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.

Implications

Path forward
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?
ENERGY BALANCE MODEL OF EARTH’S CLIMATE SYSTEM

Global energy balance: \[\frac{dH}{dt} = Q - E = \frac{\gamma J_S}{4} - \varepsilon \sigma T_s^4\]

- \(T_s\) is global mean surface temperature
- \(H\) is global heat content
- \(Q\) is absorbed solar energy
- \(E\) is emitted longwave flux
- \(J_S\) is solar constant
- \(\gamma\) is planetary co-albedo
- \(\sigma\) is Stefan-Boltzmann constant
- \(\varepsilon\) is effective emissivity

At radiative “equilibrium”: \[\frac{\gamma J_S}{4} = \varepsilon \sigma T_s^4\]

\[\gamma = 1 - \alpha \approx 0.7; \quad \varepsilon = \frac{\gamma J_S / 4}{\sigma T_s^4}; \quad \text{for } T_s = 288 \text{ K}, \varepsilon \approx 0.61\]

\(T_s\), \(\gamma\), and \(\varepsilon\) are properties of Earth’s current climate.
Global energy balance: \[
\frac{dH}{dt} = Q - E = \frac{\gamma J_s}{4} - \varepsilon \sigma T_s^4
\]

Apply step-function forcing: \[F = \Delta(Q - E)\]

At new “equilibrium” \[\Delta T_s(\infty) = SF\]

At new “equilibrium” \[
F = \left(\frac{\gamma J_s}{4} - \varepsilon \sigma T_s^4\right) - \left(\frac{\gamma_0 J_s}{4} - \varepsilon_0 \sigma T_{s0}^4\right) = \frac{\partial}{\partial T_s} \left(\frac{\gamma J_s}{4} - \varepsilon \sigma T_s^4\right) \Delta T_s
\]

Equilibrium sensitivity: \[S \equiv \frac{\Delta T_s}{F} = \left\{\frac{\partial}{\partial T_s} \left(\frac{\gamma J_s}{4} - \varepsilon \sigma T_s^4\right)\right\}^{-1}\]
In absence of feedbacks $\gamma$ and $\varepsilon$ do not depend on $T_s$

No-feedback sensitivity: $S_{\text{NF}} \equiv \frac{dT_s}{dQ} = \frac{dT_s}{dE} = \left( \frac{dE}{dT_s} \right)^{-1}$ for constant $\gamma$ and $\varepsilon$.

Change in emitted flux per change in temperature:

$$\frac{dE}{dT_s} = \frac{d(\varepsilon \sigma T_s^4)}{dT_s} = 4\varepsilon \sigma T_s^3 = \frac{4}{T_s} E = \frac{4}{T_s^4} \frac{\gamma J_s}{4} = \frac{\gamma J_s}{T_s}$$

$$S_{\text{NF}} = \frac{T_s}{\gamma J_s}$$

$J_s = 1368 \text{ Wm}^{-2}; \ T_s = 288 \text{ K}; \ \gamma = 0.7; \ \ S_{\text{NF}} = 0.30 \text{ K} / (\text{Wm}^{-2})$

$$\Delta T_{2\times} = F_{2\times} S_{\text{NF}} = 3.7 \text{ Wm}^{-2} \times 0.30 \text{ K} / (\text{Wm}^{-2}) = 1.1 \text{ K}$$
CLIMATE SENSITIVITY INCLUDING FEEDBACKS

With feedbacks $\gamma$ and $\varepsilon$ may change with changing $T_s$

Equilibrium climate sensitivity

$$S = \frac{T_s}{\gamma_0 J_S} \left( 1 + \frac{1}{4} \frac{d \ln \gamma}{d \ln T_s} \bigg|_0 + \frac{1}{4} \frac{d \ln \varepsilon}{d \ln T_s} \bigg|_0 \right)$$

K/(W m$^{-2}$)

$f$ is feedback factor

$$f = \frac{1}{1 - \Phi}$$

Sensitivity, feedback factor, feedback strength are all properties of Earth’s present climate system (just like $\gamma$ and $\varepsilon$).
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.
Total forcing includes other anthropogenic and natural (solar) forcings. Forcing by tropospheric ozone, ~0.35 W m\(^{-2}\), is the greatest of these.
EXPECTED INCREASE IN GLOBAL TEMPERATURE
Long-lived GHGs only – Dependence on climate sensitivity

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

![Graph showing increase in GMST vs CO$_2$ doubling temperature with annotation: “Likely” range ~1 σ, IPCC AR4, LLGHG, Equilibrium, Observed, Warming discrepancy.]

