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?

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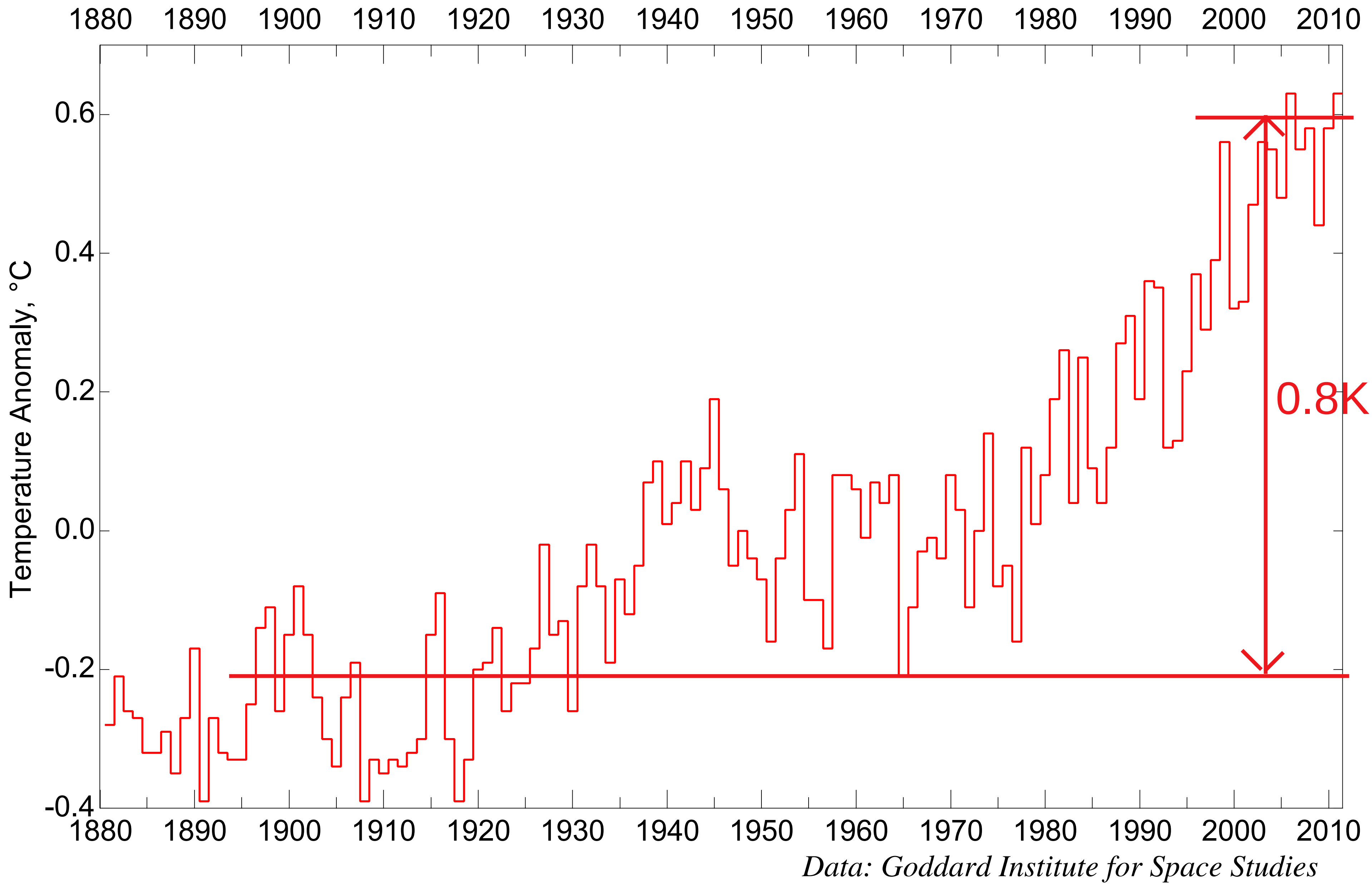
GLOBAL ANNUAL TEMPERATURE ANOMALY, 1880-2010



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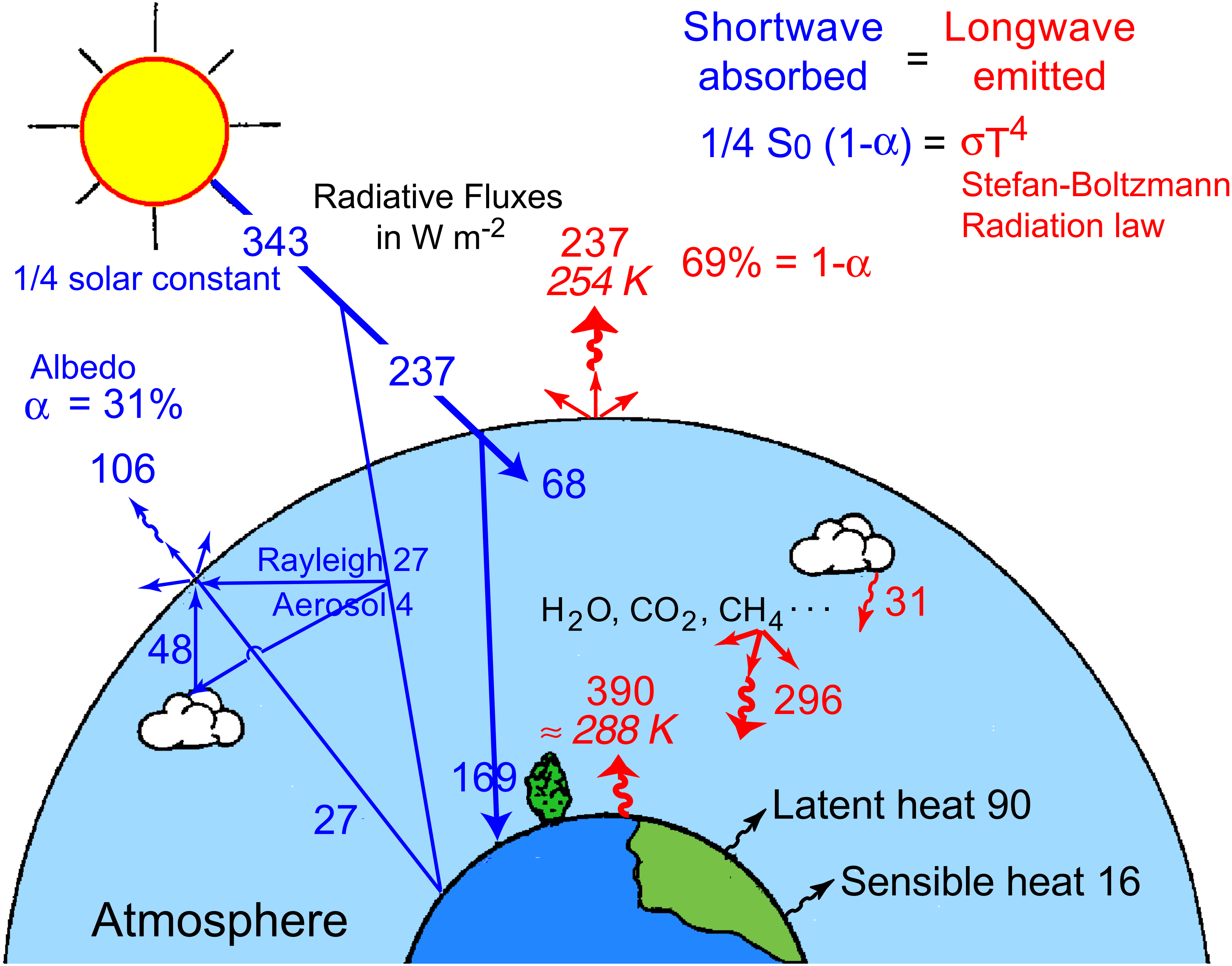
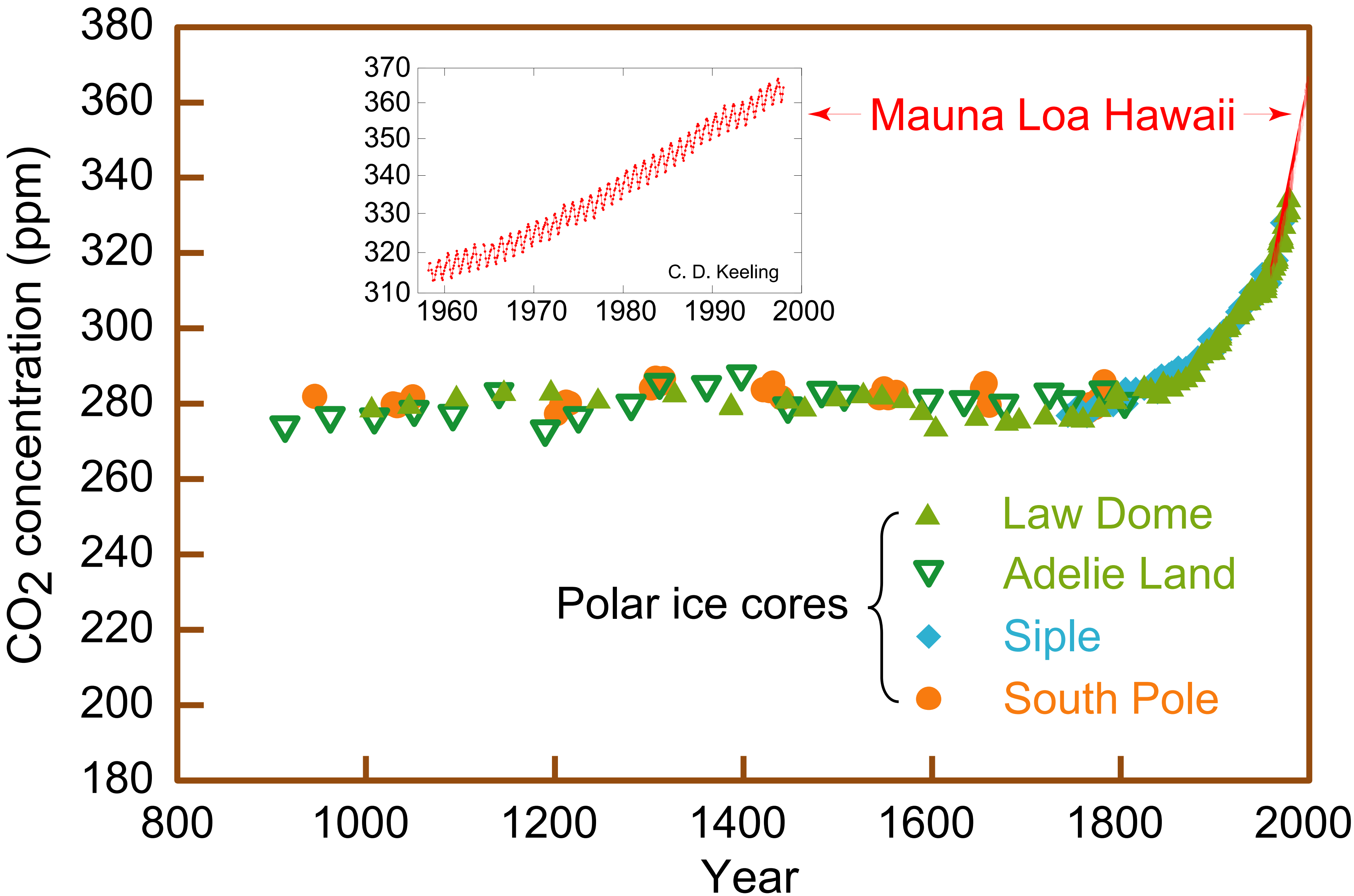
EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



Modified from Schwartz, 1996; Ramanathan. 1987

ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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.

