What Astronomers Might Want to Know About Global Warming

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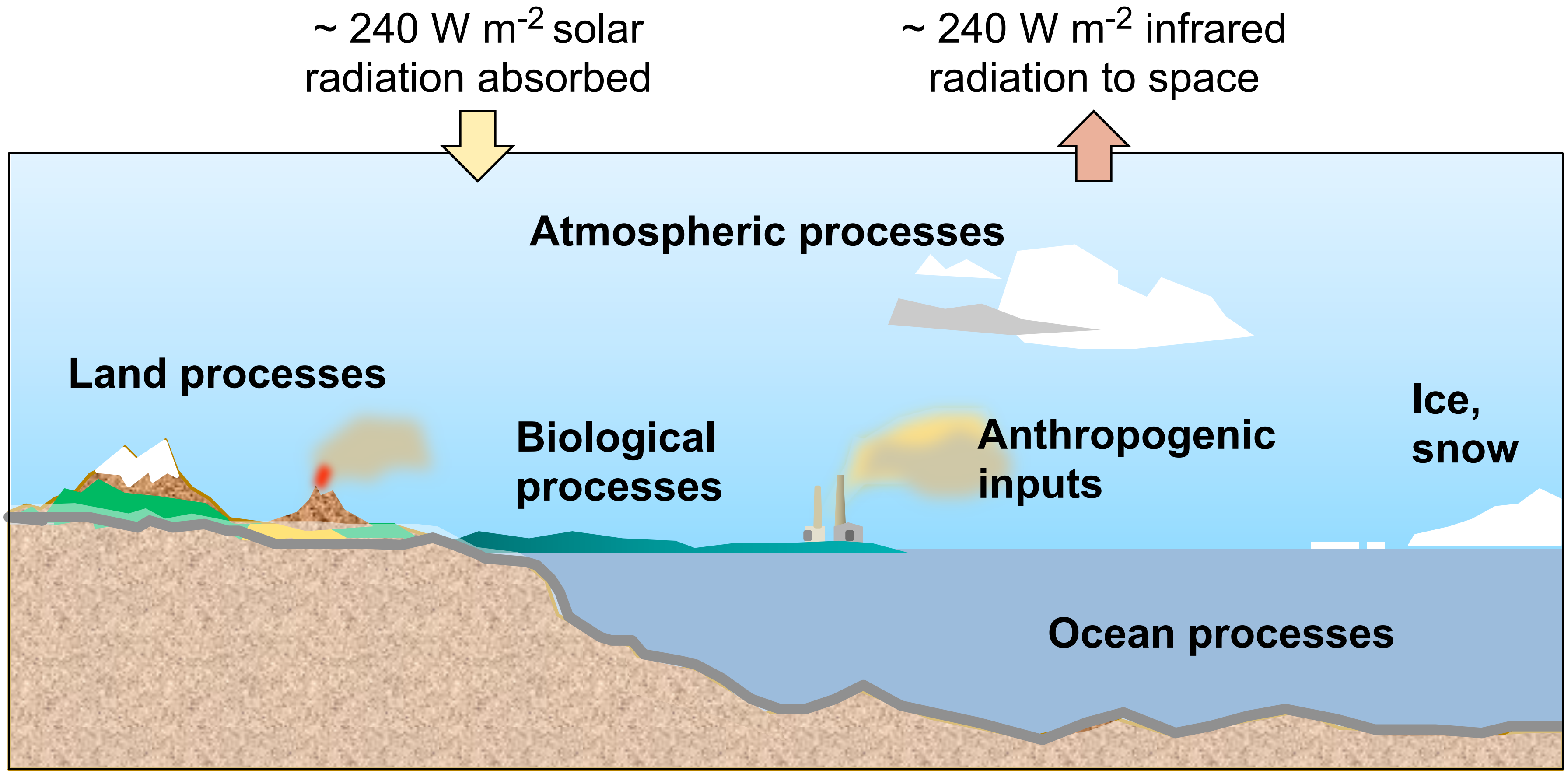
The climate system:

Extends from the top of the atmosphere to the bottom of the ocean



- Subject to external forcing (e.g. solar and anthropogenic inputs)
- Includes positive and negative feedback mechanisms

Objectives and Approach

This is about global warming, not climate change

This is a back-of-the-envelope approach.

- Avoid discussion of AOGCMs
- Emphasize the underlying physics

Take notice of analogies and concepts often used in astronomy.

Outline

I. The greenhouse effect

II. The concept of radiative forcing

III. Climate feedbacks

IV. Temperature sensitivity to radiative forcing

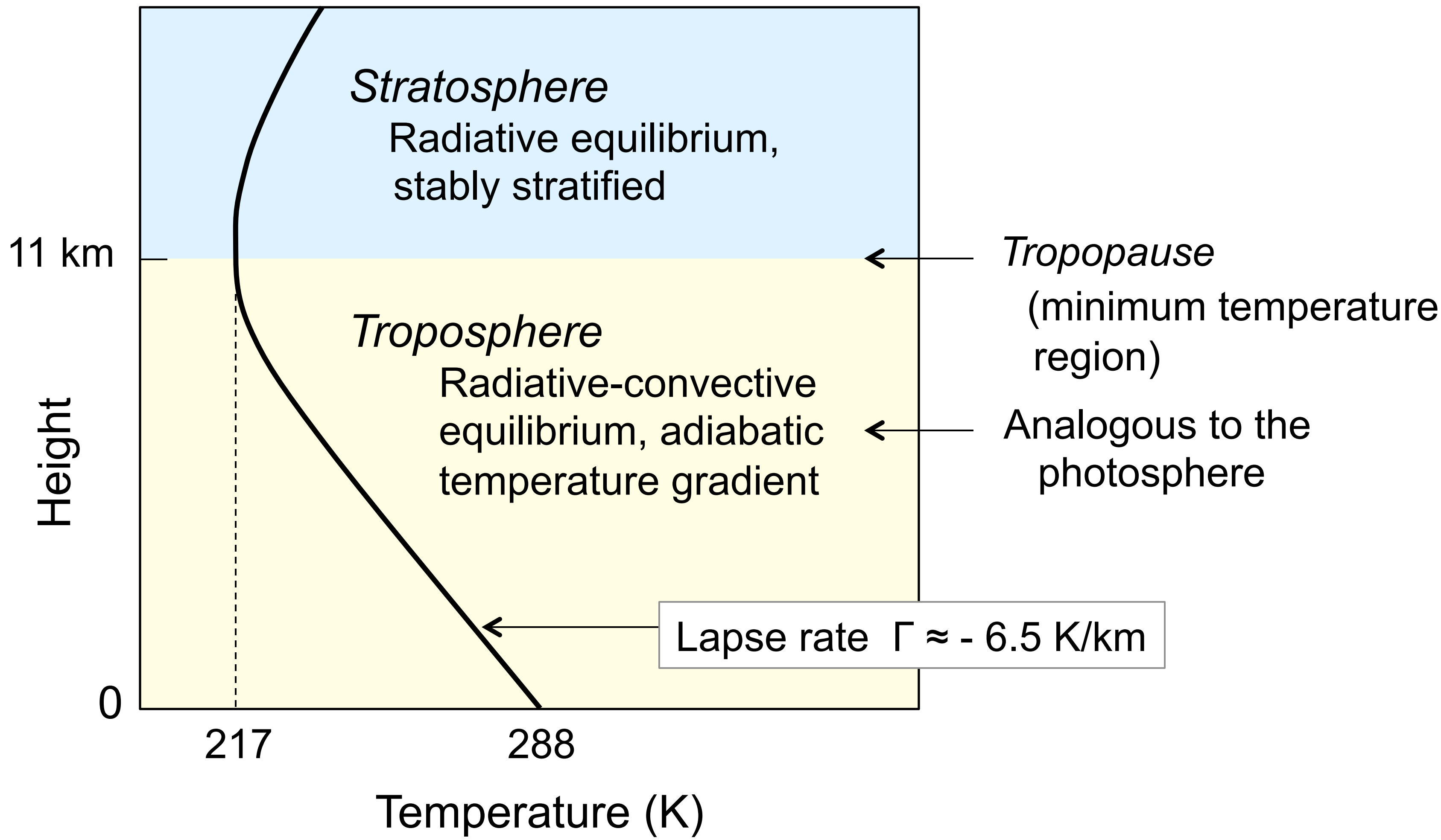
V. Energy imbalance and temperature change

VI. Diagnostics for the warming mechanism

VII. Projections for future global temperature

I. The greenhouse effect

Atmospheric temperature profile



Earth's effective (radiation) temperature

Fixed by total solar irradiance (TSI) and albedo (α)

<u>At equilibrium</u>:

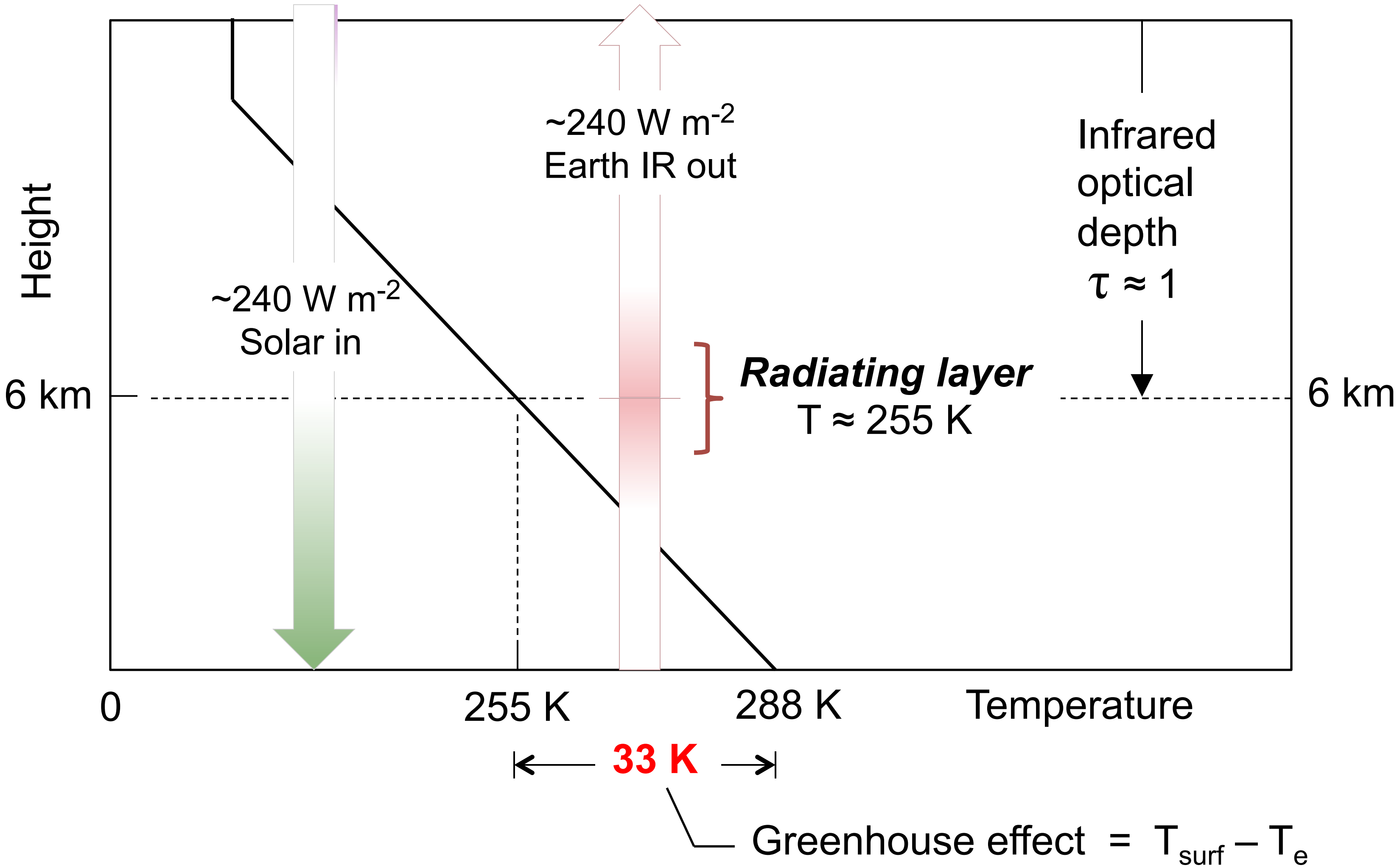
Total absorbed solar radiation = Total outgoing long-wavelength radiation (OLR)

$$\underbrace{\frac{TSI}{4}(1-\alpha)}_{\mathbf{240}\ \mathrm{W\ m^{-2}}} = \sigma T_e^4$$

For a rapidly rotating planet, and where
TSI = 1361 W m^{-2}
$\alpha \approx 0.30$

$T_e \approx 255$ K

A visualization of energy flow in an "IR-gray" atmosphere

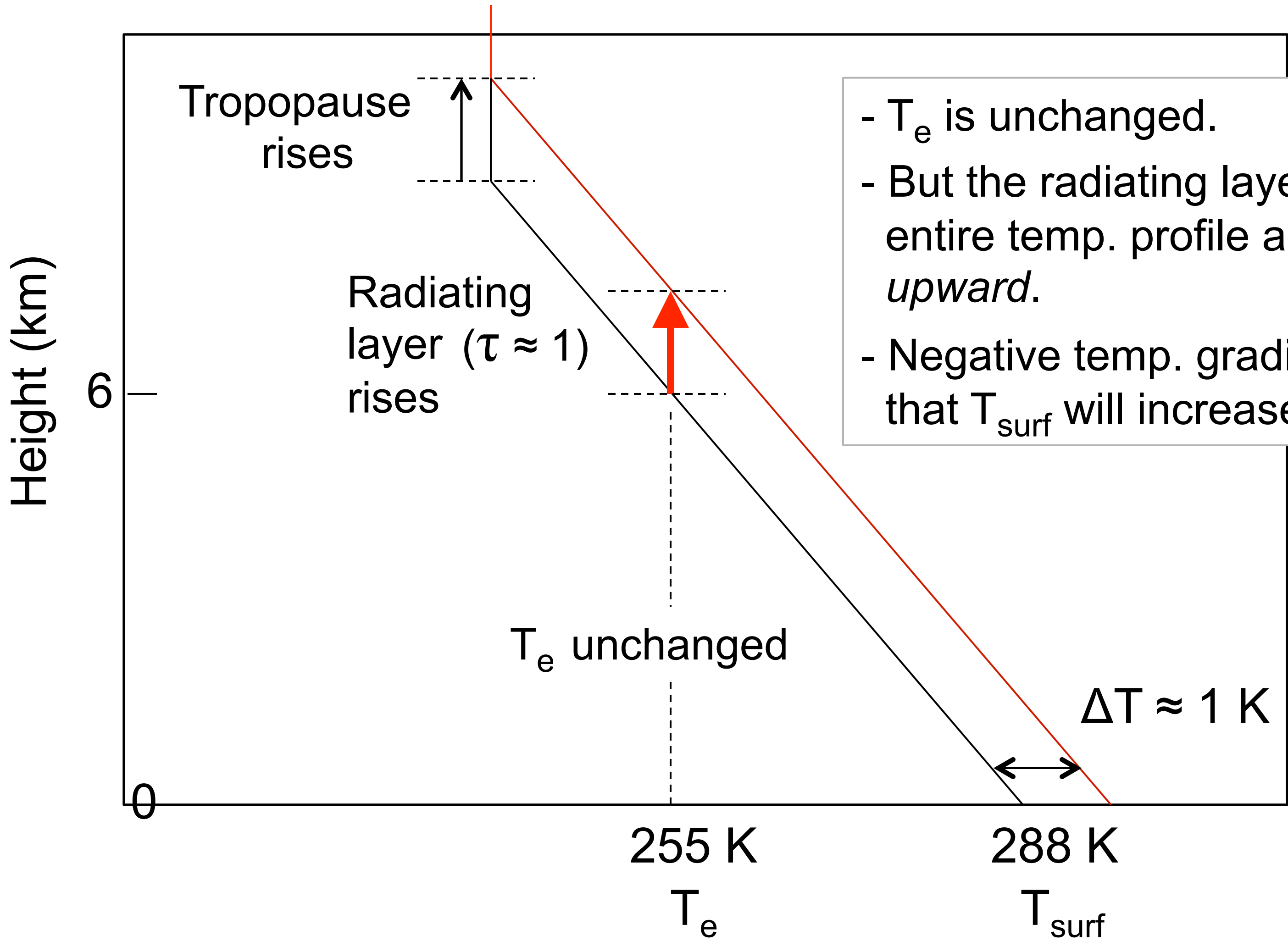


Height of the radiating layer is fixed by the infrared opacity of the atmosphere, i.e., by greenhouse gas concentration.

