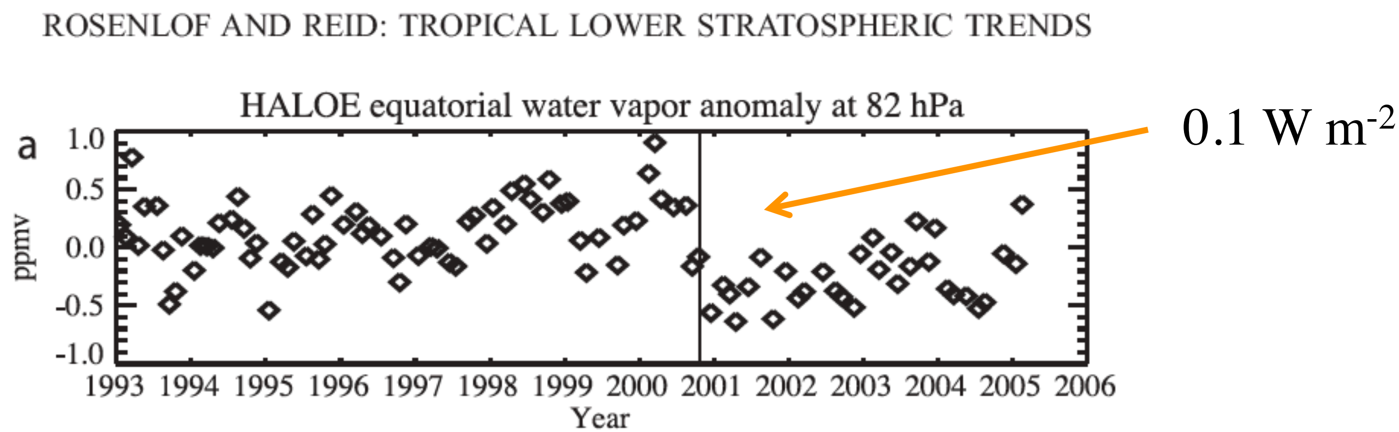
• Radiative forcing is not just radiative transfer

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* ?



Implications for satellite needs

(I recognize there are other uses than λ 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 ΔT

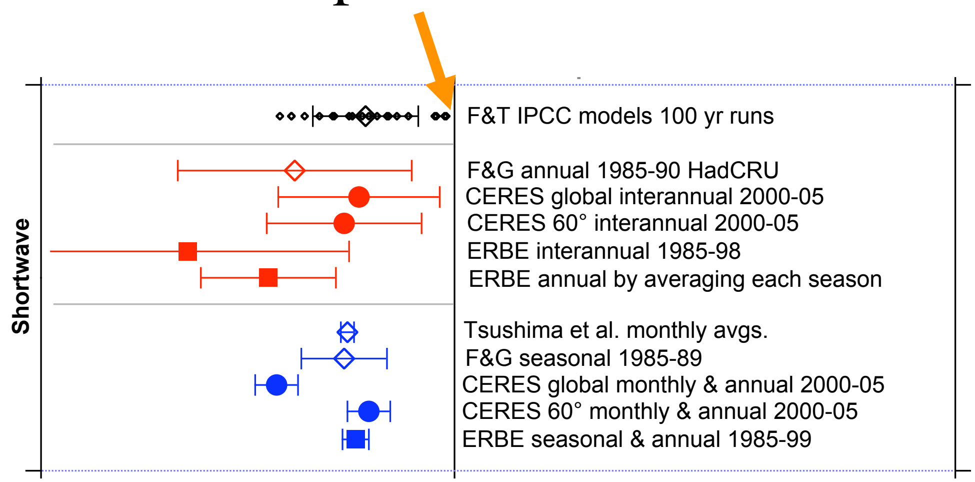
CERES absolute accuracy was sufficient.