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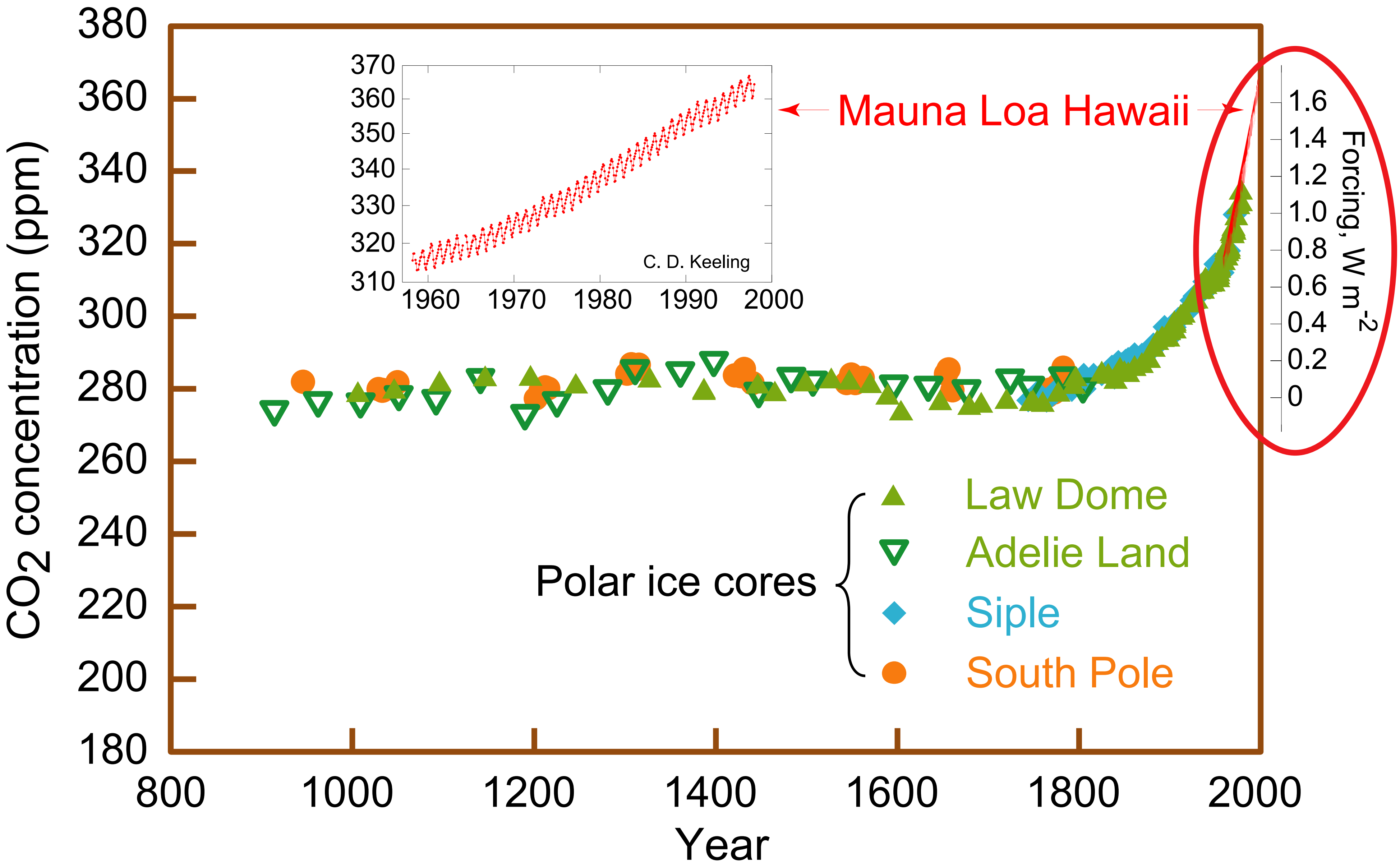
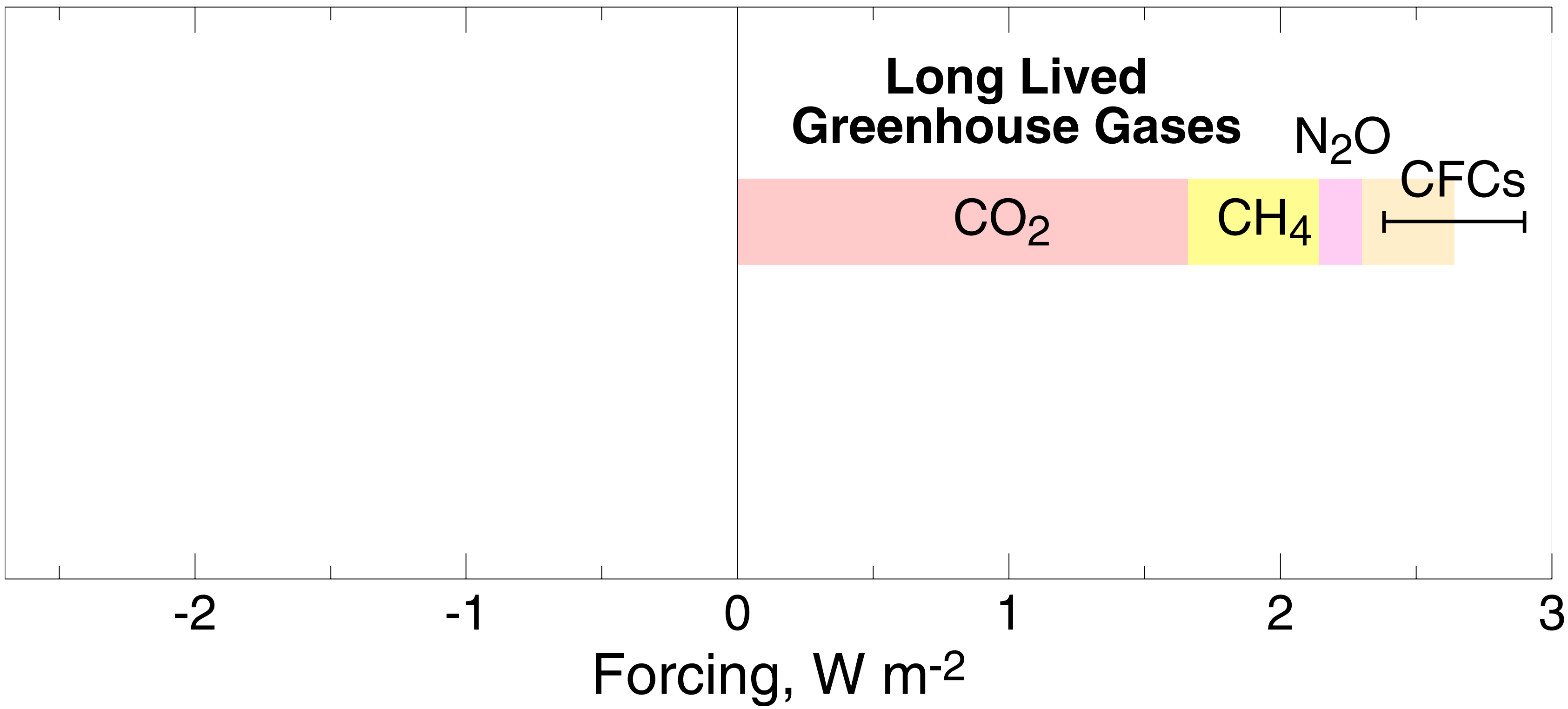


The increase in CO_2, a greenhouse gas, has produced a radiative forcing which is now 1.7 W m^{-2}.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

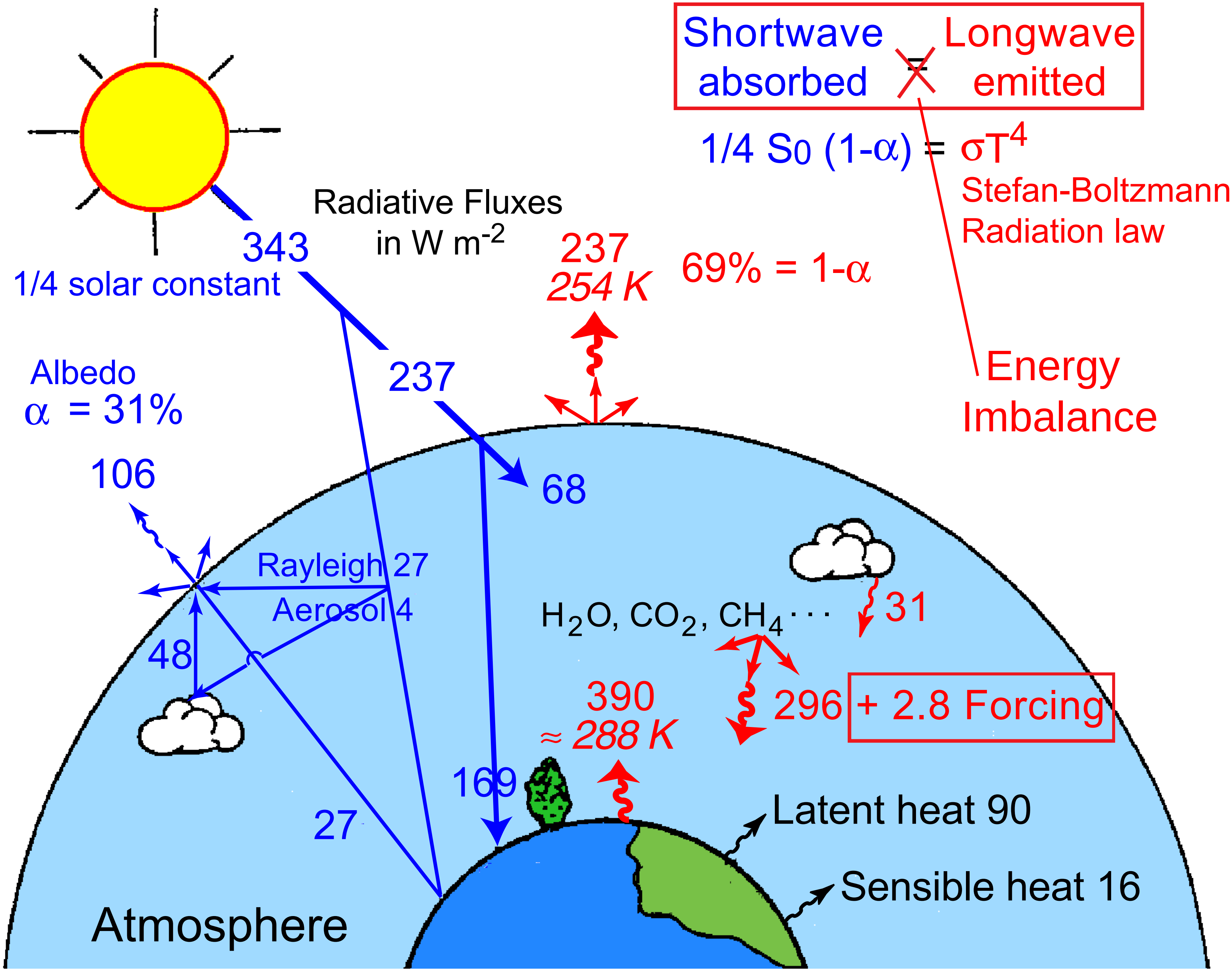
Extracted from IPCC AR4 (2007)



Gases are uniformly distributed; radiation transfer is well understood.

Greenhouse gas forcing is considered accurately known.

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



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CLIMATE SYSTEM RESPONSE

Increase in global mean surface temperature = Equilibrium climate sensitivity × Forcing

$$\Delta T = S_{\text{eq}} \times F$$

S_{eq} is Earth's ***"equilibrium" climate sensitivity***, unit: K / (W m^{-2})

CO_2 DOUBLING TEMPERATURE

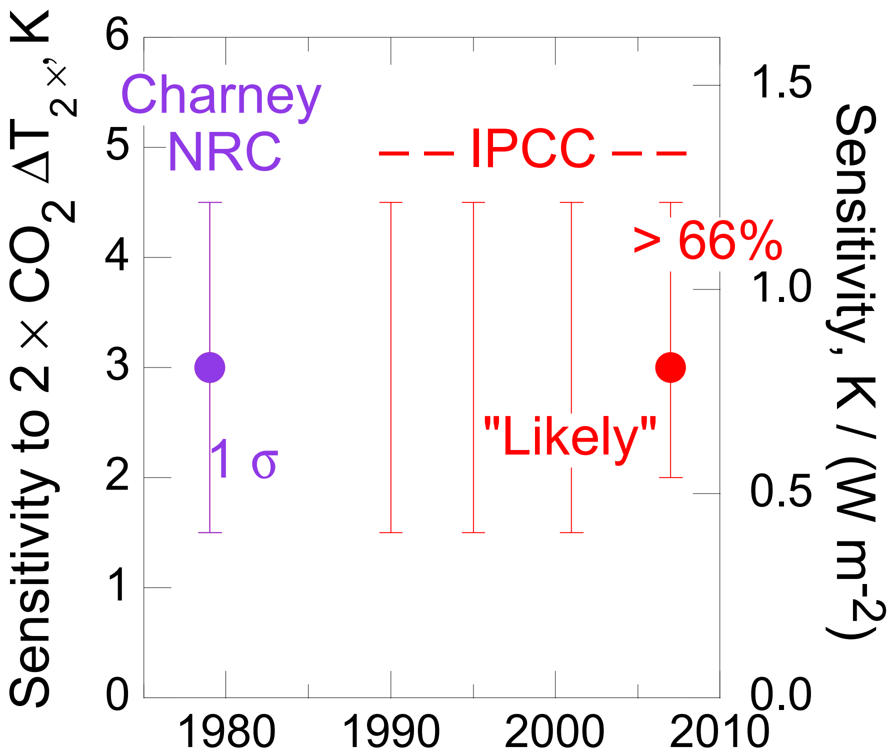
Climate sensitivity is commonly expressed as "CO_2 doubling temperature," unit: K or ˚C

$$\Delta T_{2\times} \equiv S_{\text{eq}} \times F_{2\times}$$

where $F_{2\times}$ is the CO_2 doubling forcing, *ca*. 3.7 W m^{-2}.

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

Major national and international assessments



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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EXPECTED WARMING

For increases in CO_2, CH_4, N_2O, and CFCs over the industrial period, ***forcing*** $F = 2.8\ \mathrm{W\ m^{-2}}$,

CO_2 doubling forcing $F_{2\times} = 3.7\ \mathrm{W\ m^{-2}}$,

IPCC best estimate ***doubling temperature*** $\Delta T_{2\times} = 3\ \mathrm{K}$,

The ***expected "equilibrium" temperature increase*** is

$$\Delta T_{\mathrm{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.8}{3.7} \times 3\ \mathrm{K} = 2.3\ \mathrm{K}$$

THE WARMING DISCREPANCY

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

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

How can we account for this ***warming discrepancy***?

