WHY HASN’T EARTH WARMED AS MUCH AS EXPECTED?

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ATMOSPHERIC RADIATION

Power per area

Energy per time per area

Unit: Watt per square meter
W m$^{-2}$
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

\[
\frac{1}{4} S_0 (1 - \alpha) = \sigma T^4
\]

Stefan-Boltzmann radiation law

\[\alpha = 31\%
\]

\[\frac{1}{4} S_0 = 343\]

\[237 \approx 254K\]

Schwartz, 1996, modified from Ramanathan, 1987
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

Polar ice cores
- Law Dome
- Adelie Land
- Siple
- South Pole

Mauna Loa Hawaii

Inset: Global carbon dioxide concentration and infrared radiative forcing

Year
- 800
- 1000
- 1200
- 1400
- 1600
- 1800
- 2000

CO₂ concentration (ppm)
- 180
- 200
- 220
- 240
- 260
- 280
- 300
- 320
- 340
- 360
- 380

Forcing, W m⁻²
- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1.0
- 1.2
- 1.4
- 1.6
Greenhouse gas forcing is considered accurately known. Gases are uniformly distributed; radiation transfer is well understood.
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

Schwartz, 1996, modified from Ramanathan, 1987
HOW MUCH WARMING IS EXPECTED?

Equilibrium change in global mean surface temperature = Climate sensitivity × Forcing

\[ \Delta T = S \times F \]

S is *equilibrium* sensitivity. Units: K/(W m\(^{-2}\))

Sensitivity is commonly expressed as “CO\(_2\) doubling temperature”

\[ \Delta T_{2\times} \equiv S \times F_{2\times} \]

where \( F_{2\times} \) is the “CO\(_2\) doubling forcing” *ca.* 3.7 W m\(^{-2}\).
THE WARMING DISCREPANCY

For increases in CO₂, CH₄, N₂O, and CFCs over the industrial period

\[ F = 2.6 \text{ W m}^{-2} \]

**Expected** temperature increase:

\[ \Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.6}{3.7} \times 3 \text{ K} = 2.1 \text{ K} \]

**Observed** temperature increase:

\[ \Delta T_{\text{obs}} = 0.8 \text{ K} \]

How can we account for this warming discrepancy?
EXPECTED INCREASE IN GLOBAL TEMPERATURE
Long-lived GHGs only – Dependence on climate sensitivity

Equilibrium Climate Sensitivity, K/(W m⁻²)

Increase in GMST ΔT, K

CO₂ Doubling Temperature ΔT₂ₓ, K

Warming discrepancy denotes the expected warming that has not occurred: ~60% of the expected warming.
Current estimates of Earth’s climate sensitivity are centered about a CO$_2$ doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.
Current estimates of Earth’s climate sensitivity are centered about a CO₂ doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty. Range of sensitivities of current models roughly coincides with IPCC “likely” range.
EXPECTED INCREASE IN GLOBAL TEMPERATURE
Long-lived GHGs only – Dependence on climate sensitivity

This discrepancy holds throughout the IPCC AR4 “likely” range for climate sensitivity.
From Forcing by Long-lived Greenhouse Gases
Why Hasn’t Earth Warmed as Much as Expected?

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WHY HASN’T EARTH WARMED AS MUCH AS EXPECTED.

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

- Uncertainty in greenhouse gas forcing.
- Countervailing natural cooling over the industrial period.
- Lag in reaching thermal equilibrium.
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.
WHY HASN’T EARTH WARMED AS MUCH AS EXPECTED . . . FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

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EXPECTED INCREASE IN GLOBAL TEMPERATURE
Long-lived GHGs only – Dependence on climate sensitivity

Equilibrium Climate Sensitivity, K/(W m\(^{-2}\))

Increase in GMST \(\Delta T\), K

CO\(_2\) Doubling Temperature \(\Delta T_{2X}\), K

"Likely" range \(\sim 1\) \(\sigma\)
IPCC AR4
Best estimate
LLGHG, Equilibrium
Warming discrepancy
Observed

Little of the warming discrepancy is resolved by uncertainty in GHG forcing.
WHY HASN’T EARTH WARMED AS MUCH AS EXPECTED... FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

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ESTIMATING NATURAL VARIABILITY

“Union” reconstruction of paleo temperature from ice cores, sediments, tree rings, corals

Typical variation in temperature over 150 years ~ 0.2 K.

