OBSERVATION BASED INTERPRETATION OF CLIMATE CHANGE VIA SIMPLE ENERGY-BALANCE MODELS

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viewgraphs available at www.ecd.bnl.gov/steve
SOME SIMPLE QUESTIONS ABOUT CLIMATE CHANGE

How much has *Global Mean Surface Temperature* (GMST) increased over the industrial period?

What is the magnitude of *forcing* over the industrial period? How does this compare to other energy flows in the climate system?

How is “*equilibrium climate sensitivity*” defined?

What is Earth’s equilibrium climate sensitivity?

What is the expected “*equilibrium*” increase in GMST?

Why hasn’t GMST increased as much as expected?

How much of this is due to *time lag of response* of the climate system?

What is the magnitude of the *planetary energy imbalance*?
SOME MORE SIMPLE QUESTIONS ABOUT CLIMATE CHANGE

How much of the warming discrepancy is due to *offsetting forcing by tropospheric aerosols*?

How much more warming is “in the pipeline” – committed warming? How long will it take to realize this warming?

How is “*transient climate sensitivity*” defined? What is Earth’s transient climate sensitivity?

What are the relevant time constants of the climate system? What are the relevant heat capacities?
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GLOBAL ANNUAL TEMPERATURE ANOMALY, 1880-2010

Data: Goddard Institute for Space Studies
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EARTH’S RADIATION BUDGET AND THE GREENHOUSE EFFECT

Radiative Fluxes in W m⁻²

1/4 solar constant

106

48

27

237 254 K

69% = 1-α

254 K

1/4 S₀ (1-α) = σT⁴

Stefan-Boltzmann Radiation law

Radiation law

Latent heat 90

Sensible heat 16

H₂O, CO₂, CH₄

31

390 ≈ 288 K

Latent heat 90

Sensible heat 16

Modified from Schwartz, 1996; Ramanathan, 1987
Global carbon dioxide concentration has increased in the past 200 years, mainly because of fossil fuel combustion.
RADIATIVE FORCING

An externally imposed *change* in Earth’s radiation budget, $F$, W m$^{-2}$.

**Working hypothesis:**
*On a global basis radiative forcings are additive and interchangeable.*

- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

The increase in CO$_2$, a greenhouse gas, has produced a radiative forcing which is now 1.7 W m$^{-2}$. 

The diagram shows the CO$_2$ concentration in parts per million (ppm) over the years, with polar ice core data from Law Dome, Adelie Land, Siple, and South Pole. The graph also indicates the radiative forcing in units of W m$^{-2}$.
Gases are uniformly distributed; radiation transfer is well understood. Greenhouse gas forcing is considered accurately known.
EARTH’S RADIATION BUDGET AND THE GREENHOUSE EFFECT

1/4 solar constant = 343 W m⁻²

Albedo = 31%

Radiative Fluxes

Energy Imbalance

Shortwave absorbed

Longwave emitted

1/4 S₀ (1-α) = σT⁴

Stefan-Boltzmann Radiation law

Radiative Fluxes in W m⁻²

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CLIMATE SYSTEM RESPONSE

Increase in Equilibrium
global mean surface climate × Forcing
temperature sensitivity

\[ \Delta T = S_{eq} \times F \]

\( S_{eq} \) is Earth’s “equilibrium” climate sensitivity,
unit: \( \text{K} / (\text{W m}^{-2}) \)

CO₂ DOUBLING TEMPERATURE

Climate sensitivity is commonly expressed as
“CO₂ doubling temperature,” unit: K or °C

\[ \Delta T_{2\times} = S_{eq} \times F_{2\times} \]

where \( F_{2\times} \) is the CO₂ doubling forcing, \text{ca.} 3.7 \text{ W m}^{-2}. \)
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.
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What is the magnitude of the planetary energy imbalance?
**EXPECTED WARMING**

For increases in CO₂, CH₄, N₂O, and CFCs over the industrial period, *forcing* \( F = 2.8 \ \text{W m}^{-2} \),

CO₂ doubling forcing \( F_{2\times} = 3.7 \ \text{W m}^{-2} \),

IPCC best estimate *doubling temperature* \( \Delta T_{2\times} = 3 \ \text{K} \),