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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

$$\frac{dH}{dt} \equiv N$$

$$\frac{dH}{dt} \equiv N = J_{\text{abs}} - J_{\text{emit}}$$

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, $N \rightarrow 0$ and

$$\Delta T \rightarrow \frac{F}{\lambda} = \Delta T_{\mathrm{eq}} = S_{\mathrm{eq}} F ,$$

where "equilibrium" climate sensitivity $S_{\mathrm{eq}} \equiv \lambda^{-1}$.

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*);

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

$S_{eq}N$ is *heating in the pipeline*, ***committed additional warming***.

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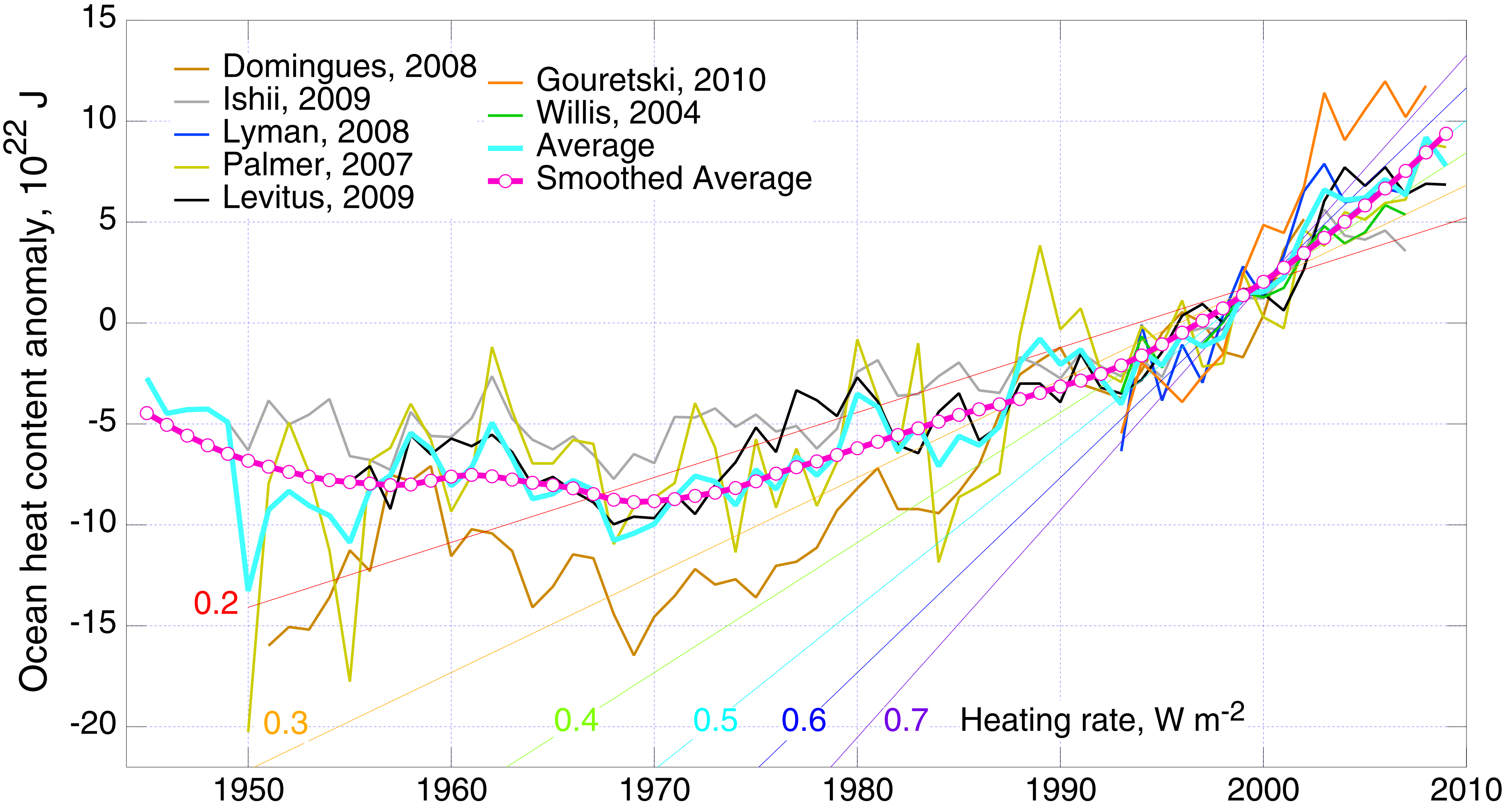
OCEAN HEAT CONTENT ANOMALY

Surface to 700 m, relative to 1993-2002



Schwartz, Surv. Geophys, 2012; Data at http://www.ncdc.noaa.gov/bams-state-of-the-climate/2009-time-series/?ts=ohc

Range of slopes, 0.45 ± 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 CO_2, CH_4, N_2O, 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 $F_{\text{eff}} = F - dH / dt = 2.0 \text{ W m}^{-2}$,

CO_2 doubling forcing $F_{2\times} = 3.7 \text{ W m}^{-2}$,

IPCC best estimate ***doubling temperature*** $\Delta T_{2\times} = 3\ ^\circ\text{C}$,

The ***expected temperature increase*** is

$$\Delta T_{\text{exp}} = \frac{F_{\text{eff}}}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.0}{3.7} \times 3\ ^\circ\text{C} = 1.6\ ^\circ\text{C}$$

THE WARMING DISCREPANCY

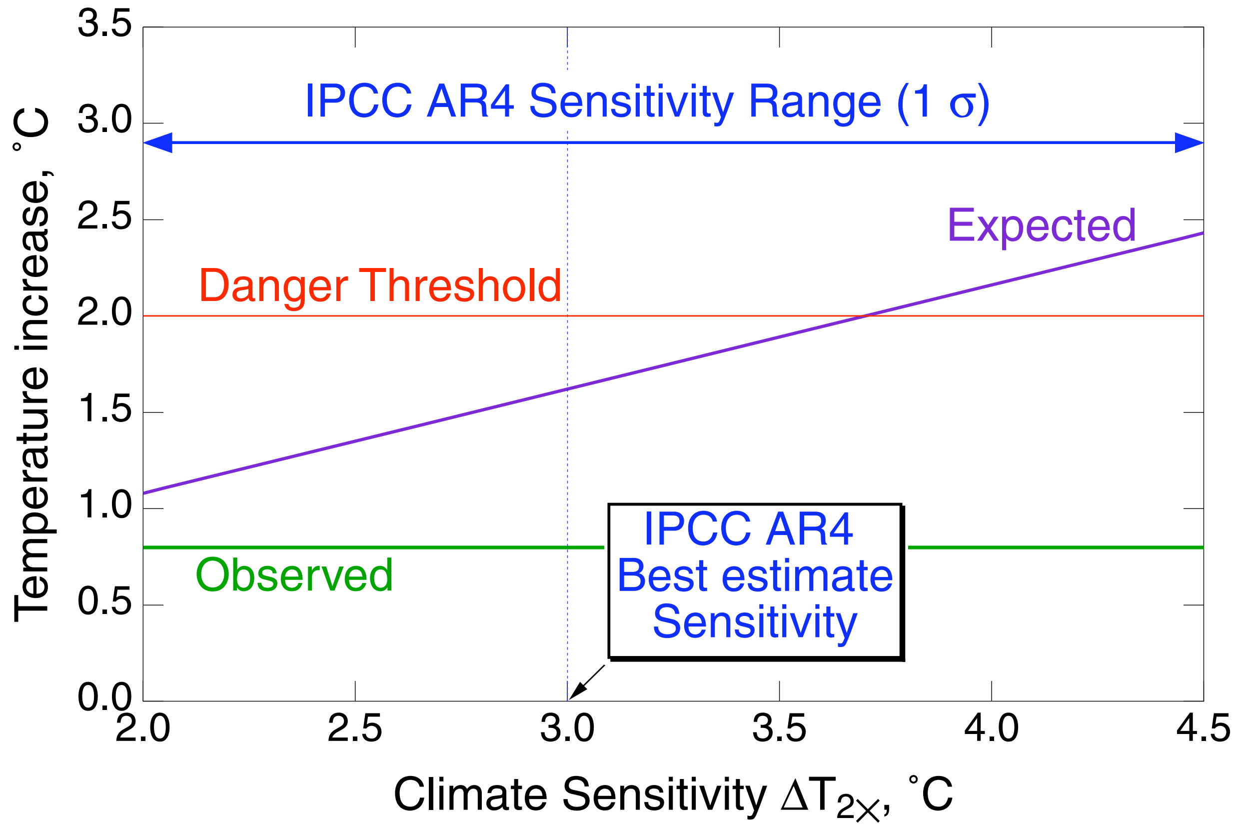
Expected temperature increase: $\Delta T_{\mathrm{exp}} = 1.6\ ^{\circ}\mathrm{C}$

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

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})



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.

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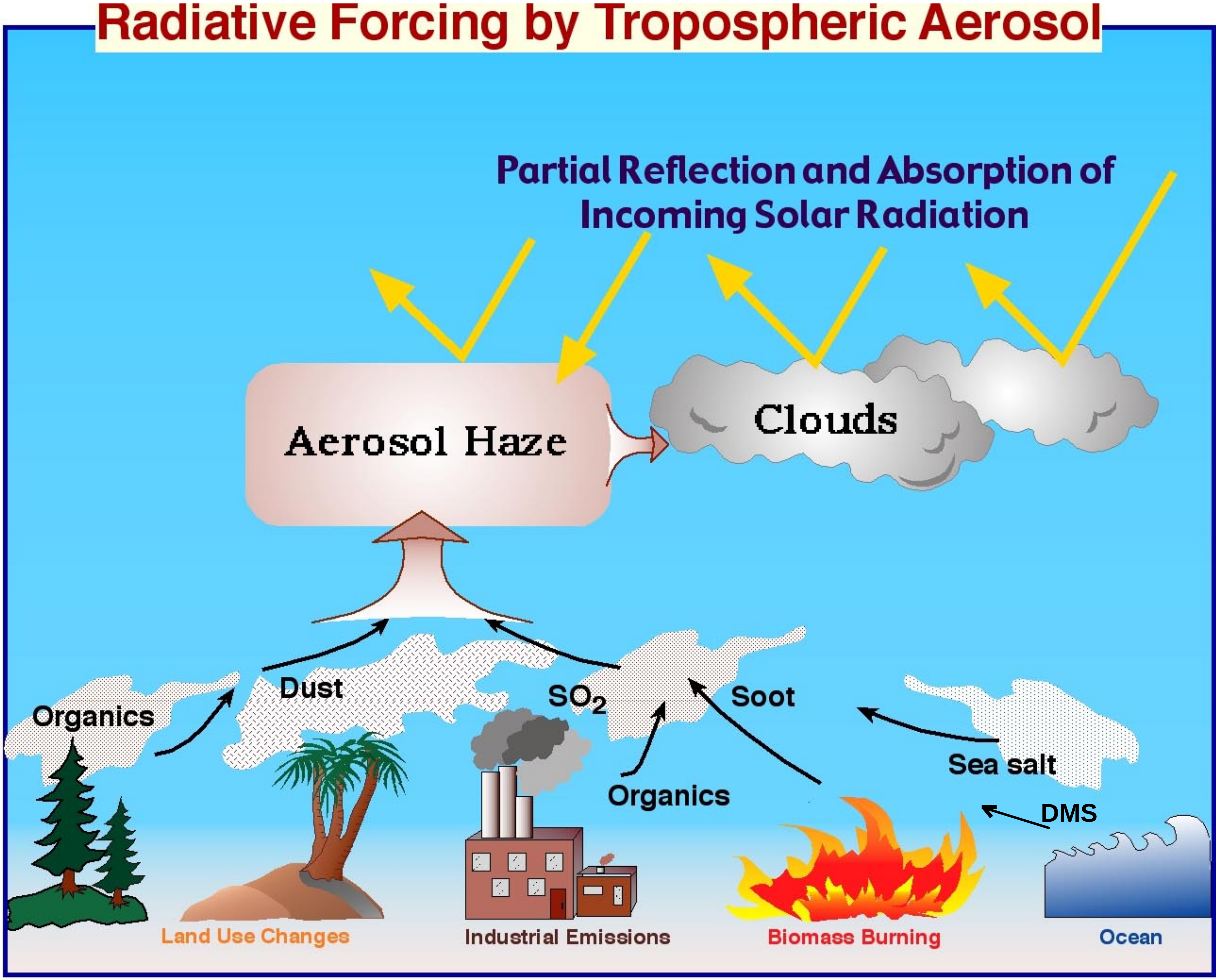
Radiative Forcing by Tropospheric Aerosol
Partial Reflection and Absorption of
Incoming Solar Radiation
Aerosol Haze
Clouds
Organics
Dust
SO_2
Soot
Organics
Sea salt
DMS
Land Use Changes
Industrial Emissions
Biomass Burning
Ocean

