REQUIREMENTS FOR
EMPIRICAL DETERMINATION OF EARTH'S CLIMATE SENSITIVITY

Stephen E. Schwartz

Brookhaven National Laboratory Upton NY 11973

BROOKHAVEN NATIONAL LABORATORY

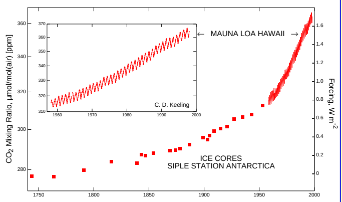
http://www.ecd.bnl.gov/steve/schwartz.html ses@bnl.gov

THE PROBLEM

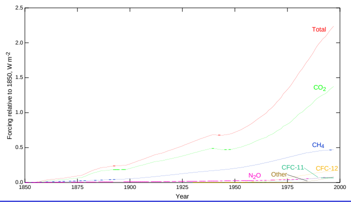
TOP-LEVEL ISSUES IN CLIMATE CHANGE SCIENCE

- How *much* will the climate change, and how *fast* will it change?
- What are the drivers of climate change?
  Changing atmospheric composition.
- How are drivers of climate change quantified?
  Radiative forcing F— change in radiative flux component (W m^{-2}).
- Prediction of future climate change, *e.g.*, for temperature, requires:
  - Predictive capability for *future radiative forcing* and
  - Knowledge the *climate sensitivity* $\lambda = \Delta T / F$.
- How can climate sensitivity be determined?
  - Climate models evaluated by performance on *prior climate change* and/or
  - Empirical determination from *prior climate change*.
- ***Either way, ΔT and F must be determined with known and sufficiently small uncertainty.***

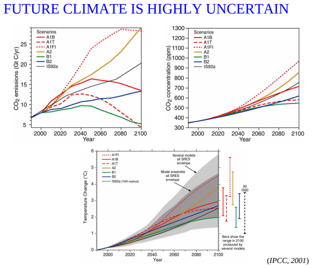
GLOBAL CARBON DIOXIDE OVER THE INDUSTRIAL PERIOD



GREENHOUSE GAS FORCING OVER THE INDUSTRIAL PERIOD



FUTURE CLIMATE IS HIGHLY UNCERTAIN



(IPCC, 2001)

Contributors to uncertainty include ***emissions***, ***concentrations***, and the Earth's ***climate sensitivity***.

Uncertainty in projections of future climate is due largely to uncertainty in climate sensitivity.

APPROACHES

MODEL-BASED ESTIMATES
Summary of 15 Current Models

Sensitivity	Mean	Standard Deviation	Range
$\Delta T_{2\times}$, K	3.5	0.92	2 - 5
λ, K/(W m^{-2})	0.87	0.23	0.5 - 1.25

IPCC *Climate Change 2001*, Cambridge University Press, 2001

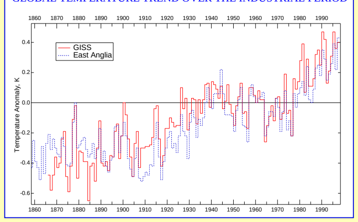
EMPIRICAL APPROACH

Empirical Sensitivity: $\lambda = \dfrac{\Delta T}{F}$

F = Forcing over the industrial period.

ΔT = Temperature increase over the industrial period.

GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD



EMPIRICAL TEMPERATURE SENSITIVITY

Greenhouse gas forcing over the industrial period is 2.5 W m^{-2}

Temperature increase over the industrial period is 0.6 K.

Empirical Sensitivity: $\lambda = \dfrac{\Delta T}{F} = \dfrac{0.6\ \text{K}}{2.5\ \text{W m}^{-2}} = 0.24\ \text{K} / (\text{W m}^{-2})$

This value is much lower than model predictions.

WHY MIGHT THE EMPIRICAL ESTIMATE BE LOW?

- Other forcings not included: Aerosol effects?

- Climate system not at equilibrium: Electric stove burner effect?

READ ON!

CAUTION!

Different investigators employ different measures of climate sensitivity.