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

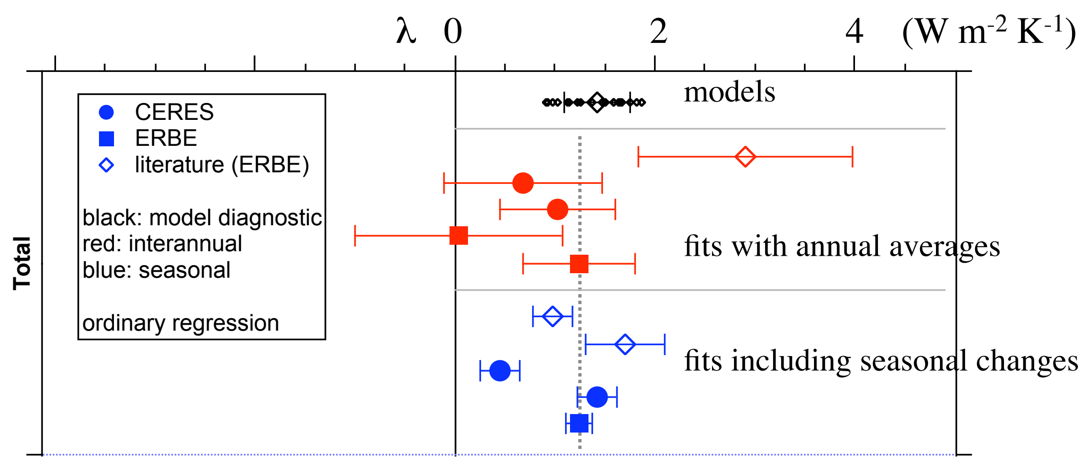
More than one in orbit more important than last bit of performance?

Climate sensitivity

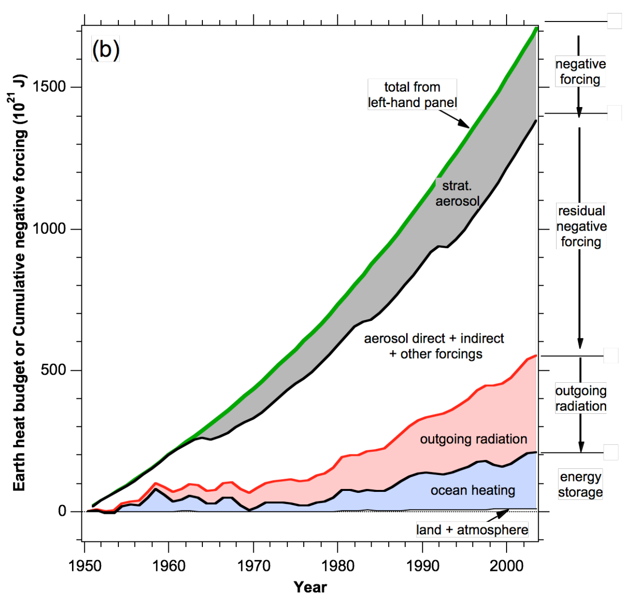
Weak lower limit from positive shortwave feedback



Upper climate sensitivity



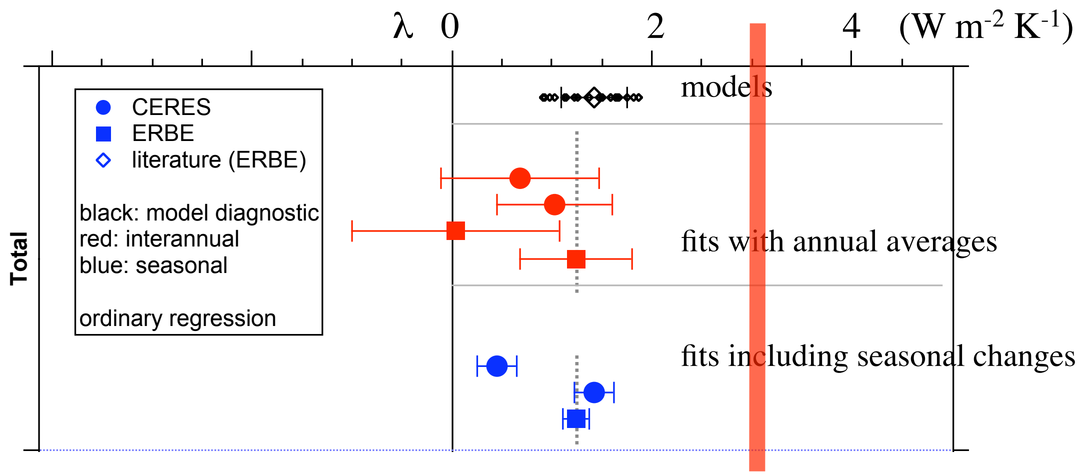
- Annual error limits overlap zero => no upper bound on sensitivity



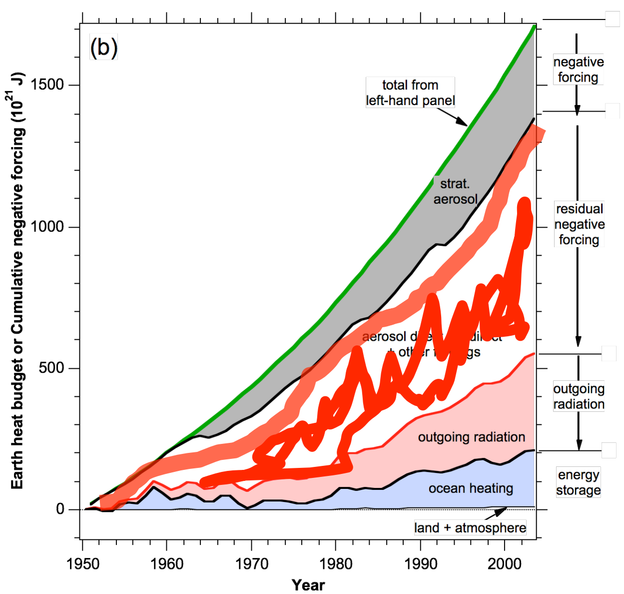
•If λ were zero, outgoing would be zero.