AEROSOL IN MEXICO CITY BASIN

Photo credit: Berk Knighton

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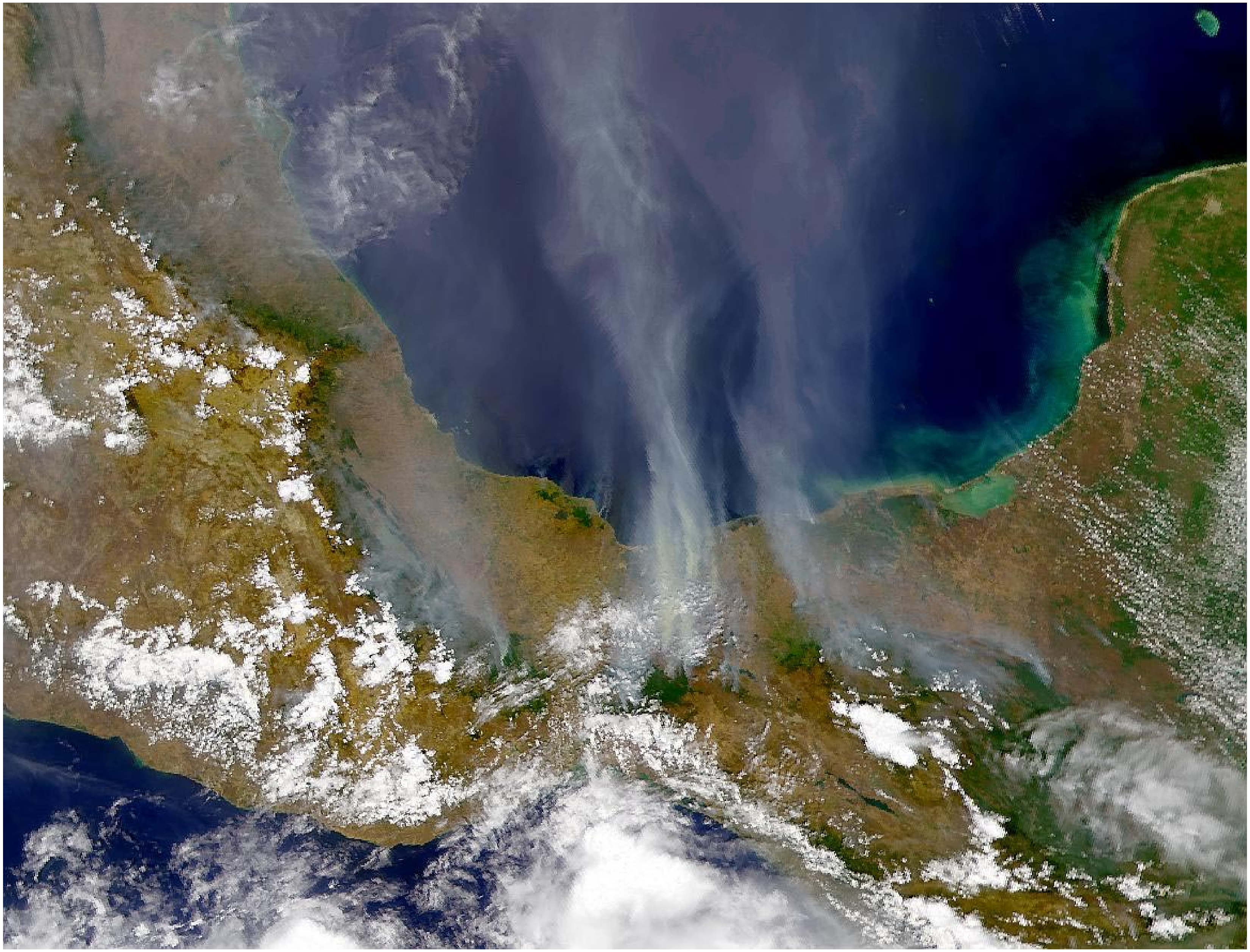
Light scattering by aerosols decreases absorption of solar radiation.

AEROSOLS AS SEEN FROM SPACE

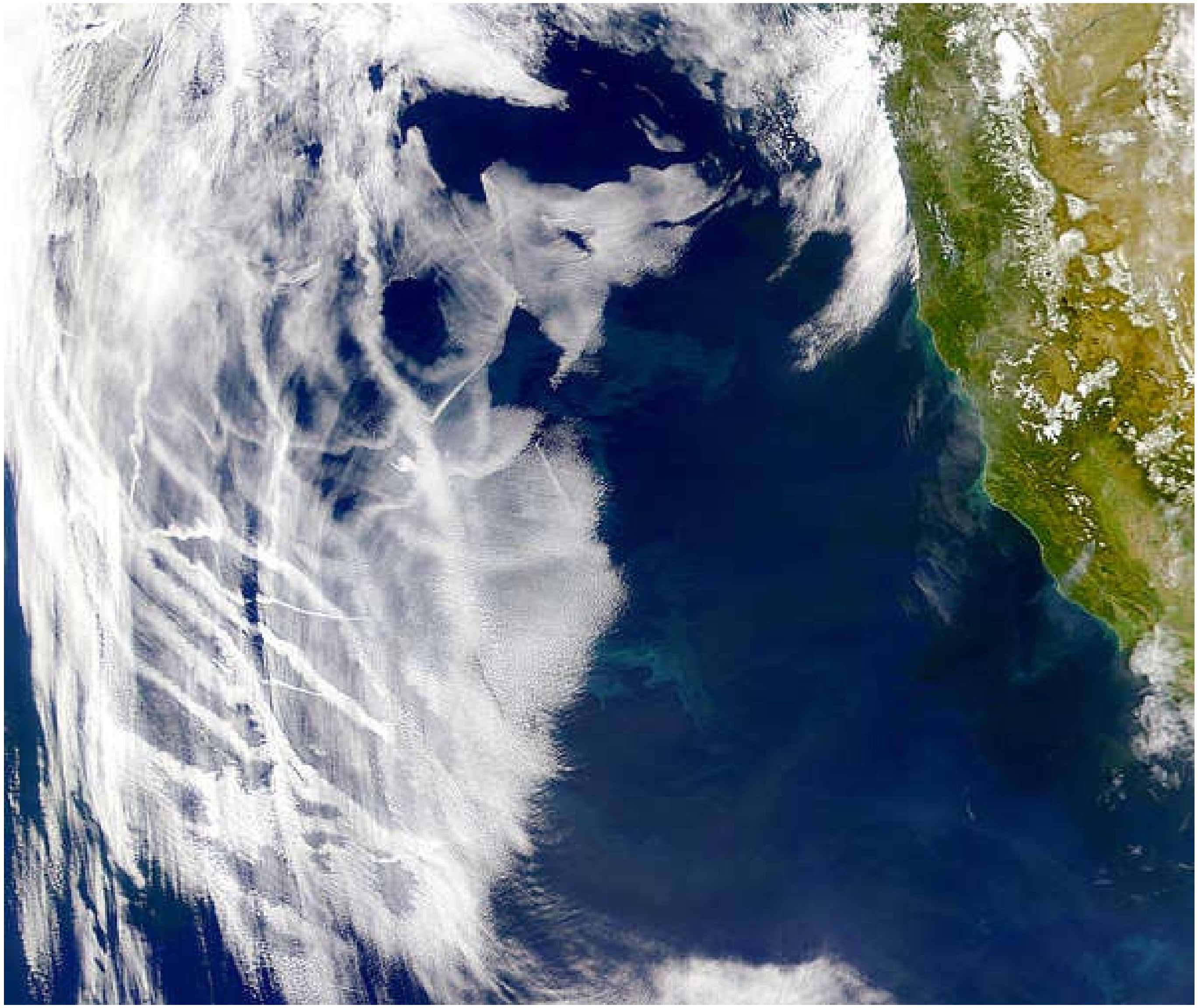


Credit: SeaWIFS

Fire plumes from southern Mexico transported north into Gulf of Mexico.

CLOUD BRIGHTENING BY SHIP TRACKS

Satellite photo off California coast

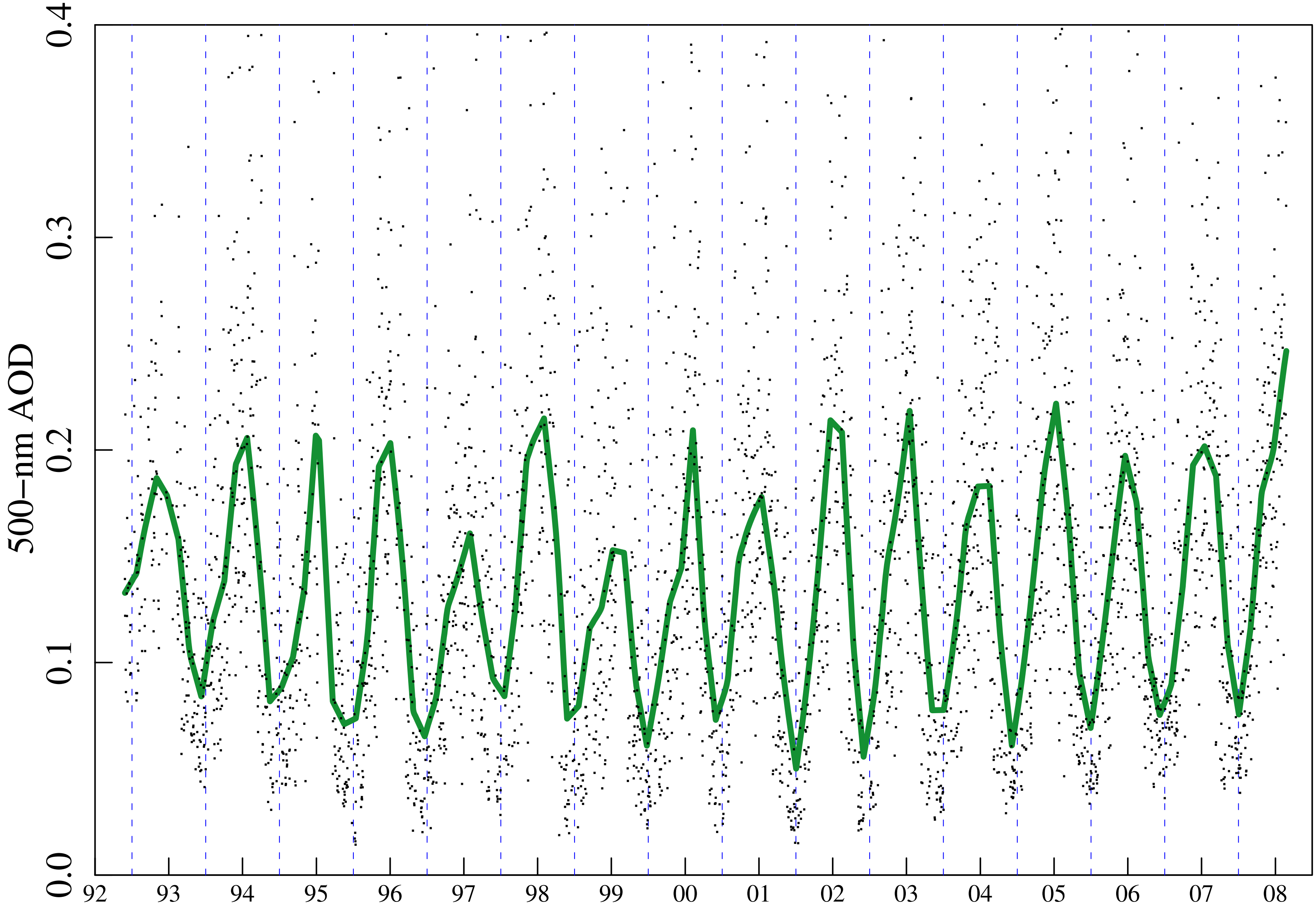


Credit: SeaWIFS

Aerosols from ship emissions enhance reflectivity of marine stratus.