The expected “equilibrium” temperature increase is

\[
\Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.8}{3.7} \times 3 \ \text{K} = 2.3 \ \text{K}
\]
THE WARMING DISCREPANCY

*Expected* temperature increase: $\Delta T_{\text{exp}} = 2.3$ K

*Observed* temperature increase: $\Delta T_{\text{obs}} = 0.8$ K

How can we account for this *warming discrepancy*?
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What is the magnitude of the planetary energy imbalance?
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.
GLOBAL ENERGY BUDGET

\[
\frac{dH}{dt} \equiv N = J_{\text{abs}} - J_{\text{emit}} = 0
\]

For unperturbed climate system (steady state),

\[
\frac{dH}{dt} \equiv N = J_{\text{abs}} - J_{\text{emit}} = 0
\]

Apply a forcing:

\[
\frac{dH}{dt} \equiv N = F
\]

Climate system responds:

\[
\frac{dH}{dt} \equiv N = F - R
\]

Linear response ansatz:

\[
R = \lambda \Delta T
\]

Energy budget equation:

\[
N = F - \lambda \Delta T
\]
“EQUILIBRIUM” CLIMATE SENSITIVITY

\[ N = F - \lambda \Delta T \]

\[ \lambda \Delta T = F - N \]

\[ \Delta T = \frac{F - N}{\lambda} \]

At new **steady state** following response to constant forcing \( F \),
\( N \to 0 \) and

\[ \Delta T \to \frac{F}{\lambda} = \Delta T_{eq} = S_{eq} F, \]

where “equilibrium” climate sensitivity \( S_{eq} \equiv \lambda^{-1} \).
EARTH’S ENERGY IMBALANCE AND EXPECTED WARMING

In general

$$\Delta T = \frac{F - N}{\lambda}$$

Hence

$$\Delta T = S_{eq} (F - N)$$

Energy imbalance is subtractive from forcing (effective forcing);

$$F_{\text{eff}} \equiv (F - N); \quad \Delta T = S_{eq} F_{\text{eff}}$$

$S_{eq}N$ is heating in the pipeline, committed additional warming.
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OCEAN HEAT CONTENT ANOMALY

Surface to 700 m, relative to 1993-2002

Range of slopes, $0.45 \pm 0.25$ W m$^{-2}$, brackets most analyses.
Slope is increasing, from 0.2 W m$^{-2}$ (1970-95) to 0.5 W m$^{-2}$ (2000-08).

EXPECTED WARMING

For increases in CO₂, CH₄, N₂O, and CFCs over the industrial period, forcing \( F = 2.8 \text{ W m}^{-2} \),

Planetary heating rate \( dH / dt = 0.8 \text{ W m}^{-2} \),

Effective forcing \( F_{\text{eff}} = F - dH / dt = 2.0 \text{ W m}^{-2} \),

CO₂ doubling forcing \( F_{2\times} = 3.7 \text{ W m}^{-2} \),

IPCC best estimate doubling temperature \( \Delta T_{2\times} = 3 \text{ °C} \),

The expected temperature increase is

\[
\Delta T_{\text{exp}} = \frac{F_{\text{eff}}}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.0}{3.7} \times 3 \text{ °C} = 1.6 \text{ °C}
\]
THE WARMING DISCREPANCY

*Expected* temperature increase: $\Delta T_{\text{exp}} = 1.6 \, ^\circ\text{C}$

*Observed* temperature increase: $\Delta T_{\text{obs}} = 0.8 \, ^\circ\text{C}$

There is still a substantial *warming discrepancy*. 
EXPECTED TEMPERATURE INCREASE

Based on greenhouse gas forcing only, 2.8 W m$^{-2}$, with planetary heating rate 0.8 W m$^{-2}$ (effective forcing 2.0 W m$^{-2}$)

![Diagram showing temperature increase vs climate sensitivity]

Expected temperature increase exceeds observed for entire IPCC (2007) sensitivity range.

