Contributors to uncertainty include:

- Small uncertainty in radiative forcing for molecules (W m⁻²).
- Prediction of future climate change, e.g., for temperatures, requires:
  - Predictive capability for future radiative forcing and
  - Knowledge about climate sensitivity.
- How can climate sensitivity be determined?
- Climate models evaluated by performance on prior climate change data.
- Empirical determination from prior climate change data.
- Either way, Total uncertainty must be determined with known and sufficiently small uncertainty.

**Contributors to Uncertainty**

Climate is due largely to uncertainty in drivers of climate change.

**Problem**

**Aerosol forcing**

**Empirical approach**

Emission sensitivity:

\[ F = \text{Radiative forcing} \]

Temperature increase over the industrial period:

\[ T = \frac{F}{C} \]

This 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 forces benefit earth)

**Read on!**

**Aerosol influences on radiation budget and climate**

**Direct Effect** (Case 1)

Light scattering -- Cooling influence

Air absorption -- Warming influence, depending on surface

Indirect Effects (Aerosols influence cloud properties)

- More droplets -- Brighter clouds (Twomey)
- More droplets -- Enhanced cloud extinction (Albrecht)

- Extra-Direct Effects

Absorbing aerosols heat air and evaporate clouds

**Light scattering by widespread aerosols**

**The Twomey effect**

Enhancement of Cloud Reflectivity by Aerosols

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

**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.

For comparison, the latest heat of 1 m of precipitation per year is 72 W m⁻².

The time constant is proportionally to the heat capacity of the system:

\[ \tau = \frac{C_{\text{sys}}}{F} \]

The heat capacity of the system is dominated by that of the ocean:

- The heat capacity of the atmosphere is equal to the total of the top 10 m of the oceans, and the heat capacity of the atmosphere is equal to the heat capacity of the top 2-3 m of the oceans.
- Land surfaces equilibrate quickly compared to oceans (heat capacity, low thermal diffusion).

Estimates of total forcing and uncertainty

Several estimates of total forcing and associated uncertainty are presented at the right of the figure. (See also Broecker and Hayswood, Climate Processes, 2001.)

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

If aerosol forcing is small, the total forcing will be near the forcing by greenhouse gases.

If aerosol forcing is in the high end of the uncertainty range, the total forcing will be close to the radiative forcing.

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

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

This 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**

1. The ‘‘committably accepted’’ estimate of the sensitivity to global warming today is 16°C (±2°C) W m⁻². This value is an upper bound to the range 3.5 to 7°C in the range 1°C to 5°C.

2. The uncertainty in the sensitivity to global warming today is ±3°C (±1°C to 2°C, IPCC 2001).

3. The uncertainty in the sensitivity to forcing over the industrial period is ±2°C to 3°C, IPCC (2001).

This uncertainty is due to the committably accepted uncertainty range in aerosols and other forcings.

**Requirements for empirical determination of Earth’s climate sensitivity**

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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?
- How well do we understand how changing atmosphere affects climate?
- How are the drivers of climate change quantified?

**Irreducible uncertainty**

- 2°C to 3°C warming over the industrial period
- 2°C of uncertainty is due to uncertainty in forcing
- Proportionate uncertainty in temperature change
- Empirical determination from prior climate change data
- Contribution of uncertainty includes:
  - Observations, conceptual understanding, and the Earth’s climate sensitivity.

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