AEROSOL OPTICAL DEPTH AT ARM SGP

Fifteen years of daily average 500 nm AOD in North Central Oklahoma

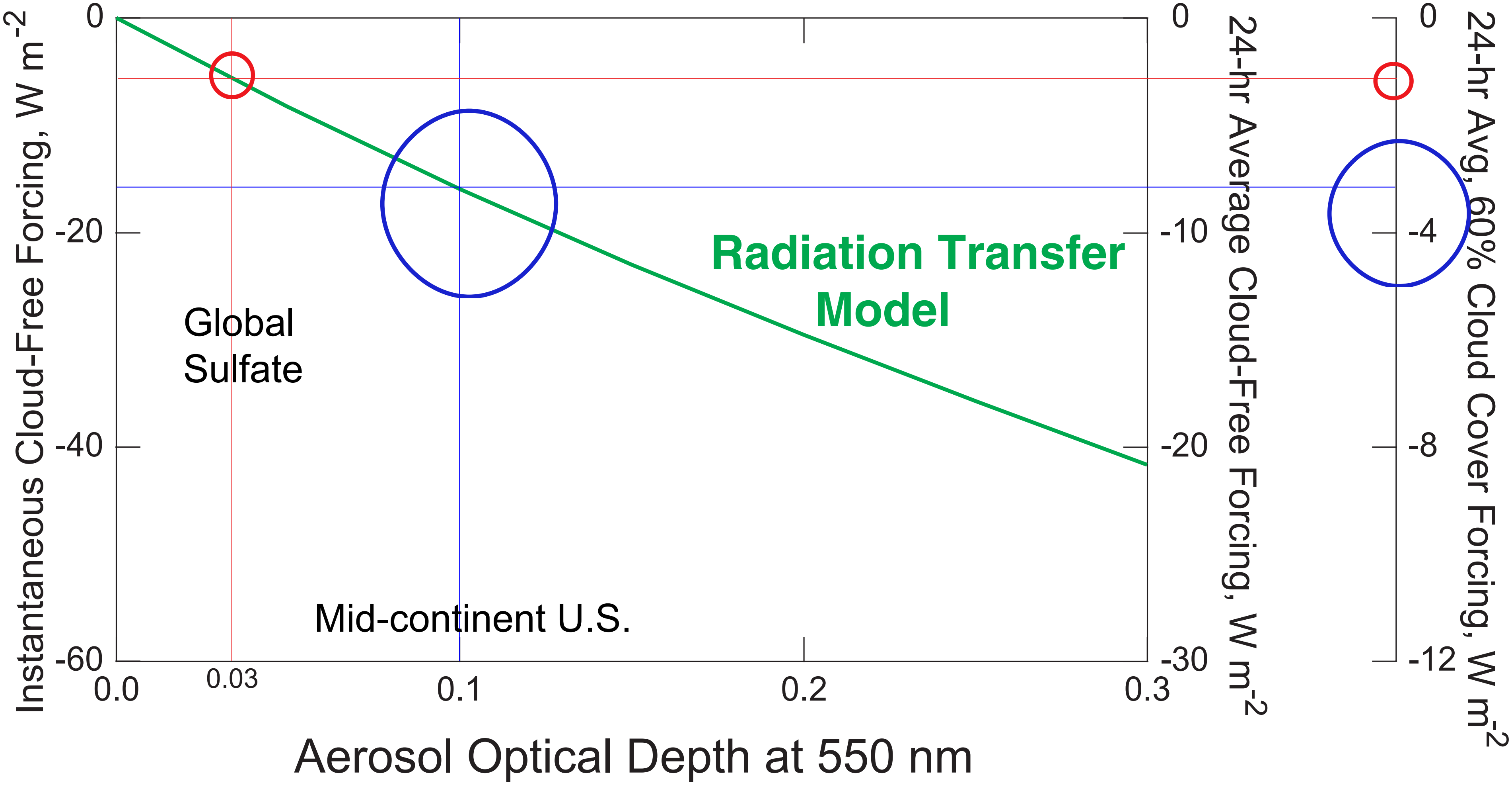


Michalsky, Denn, Flynn, Hodges, Kiedron, Koontz, Schlemmer, Schwartz, JGR, 2010

Green curve is LOWESS (locally weighted scatterplot smoothing) fit.

ESTIMATES OF AEROSOL DIRECT FORCING

By radiation transfer modeling

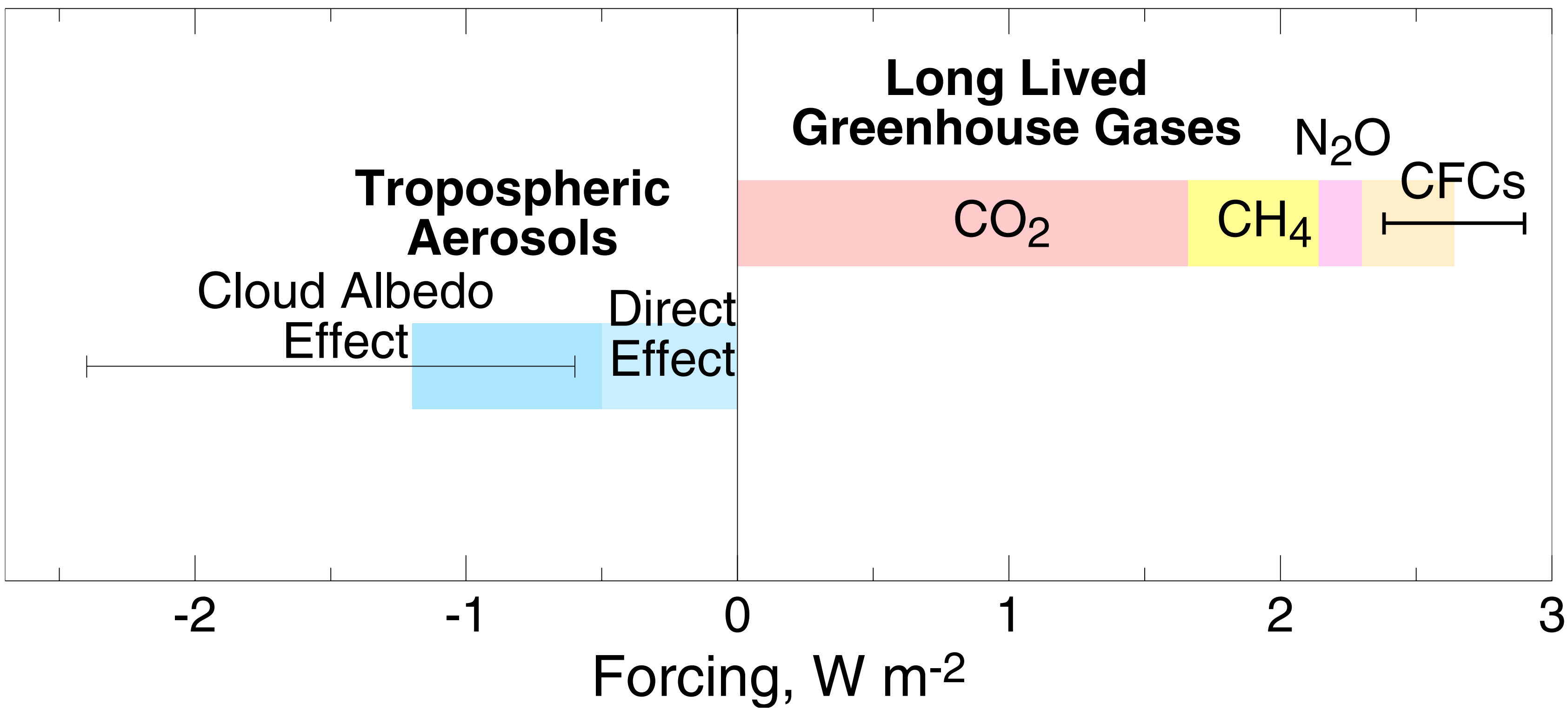


Global average sulfate optical thickness is 0.03: ***1 W m^{-2} cooling***.

In ***continental U. S.*** typical aerosol optical thickness is 0.1: ***3 W m^{-2} cooling***.

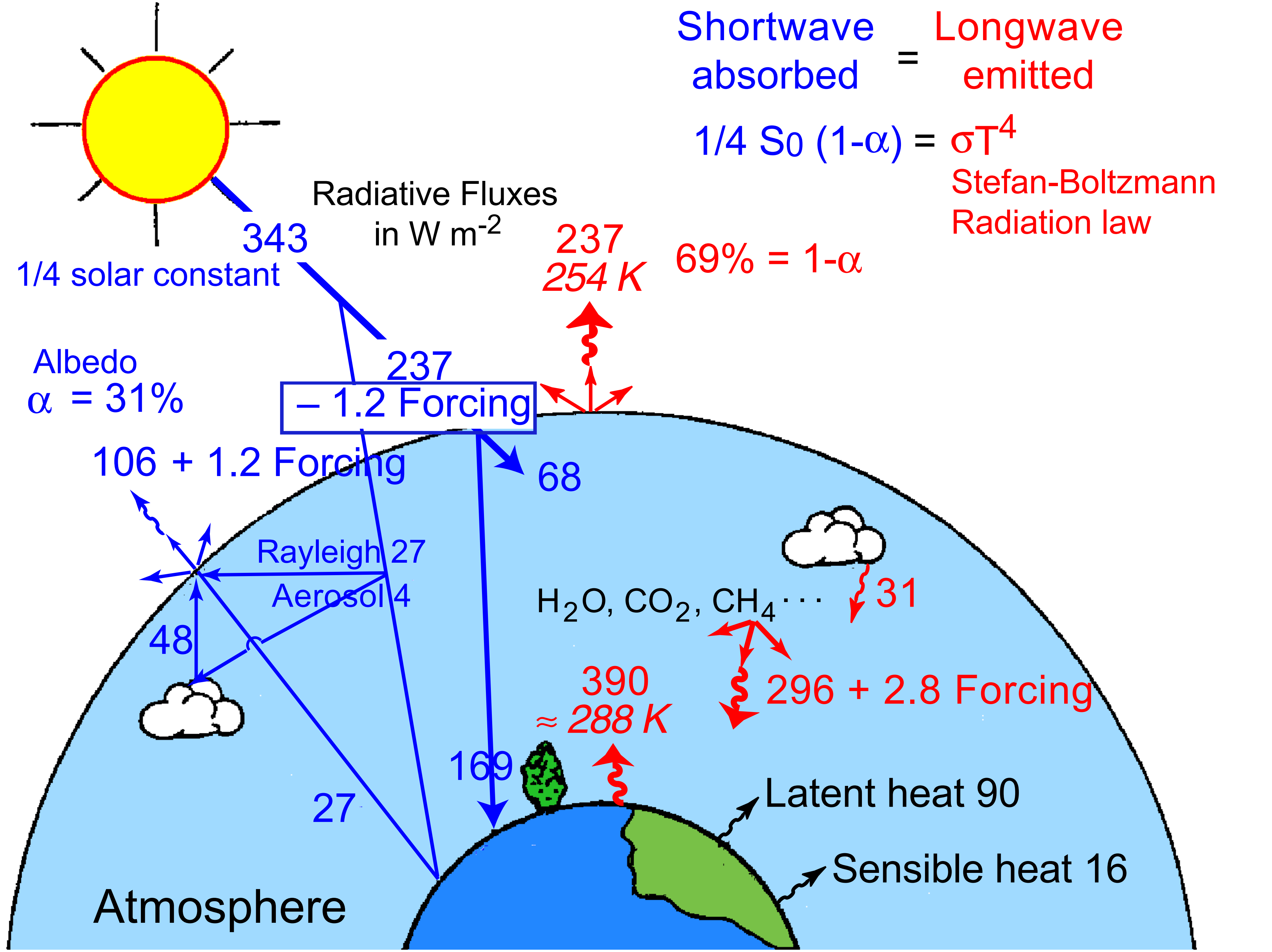
CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



Aerosols exert a negative (cooling) forcing, opposite to greenhouse gases.