It could be absorbed into other terms.

Lower climate sensitivity



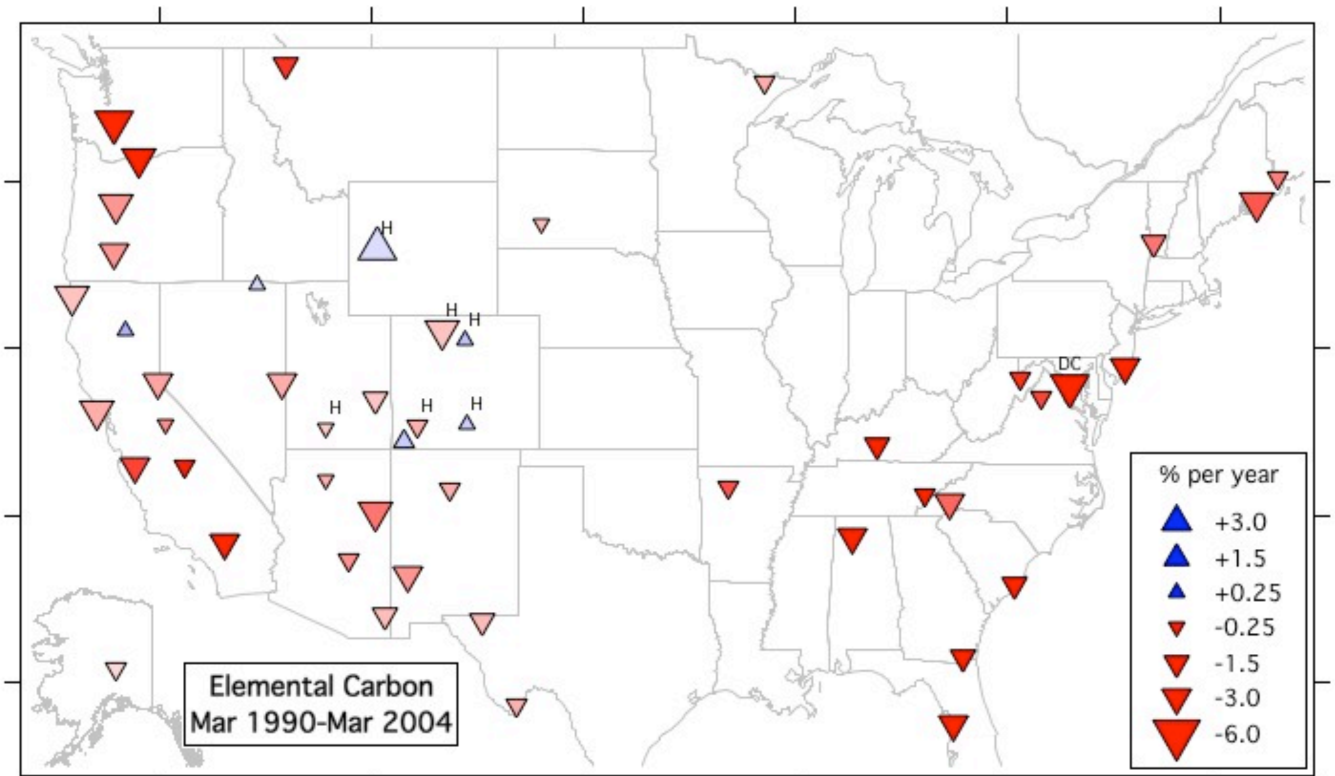
- λ for recent past from satellite data < about 3 W m^{-2} K^{-1} (my fits, > 2σ)



- If λ were > about 3 W m^{-2} K^{-1}

aerosol indirect effects would have to be positive

extra



Elemental Carbon
Mar 1990-Mar 2004
% per year
+3.0
+1.5
+0.25
-0.25
-1.5
-3.0
-6.0
DC
H

Averaging satellite data

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%

Annual

\+ No seasonal assumptions

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

\- Greater demands on satellite stability.