Depending on sensitivity, expected temperature increase approaches or exceeds 2°C, widely accepted threshold for onset of dangerous anthropogenic interference with the climate system.
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.
SOME MORE SIMPLE QUESTIONS ABOUT CLIMATE CHANGE

How much of the warming discrepancy is due to \textit{offsetting forcing by tropospheric aerosols}?\footnote{\	extbf{Ans} \textit{Future warming in the pipeline} is about 2°C for RCP8.5, which is \\amounting to orders of magnitude less than the warming due to \textit{transient climate sensitivity}.}

How much more warming is “\textit{in the pipeline}” – committed warming? How long will it take to realize this warming?

How \textit{“transient climate sensitivity”} defined? What is Earth’s transient climate sensitivity?

What are the relevant time constants of the climate system? What are the relevant heat capacities?
AEROSOL IN MEXICO CITY BASIN

Photo credit: Berk Knighton
Light scattering by aerosols decreases absorption of solar radiation.
AEROSOLS AS SEEN FROM SPACE

Fire plumes from southern Mexico transported north into Gulf of Mexico.
Aerosols from ship emissions enhance reflectivity of marine stratus.
Green curve is LOWESS (locally weighted scatterplot smoothing) fit.
Global average sulfate optical thickness is 0.03: 1 W m\(^{-2}\) cooling.

In continental U. S. typical aerosol optical thickness is 0.1: 3 W m\(^{-2}\) cooling.
Aerosols exert a negative (cooling) forcing, opposite to greenhouse gases.
THE GREENHOUSE EFFECT AND EARTH’S RADIATION BUDGET

Radiative Fluxes in W m\(^{-2}\)

- \(106 + 1.2\) Forcing
- \(1/4\) solar constant
  - \(343\) W m\(^{-2}\)
- Rayleigh
  - 27
- Aerosol
  - 4
- Albedo
  - \(\alpha = 31\%\)

Atmosphere

Latent heat 90
Sensible heat 16

H\(_2\)O, CO\(_2\), CH\(_4\)...

Shortwave absorbed = Longwave emitted

\(1/4 \ S_0 \ (1-\alpha) = \sigma T^4\)

Stefan-Boltzmann Radiation law

69\% = 1-\(\alpha\)

237 K

254 K

296 + 2.8 Forcing

31

390 ≈ 288 K

68

Modified from Schwartz, 1996; Ramanathan. 1987
Aerosol forcing may offset much of the greenhouse gas forcing.

*Uncertainty in total forcing is dominated by uncertainty in aerosol forcing.*
GLOBAL ENERGY BALANCE MODELS
Single compartment climate model
Energy conservation in the climate system:

\[
\frac{dH}{dt} \equiv N = Q - E
\]

\(H\) = planetary heat content;

\(N\) = net heating rate of planet;

\(Q\) = absorbed shortwave at TOA;

\(E\) = emitted longwave at TOA.

Unperturbed steady state (equilibrium) climate:

\(N = 0; \quad Q_0 = E_0\)
**Net heating rate with external forcing $F$ applied:**

$$N(t) = Q(t) - E(t) + F(t)$$

**Initially after onset of forcing**

$$Q = Q_0; \quad E = E_0; \quad N = F$$

**Climate response to forcing**

$$N(t) = F(t) + \frac{\partial(Q - E)}{\partial T} \Delta T(t)$$

$$N(t) = F(t) - \lambda \Delta T(t)$$

where $\lambda \equiv -\frac{\partial(Q - E)}{\partial T}$ is *climate response coefficient*.

$\lambda$ is a geophysical property of Earth’s climate system.
At new steady state (equilibrium) following application of constant forcing $F$

\[ N = 0; \quad \lambda \Delta T = F; \quad \Delta T = \lambda^{-1} F = S_{eq} F \]

$S_{eq}$ = equilibrium climate sensitivity $= \lambda^{-1}$.