THE GREENHOUSE EFFECT AND EARTH'S RADIATION BUDGET



Modified from Schwartz, 1996; Ramanathan. 1987

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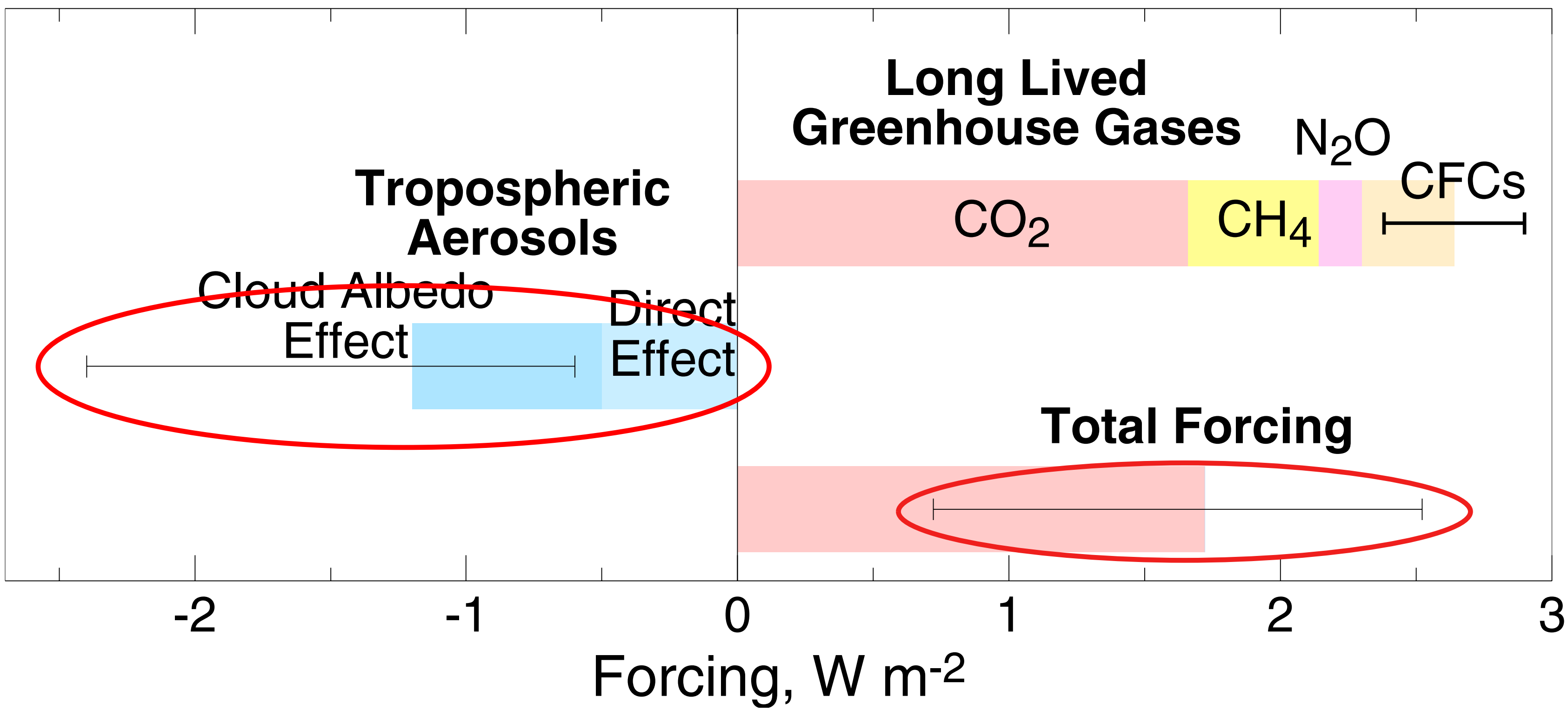
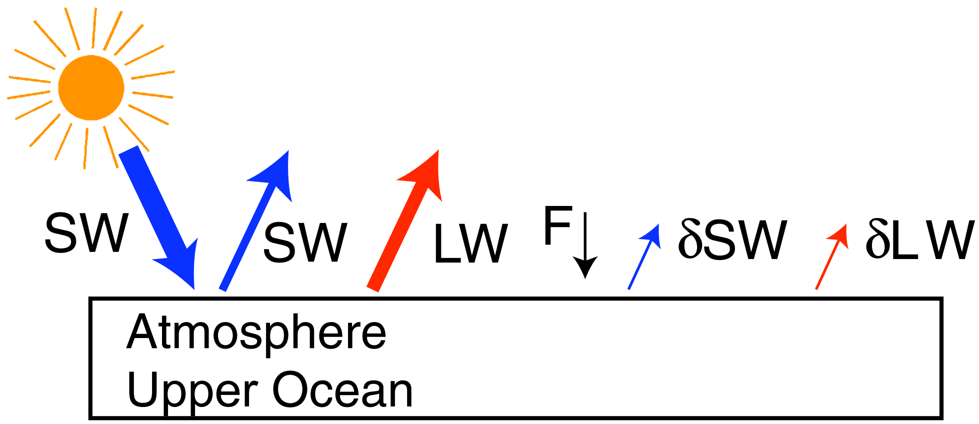


Aerosol forcing may offset much of the greenhouse gas forcing.

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:

$$N = 0; \qquad Q_0 = E_0$$

Net heating rate with external forcing F applied:

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

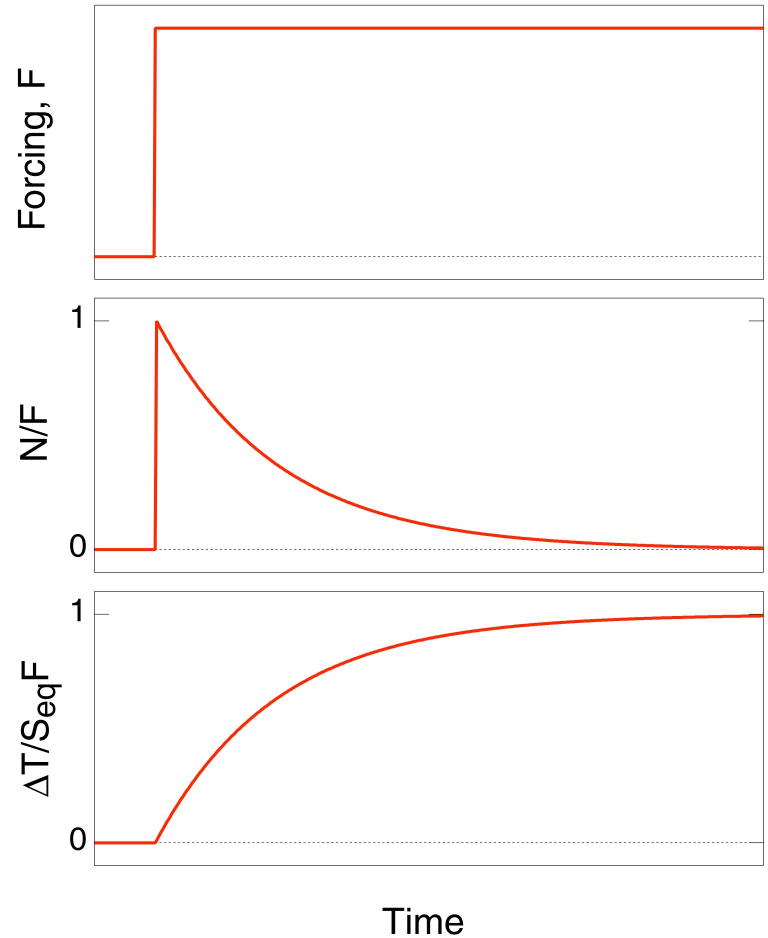
Initially after onset of forcing

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

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*.

λ is a geophysical property of Earth's climate system.

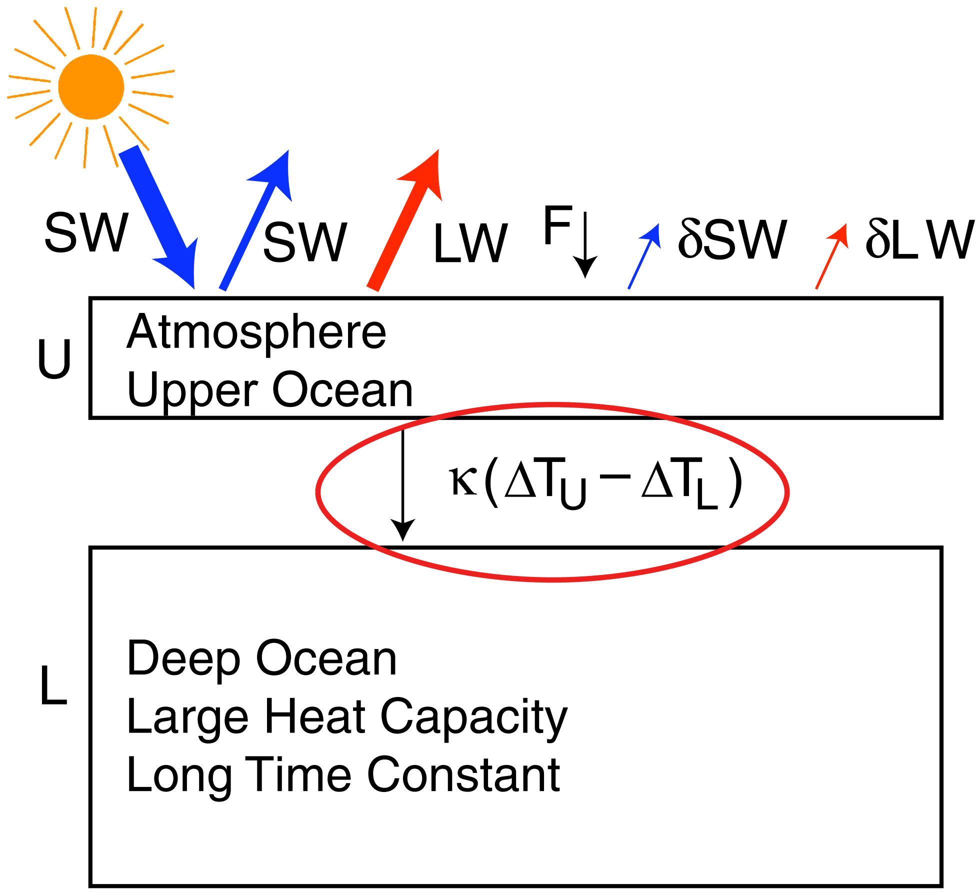
At new steady state (equilibrium) following application of constant forcing *F*

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

S_{eq}= *equilibrium climate sensitivity* = λ^{-1}.

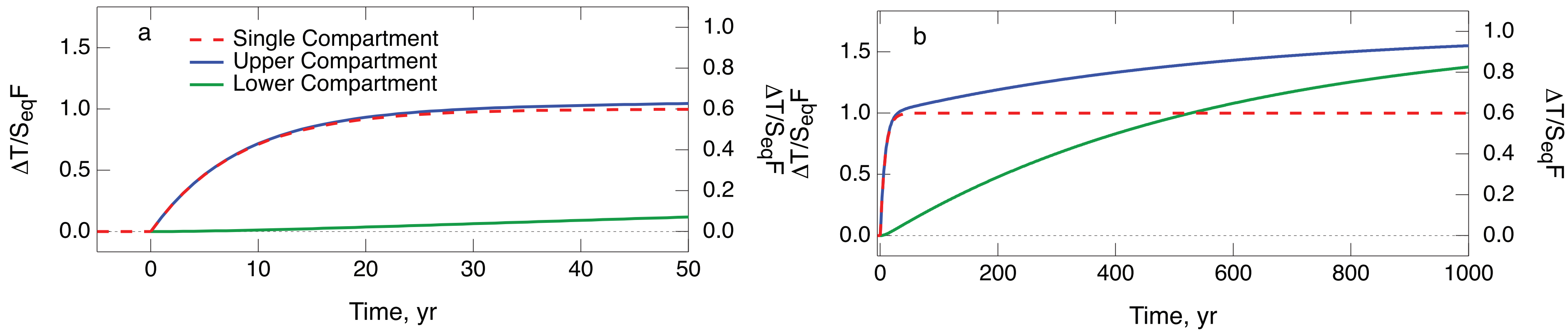
S_{eq} is a geophysical property of Earth’s climate system.

Two compartment climate model



TIME RESPONSE IN TWO-COMPARTMENT MODEL

Response to step-function forcing



Parameters:

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

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

$$cd_{\mathrm{u}} \frac{\mathrm{d}T_{\mathrm{u}}}{\mathrm{d}t} = H - k(T_{\mathrm{u}} - T_{\mathrm{l}})$$

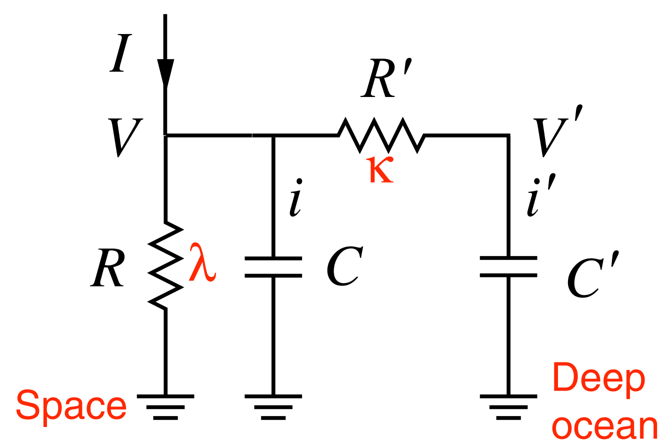
$$cd_{\mathrm{l}} \frac{\mathrm{d}T_{\mathrm{l}}}{\mathrm{d}t} = k(T_{\mathrm{u}} - T_{\mathrm{l}})$$

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



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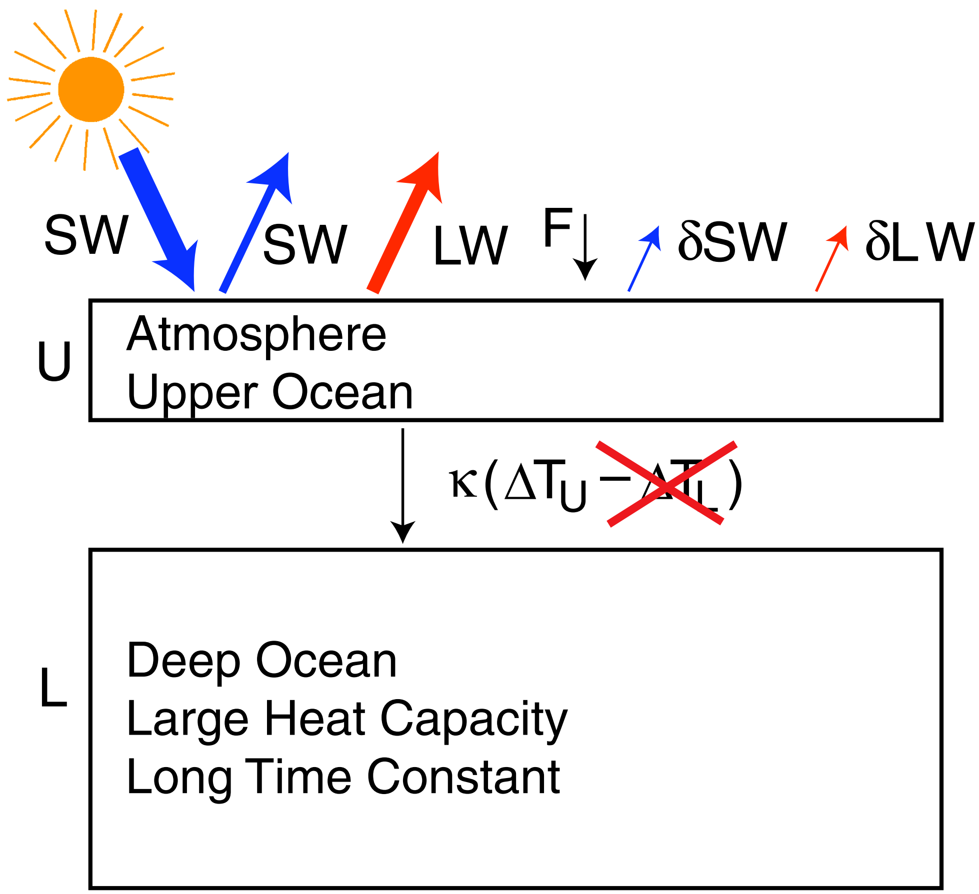

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TRANSIENT CLIMATE SENSITIVITY

Hypothesis: Planetary heating rate proportional to ΔT

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

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

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

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

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

Contrast equilibrium sensitivity, $S_{\mathrm{eq}} = \lambda^{-1}$

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Response times in two-compartment model

$$\tau_{\mathrm{s}} = \frac{C_{\mathrm{U}}}{\kappa + \lambda} \qquad \tau_{1} = C_{\mathrm{L}}\left(\frac{1}{\lambda} + \frac{1}{\kappa}\right)$$

Obtained from eigenvalues, to first order in $C_{\mathrm{U}} / C_{\mathrm{L}}$.