Often climate sensitivity is expressed as the equilibrium temperature change for a doubling of CO_2, $\Delta T_{2\times}$.

Here climate sensitivity λ is the increase in global-mean surface temperature for a unit increase in radiative forcing F.

$\lambda = \dfrac{\Delta T}{F}$ Unit: K/(W m^{-2})

Note: Different investigators use the symbol λ to represent a variety of different quantities.

$F_{2\times} \equiv 4$ W m^{-2}, so $\lambda \equiv \Delta T_{2\times}/4$(W m^{-2})

AEROSOL FORCING

AEROSOLS
THE "MONKEY WRENCH" OF FORCING

AEROSOL INFLUENCES ON RADIATION BUDGET AND CLIMATE

Direct Effect (Clear sky)
Light scattering -- Cooling influence
Light absorption -- Warming influence, depending on surface

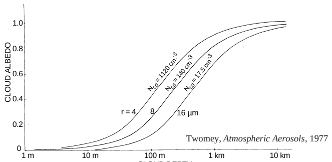
Indirect Effects (Aerosols influence cloud properties)
More droplets -- Brighter clouds (Twomey)
More droplets -- Enhanced cloud lifetime (Albrecht)

Semi-Direct Effect
Absorbing aerosol heats air and evaporates clouds

LIGHT SCATTERING BY WIDESPREAD AEROSOL

Agricultural burning in northeastern Oklahoma, 2000-12-01

THE TWOMEY EFFECT
Enhancement of Cloud Reflectivity by Aerosols



Increased aerosol concentration increases cloud droplet concentration. Increased cloud droplet concentration increases multiple scattering in clouds and in turn increases cloud reflectivity.

ESTIMATES OF AEROSOL RADIATIVE FORCING

Present estimates of direct and indirect radiative forcing by aerosols are based on aerosol loadings, properties, and distributions from chemical transport models.

These estimates indicate that aerosol forcing over the industrial period is *negative* (that is, cooling influence) and of magnitude comparable to forcing by anthropogenic greenhouse gases.

These model-based estimates are *very uncertain*. See IPCC bar graph.

UNCERTAINTIES

IPCC ESTIMATES OF FORCINGS AND UNCERTAINTIES

The Intergovernmental Panel on Climate Change (IPCC) reviews and assesses the science of climate change every 5 years.

The 2001 review examined all known forcings over the industrial period:
- Long-lived greenhouse gases (GHGs)
- Decreases in stratospheric ozone
- Increases in tropospheric ozone
- Direct and indirect effects of aerosols
- Aviation induced contrails and cirrus
- Changes in solar irradiance

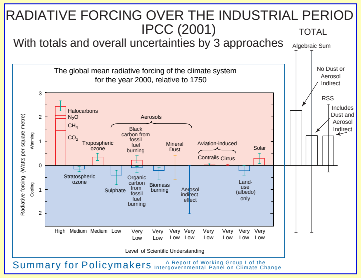
The IPCC estimated the several forcings (bars) and their uncertainties (I-beams).

For aerosol indirect forcing and forcing by mineral dust the IPCC provided ***no estimates of forcing***, only uncertainty ranges.

An assessment of present scientific understanding was also provided.

The IPCC declined to sum the several forcings or to propagate their uncertainties!

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
With totals and overall uncertainties by 3 approaches



ESTIMATES OF TOTAL FORCING AND UNCERTAINTY

Several estimates of total forcing and associated uncertainty are presented at the right of the figure. (See also Boucher and Haywood, *Climate Dynamics*, 2001).

By any standard the ***total forcing over the industrial era must be considered highly uncertain***.

If aerosol forcing is small, the total forcing will be near the forcing by long-lived GHGs.

If aerosol forcing is at the high end of the indicated uncertainty range, the ***total forcing will be much less*** (maybe even negative)**!**

The uncertainty in forcing results in a corresponding uncertainty in empirically determined climate sensitivity.

The uncertainty in forcing pertains also when aerosol forcing is represented in climate models.

