How Climate Changes

How Many Degrees of Warming per Watt/m^2 of Heating?

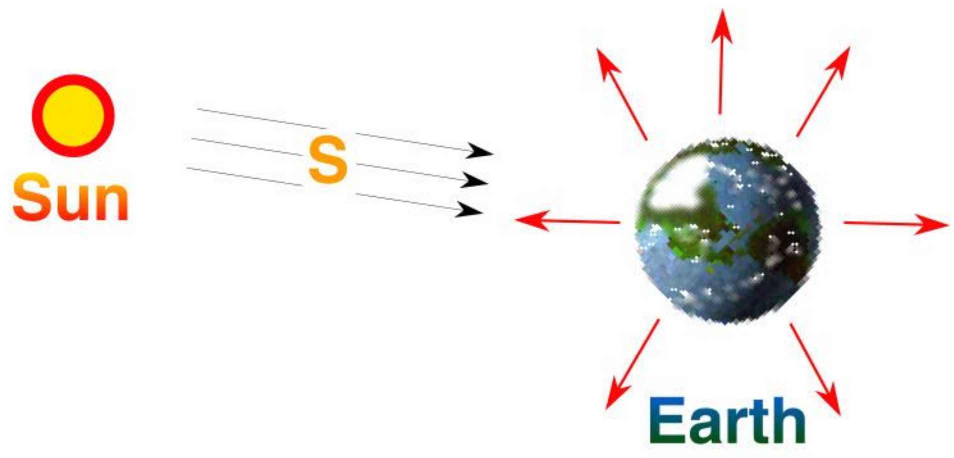
MODULE 4

Climate Forcing, Feedback, & Sensitivity

How Many Degrees of Warming per Watt/m^2 of Heating?

Consider reading Dessler Chapter

Planetary Energy Balance



Energy In = Energy Out

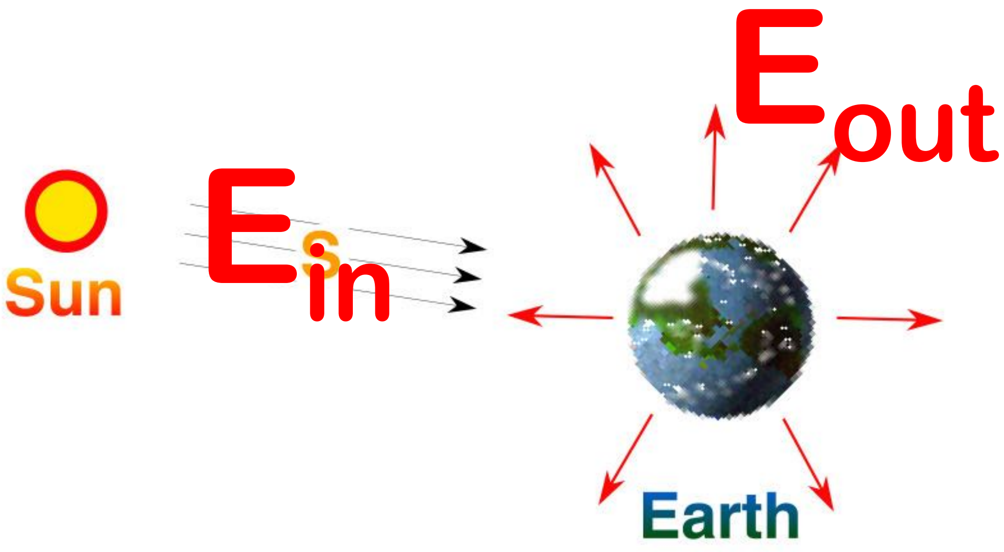
$$S(1-\alpha)\pi R^2 = 4\pi R^2 \sigma T^4$$