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

$$\tau_{\text{s}} = \frac{C_{\text{U}}}{\kappa + \lambda} \qquad \text{Hence, } S_{\text{tr}} = \frac{\tau_{\text{s}}}{C_{\text{U}}}$$

One equation in three unknowns!

Approach: Determine τ_{s} and C_{U} from observations.

Determination of equilibrium sensitivity

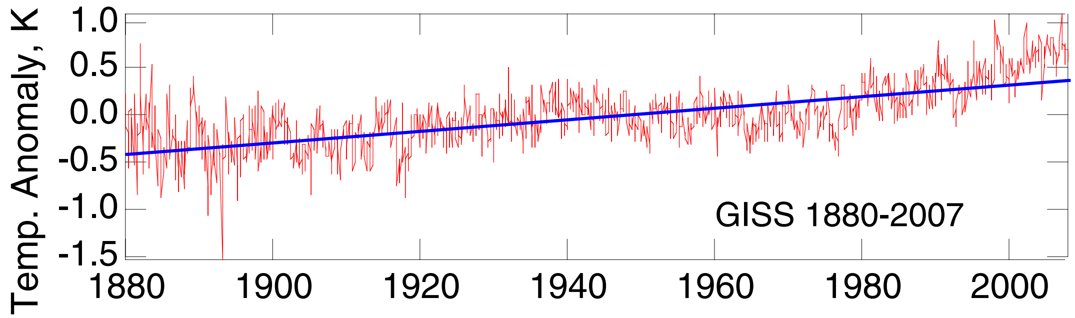
$$S_{\text{eq}} = \lambda^{-1} = \left(S_{\text{tr}}^{-1} - \kappa\right)^{-1}$$

Approach: Determine κ from observations.

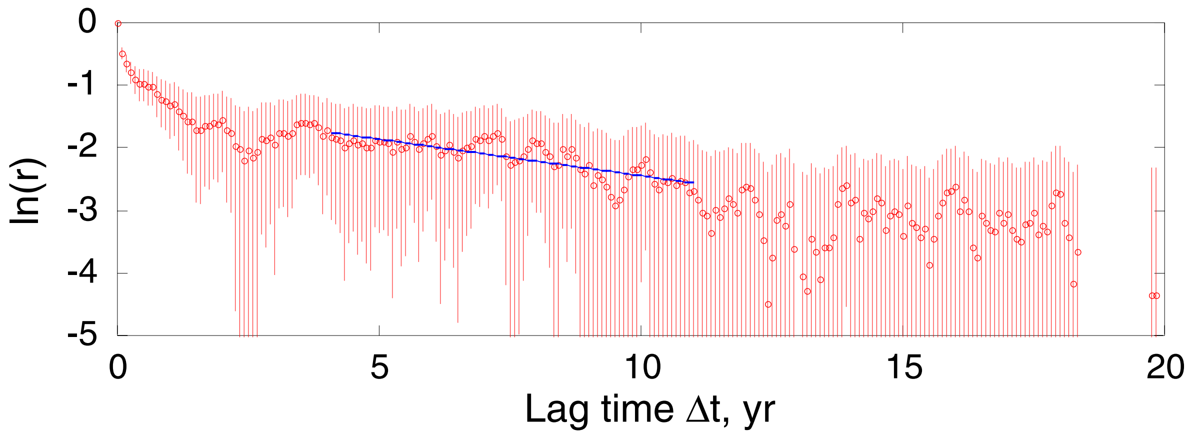
TIME CONSTANT OF UPPER COMPARTMENT OF EARTH'S CLIMATE SYSTEM

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 Δt, $r(\Delta t)$.



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

Schwartz, JGR, 2008

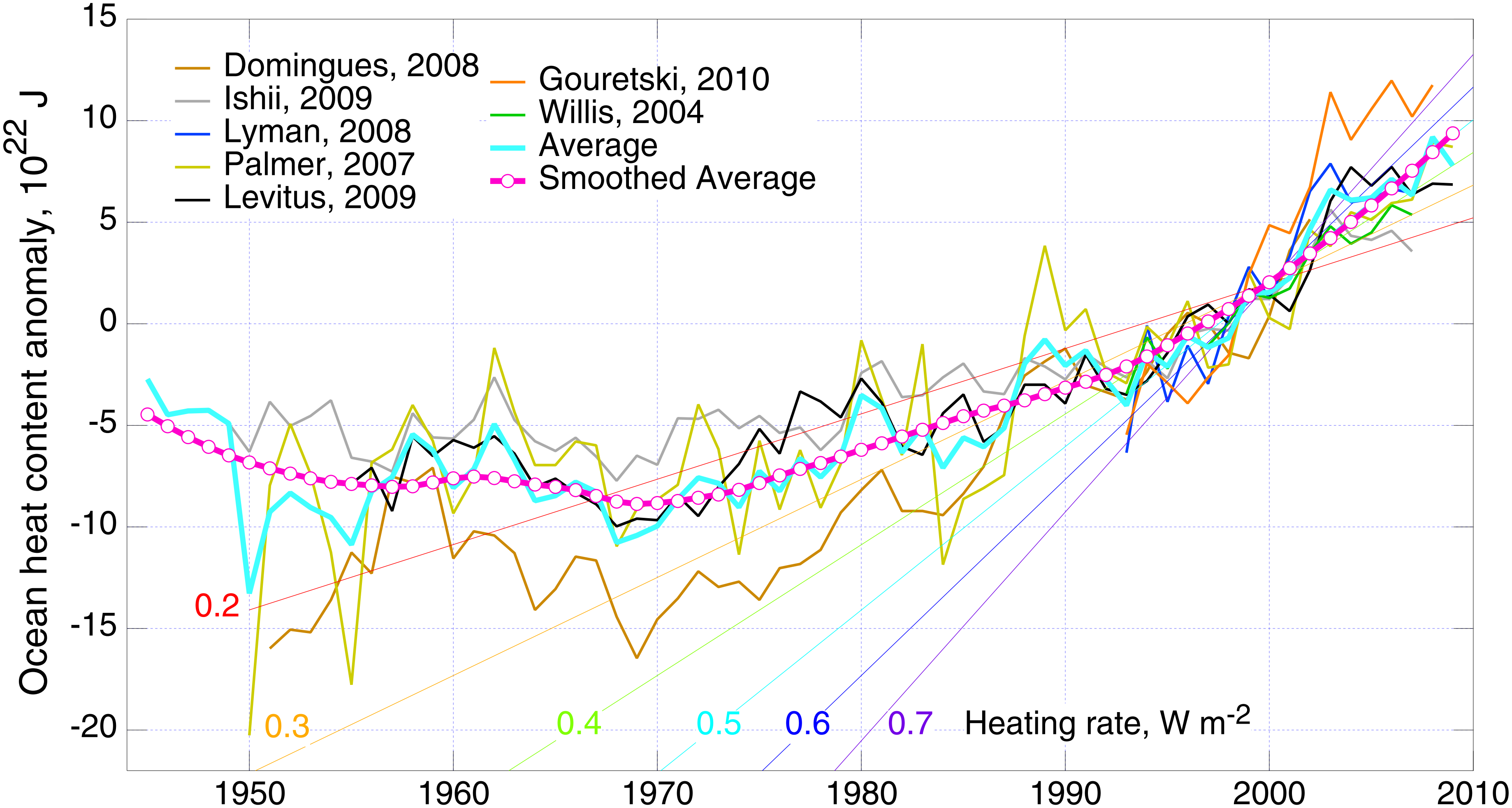
EMPIRICAL DETERMINATION OF UPPER COMPARTMENT HEAT CAPACITY

Hypothesis: Planetary heat content increases linearly with surface temperature ΔT.

Plot $H(t)$ vs $\Delta T(t)$; determine C_{U} as slope.

OCEAN HEAT CONTENT ANOMALY

Surface to 700 m, relative to 1993-2002

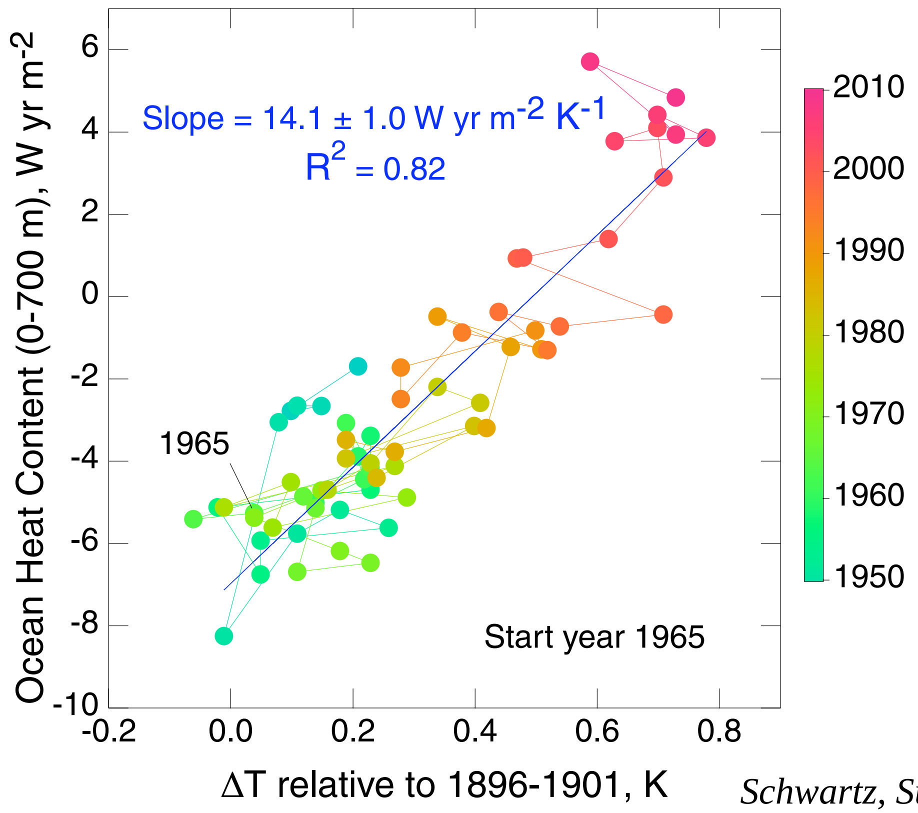


Schwartz, Surv. Geophys, 2012; Data at http://www.ncdc.noaa.gov/bams-state-of-the-climate/2009-time-series/?ts=ohc

Range of slopes, 0.45 ± 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).

World ocean heat content vs temperature anomaly



Schwartz, Surv. Geophys, 2012

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 $C_U = 21.8 \pm 2.1$ W yr m^{-2} K^{-1} (1 σ, based on fit, not systematic errors); equivalent to 170 m of seawater, globally.