Example: Effect of doubling CO_2 concentration

(At equilibrium, <u>with no feedbacks</u>)

"Forces" the climate by 3.8 W m^{-2} (radiative transfer calculation)

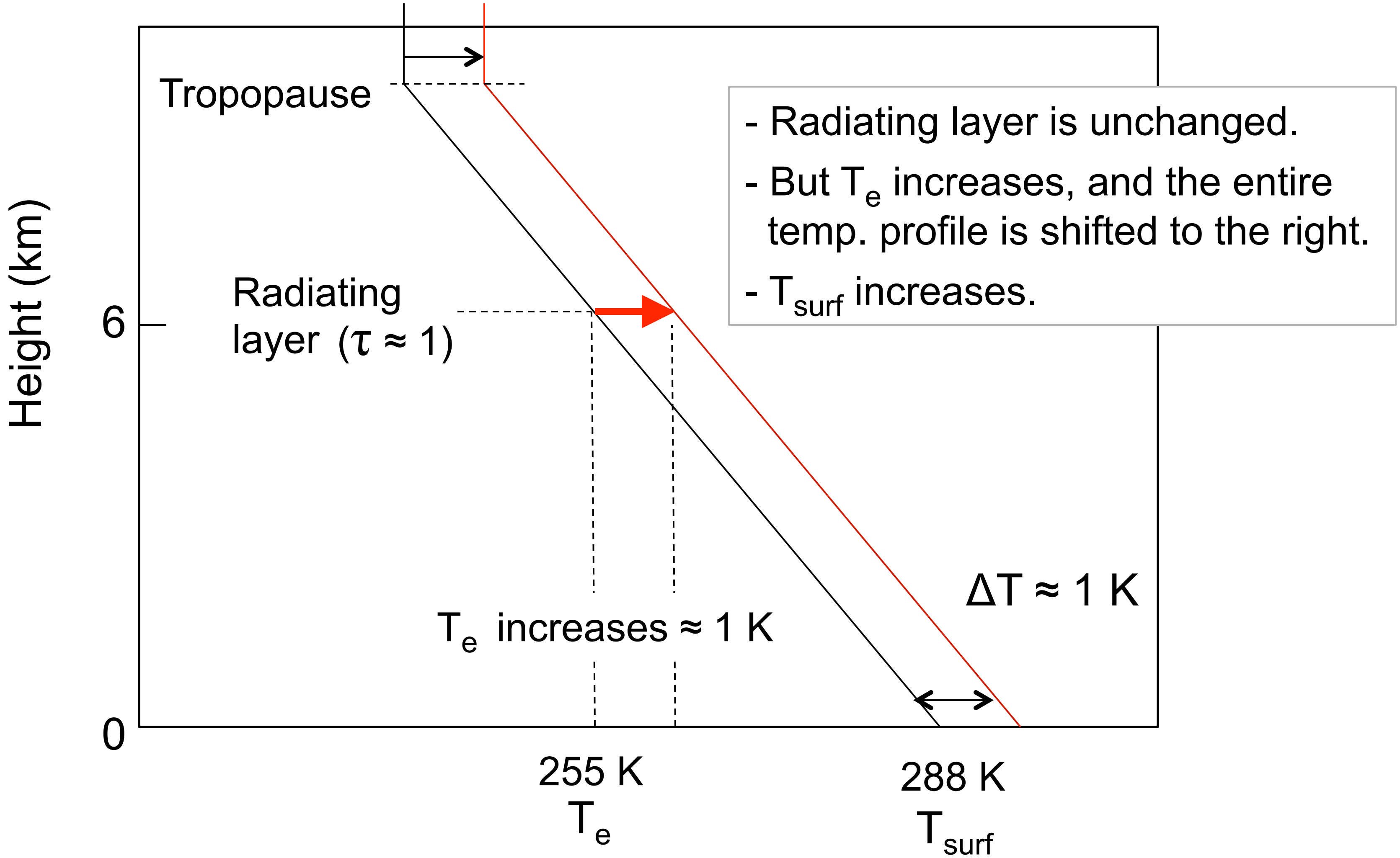


- T_e is unchanged.
- But the radiating layer and the entire temp. profile are shifted *upward*.
- Negative temp. gradient assures that T_{surf} will increase.

Example: Effect of increasing total solar irradiance (TSI)

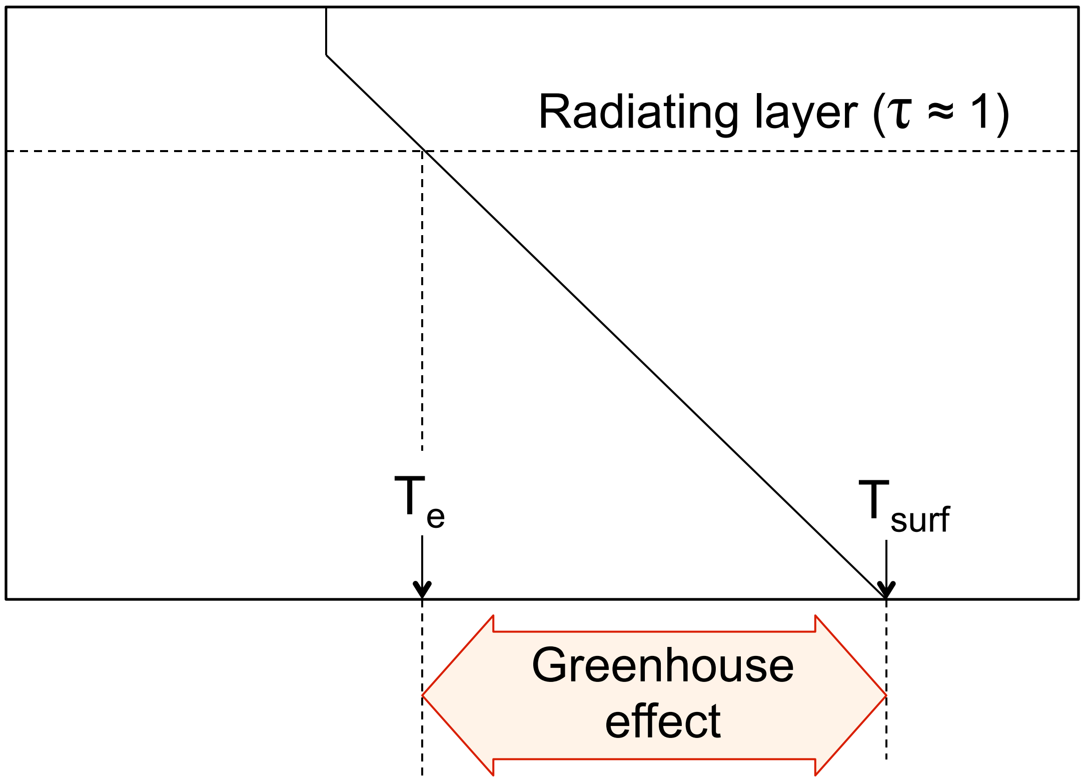
(At equilibrium, with no feedbacks)

Increase TSI by 1.6 percent: also "forces" the climate system by 3.8 W m^{-2}



Visualizing the greenhouse effect

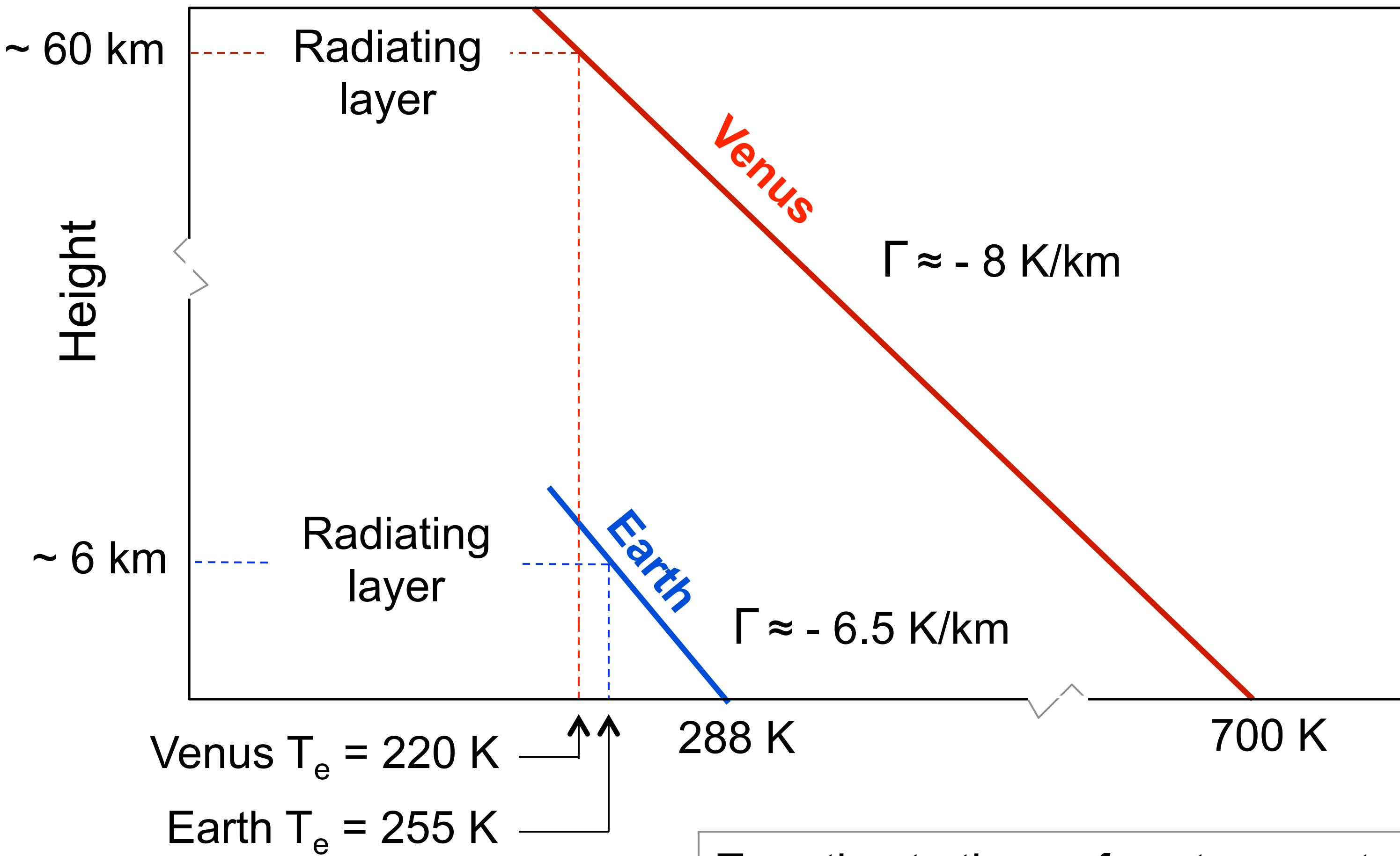
Surface temperature depends on the vertical distance between the planet's surface and its radiating layer.



The greenhouse effect enables a planet to radiate at a temperature less than the ground temperature.

The description shown here was given by E. O. Hulbert in the 1930s.

Aside: Venus vs. Earth

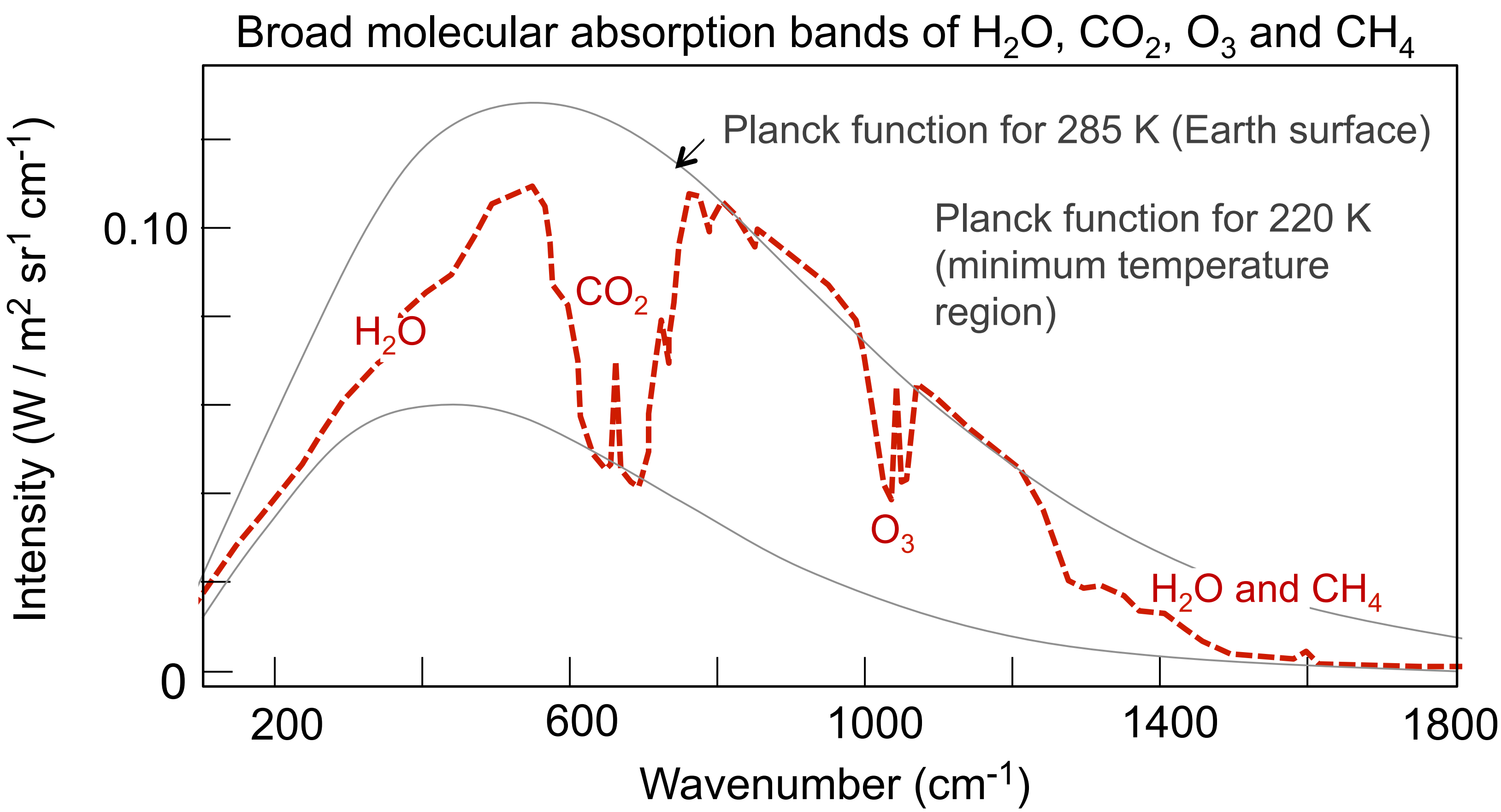


To estimate the surface temperature of a planet, need only:

(1) the radiation temperature T_e
(2) the height of the radiating layer
(3) the lapse rate Γ

Non-gray atmosphere

Infrared spectrum of a portion of Earth as observed from space



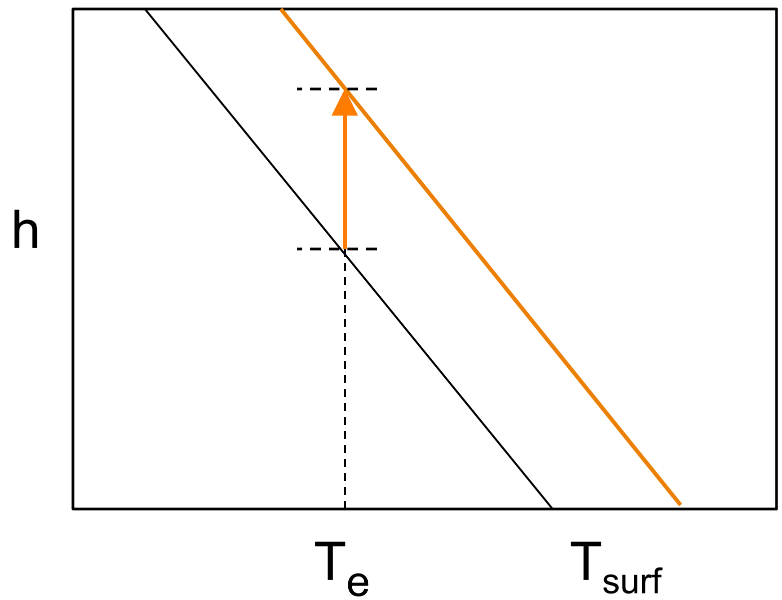
- Intensity at each wavenumber ν characterizes the temperature at $\tau_\nu \approx 1$
- Tropospheric bands in absorption, analogous to solar photospheric lines
- Central reversals in absorption features are formed in the stratosphere, where temperature is increasing with altitude.

