WHY HASN'T EARTH WARMED AS MUCH AS EXPECTED? ✳

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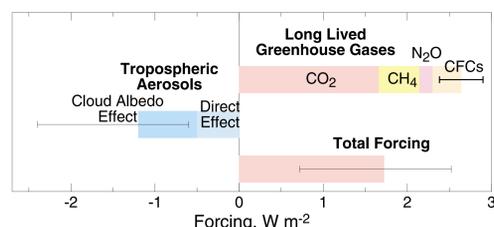Department of Meteorology, Stockholm University, Stockholm, Sweden

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✳ FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

Total forcing includes other anthropogenic and natural (solar) forcings.
Forcing by tropospheric ozone, ~0.35 W m^{-2}, is the greatest of these.

HOW MUCH WARMING IS EXPECTED?

$$\text{Equilibrium change in global mean surface temperature} = \text{Climate sensitivity} \times \text{Forcing}$$

$$\Delta T = S \times F$$

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

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

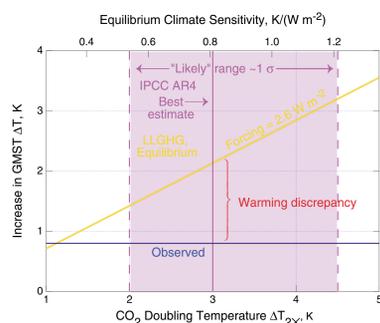IPCC best estimate sensitivity

Expected temperature increase:

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

Observed temperature increase:

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

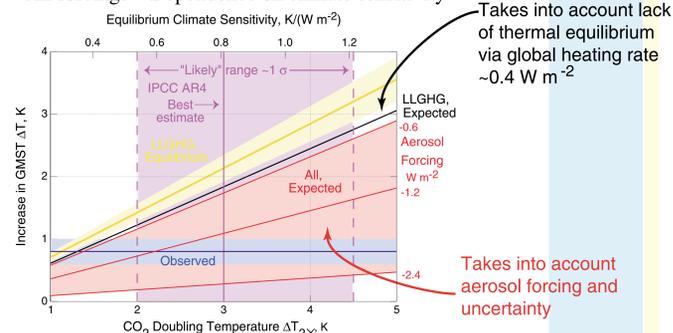### EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity

This discrepancy holds throughout the IPCC AR4 "likely" range for climate sensitivity.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

All forcings – Dependence on climate sensitivity

Takes into account lack of thermal equilibrium via global heating rate ~0.4 W m^{-2}

Takes into account aerosol forcing and uncertainty

The warming discrepancy is certainly resolved by countervailing aerosol forcing (within the IPCC range) for virtually any value of sensitivity.

WHY THE EARTH CLIMATE HASN'T WARMED AS MUCH AS EXPECTED FROM FORCING BY LONG-LIVED GREENHOUSE GASES

- Uncertainty in greenhouse gas forcing. minor
- Countervailing natural cooling over the industrial period. minor   ~ 0.4 W m^{-2};
- Lag in reaching thermal equilibrium. about 15%
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.

Warming discrepancy is attributed to a mix of these two causes.

IMPLICATIONS

EMPIRICAL OR MODEL DETERMINATION OF CLIMATE SENSITIVITY
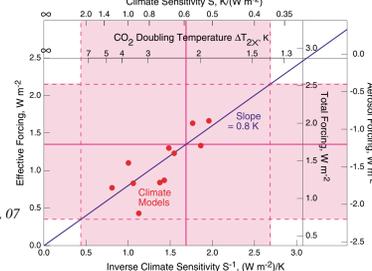
Effect of uncertainty in forcing

$$F_{\text{eff}} = F - H$$
$$\Delta T = SF_{\text{eff}}$$
$$F_{\text{eff}} = \Delta T S^{-1}$$

H = global heating rate, from ocean heating rate, ~0.4 W m^{-2}.

Model sensitivities and forcings from Kiehl, GRL, 07

Present uncertainty in aerosol forcing precludes meaningful determination of climate sensitivity from temperature increase over industrial period.
Uncertainty in aerosol forcing allows climate models with widely differing sensitivities to reproduce temperature increase over industrial period.

ALLOWABLE FUTURE CO$_2$ EMISSIONS

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

For $\Delta T_{\max}$ = 2 K . . .
If sensitivity $\Delta T_{2\times}$ is 3 K, *no more emissions*.
If sensitivity $\Delta T_{2\times}$ is 2 K, *~ 30 more years of emissions at present rate*.
If sensitivity $\Delta T_{2\times}$ is 4.5 K, *threshold is exceeded by ~30 years*.

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 CO$_2$ (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*.