$$T \approx -18^{\circ}\mathrm{C}$$

But the observed T_s is about 15° C

What If …

Energy Out is ***NOT*** *equal to Energy In?*

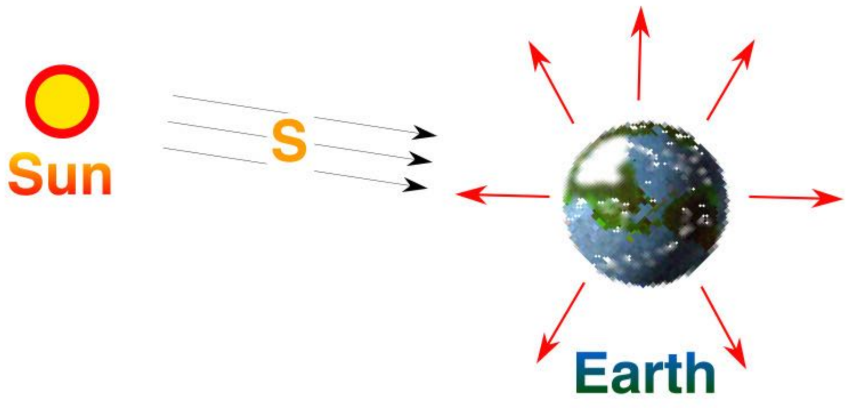


- Suppose the Sun suddenly gets brighter
- Eventually the Earth will warm up & emit more to re-establish equilibrium
- But for awhile …

$E_{in} > E_{out}$

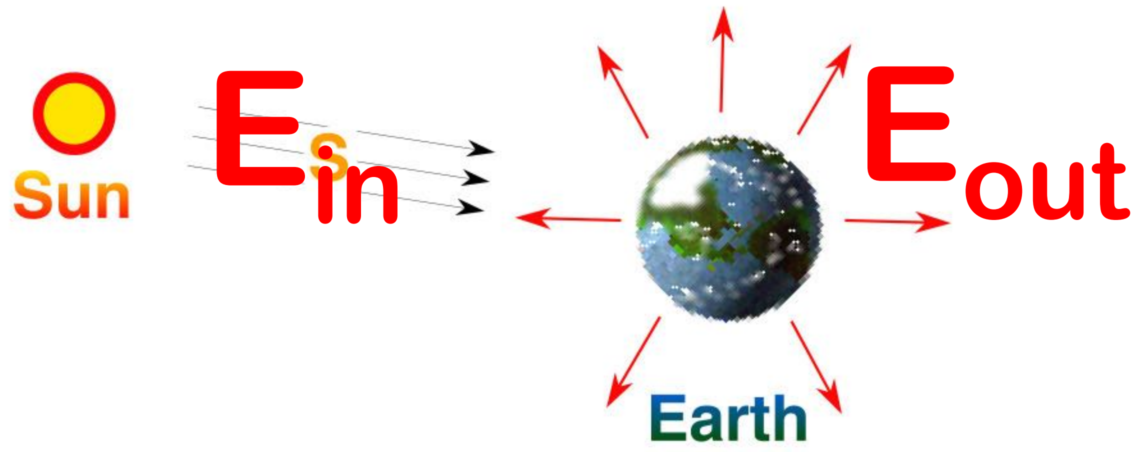
WE *DEFINE* "Climate Forcing"

$$= F_{in} - F_{out}$$



- The rate at which energy enters the climate system minus the rate at which it's emitted equals the rate of change in stored energy in the system
- We DEFINE this rate to be the "forcing" of the climate system, before the climate can adjust by warming or cooling