Aside: Debunking a myth

"Adding CO_2 to the atmosphere can't produce global warming because the CO_2 absorption bands are already saturated."

Wrong and doubly wrong.

- The CO_2 absorption bands are not saturated*.
- But even if they were, adding more CO_2 would continue to raise the height of the radiating layer, forcing surface temperature higher.



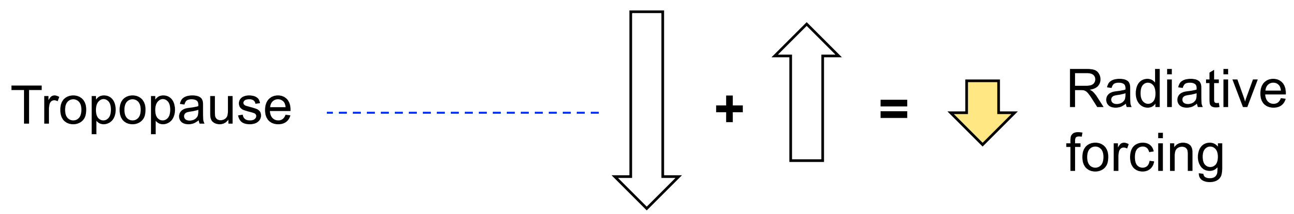
Regime where absorption increases as $\sqrt{\text{(mole fraction)}}$

II. Radiative forcing

Radiative forcing: A formal definition

Radiative forcing (R) is the change in net radiative flux at the tropopause, *if surface and tropospheric temperatures were held at their unperturbed values.*

Radiative forcing is usually expressed relative to its value in 1750 (preindustrial).

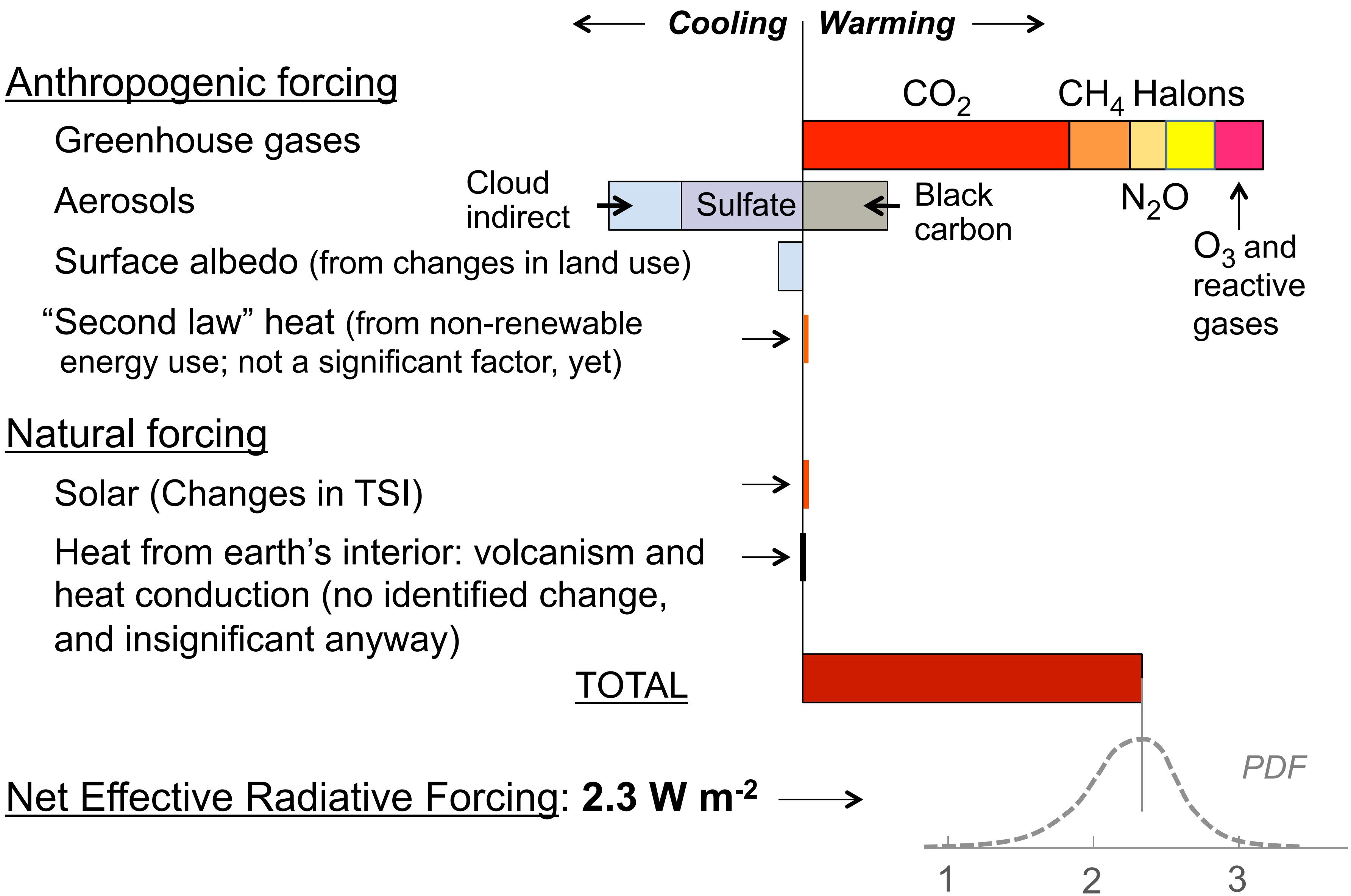


R (1750) is defined to be zero.

R (2013) ≈ 2.3 W m^{-2}

Owes to changes in GHGs, aerosols, solar activity and land use, relative to conditions in 1750 (based on radiative transfer calculations, observations, and laboratory spectroscopy)

Contributors to radiative forcing (2011), relative to 1750



Radiative forcing is a useful concept for analysis because:

- It is purely an energy term
- Individual radiative forcings are *additive* (approximately)
- Radiative forcing produces a similar tropospheric *temperature* response* irrespective of the *type* of forcing (approximately).
  - This property derives from the tendency for the troposphere to maintain an adiabatic temperature gradient, so that the details of energy deposition in the troposphere are not major factors.

* But not necessarily the same *precipitation* response.

Relationship between radiative forcing and temperature change

Obtain temperature sensitivity to forcing, without feedbacks

The "Planck" response:

Gives temperature sensitivity to forcing, at equilibrium

$$E = \sigma T_e^4$$

$$\Delta T_o = [4\sigma T_e^3]^{-1} \Delta E,$$

In differential form, where

ΔT_o is the temperature change without feedbacks

T_e = 255 K

ΔE is the change in energy input rate, identified here as the forcing, R

$$\Delta T_o = \lambda_o R,$$

(Eqn. 1)

where λ_o is the ***climate sensitivity parameter*** without feedbacks

$$\lambda_o \approx 0.3 \text{ K/Wm}^{-2}$$

III. Climate feedbacks

Feedbacks:

Components of the climate system that are constrained by climate itself

Short-term temperature feedbacks (happening now)

- Water vapor as GHG: Positive feedback (huge)
- Lapse rate: Negative feedback on *surface* temperature
- Ice-albedo: Positive feedback
- Cloud: Positive and negative feedbacks (net effect is very likely positive)

Long-term (Earth system) temperature feedbacks

- CO_2 and CH_4 from permafrost thaw: Positive feedback
- Ocean circulation changes
- Carbon cycle: Effects on soils and vegetation (Positive feedback?)
- CO_2 removal by silicate weathering: Negative feedback (very long term)

System gain resulting from feedback

(Linear analysis; higher order terms not included here)

$\Delta T_o = \lambda_o R$ Planck response (no feedback)

Now let ΔT_f be the final temperature response <u>including</u> <u>feedbacks</u>

$\Delta T_f = \lambda_o [\, R + c_1 \Delta T_f + c_2 \Delta T_f + \ldots \,]$ (c_i in Wm^{-2}/K)

$= \lambda_o R + f_1 \Delta T_f + f_2 \Delta T_f + \ldots$ where $f_i = \lambda_o c_i$ is a dimensionless feedback factor

$= \Delta T_o + \Delta T_f [\, f_1 + f_2 + f_3 + \ldots \,]$

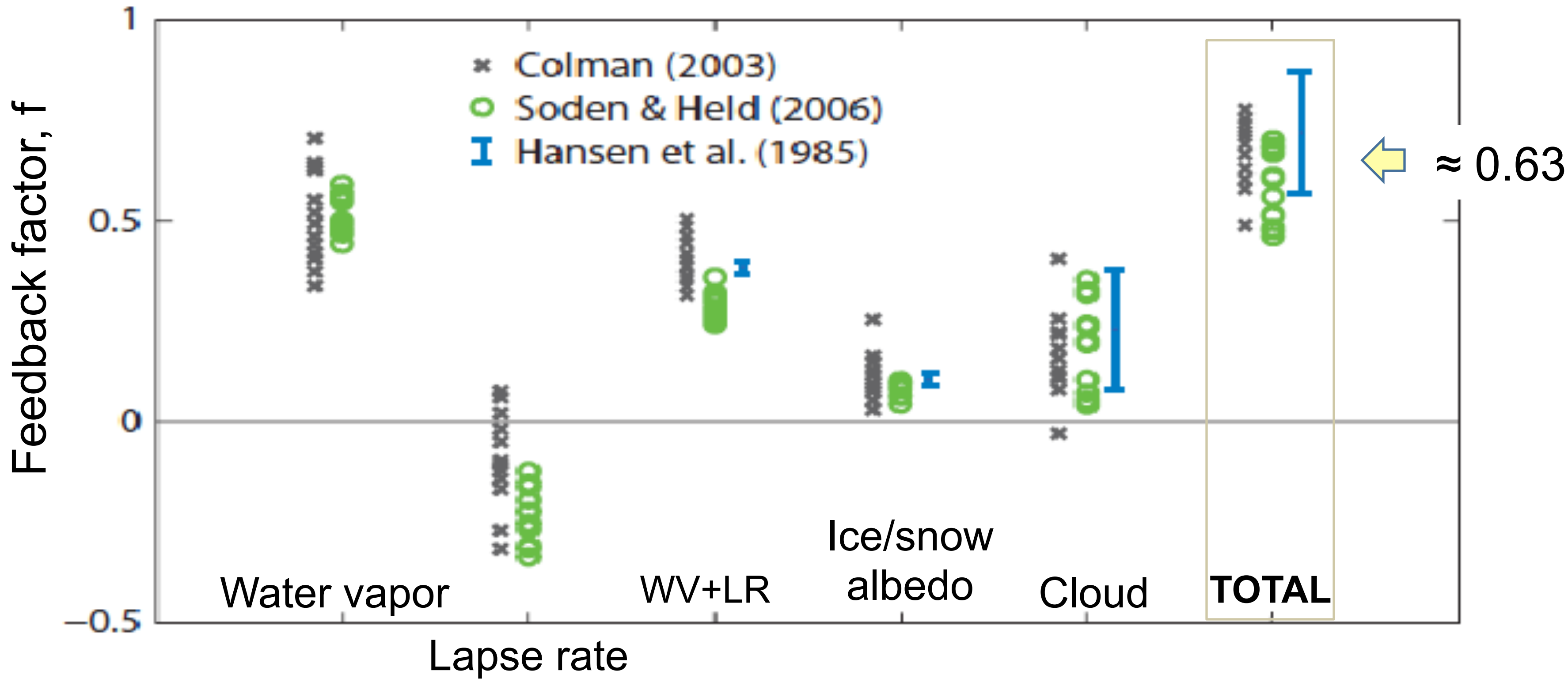
$$\Delta T_f = \left[\frac{1}{1 - (f_1 + f_2 + \ldots .)} \right] \Delta T_o$$

⇧

System Gain

The major short-term feedback factors (f)

Obtained from a number of different climate models



Note: All short-term feedbacks involve water in one form or another

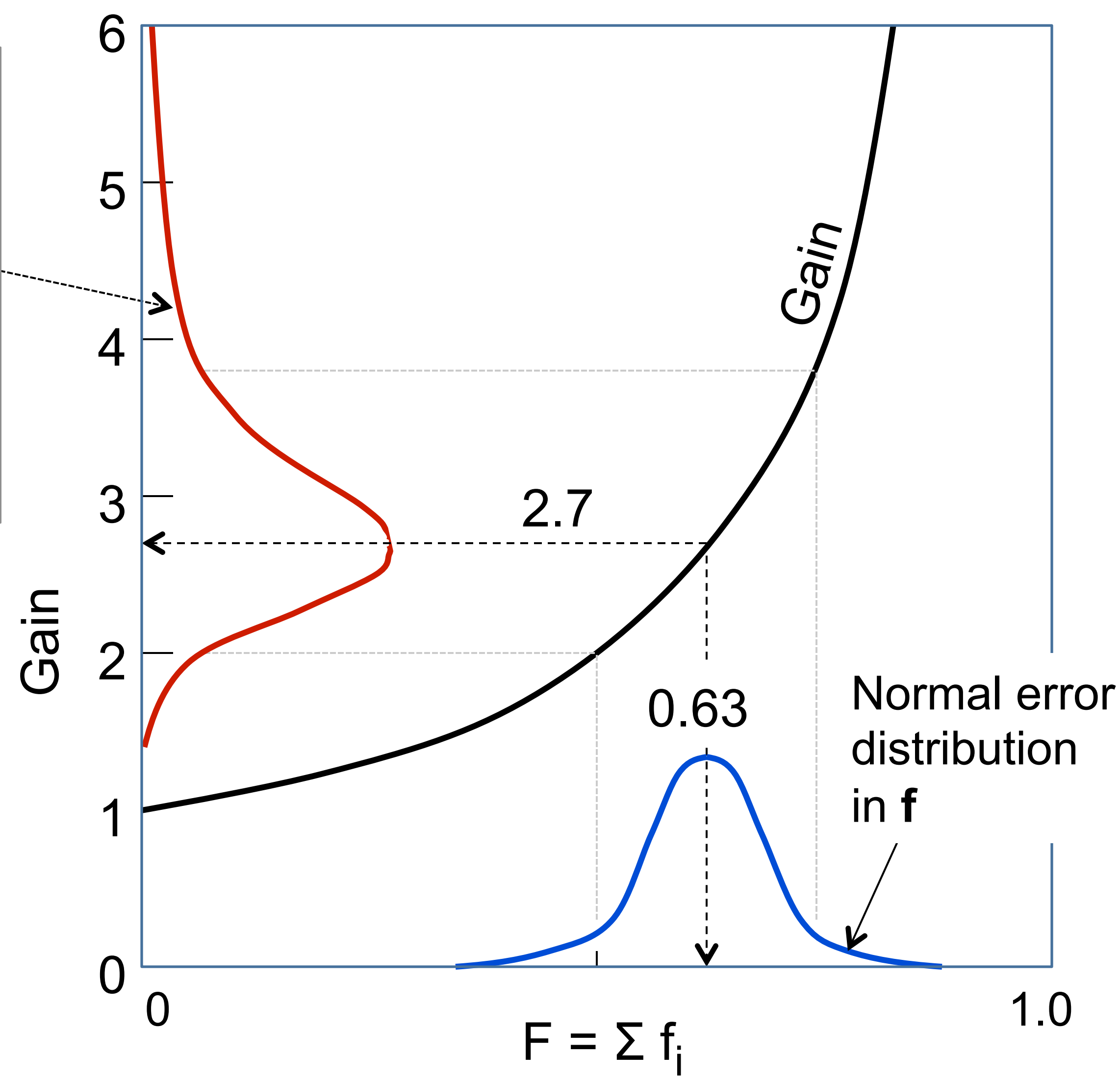
Relationship between total feedback factor and system gain

Showing how a normal error distribution in **F** produces a gain distribution that is:

- Widened
- Skewed
- Amplified disproportionately in modal value as additional contributors **f** are included

$$\text{Gain} = \frac{1}{1 - (f_1 + f_2 + \ldots)}$$

$$= 2.7$$



Climate sensitivity parameter, with feedbacks

Thus $\Delta T_f = 2.7\ \lambda_o\ R$, with feedback

$$\Delta T_f = \lambda_f\ R \quad \text{(Eqn. 2)}$$

where $\lambda_f = 2.7\ \lambda_o \approx 0.8\ K/(Wm^{-2})$ is the ***climate sensitivity parameter including feedbacks***, at equilibrium,

$$\lambda_f \approx 0.8\ K/(Wm^{-2})$$

IV. Climate sensitivity to forcing

Equilibrium climate sensitivity (ECS)

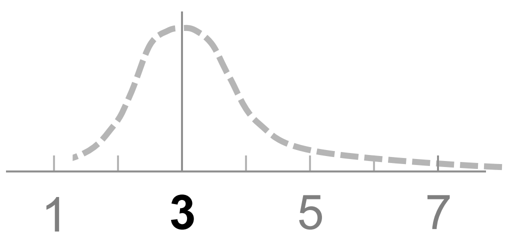
Defined as the change in surface temperature, at <u>equilibrium</u>, associated with a doubling of CO_2

Recall that $R_{2X} = 3.8\ Wm^{-2}$ for doubling CO_2 (result from radiative transfer).