$S_{eq}$ is a geophysical property of Earth’s climate system.
Two compartment climate model

\[ \kappa (\Delta T_U - \Delta T_L) \]
TIME RESPONSE IN
TWO-COMPARTMENT MODEL

Response to step-function forcing

Parameters:

<table>
<thead>
<tr>
<th></th>
<th>Single</th>
<th>Upper</th>
<th>Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Constant, yr</td>
<td>8</td>
<td>8</td>
<td>567</td>
</tr>
<tr>
<td>Heat Capacity, W yr m^{-2} K^{-1}</td>
<td>20</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td>Sensitivity K(W m^{-2})^{-1}</td>
<td>0.4</td>
<td>$S_{tr} = 0.4$</td>
<td>$S_{eq} = 0.67$</td>
</tr>
</tbody>
</table>

Heat exchange coefficient, $\kappa = 1$ W m^{-2} K^{-1}

One-compartment model is indistinguishable from two-compartment model on time scales of 50 years or more, but levels off to transient sensitivity.
PREDECESSORS TO THIS MODEL

Gregory,  
*Climate Dynamics*,  
2001

\[ cd_u \frac{dT_u}{dt} = H - k(T_u - T_l) \]

\[ cd_l \frac{dT_l}{dt} = k(T_u - T_l) \]

Held et al,  
*J. Climate*,  
2010

\[ c_F \frac{dT}{dt} = \mathcal{F} - \beta T - \gamma(T - T_D) \]

\[ c_D \frac{dT_D}{dt} = \gamma(T - T_D) \]

Schwartz,  
*JGR*,  
2008

\[ I \]

\[ V \]

\[ R' \]

\[ K \]

\[ V' \]

\[ C' \]

\[ \lambda \]

Space

Deep ocean
Two compartment climate model

\[
\begin{align*}
\text{SW} & \quad \text{SW} & \quad \text{LW} & \quad F \downarrow & \quad \delta \text{SW} & \quad \delta \text{LW} \\
\text{U} & \quad \text{Atmosphere} & \quad \text{Upper Ocean} \\
\downarrow & \quad \kappa (\Delta T_U - \Delta T_L) \\
\text{L} & \quad \text{Deep Ocean} & \quad \text{Large Heat Capacity} & \quad \text{Long Time Constant}
\end{align*}
\]
How much of the warming discrepancy is due to *offsetting forcing by tropospheric aerosols*?

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What are the relevant time constants of the climate system? What are the relevant heat capacities?
**TRANSIENT CLIMATE SENSITIVITY**

*Hypothesis: Planetary heating rate proportional to $\Delta T$*

$$N(t) = \kappa \Delta T(t)$$

$\kappa =$ *heat exchange coefficient*, a geophysical property of Earth’s climate system.

$$N(t) = F(t) - \lambda \Delta T(t)$$

$$F(t) = (\kappa + \lambda) \Delta T(t); \quad \Delta T(t) = (\kappa + \lambda)^{-1} F(t) = S_{tr} F(t)$$

$S_{tr} =$ *transient climate sensitivity*, $S_{tr} \equiv (\kappa + \lambda)^{-1}$, a geophysical property of Earth’s climate system.

Contrast equilibrium sensitivity, $S_{eq} = \lambda^{-1}$
SOME MORE SIMPLE QUESTIONS ABOUT CLIMATE CHANGE

How much of the warming discrepancy is due to \textit{offsetting forcing by tropospheric aerosols}?

How much more warming is \textit{“in the pipeline”} – committed warming? How long will it take to realize this warming?

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Response times in two-compartment model

\[ \tau_s = \frac{C_U}{\kappa + \lambda} \quad \tau_1 = C_L \left( \frac{1}{\lambda} + \frac{1}{\kappa} \right) \]

Obtained from eigenvalues, to first order in \( C_U / C_L \).

\( \tau_s \) and \( \tau_1 \) are geophysical properties of Earth’s climate system.

\( C_L \) is heat capacity of deep ocean (average depth 3.8 km; fractional area 0.71).

Other quantities to be determined empirically.
Determination of transient sensitivity

Recall $S_{tr} = \text{transient climate sensitivity}$, $S_{tr} \equiv (\kappa + \lambda)^{-1}$

$$\tau_s = \frac{C_U}{\kappa + \lambda}$$

Hence, $S_{tr} = \frac{\tau_s}{C_U}$

One equation in three unknowns!