Juckes et al., Climate of the Past, 2007
ESTIMATING NATURAL VARIABILITY

Anomaly relative to 1901-1950; 5 Models, 19 runs, from IPCC AR4

![Graph showing temperature anomaly from 1900 to 2000. The graph compares models using only natural forcings (light blue), models using both natural and anthropogenic forcings (pink), and observations (black). The y-axis represents temperature anomaly in °C, and the x-axis represents years from 1900 to 2000. The graph indicates a steady increase in temperature anomaly over time.]
ESTIMATING NATURAL VARIABILITY
Anomaly relative to 1901-1950; 5 Models, 19 runs, from IPCC AR4
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ESTIMATING NATURAL VARIABILITY
Anomaly relative to 1901-1950; 5 Models, 19 runs, from IPCC AR4
ESTIMATING NATURAL VARIABILITY
Anomaly relative to 1900; 5 Models, 19 runs, from IPCC AR4

100-year difference: Average, 0.09 K; std dev, 0.19 K; maximum, 0.49 K.
EXPECTED INCREASE IN GLOBAL TEMPERATURE
Long-lived GHGs only – Dependence on climate sensitivity

The warming discrepancy cannot be resolved by countervailing natural cooling over the industrial period.
WHY HASN’T EARTH WARMED AS MUCH AS EXPECTED...

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

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ỹs the time constant of the system response to a perturbation.
ACCOUNTING FOR DISEQUILIBRIUM

Upon application of a forcing to climate initially at equilibrium

\[
\text{Global heating rate} = \text{Forcing} - \text{Response}
\]

\[
N = F - S^{-1} \Delta T_s
\]

For positive forcing net downwelling radiation at top of atmosphere immediately increases by the amount of the forcing.

As surface temperature \( T_s \) increases, outgoing longwave radiation increases and net downwelling radiation decreases until new equilibrium is reached.
EFFECTIVE FORCING

\[ N = F - S^{-1} \Delta T_s \]

In general, not at equilibrium,

\[ \Delta T_s = S(F - N) \]

Define effective forcing, \( F_{\text{eff}} \equiv F - N \)

Use of effective forcing permits determination of expected temperature increase \( \Delta T_s \) as

\[ \Delta T_s = S F_{\text{eff}} \]

Need to determine net heating rate of Earth, \( N \).
Determine global heating rate from *increase in heat content of global ocean*.

Evaluate effective forcing as \( F_{\text{eff}} \equiv F - N \).

Compare observed \( \Delta T_s \) to that expected for effective forcing.
GLOBAL HEATING RATE FROM OCEAN HEAT CONTENT

Heat content of global ocean – surface to 700 m

Average: $0.21 \pm 0.07 \text{ W m}^{-2}$

Accounting for heat to 3 km: factor of 1.44.
Accounting for other heat sinks (air, land, melting of ice) factor of 1.19.
Total heating rate $0.37 \pm 0.12 \text{ W m}^{-2}$. 

Levitus et al., GRL, 2009
EXPECTED INCREASE IN GLOBAL TEMPERATURE
Long-lived GHGs only – Dependence on climate sensitivity

Equilibrium Climate Sensitivity, K/(W m\(^{-2}\))

Increase in GMST \(\Delta T\), K

CO\(_2\) Doubling Temperature \(\Delta T_{2X}\), K

"Likely" range \(\sim 1 \sigma\)
IPCC AR4
Best estimate
LLGHG, Equilibrium
LLGHG, Expected

Little of the warming discrepancy can attributed to thermal disequilibrium.
WHY HASN’T EARTH WARMED AS MUCH AS EXPECTED... FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

- Uncertainty in greenhouse gas forcing.
- Countervailing natural cooling over the industrial period.
- Lag in reaching thermal equilibrium.
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.
Radiative Forcing by Tropospheric Aerosol