Thus:

$$\Delta T_{2X} = \lambda_f R = 0.8 \times 3.8 \approx 3\ K,$$ with <u>feedbacks</u>

$ECS \approx 3\ K$

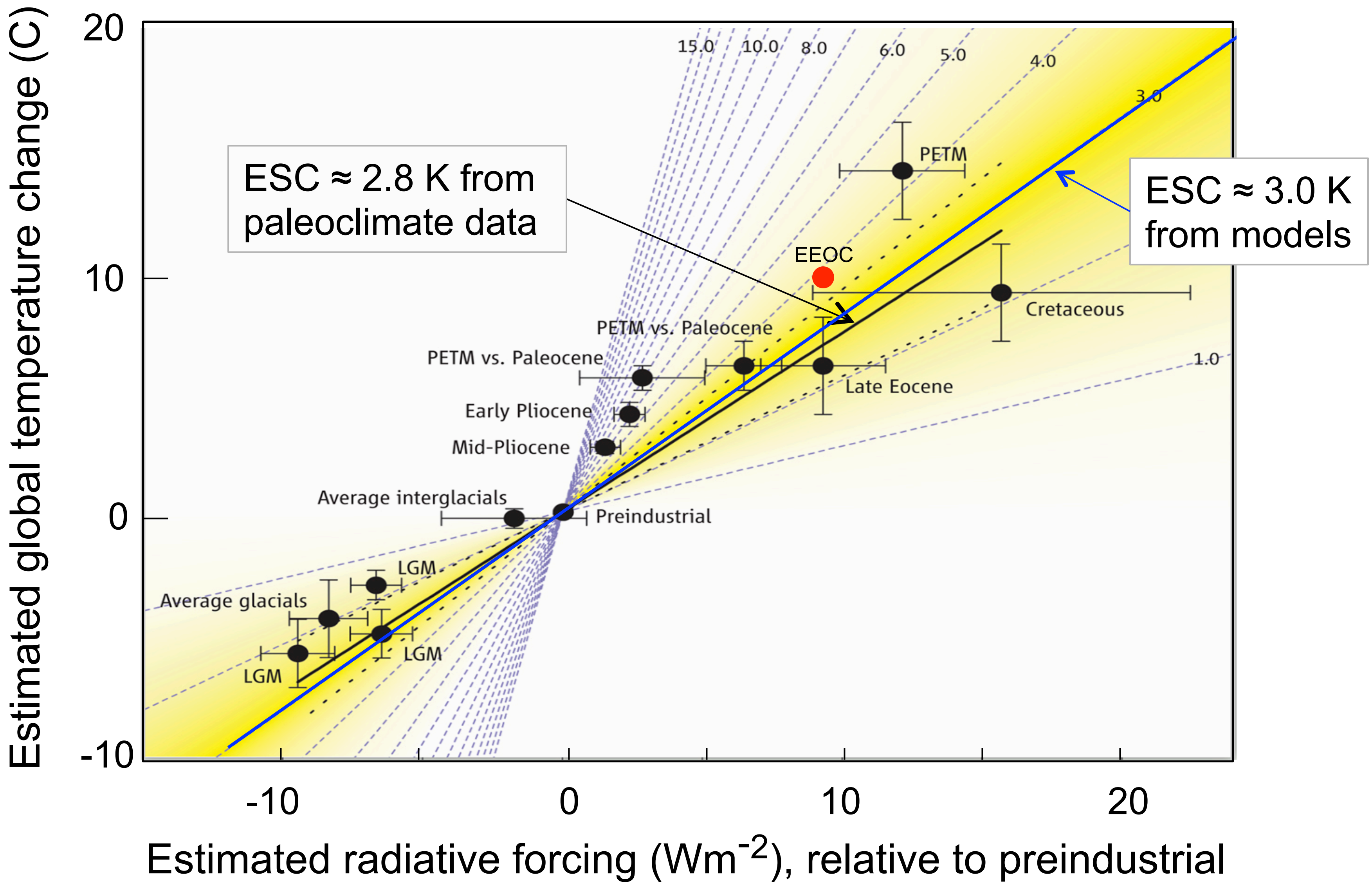


The form of the gain function leads to a poorly constrained upper limit on ESC.

IPCC states that ECS is *likely* in the range 1.5 to 4.5 C

ECS as observed from paleoclimate data

(Temperature responses here automatically include feedbacks)



(From estimates of GHGs, albedo, dust, ice sheet extent)

V. Climate change and energy imbalance

In what follows, use data current to 2013:

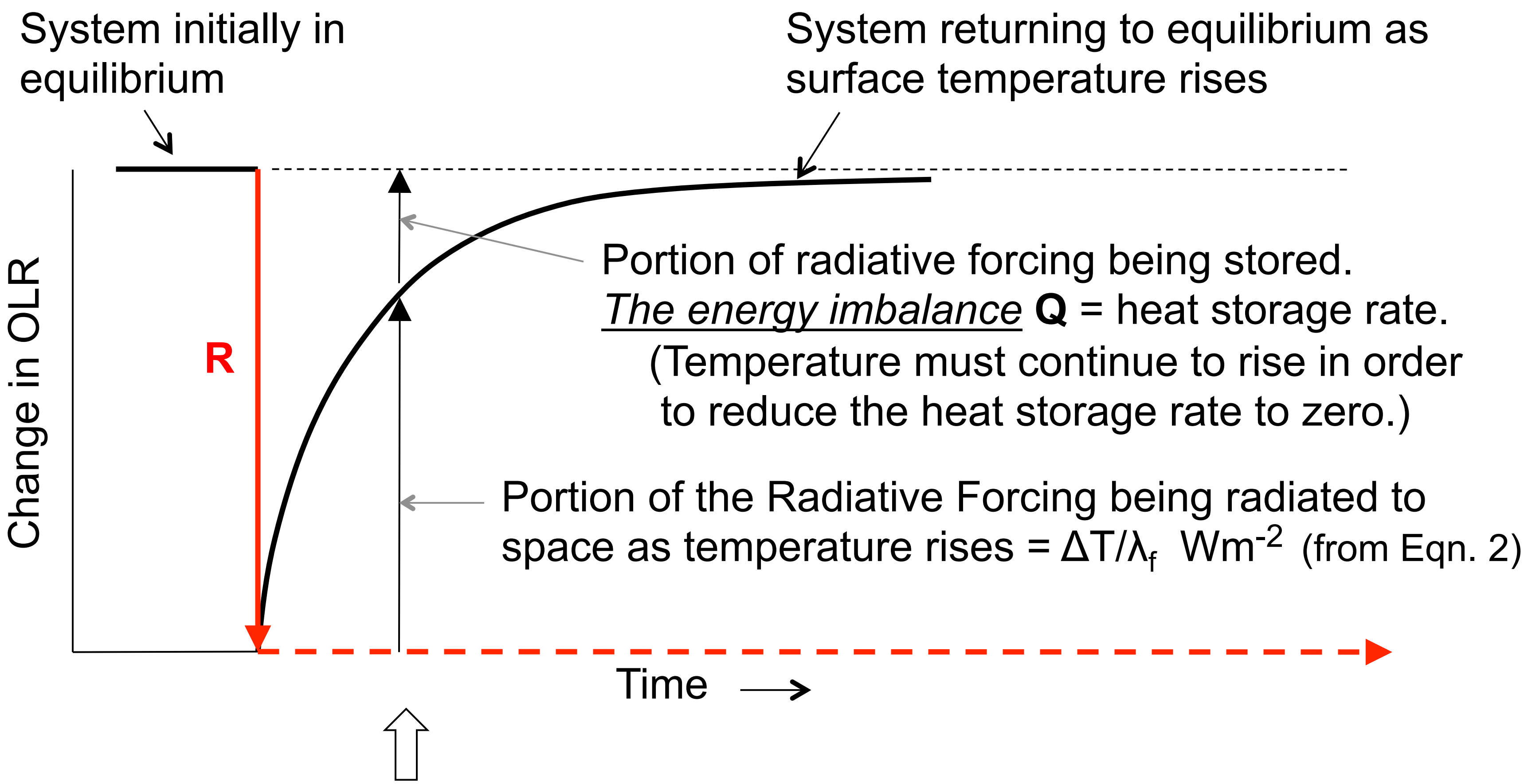
$\Delta T \approx 1.1$ C relative to preindustrial

$R \approx 2.3$ W m^{-2}

$Q \approx 0.7$ W m^{-2} (heat storage rate)

Climate response to an instantaneous radiative forcing, R

Case of an instantaneous GHG forcing which is then held constant in time



Conservation of energy
Applies at all instants:

$$R = Q + \Delta T/\lambda_f \quad \text{(Eqn. 3)}$$

Measuring Q:

Energy imbalance = energy storage rate (rate of change in heat content of the climate system)

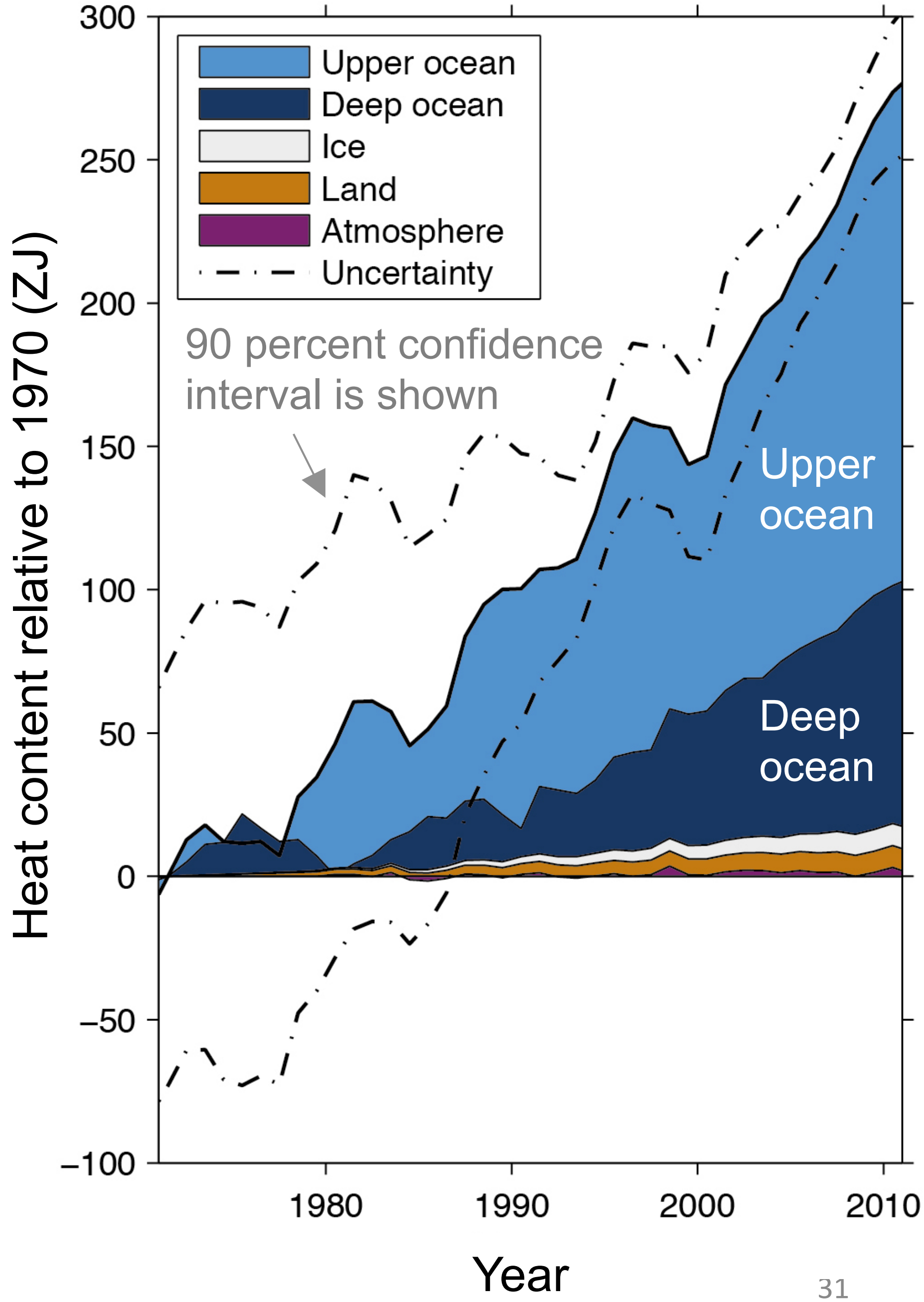
Where is the heat going?

Ocean	93 %
Land mass	3 %
Ice melt	3 %
Atmosphere	1 %

Rate of change in total heat content (2001-2011):

$Q \approx 0.7$ W m^{-2}

Energy imbalance:
The "smoking gun" of global warming



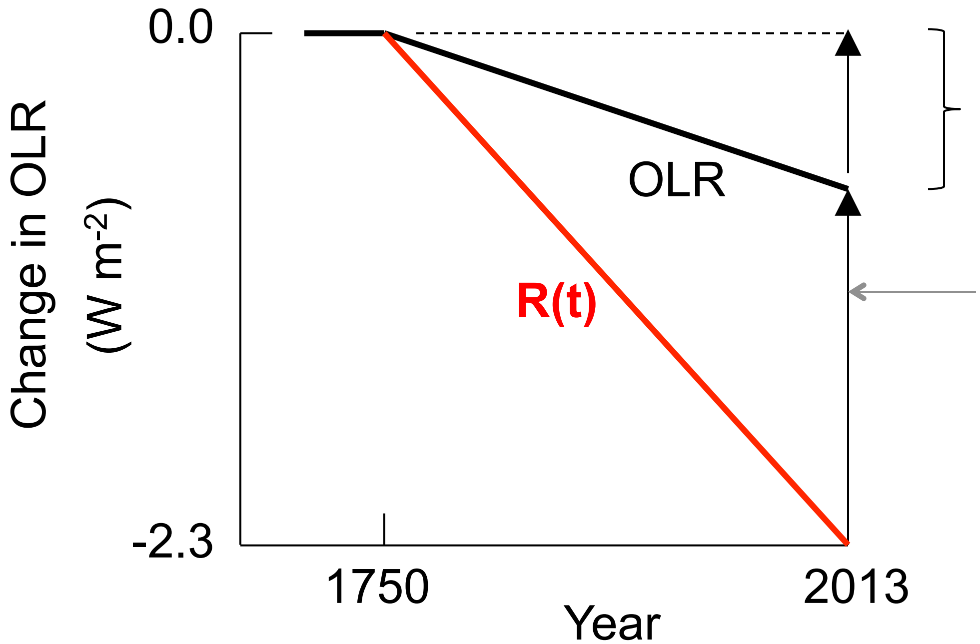
1 ZJ (zettajoule) = 10^{21} joule

“How inappropriate to call this planet Earth when clearly it is ocean.”