The uncertainty in forcing must be substantially reduced to permit meaningful empirical determination of climate sensitivity or meaningful comparison of modeled and observed temperature trends.

UNCERTAINTY PRINCIPLES

- The "commonly accepted" estimates of the sensitivity for global temperature change for a doubling of CO_2 (4 W m^{-2}) range from 1.5 to 4.5 K (IPCC, 2001), equivalent to (3 ± 1.5) K — a factor of three! [λ = 0.75 ± 0.375 K/(W m^{-2})]. ***Fractional uncertainty $\delta\lambda/\lambda$ = 0.5.***
  Such an uncertainty is not very useful for policy planning purposes.

The fractional uncertainty in climate sensitivity λ is evaluated from fractional uncertainties in temperature change ΔT and forcing F as:

$$\frac{\delta\lambda}{\lambda} = \sqrt{\left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta F}{F}\right)^2}$$

- The increase in global mean temperature over the industrial period is 0.6 ± 0.2 K, *i.e.*, $\delta\Delta T/\Delta T$ = 0.33. (IPCC, 2001)
- This uncertainty in response, together with the "commonly accepted" uncertainty range in λ implies uncertainty in forcing $\delta F/F$ = 0.37.
  This is wholly inconsistent with present physically based estimates!
- A reasonable target might be $\delta\lambda/\lambda$ = 0.3
  This would require $\delta F/F = \delta\Delta T/\Delta T = 0.2$.

EQUILIBRIUM?

REQUIREMENT TO REACH THERMAL EQUILIBRIUM

Empirical estimates of climate sensitivity will be too small if the climate system has not reached thermal equilibrium (*strictly*, steady state).

Compare the heating element of an electric stove: it takes some time to reach the new equilibrium temperature after changing the setting (imposing a forcing).

For climate change the time constant for approaching a new equilibrium depends on what one considers the "climate system".

Here I argue that the climate system should be taken as the ***Atmosphere plus the Mixed Layer of the ocean (AML)***, excluding the deep ocean.

The atmosphere and the mixed layer are coupled on relevant time scales, decades to centuries.

This treatment requires consideration of heat loss from the AML to the deep ocean, which does not reach steady state on relevant time scales.

TIME CONSTANT TO REACH THERMAL EQUILIBRIUM

Exchange of energy from the ocean to the atmosphere is dominated by Stefan-Boltzmann thermal radiation:

$$F^{\uparrow} = \sigma T^4.$$

For T = 288 K, $F^{\uparrow}$ = 390 W m^{-2}.

For comparison, the latent heat of 1 m of precipitation per year is 72 W m^{-2}.

The ***time constant*** is proportional to the heat capacity of the system:

$$\tau = \frac{TC_{sys}}{4F^{\uparrow}}$$

The ***heat capacity*** of the system is dominated by that of the ocean mixed layer.

The ***mass*** of the atmosphere is equal to the mass of the top 10 m of the ocean, and the ***heat capacity*** of the atmosphere is equal to the heat capacity of the top 2.4 m of the ocean.

Land surfaces equilibrate rapidly compared to oceans (low heat capacity, low thermal diffusion).

$$C_{sys} = z_m \rho_w C_w$$

where z_m is the mixed layer depth, ρ is the density of water, and C_w is the specific heat capacity of water.

Hence

$$\tau = \frac{T z_m \rho_w C_w}{4F^{\uparrow}}$$

For ocean mixed layer depth 100 m, ***τ = 2 to 3 years***.

This time constant is short compared to the duration of forcing over the industrial period, so ***the system is in near equilibrium with a lag of only 2 - 3 years***.

This argument validates the empirical approach.

CONCLUSIONS

Present estimates of climate sensitivity rest entirely on climate model calculations.

The spread among these calculations is unacceptably large and their accuracy is unknown.

Empirical determination is an attractive, practical alternative.

Useful empirical determination of Earth's climate sensitivity requires great reduction in uncertainty in forcing over the industrial period.

Great reduction in uncertainty in forcing is required also for evaluation of performance of climate models over the industrial period.