This discrepancy holds throughout the IPCC AR4 “likely” range for climate sensitivity.
UNCERTAINTY IN GREENHOUSE GAS FORCING

± 10%, 2σ – IPCC
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 ~1 $\sigma$
IPCC AR4
Best estimate
LLGHG, Equilibrium
Warming discrepancy
Observed

Little of the warming discrepancy is resolved by uncertainty in GHG forcing.
COUNTERVAILING NATURAL COOLING OFFSETTING EXPECTED WARMING
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

Temperature anomaly (°C)

- models using only natural forcings
- models using both natural and anthropogenic forcings
- observations

1900 1950 2000
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.
The warming discrepancy cannot be resolved by countervailing natural cooling over the industrial period.
LAG IN REACHING THERMAL EQUILIBRIUM
LAG OF TEMPERATURE RESPONSE

Increase in GMST in year 70 of 1% yr\(^{-1}\) CO\(_2\) increase vs. equilibrium doubling temperature in 17 climate models from IPCC AR4

Transient sensitivity in models is only about 40% of equilibrium sensitivity. Implies substantial unrealized “heating in the pipeline” as forcing increases.
ACCOUNTING FOR DISEQUILIBRIUM

Upon application of a forcing to climate initially at equilibrium

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

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

Response is increased outgoing longwave irradiance as surface temperature \(T\) increases; \(S^{-1}\) is inverse of sensitivity.

At new equilibrium \(H = 0\) and \(\Delta T_{eq} = SF\).

In general \(S = \Delta T / F_{\text{eff}}\) where \(F_{\text{eff}} \equiv F - H\) is “effective forcing”.
ACCOUNTING FOR DISEQUILIBRIUM

Approach

Determine global heating rate from increase in heat content of global ocean.

Evaluate effective forcing as $F_{\text{eff}} \equiv F - H$.

Compare observed $\Delta T$ 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
GLOBAL ANNUAL ENERGY BUDGET
Fluxes in W m\(^{-2}\)

Note energy imbalance, 0.9 W m\(^{-2}\) inferred from ocean heating rate.

Trenberth, Fasullo, Kiehl, BAMS, 2008
EXPECTED INCREASE IN GLOBAL TEMPERATURE
Long-lived GHGs only – Dependence on climate sensitivity

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

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

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

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

Little of the warming discrepancy can attributed to thermal disequilibrium.
Total forcing includes other anthropogenic and natural (solar) forcings. Forcing by tropospheric ozone, \(~0.35\text{ W m}^{-2}\), is the greatest of these.
The warming discrepancy is certainly resolved by countervailing aerosol forcing (within the IPCC range) for virtually any value of sensitivity.
IMPLICATIONS

ALLOWABLE FUTURE CO₂ EMISSIONS

How much fossil carbon can be burned and emitted into the atmosphere (as CO₂) 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 CO₂.
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 \( \Delta T_{\text{max}} \).
MAXIMUM ALLOWABLE CO₂ MIXING RATIO

\[
\text{Max} \Delta \text{CO}_2 \text{ mixing ratio} = \left( \frac{\text{Max} \Delta \text{temp} - \text{Current committed} \Delta \text{temp}}{\Delta \text{temp}} \right) / \left( \text{Sensitivity} \times \text{Forcing per} \Delta \text{CO}_2 \right)
\]

\[
\Delta m_{\text{CO}_2} = \frac{\Delta T_{\text{max}} - \Delta T_c}{Sf}
\]

\[
\Delta m_{\text{CO}_2} = \frac{\Delta T_{\text{max}}}{Sf} - \frac{F_c}{f}
\]

\[
f \approx \frac{F_{2x}}{m_c \ln 2} = 0.014 \text{ W m}^{-2} \text{ ppm}^{-1}
\]
ALLOWABLE FUTURE CO₂ EMISSIONS

Allowable CO₂ emissions = \text{Max} \ \Delta \text{CO₂ mixing ratio} / \left( \begin{array}{c}
\text{Conversion factor, ppm per PgC} \\
\times \text{Airborne fraction of emitted CO₂,}\end{array} \right) \\
\sim 0.5

E_{\text{CO₂}} = \Delta m_{\text{CO₂}} / cr
HOW LONG CAN WE CONTINUE TO EMIT CO\textsubscript{2} AT THE PRESENT RATE?

<table>
<thead>
<tr>
<th>Years at present</th>
<th>Allowable CO\textsubscript{2} emissions</th>
<th>Present CO\textsubscript{2} emission rate, 9 Pg yr\textsuperscript{-1}</th>
</tr>
</thead>
</table>

\[ t_{\text{CO}_2} = \frac{E_{\text{CO}_2}}{q} \]
ALLOWABLE FUTURE CO₂ 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, 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, threshold is exceeded by \( \sim 30 \) years.
APPROACHES TO DETERMINING CLIMATE SENSITIVITY

Climate models

Empirical
  Paleo: Concerns over accuracy
  Sensitivity = Time constant/Heat Capacity

Instrumental record
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.

How can this be?  

IPCC AR4, 2007
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
From known forcing, temperature change, and heating rate

\[
\text{Temp change} = \text{Sensitivity} \times \left( \text{Forcing} - \text{Heating rate} \right) = \text{Sensitivity} \times \text{Effective forcing}
\]

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

or

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

Effect of uncertainty in forcing

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

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.
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.