**Approach:** Determine $\tau_s$ and $C_U$ from observations.

Determination of equilibrium sensitivity

$$S_{eq} = \lambda^{-1} = \left(S_{tr}^{-1} - \kappa\right)^{-1}$$

**Approach:** Determine $\kappa$ from observations.
TIME CONSTANT OF UPPER COMPARTMENT OF EARTH’S CLIMATE SYSTEM
Determination from autocorrelation of time series

*Input:* Monthly global-mean surface temperature anomaly $T_s$

*Calculate* correlation coefficient of detrended time series with itself, lagged by $\Delta t$, $r(\Delta t)$.

$$r(\Delta t) = e^{-\Delta t/\tau}, \text{ whence } \tau(\Delta T) = -\Delta T / \ln r(\Delta T) = 8.6 \pm 0.7 \text{ yr.}$$

_Schwartz, JGR, 2008_
Hypothesis: Planetary heat content increases linearly with surface temperature $\Delta T$.

Plot $H(t)$ vs $\Delta T(t)$; determine $C_U$ as slope.
OCEAN HEAT CONTENT ANOMALY

Surface to 700 m, relative to 1993-2002

Range of slopes, $0.45 \pm 0.25$ W m$^{-2}$, brackets most analyses.
Slope is increasing, from 0.2 W m$^{-2}$ (1970-95) to 0.5 W m$^{-2}$ (2000-08).
Heat content varies linearly with temperature anomaly.

Heat capacity determined as slope, accounting for additional heat sinks (deep ocean, air, land, ice melting).

Upper compartment heat capacity $C_U = 21.8 \pm 2.1 \text{ W yr m}^{-2} \text{ K}^{-1}$ (1 $\sigma$, based on fit, not systematic errors); equivalent to 170 m of seawater, globally.
EMPIRICAL DETERMINATION OF TRANSIENT CLIMATE SENSITIVITY

\[ S_{tr} = \frac{\tau_s}{C_U} \]

\[ \tau_s = 8.6 \pm 0.7 \text{ yr} \]

\[ C_U = 21.8 \pm 2.1 \text{ W yr m}^{-2} \]

Hence \( S_{tr} = 0.39 \pm 0.05 \text{ K / (W m}^{-2}) \)

\[ \Delta T_{2x, tr} = 1.5 \pm 0.2 \text{ K} \]
EMPIRICAL DETERMINATION OF HEAT EXCHANGE COEFFICIENT

**Hypothesis:** Planetary heating rate proportional to $\Delta T$

$$N(t) = \kappa \Delta T(t)$$

$\kappa = \text{heat exchange coefficient.}$

**Plot** $N(t)$ vs $\Delta T(t)$; determine $\kappa$ as slope (with zero origin).

$\kappa$ is a geophysical property of Earth’s climate system.
GLOBAL OCEAN HEATING RATE

Derivative of global heat content, from smoothed ocean heat content

Are fluctuations "real? What is the uncertainty?

Should do for individual reconstructions of ocean heat content to get sense of uncertainty.

Schwartz, Surv. Geophys, 2012
Global heating rate vs temperature anomaly

Heating rate (time derivative of ocean heat content) is linearly proportional to temperature anomaly.

Heat exchange coefficient $\kappa = 1.05 \pm 0.06 \text{ W m}^{-2} \text{ K}^{-1}$ (1$\sigma$, based on fit, not systematic errors).

Start Year 1965

- $a = 0$
- $b = 1.05 \pm 0.06$
- $R^2 = 0.679$

- $a = -0.02 \pm 0.05$
- $b = 1.09 \pm 0.11$
- $R^2 = 0.681$
Recall $S_{tr} = transient\ climate\ sensitivity$, $S_{tr} \equiv (\kappa + \lambda)^{-1}$

$S_{eq} = \lambda^{-1} = \left( S_{tr}^{-1} - \kappa \right)^{-1}$

$S_{tr} = 0.39 \pm 0.05\ K / (W\ m^{-2})$

*Heat exchange coefficient* $\kappa = 1.06 \pm 0.05\ W\ m^{-2}\ K^{-1}$

Hence *equilibrium climate sensitivity*

$S_{eq} = 0.68 \pm 0.09\ K / (W\ m^{-2})$

CO$_2$ doubling temperature $\Delta T_{2\times,eq} = 2.5 \pm 0.3\ K$

Remarkably close to central value of IPCC AR4 assessment: 3K, range 2 – 4.5 K.
DETERMINATION OF TWENTIETH CENTURY FORCING