— *Arthur C. Clarke*

Response to a time-dependent forcing, R(t)

(Roughly illustrating what has happened since 1750)



Portion of forcing being stored:

$Q \approx 0.7$ W m^{-2}

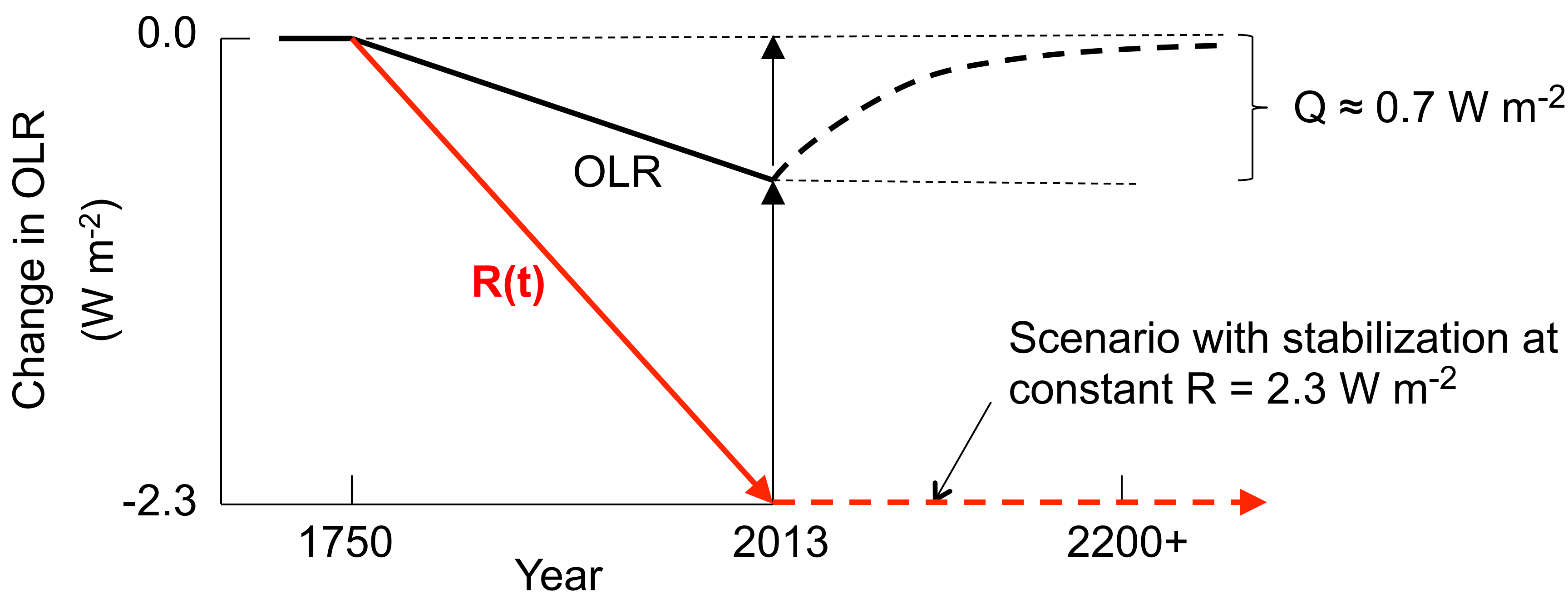
Portion of forcing being radiated to space as temperature rises:

From (Eqn. 2):

$\Delta T/\lambda_f \approx 1.1/0.8 = 1.4$ Wm^{-2}

(Reminder: Numbers here apply to 2013)

Response if forcing were held constant at its current value



Committed additional ΔT if forcing were held constant: $\Delta T = \lambda_f Q \approx 0.6$ C

Even if GHGs were to stabilize at present concentrations, an additional temperature increase of 0.6 C would be required in order to make the energy imbalance return to zero: This temperature increase is known as the **"constant composition commitment"**

The Paris Climate Accord:

An unrealistic goal?

Goal: To limit warming to no more than of 2 C relative to preindustrial.

Factors to consider

1. Observed global surface warming as of 2016: 1.2 C*

2. Constant composition commitment: + 0.6 C (At equilibrium)

3. Reducing carbon emissions to nearly zero would also reduce the aerosol cooling effect to nearly zero.
   - Increases forcing by 0.7 W m^{-2} (see Slide 17)
   - Thus $\Delta T \approx 0.7\lambda_f \approx 0.6$ C: + 0.6 C (Immediate)

* Average result from four institutions

Factors to consider (cont'd)

4. And still, GHG concentrations continue to rise!

5. Goal might be met in the long run, but probably not before passing through the 2 C threshold. (See Slide 43)

6. Neither immediate nor complete cessation of carbon emissions is possible, for economic reasons.

7. A likely outcome is that global temperature will exceed a dangerous level for a hundred years or more. Critical decisions were not made soon enough (and in fact many still haven't been made) to avoid this outcome.

VI. Diagnostics for the mechanism of tropospheric warming

Fingerprints unique to anthropogenic change

- Increase in height of the tropopause (is happening)
- Stratospheric cools while the troposphere warms (has happened)
- No change in Earth’s radiation temperature
- Reduction in diurnal temperature range (has happened)

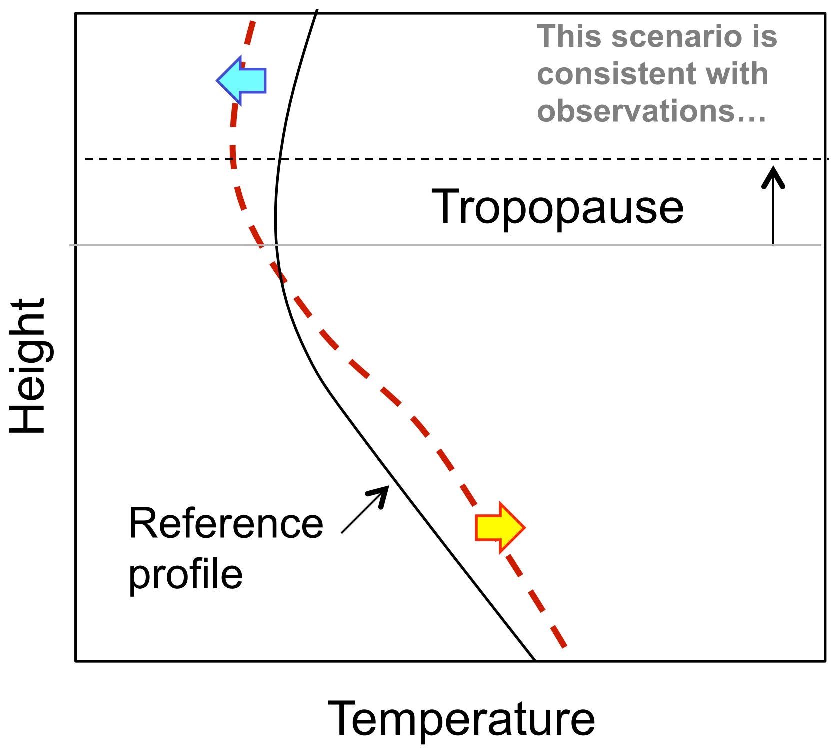
Expected changes in the atmospheric profile and T_e

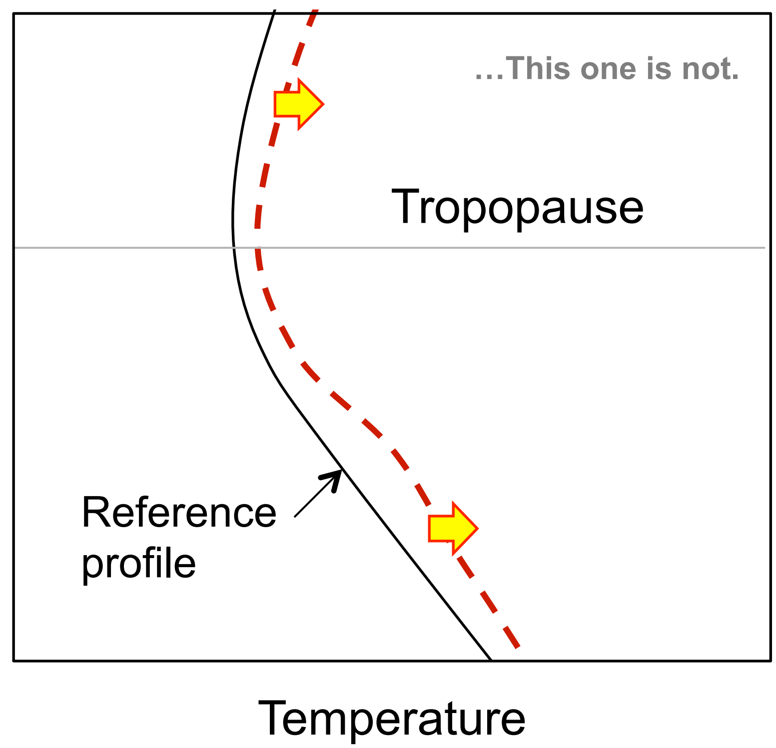
Added GHGs and ozone depletion:

- ✔ Warms the troposphere
- ✔ Cools the stratosphere
- ✔ Raises the tropopause height
- ✔ Unchanged radiation temperature

No changes in composition, but increase in direct energy input*

- ✔ Warms the troposphere
- ✗ Warms the stratosphere
- ✗ Unchanged tropopause height
- ✗ Increased radiation temperature

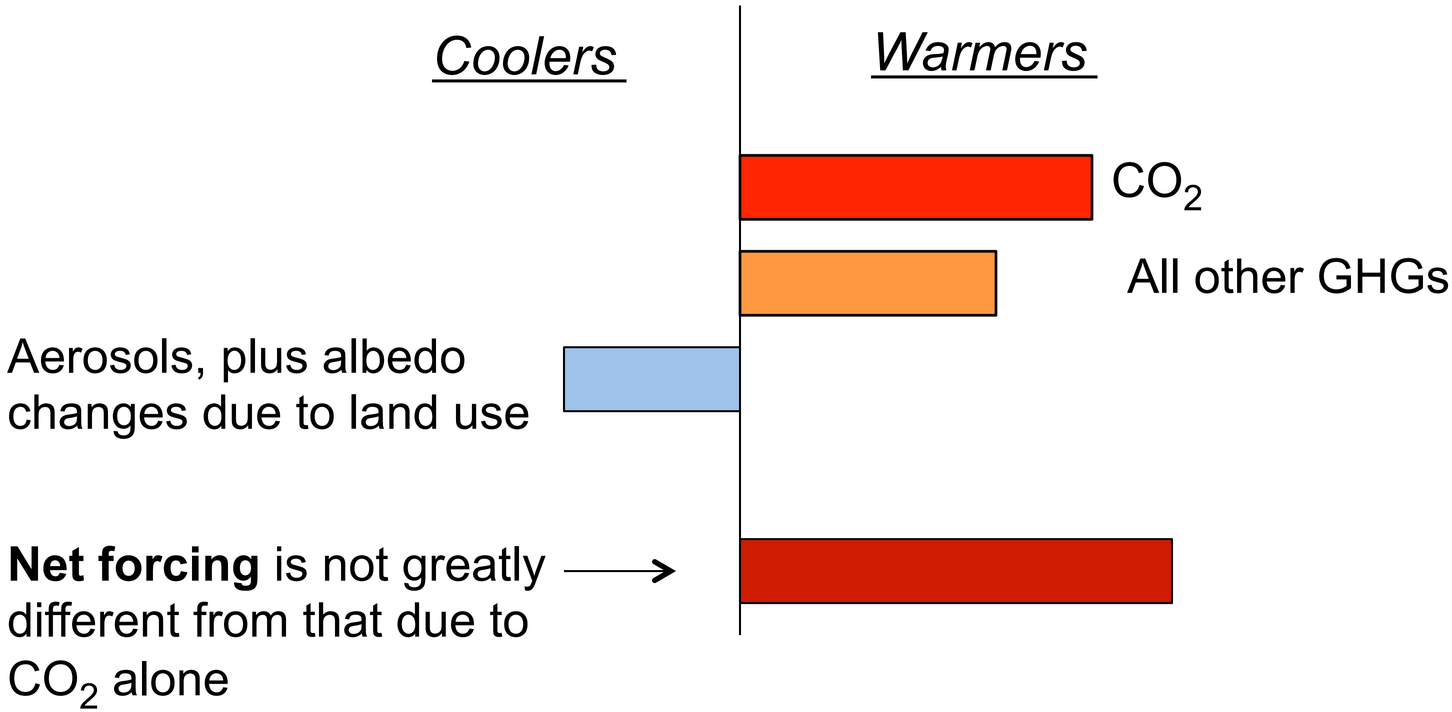




* e.g. by increasing solar, decreasing albedo, or increasing heat input from earth's interior

VII. Projections for future climate

Major contributors to radiative forcing, by group



The above contributors usually vary together, therefore:

Rule of thumb for future temperature projections: just figure from the CO_2 concentration alone

Comparing "rule of thumb" with climate model projections for several IPCC Representative Concentration Pathways (RCPs)

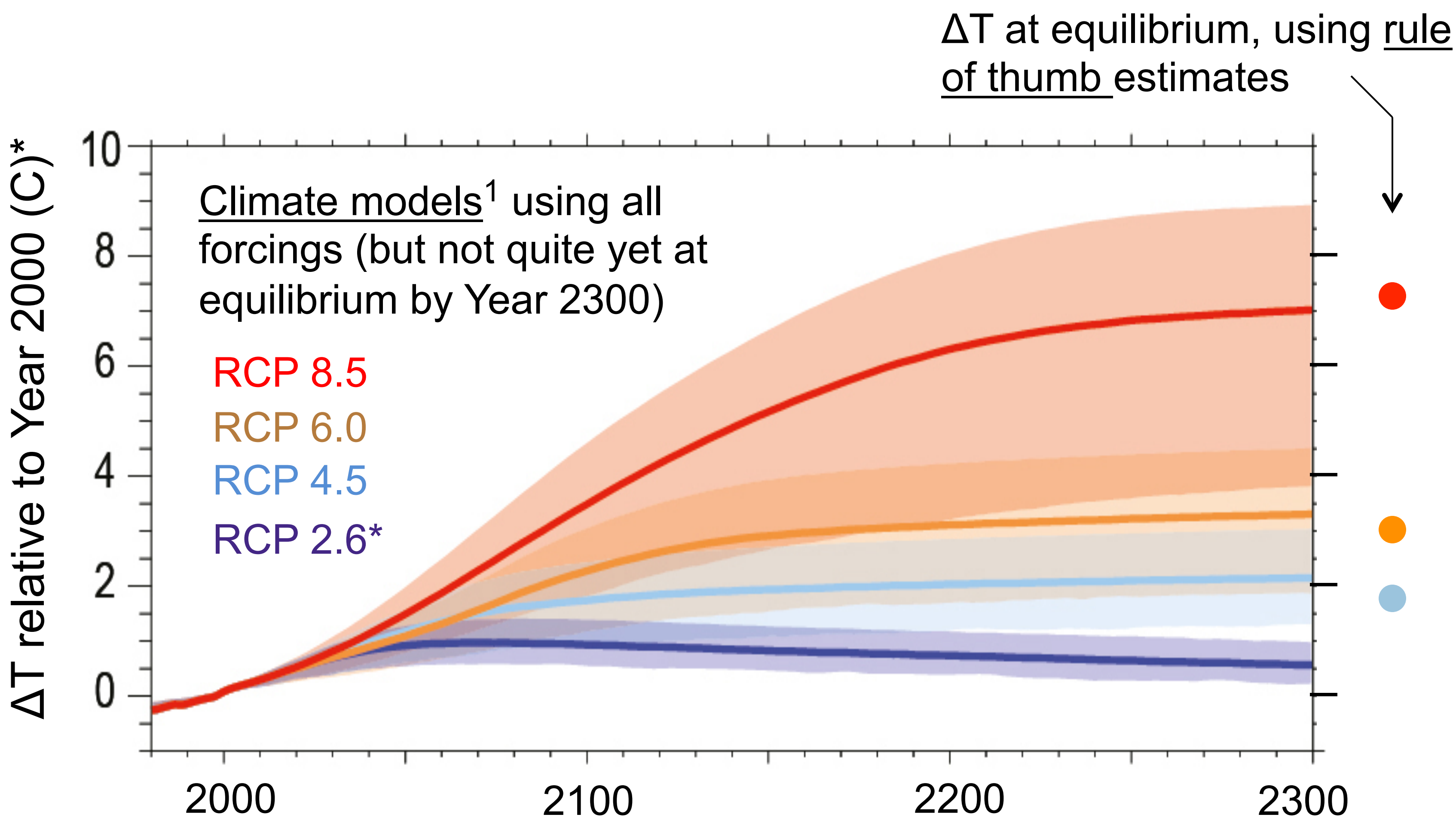
RCPs include all GHG and aerosol contributors

	RCP 8.5	RCP 6.0	RCP 4.5
CO_2 peak level (ppmv):	1950	750	540
Number of CO_2 doublings* relative to 2000 (ref. 367 ppm):	2.4	1.03	0.56
ΔT at Year 2300 from models, relative to Year 2000:	7.0	3.3	2.1
ΔT at equilibrium from Rule of Thumb, relative to 2000:	7.2	3.1	1.7

$\Delta T \approx$ ECS x Number of CO_2 doublings, where ECS ≈ 3 C

* Number of doublings = log ($CO_2/CO_{2\ ref}$) / log 2. $CO_{2\ ref}$ = 367 ppm in Year 2000)

ΔT Comparisons, relative to Year 2000



Note: Add ≈ 1 C everywhere to obtain ΔT relative to preindustrial.