Partial Reflection and Absorption of Incoming Solar Radiation

Aerosol Haze

Clouds

Organics

Dust

SO₂

Soot

Sea salt

Organics

Industrial Emissions

Biomass Burning

Land Use Changes

Ocean

DMS
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

\[ \Delta F = -1.2 \text{ W m}^{-2} \]
\[ \alpha = 31\% \]
\[ \frac{1}{4} S_0 = 343\text{ W m}^{-2} \]
\[ 69\% = 1 - \alpha \]
\[ 237 \approx 254K \]
\[ 1/4 S_0 (1 - \alpha) = \sigma T^4 \]

Shortwave  Longwave

\[ \text{H}_2\text{O, CO}_2, \text{CH}_4 \ldots \]
\[ \approx 288K \]
\[ 390 \]
\[ 31 \]

Atmosphere

Latent heat
Sensible heat

Schwartz, 1996, modified from Ramanathan, 1987
Total forcing includes other anthropogenic and natural (solar) forcings. Forcing by tropospheric ozone, \(~0.35\) W m\(^{-2}\), is the greatest of these. Uncertainty in aerosol forcing dominates uncertainty in total forcing.
The warming discrepancy might be resolved by countervailing aerosol forcing (at the IPCC best-estimate value) together with low sensitivity.
The warming discrepancy is certainly resolved by countervailing aerosol forcing (within the IPCC range) for virtually any value of sensitivity.
WHY HASN’T EARTH WARMED AS MUCH AS EXPECTED . . .

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

• Uncertainty in greenhouse gas forcing.
• Countervailing natural cooling over the industrial period.
• Lag in reaching thermal equilibrium.
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• Climate sensitivity lower than current estimates.
IMPLICATIONS

ALLOWABLE FUTURE CO$_2$ EMISSIONS

How much fossil carbon can be burned and emitted into the atmosphere (as CO$_2$) without exceeding a given threshold for “dangerous anthropogenic interference” with the climate system?

Answer depends on target threshold and climate sensitivity.

Premise of the calculation:

Forcings by LLGHG’s only; result expressed as equivalent CO$_2$. 
HOW MUCH WARMING IS EXPECTED?

For increases in CO$_2$, CH$_4$, N$_2$O, and CFCs over the industrial period

$$F = 2.6 \text{ W m}^{-2}$$

**Expected** temperature increase:

$$\Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.6}{3.7} \times 3 \text{ K} = 2.1 \text{ K}$$

**Observed** temperature increase:

$$\Delta T_{\text{obs}} = 0.8 \text{ K}$$

*Because of uncertainty in climate sensitivity the committed warming is likewise uncertain.*
ALLOWABLE FUTURE CO₂ EMISSIONS

Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial

If \( \Delta T_{\text{max}} > 2.1 \) K and/or sensitivity \( \Delta T_{2\times} < 3 \) K, further emissions are allowed without exceeding \( \Delta T_{\text{max}} \).

If \( \Delta T_{\text{max}} < 2.1 \) K and/or sensitivity \( \Delta T_{2\times} > 3 \) K, committed temperature increase already exceeds \( \Delta T_{\text{max}} \).
ALLOWABLE FUTURE CO\textsubscript{2} EMISSIONS
Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial

For $\Delta T_{\text{max}} = 2$ K . . .
If sensitivity $\Delta T_{2\times}$ is 3 K, \textit{no more emissions}.
If sensitivity $\Delta T_{2\times}$ is 2 K, $\sim$ 30 more years of emissions at present rate.
If sensitivity $\Delta T_{2\times}$ is 4.5 K, \textit{threshold is exceeded by $\sim$30 years}.
APPROACHES TO DETERMINING CLIMATE SENSITIVITY
APPROACHES TO DETERMINING CLIMATE SENSITIVITY

Climate models
Evaluate by performance on current climate
Evaluate by performance over instrumental record

Empirical

Sensitivity = \( \text{Time constant/Heat Capacity} \)
Paleo: \( \Delta Temperature/\Delta Flux \), paleo to present
Instrumental record \( \Delta Temperature/(\text{Forcing} – \Delta Flux) \)
Satellite measmt.: \( [d(\text{Forcing} – \Delta Flux)/dT]^{-1} \)
Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a consistent explanation of the observed temperature record.