EMPIRICAL DETERMINATION OF TRANSIENT CLIMATE SENSITIVITY

$$S_{\mathrm{tr}} = \frac{\tau_{\mathrm{s}}}{C_{\mathrm{U}}}$$

$\tau_{\mathrm{s}} = 8.6 \pm 0.7$ yr

$C_{\mathrm{U}} = 21.8 \pm 2.1$ W yr m^{-2}

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

$\Delta T_{2\times,\mathrm{tr}} = 1.5 \pm 0.2$ K

EMPIRICAL DETERMINATION OF HEAT EXCHANGE COEFFICIENT

Hypothesis: Planetary heating rate proportional to ΔT

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

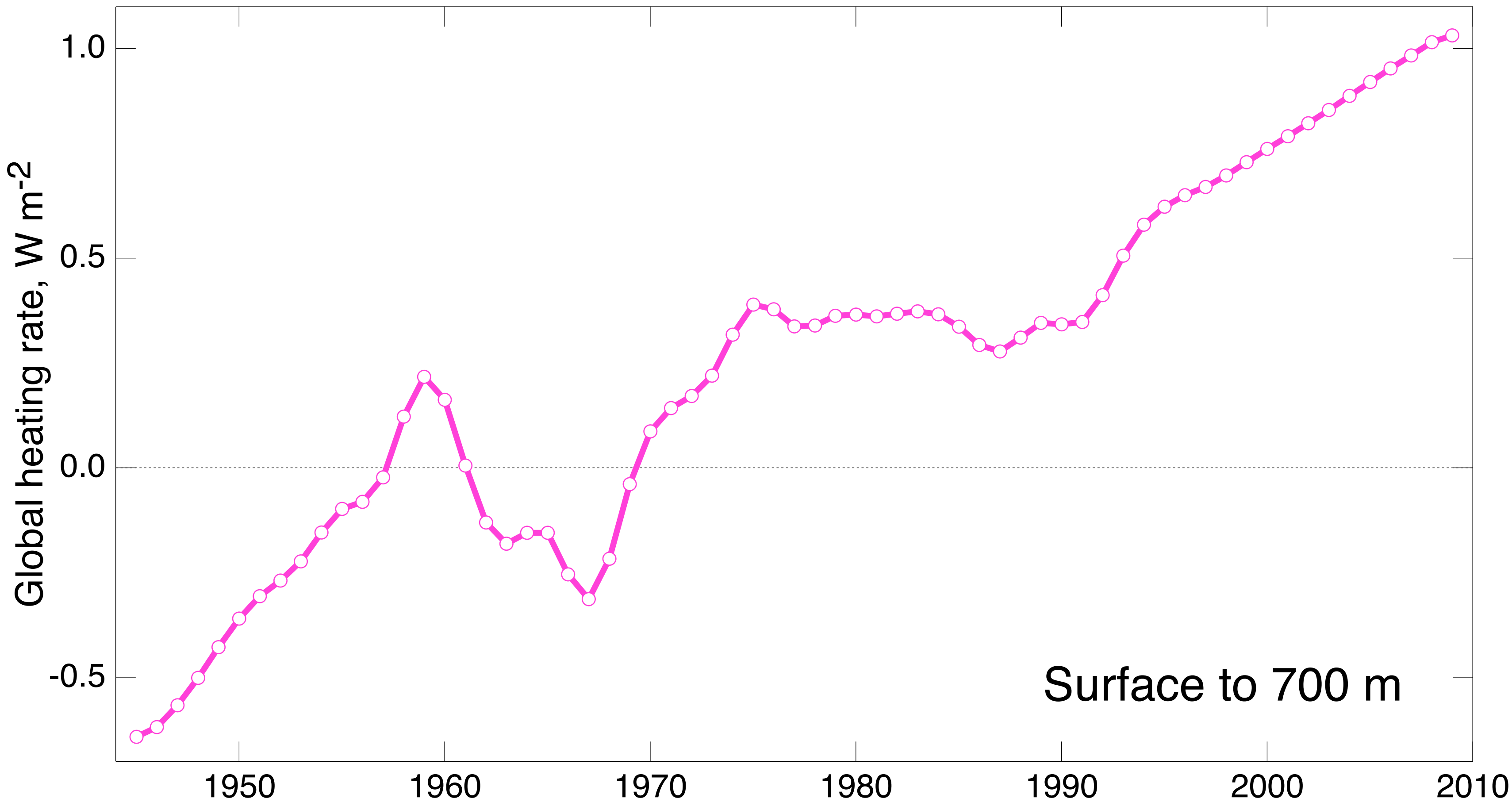
$\kappa = \textit{heat exchange coefficient.}$

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

κ is a geophysical property of Earth's climate system.

GLOBAL OCEAN HEATING RATE

Derivative of global heat content, from smoothed ocean heat content

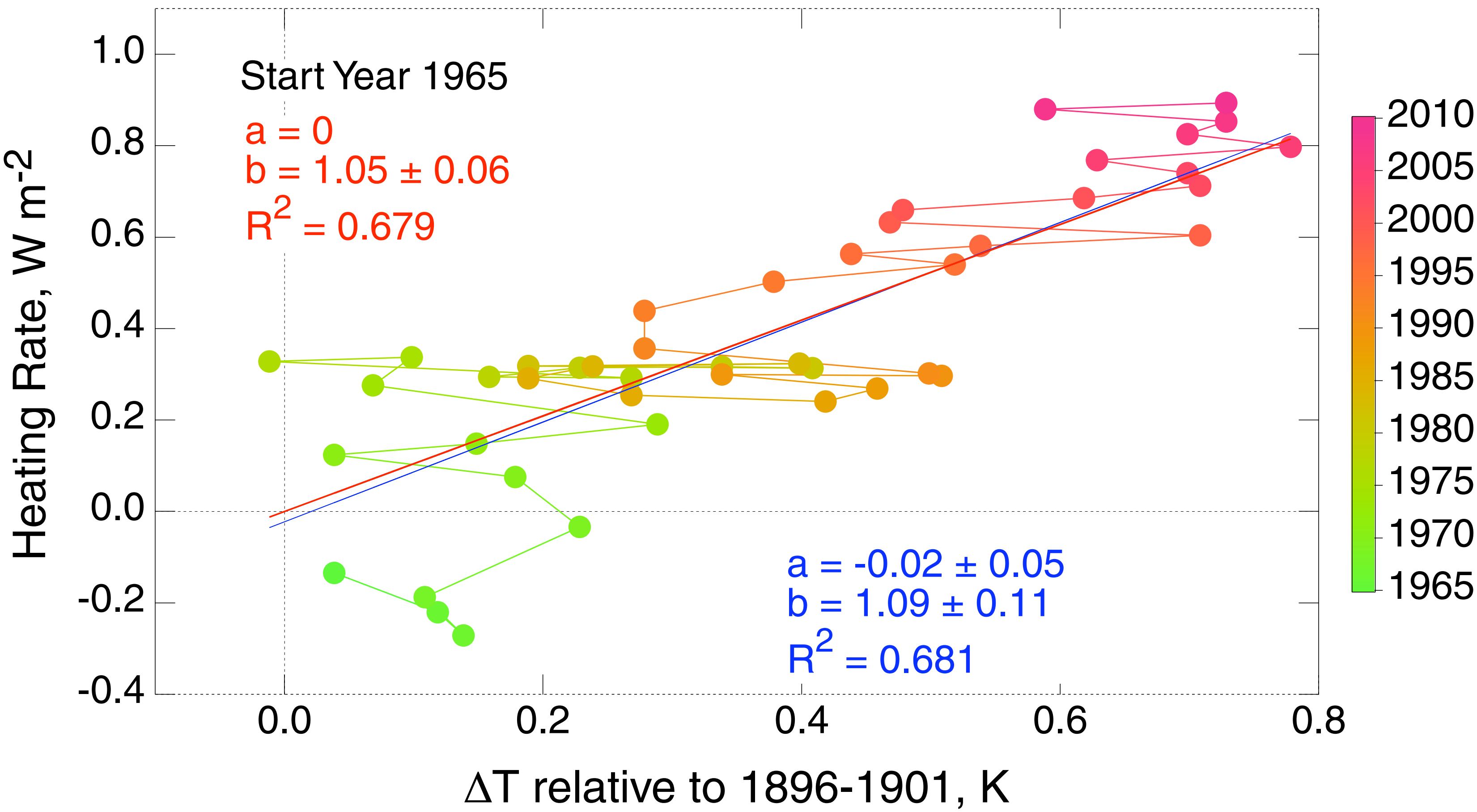


Schwartz, Surv. Geophys, 2012

Are fluctuations “real? What is the uncertainty?

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

Global heating rate vs temperature anomaly



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

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

EMPIRICAL DETERMINATION OF EQUILIBRIUM CLIMATE SENSITIVITY

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

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

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

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

Hence *equilibrium climate sensitivity*
$S_{\mathrm{eq}} = 0.68 \pm 0.09$ K / (W m^{-2})

CO_2 doubling temperature $\Delta T_{2\times,\mathrm{eq}} = 2.5 \pm 0.3$ 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}

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

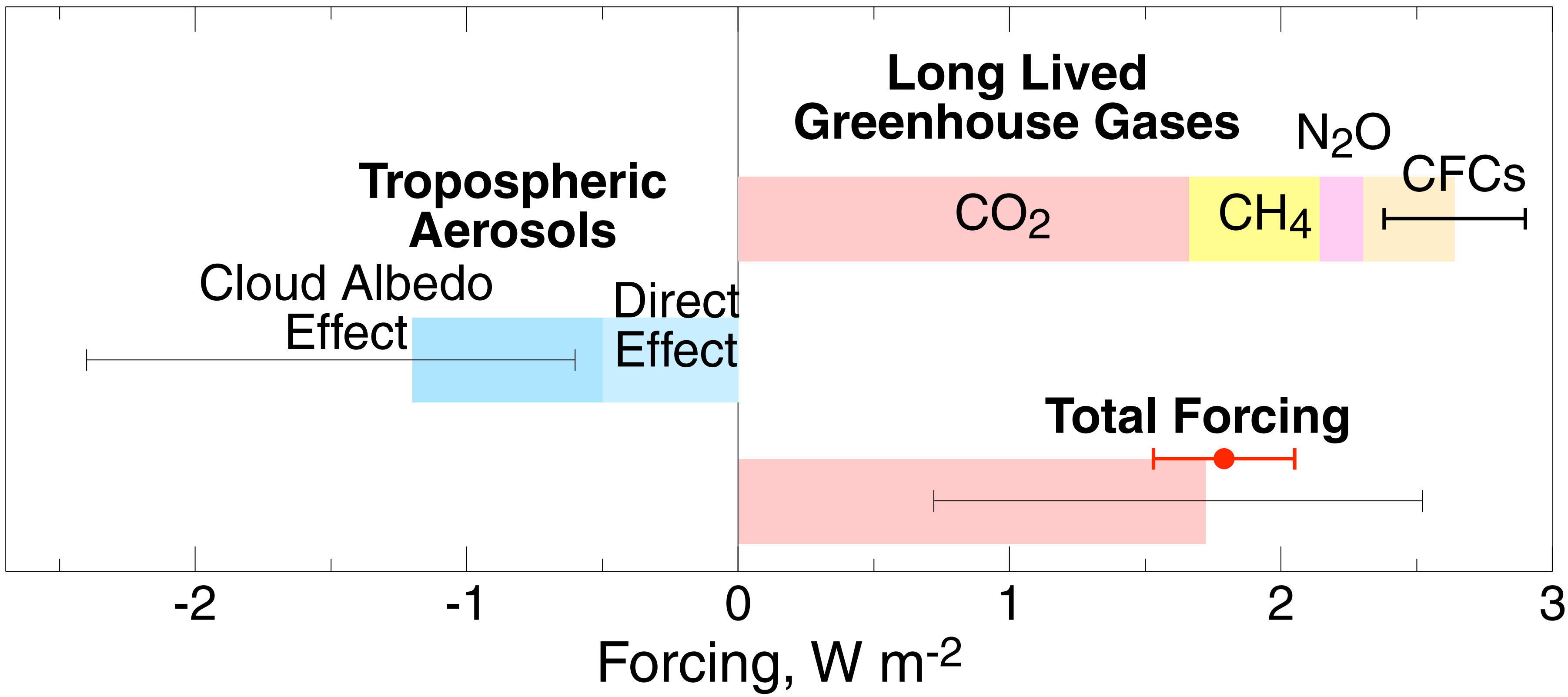
Hence $$F(t) = \frac{\Delta T_{\mathrm{obs}}(t)}{S_{\mathrm{tr}}}$$

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

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

$F_{1900\text{-}2005} = 1.79 \pm 0.26$ W m^{-2}

Climate forcing (1900 – 2005)



Twentieth century forcing is also ***remarkably close to IPCC central estimate*** (well within 1 σ).

GEOPHYSICAL QUANTITIES DETERMINED IN THIS STUDY

Quantity	Unit	Value	σ
C_U	W yr m^{-2} K^{-1}	21.8	2.1
C_L	W yr m^{-2} K^{-1}	340	
τ_s	yr	8.6	0.7
τ_l	yr	550	
κ	W m^{-2} K^{-1}	1.05	0.06
λ	W m^{-2} K^{-1}	1.5	0.2
S_{tr}	K/(W m^{-2})	0.39	0.05
$\Delta T_{2\times,\ tr}$	K	1.5	0.2
S_{eq}	K/(W m^{-2})	0.68	0.09
$\Delta T_{2\times,\ eq}$	K	2.5	0.3

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}); $\Delta T_{2\times} = 2.5 \pm 0.3$ 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}**.

SOME ***MORE*** SIMPLE QUESTIONS ABOUT CLIMATE CHANGE

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*** $\kappa = 1.05 \pm 0.06$ W m^{-2} K^{-1} (1 σ).

SUMMARY & CONCLUSIONS (2)

Earth's present ***energy imbalance*** is 0.80 ± 0.05 W m^{-2}.

The two-compartment model suggests that Earth's ***transient climate sensitivity***, expressed as a CO_2 doubling temperature is 1.5 ± 0.2 K. The ***equilibrium sensitivity*** 2.5 ± 0.3 K is ***close to IPCC central estimate***.

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

For transient sensitivity, present GHG forcing of 2.8 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!*