[1] From IPCC 2013. Shaded areas show 90% confidence intervals

* RCP 2.6 is a scenario with zero GHG emission *rates* after 2050

Thank you for your interest in global climate change

For a copy of these slides, contact Don at:

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Best-pick references on climate science

Introductory text:

F. W. Taylor, *Elementary Climate Physics*, Oxford Univ. Press, 2005.

(Assumes a science background)

Advanced text:

R. T. Pierrehumbert, *Principles of Planetary Climate*, Cambridge University Press, 2010.

(Suitable for graduate or advanced undergraduate level)

Intergovernmental Panel on Climate Change, 2013: *Climate Change 2013* (*Vol I): The Physical Science Basis*, Cambridge Univ. Press.

(1500 pages; available online; summarizes all research up to 2012; pedagogy is not an objective, although a summary for policy makers, a technical summary chapter, and numerous "FAQ" sidebars are included)

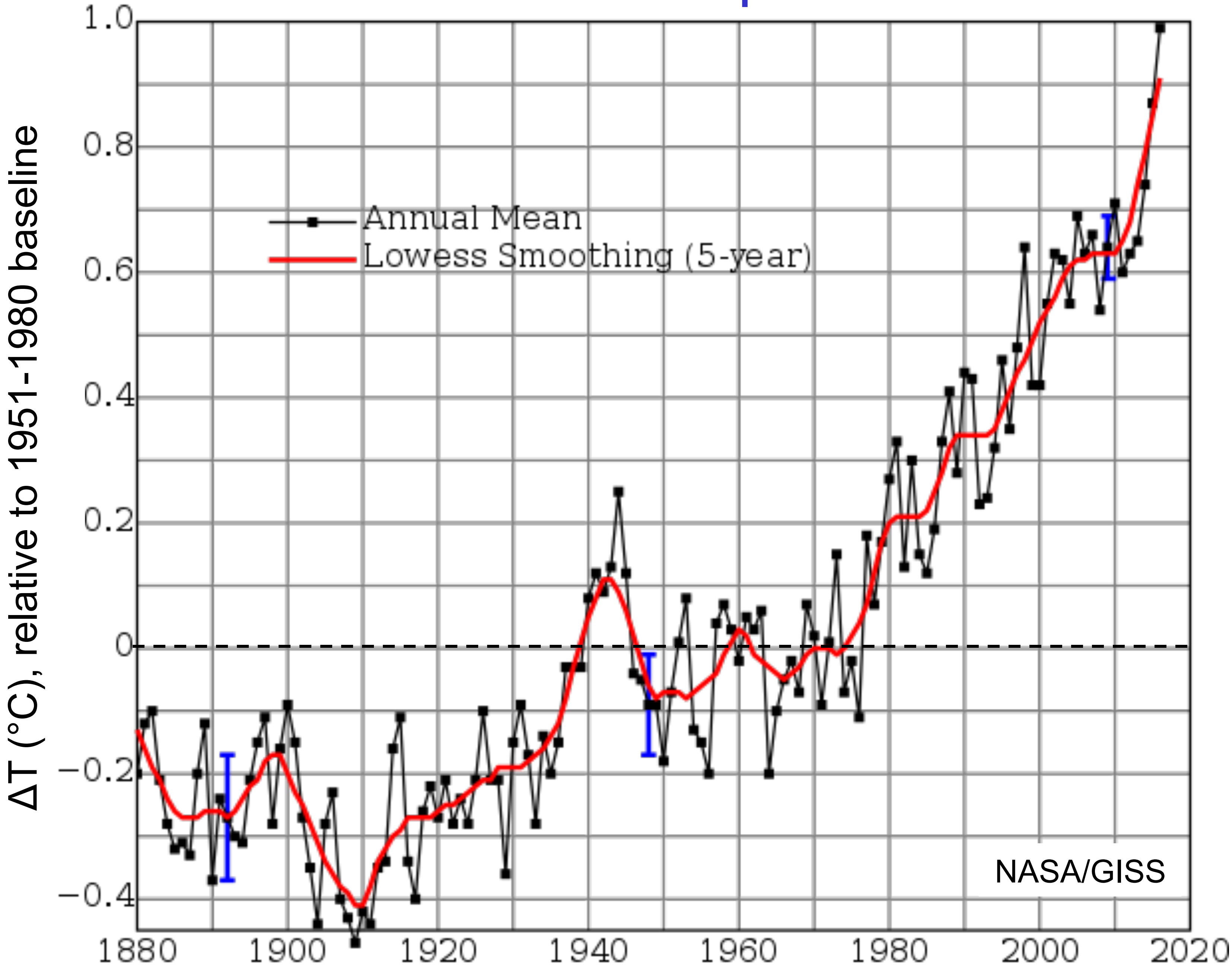
Review article:

R. T. Pierrehumbert, *Infrared Radiation and Planetary Temperature*, Physics Today, January 2011, p. 33.

(Excellent review of the greenhouse effect on Earth and other planets)

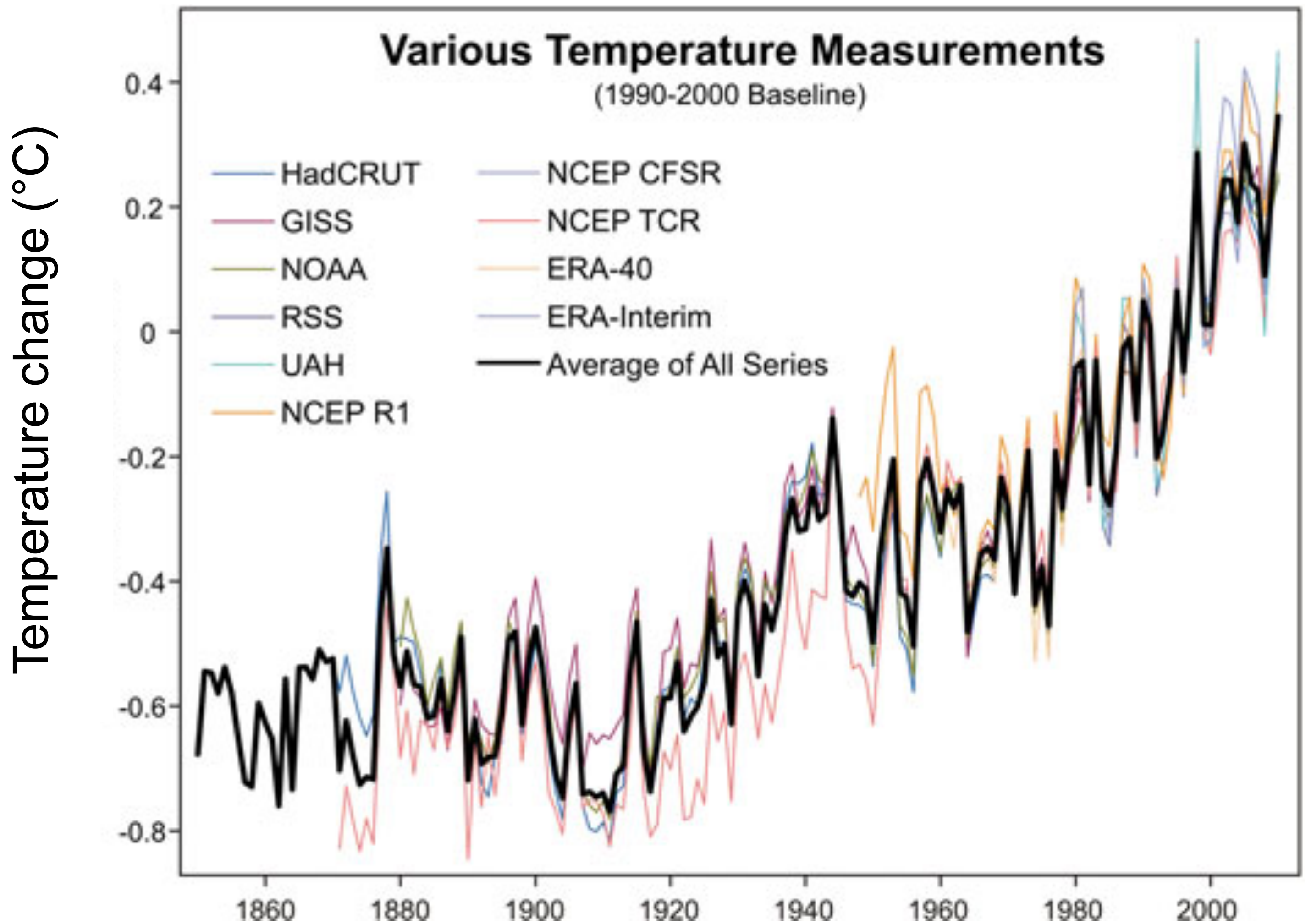
Supplement slides

Global land-ocean temperature index

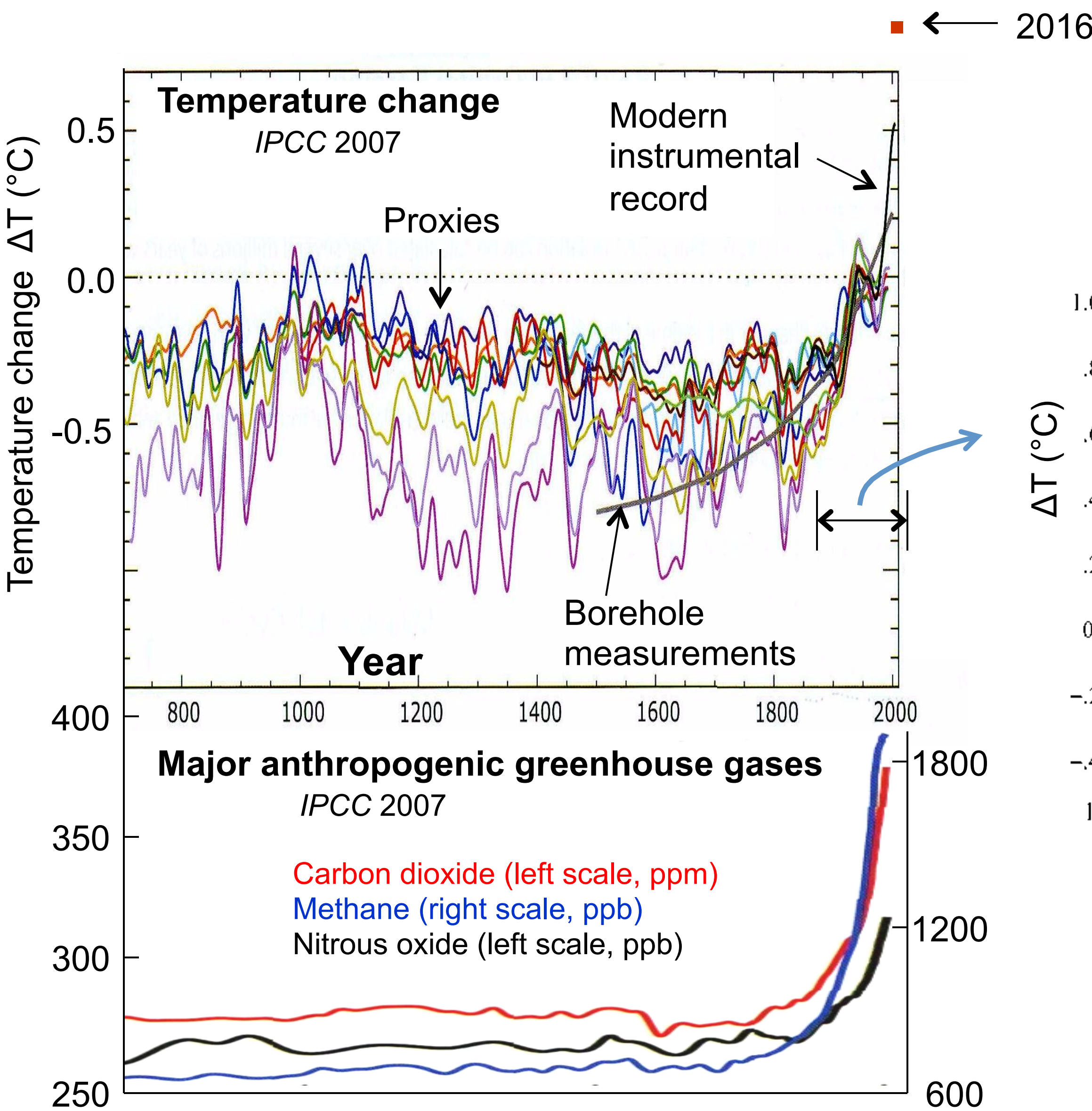


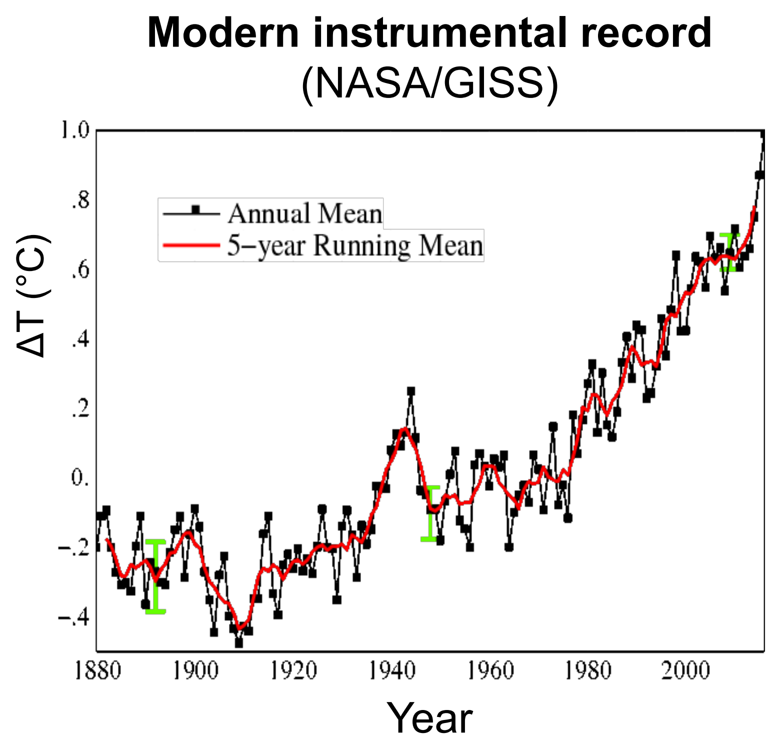
Comparison of measurements of global temperature change

Includes measurements of surface temperature as well as satellite and radiosonde measurements of free tropospheric temperature