Observed increase in temperature is proportional to forcing by the transient climate sensitivity, $S_{tr}$

$$\Delta T_{obs}(t) = S_{tr} F(t)$$

Hence

$$F(t) = \frac{\Delta T_{obs}(t)}{S_{tr}}$$

For $S_{tr} = 0.39 \pm 0.05 \text{ K} / (\text{W} \text{ m}^{-2})$

$\Delta T_{1900-2005} = 0.71 \pm 0.05 \text{ K}$

$F_{1900-2005} = 1.79 \pm 0.26 \text{ W} \text{ m}^{-2}$
Twentieth century forcing is also remarkably close to IPCC central estimate (well within 1 σ).
<table>
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<tr>
<th>Quantity</th>
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<th>Value</th>
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<tr>
<td>$C_U$</td>
<td>W yr $m^{-2} K^{-1}$</td>
<td>21.8</td>
<td>2.1</td>
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<td>$\tau_l$</td>
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SOME SIMPLE QUESTIONS ABOUT CLIMATE CHANGE

How much has *Global Mean Surface Temperature* (GMST) increased over the industrial period? **0.8 K**

What is the magnitude of *forcing* over the industrial period? **1.8 ± 0.3 W m\(^{-2}\)**

How is “*equilibrium climate sensitivity*” defined?

What is Earth’s equilibrium climate sensitivity? **0.68 ± 0.09 K/(W m\(^{-2}\)); ΔT\(_{2\times}\) = 2.5 ± 0.3 K**

What is the expected “*equilibrium*” increase in GMST? **1.9 K for GHG's**

Why hasn’t GMST increased as much as expected?

How much of this is due to *time lag of response* of the climate system?

What is the *planetary energy imbalance*? **0.8 W m\(^{-2}\)**
How much of the warming discrepancy is due to **offsetting forcing by tropospheric aerosols**? 0.7 K

How much more warming is “**in the pipeline**” – committed warming? How long will it take to realize this warming? 1.1 K for GHGs; 500 years

How is “**transient climate sensitivity**” defined? What is Earth’s transient climate sensitivity? 1.5 ± 0.2 K

What are the relevant time constants of the climate system? 10 years; 500 years

What are the relevant heat capacities? 20, 340 W yr m⁻² K
SUMMARY & CONCLUSIONS (1)

Global energy-balance models use observations to determine key properties of Earth’s climate system: heat capacities, heating rate, and time constants of response to perturbations.

These models thus afford the possibility of accurate determination of the transient and equilibrium sensitivities of the climate system.

For a two-compartment model the time constants are about 9 years and 500 years, pertinent to the transient and equilibrium sensitivities, respectively.

The rate of planetary heat uptake is found to be proportional to the increase in global temperature relative to the beginning of the twentieth century with heat transfer coefficient \( \kappa = 1.05 \pm 0.06 \text{ W m}^{-2} \text{ K}^{-1} (1 \sigma) \).
SUMMARY & CONCLUSIONS (2)

Earth’s present *energy imbalance* is $0.80 \pm 0.05 \text{ W m}^{-2}$.

The two-compartment model suggests that Earth’s *transient climate sensitivity*, expressed as a CO$_2$ doubling temperature is $1.5 \pm 0.2$ K. The *equilibrium sensitivity* $2.5 \pm 0.3$ K is close to IPCC central estimate.

*Total forcing* over the twentieth century (to 2005) is estimated as $1.8 \pm 0.3 \text{ W m}^{-2}$, indicative of *aerosol offset* of $0.8 \text{ W m}^{-2}$.

For transient sensitivity, present GHG forcing of $2.8 \text{ W m}^{-2}$ implies *committed warming* of $1.1$ K; for this forcing indefinitely sustained, this committed GHG warming would increase to $1.9$ K.

Would I “bet the ranch” on this analysis? **NO!**