These simulations used models with different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings.
CORRELATION OF AEROSOL FORCING, TOTAL FORCING, AND SENSITIVITY IN CLIMATE MODELS

Nine coupled ocean-atmosphere models; two energy balance models

\[
S = \frac{\Delta T}{F} \\
F = \Delta T S^{-1}
\]

Total forcing is linearly correlated with inverse sensitivities of the models. Climate models with lower sensitivity (higher inverse sensitivity) employed a greater total forcing.

Slope (0.8 K) is approximately equal to observed temperature change. Models accurately reproduce known temperature change.

Greater total forcing is due to smaller (less negative) aerosol forcing.

Modified from Kiehl, GRL, 2007
**Approaches to Determining Climate Sensitivity**

*Climate models*
- Evaluate by performance on current climate
- Evaluate by performance over instrumental record

*Empirical*

\[
\text{Sensitivity} = \frac{\text{Time constant}}{\text{Heat Capacity}}
\]

Paleo: \(\Delta Temperature / \Delta Flux\), paleo to present

Instrumental record \(\Delta Temperature / (\text{Forcing} - \text{Flux})\)

Satellite measmt.: \([d(\text{Forcing} - \text{Flux})/dT Temperature]^{-1}\)
EMPIRICAL DETERMINATION OF CLIMATE SENSITIVITY

From known forcing, temperature change, and heating rate

\[
\Delta T = S(F - H) = SF_{\text{eff}}
\]

or

\[
F_{\text{eff}} = \Delta TS^{-1}
\]
CLIMATE MODEL DETERMINATION OF CLIMATE SENSITIVITY

Effect of uncertainty in forcing

\[ F_{\text{eff}} = F - H \]
\[ \Delta T = S F_{\text{eff}} \]
\[ F_{\text{eff}} = \Delta T S^{-1} \]

Uncertainty in aerosol forcing allows climate models with widely differing sensitivities to reproduce temperature increase over industrial period.
Climate sensitivity and aerosol forcing are *intrinsically coupled*, in climate models and in empirical determination of sensitivity.

Confident determination of climate sensitivity requires *great reduction in uncertainty in aerosol forcing* over the industrial period.
THE PATH FORWARD

Determine aerosol forcing with high accuracy.

Multiple approaches are required:

*Laboratory studies* of aerosol processes.

*Field measurements* of aerosol processes and properties: emissions, new particle formation, evolution, size distributed composition, optical properties, CCN properties, removal processes . . .

Represent aerosol processes in *chemical transport models*.

Evaluate models by *comparison with observations*.

*Satellite measurements* for spatial coverage.

Calculate forcings in *chemical transport models and GCMs*.

*Measurement based determination of aerosol forcings.*
CONCLUSIONS

The increase in global mean surface temperature over the industrial period is less than 40% of what would be expected from forcing by incremental long-lived greenhouse gases for the IPCC best estimate of equilibrium climate sensitivity (CO$_2$ doubling temperature 3 K).

This “warming discrepancy” cannot be resolved by uncertainty in GHG forcing, lag in reaching thermal equilibrium or countervailing natural cooling of the climate system.

The warming discrepancy is due to aerosol forcing and/or climate sensitivity less than IPCC best estimate.

cont'd
CONCLUSIONS (cont’d)

The amount of incremental CO₂ (and other greenhouse gases) that can be added to the present atmosphere consonant with a given maximum increase in global mean surface temperature above preindustrial is unknown even in sign.

This uncertainty is a consequence of present uncertainty in climate sensitivity.

Uncertainty in climate sensitivity is intrinsically linked to uncertainty in climate forcing, mainly due to uncertainty in forcing by tropospheric aerosols.

Confident determination of climate sensitivity requires greatly reducing uncertainty in forcing by aerosols.