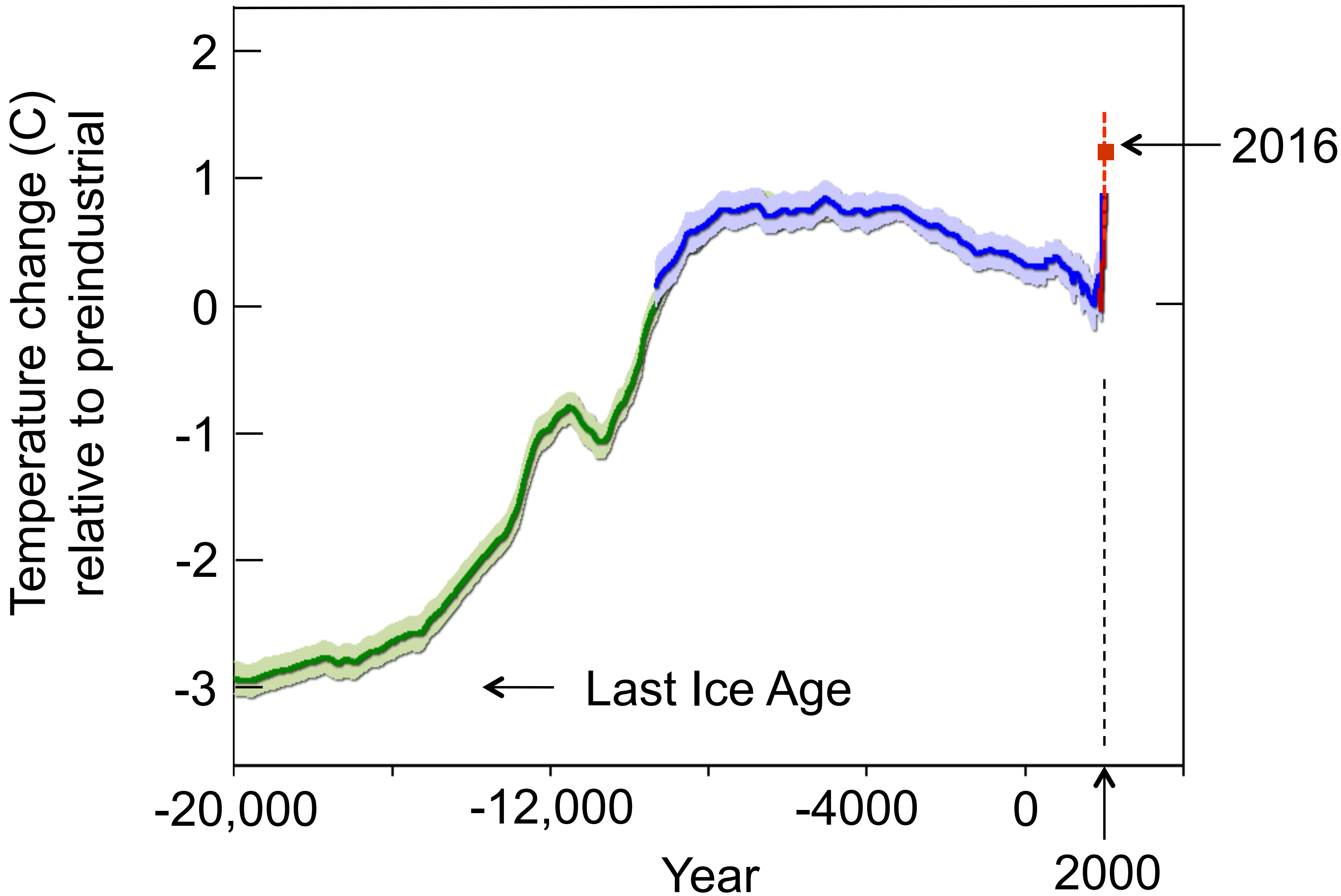


Global surface temperature change and greenhouse gases



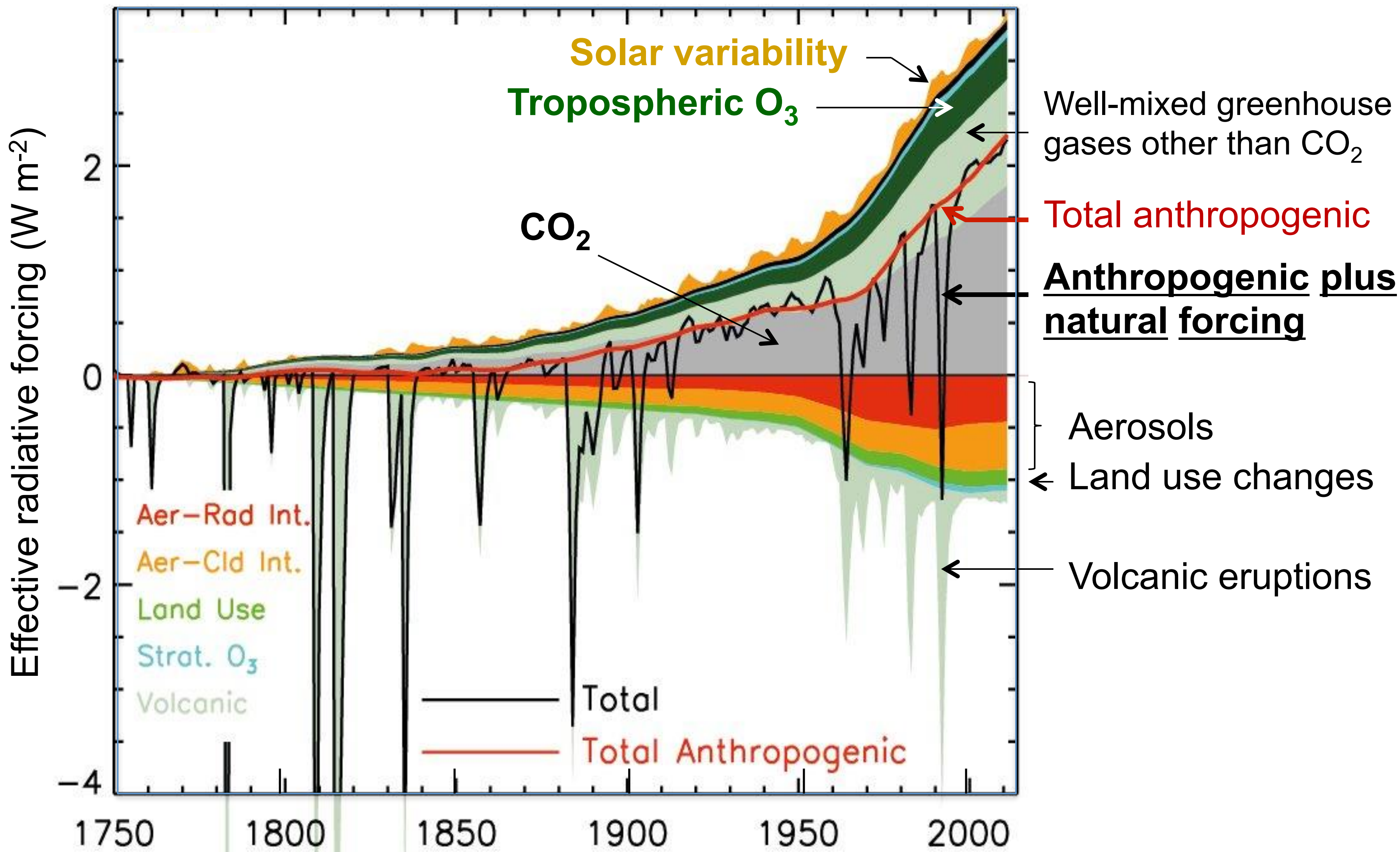


Change in global temperature over the last 22,000 years (perspective relative to the Last Ice Age)



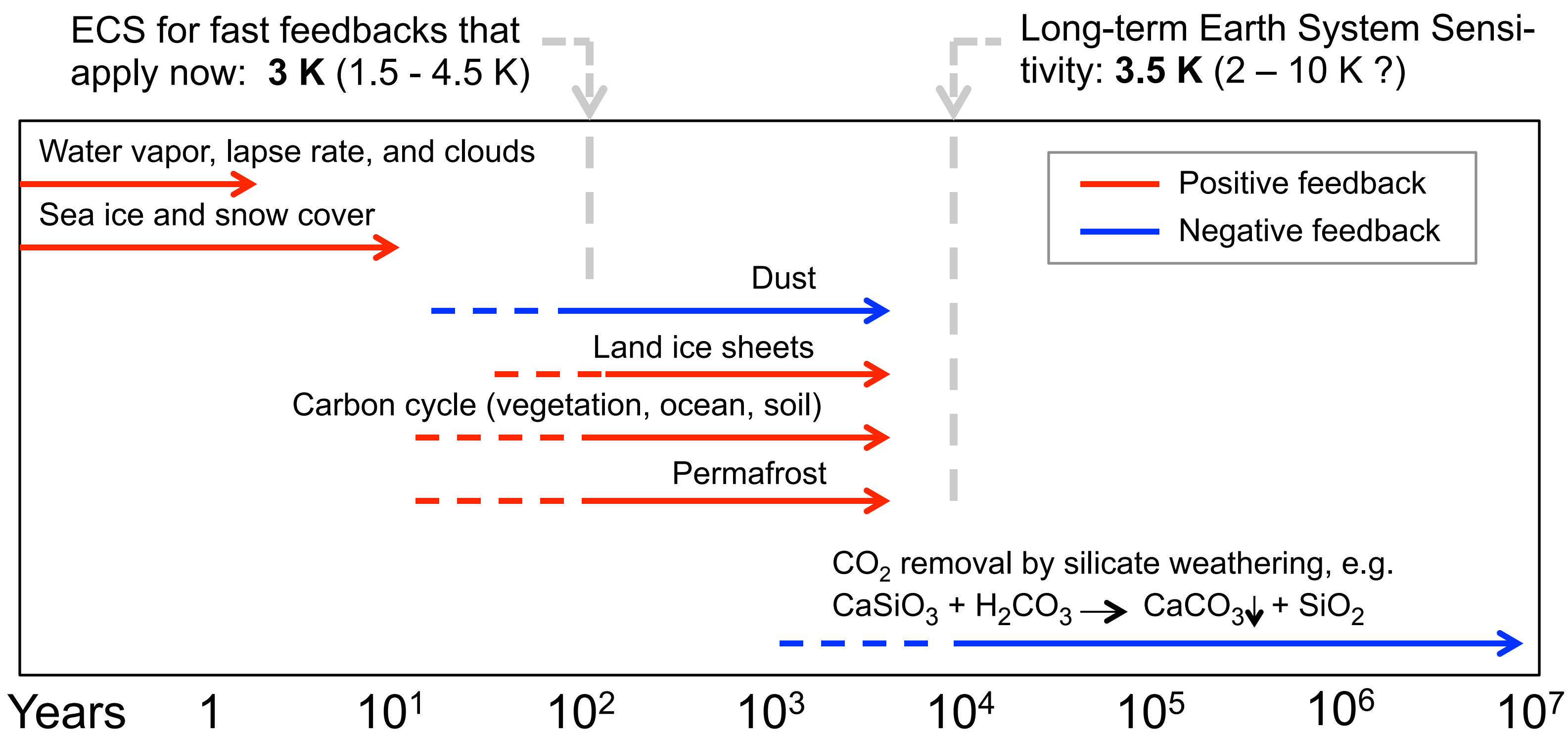
Merging of data from Shakun et. al., 2013 (green) representing 80 geographic locations, and data from Marcott et al., 2013 (blue) representing 73 locations. During the current warming, global temperature is rising more than 10 times faster than during the transition from the last ice age.

Time evolution of radiative forcing, 1750 - 2010



IPCC 2013

Time scales for feedback processes



The chart above depicts time scales on which various feedback processes are initiated in response to temperature change. The current global warming includes feedbacks that come into play on time scales of decades or less, although these processes do not necessarily diminish on longer time scales. Elevated temperature sustained over longer periods of time initiate additional feedbacks which may drive sensitivity higher. Prolonged periods of elevated warming would melt ice sheets (thus reducing albedo) and would release additional GHGs from thawing permafrost. "Earth System" sensitivity, which would likely apply after thousands of years of elevated temperature, remains quantitatively uncertain. On time scales of millions of years climate is governed by secular changes in solar luminosity (about 1 percent increase per 100 million years), changes in biota, and release of CO_2 due to tectonic activity. These long-term processes interact with slow CO_2 removal by temperature-dependent rates of rock weathering.

Diagram above is derived (with modification) from the Palaeosens Project, 2012 (*Nature* v.491, 683). The high upper bound (10 K) on Earth System Sensitivity is attributed to Roe, 2009: *Ann. Rev. Earth & Planetary Sci.,* v. 37, 91.

Forcing as a function of GHG concentration

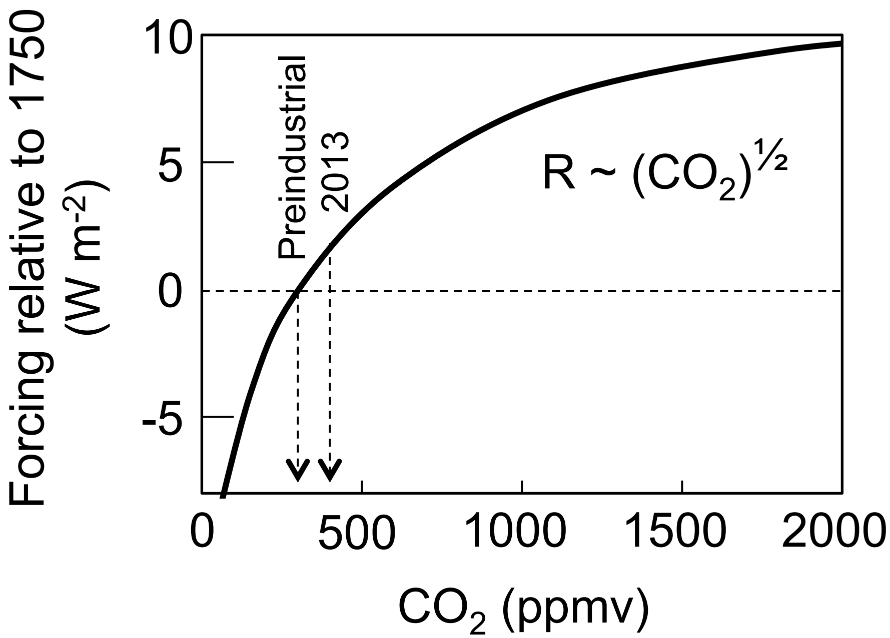
Radiative forcing typically bears a logarithmic dependence on GHG concentration, as most of the change in absorption owes to broadening of spectral features.

For example, a rule-of-thumb for CO_2:

$R \approx R_{2X} \log (CO_2/CO_{2\,ref}) / \log 2$, where $R_{2X} = 3.8\ W\ m^{-2}$

$CO_{2\,ref}$ = 278 ppmv (preindustrial); CO_2 (2013) = 395 ppmv

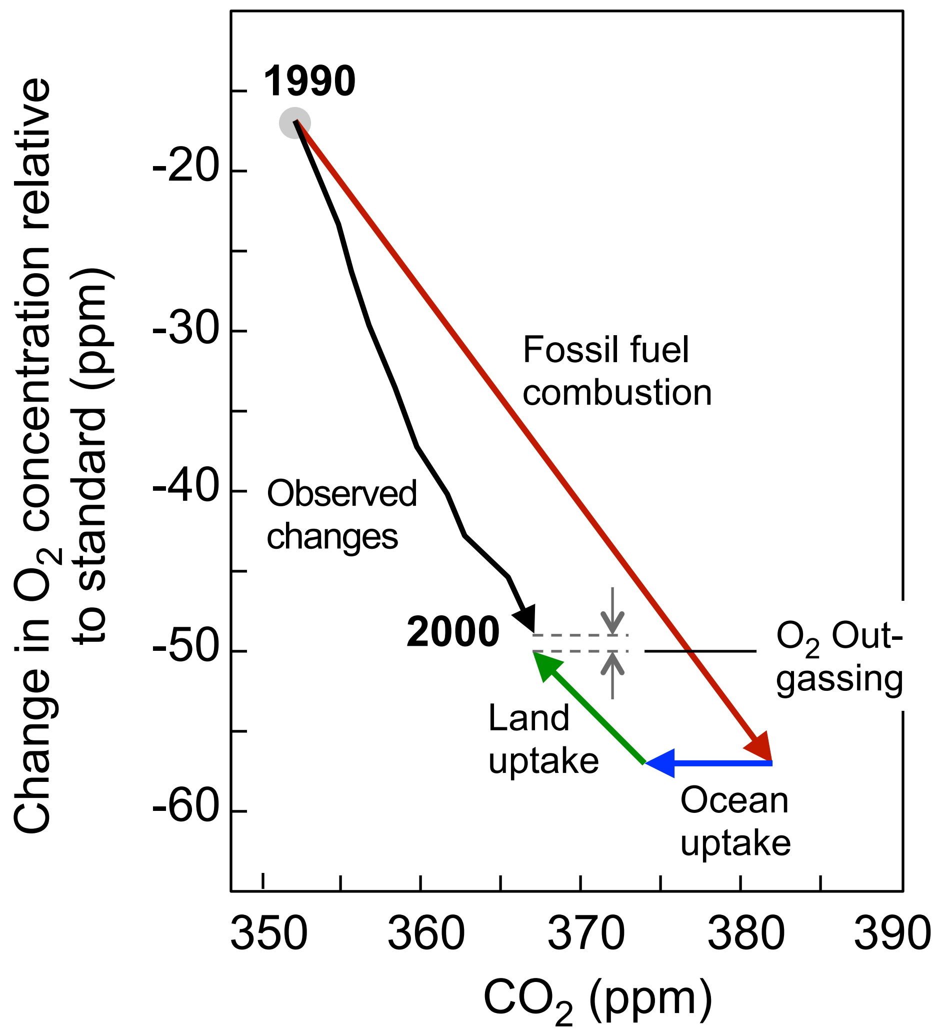
Result: $R \approx 1.9\ W\ m^{-2}$ from CO_2 alone (compares well with the value 1.8 in Slide 17)



At current rate of increase, CO_2 will double from its pre-industrial level by late 21st century.

The logarithmic dependence assures that a given addition of GHG will produce a relatively larger increase in forcing when the initial concentration is small. Thus an addition of methane (the concentration of which is presently very small), will produce a larger increase in forcing than an equal addition of CO_2 which is already in relatively high concentration. It is therefore often stated that methane is a stronger greenhouse gas than CO_2. Actually, on a molecule-for-molecule basis, CO_2 is the stronger greenhouse gas.

Stoichiometric diagram showing the partitioning of changes in CO_2 and O_2 over a ten-year period



Observed changes in atmospheric concentrations of CO_2 and O_2 during 1990-2000 are shown by the black line. *Expected* changes in CO_2 and O_2 during the same period are shown by the red arrow, based on the amount of fossil fuel combusted. Subsequent uptake of CO_2 by the ocean (blue arrow) partially reverses the increase in CO_2 but does not alter the O_2 concentration. Land processes further reduce CO_2 but also release O_2 due to photosynthesis, as shown by the green arrow. Ocean warming over the ten-year period produces a relatively small outgassing of O_2 (shown by the gap). The sum of all of these processes effectively closes the stoichiometric loop.

Diagram adapted from *IPCC* 2001, p. 206

Aside: Nomenclature on climate sensitivity

Equilibrium Climate Sensitivity (≈ 3 C):

The climate response, *at equilibrium*, to a doubling of CO_2

- Requires a few hundred years (for surface temperature)
- Requires a thousand years for the deep ocean
- Requires quantitative information on feedbacks

Transient Climate Response (≈ 1.8 C):

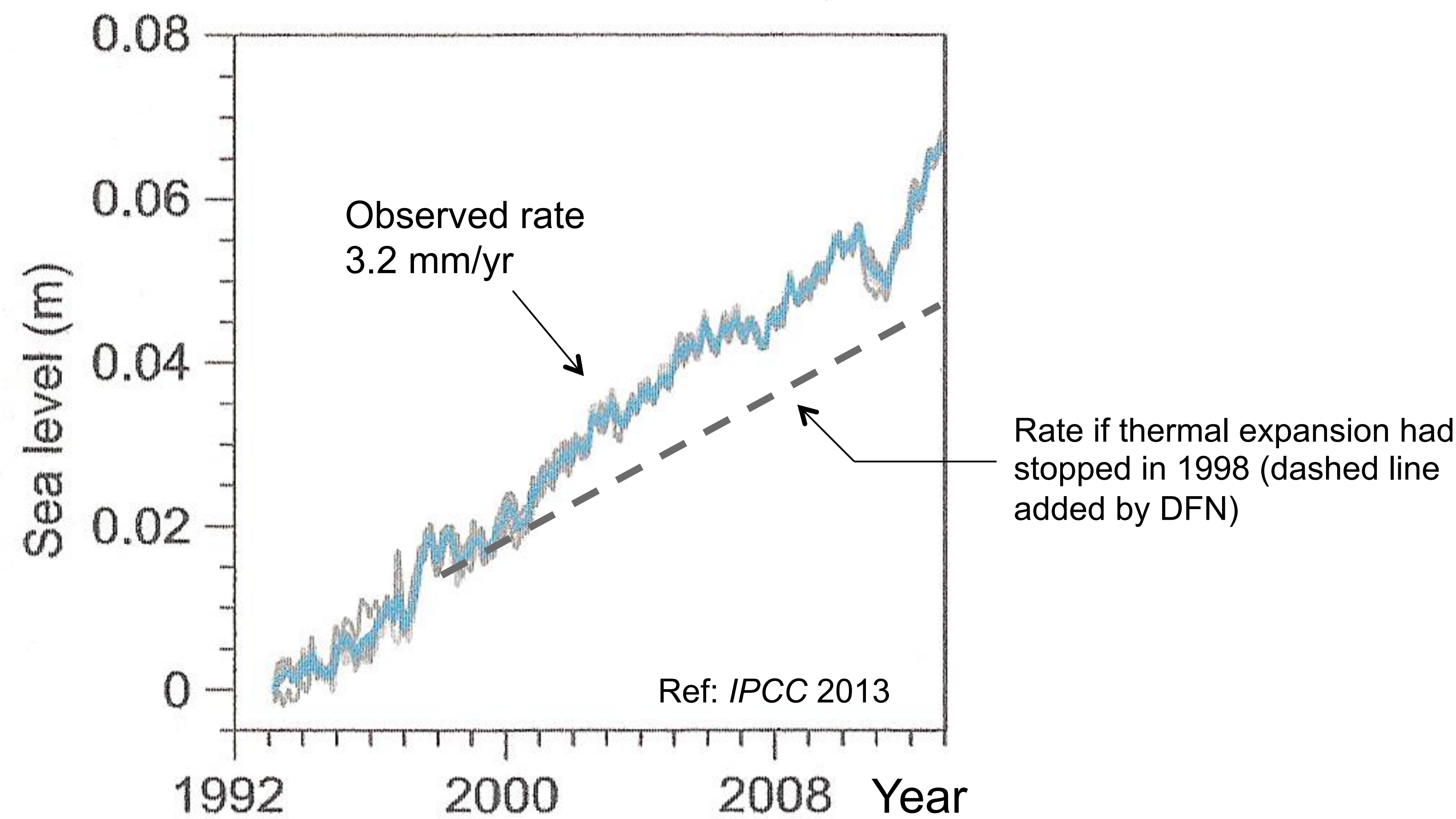
The climate response *before equilibrium* is obtained

TCR definition: The change in surface temperature at the time of CO_2 doubling, when CO_2 is increased at the rate of 1 percent per year (requires 70 years for doubling)

TCR is obtained from climate models

Change in sea level

Due mostly to thermal expansion and the melting of land ice



If heat input to the ocean had ceased or significantly declined after 1998 the component of sea level rise due to thermal expansion would have declined accordingly, resulting in a detectable difference from what is observed (see above). [The temporary drop in sea level in 2011-2012 was caused by torrential rainfall in Australia, which sequestered a large amount of water on land with no outlet to the sea. This water was slowly returned to the ocean via evaporation and subsequent rainfall.]

Global ice mass and loss rate (recent decade)

	Mass (Gt*)	Approximate melt rate* (Gt/yr)
Ice sheets	2.4×10^7	400
Glaciers	1.5×10^5	300
Sea ice*	2.0×10^4	~300
Permafrost		>0
Snow	4	>0
Total		~ 1000 Gt/yr

Ice sheets + Glaciers → Raises sea level about 1.8 mm/yr

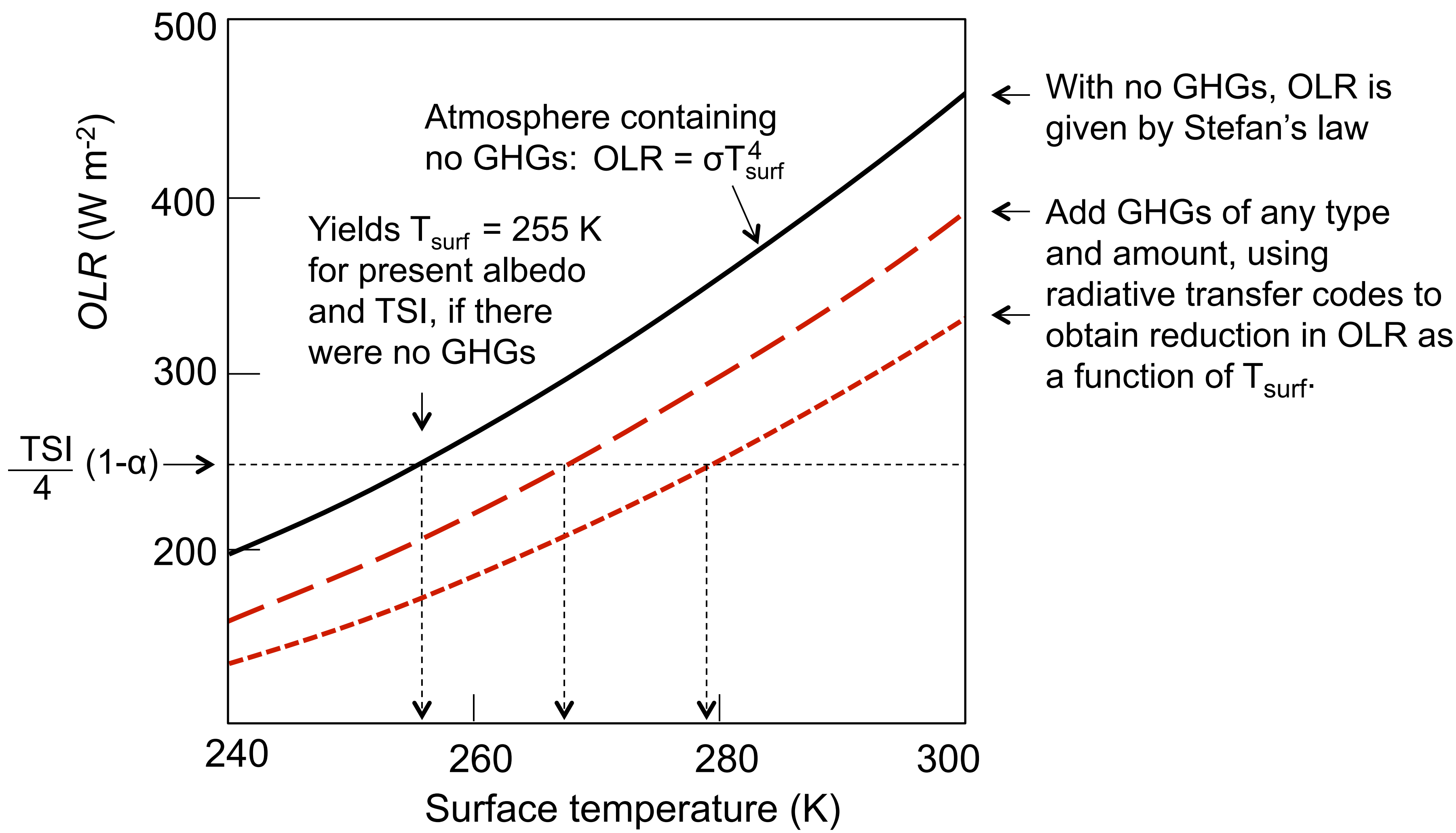
Total ↓

Heat equivalent: 3.4×10^{20} J/yr (0.02 W m^{-2} averaged over Earth's surface, or about 3% of the current global energy imbalance)

* Gt = gigatonne = 10^{12} kg. Sea ice melt rate refers to Arctic and Antarctic sea ice combined. Melt rates shown above are accurate to about ± 20 percent.

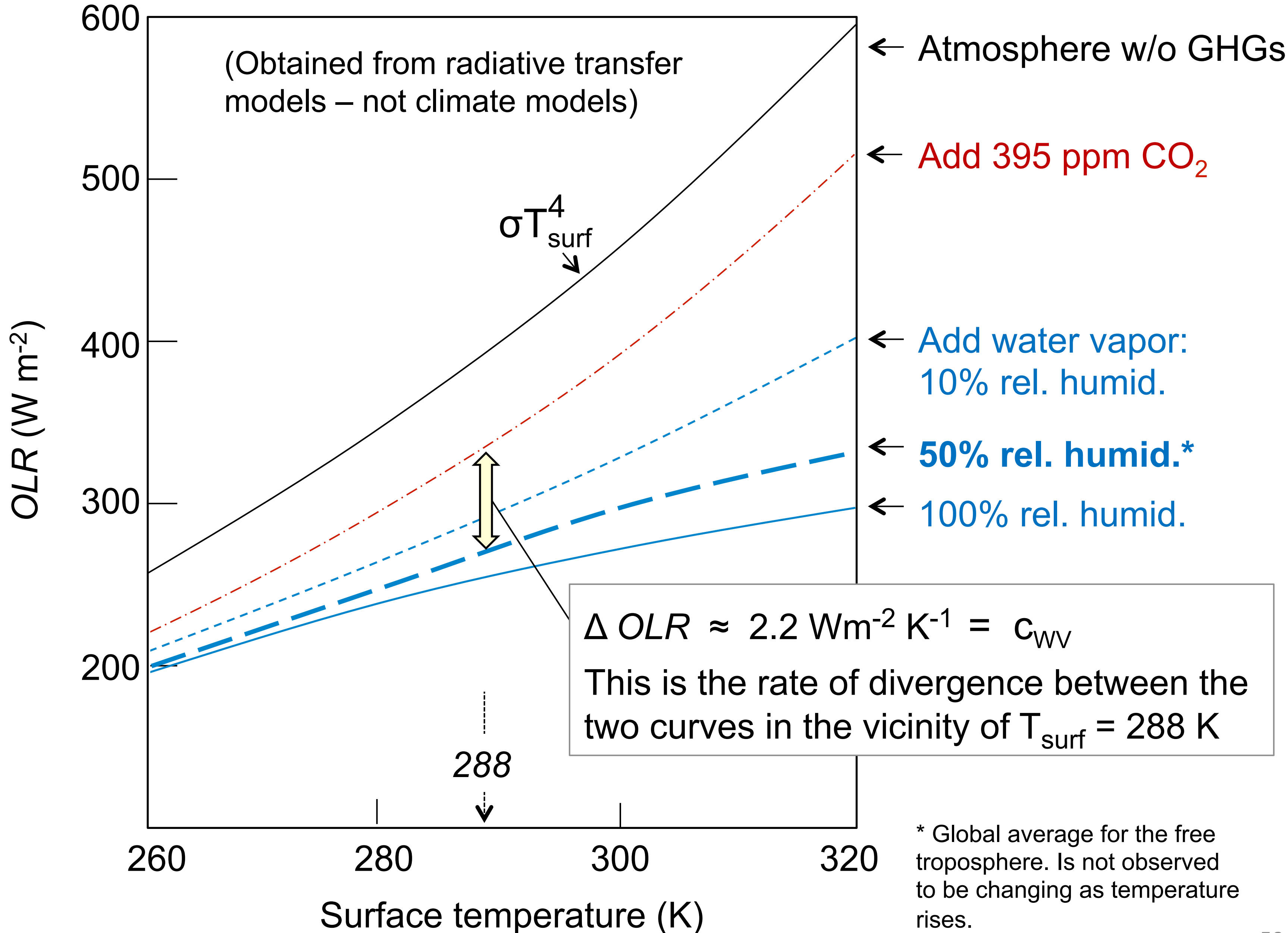
References for data above: *IPCC* 2013; and APL Polar Sci. Ctr., ice volume model trend 1980-2013.

Graphical method for estimating T_{surf} without using climate models



- Method requires that albedo and atmospheric composition be specified
- Method has no ability to pre-determine feedbacks on its own
- Although, for water vapor, absolute humidity increases by 7% per °C

Deriving water vapor feedback, without using climate models



* Global average for the free troposphere. Is not observed to be changing as temperature rises.

(Comparing the simple graphical derivation on the previous slide with results from climate models)

Recall feedback factor definition: $f_i = \lambda_o c_i$ (Slide 22)

Thus $f_{WV} = \lambda_o c_{WV}$

$= 0.3 \times 2.2 = 0.66$