Climate Forcing Example 1

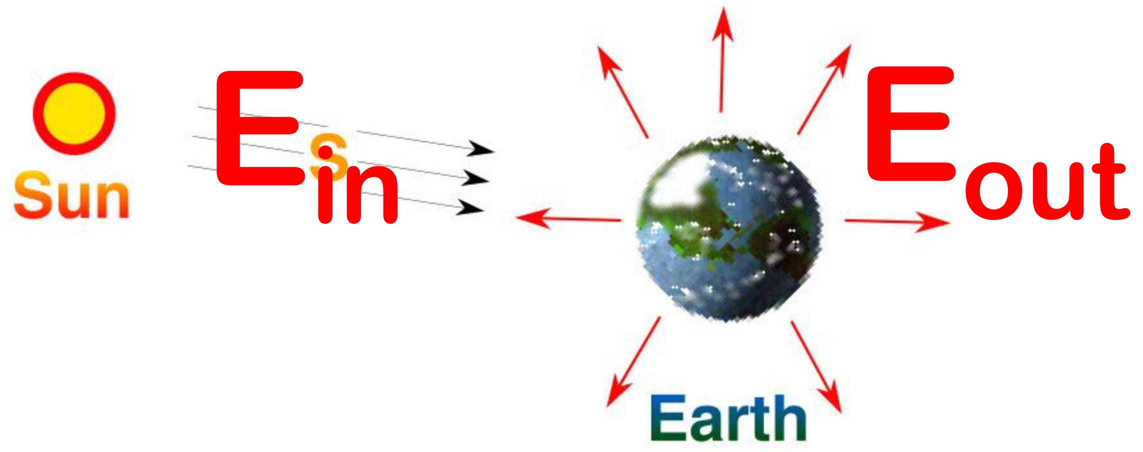


$$E_{in} = \frac{S_0(1-\alpha)}{4} x1.01 = 241.8 Wm^{-2}$$

$$E_{out} = \sigma T_e^{\ 4} = 239.4 Wm^{-2}$$

- Suppose the Sun suddenly increased in brightness by 1%
- E_{in} would increase suddenly by 2.394 W m^{-2}
- In that instant, T_e would not yet have changed
- So E_{out} would still be 239.4 W m^{-2}
- Radiative Forcing (RF) = $E_{in} - E_{out}$ = 2.394 W m^{-2}

Climate Forcing Example 2

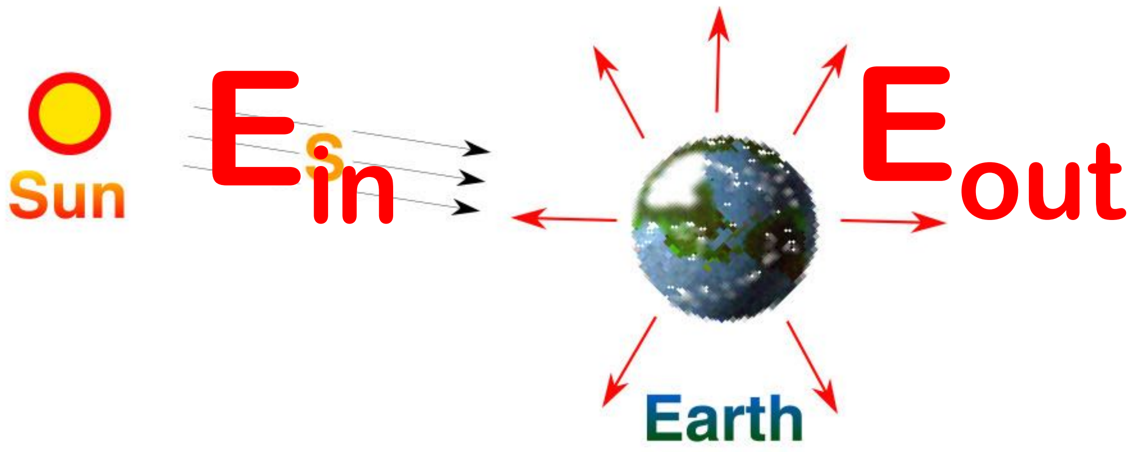


$$E_{in} = \frac{S_0(1-\alpha)}{4} = 239.4\ Wm^{-2}$$

$$E_{out} = \sigma T_e^{\,4} - 1 = 238.4\ Wm^{-2}$$

- Suppose the Earth's atmosphere suddenly became more IR opaque and absorbed 1 W m^{-2} of the outgoing IR
- Incoming energy would remain unchanged
- In that instant, T_e would not yet have changed
- Radiative Forcing (RF) = $E_{in} - E_{out}$ = 1.0 W m^{-2}

Climate Forcing Example 3

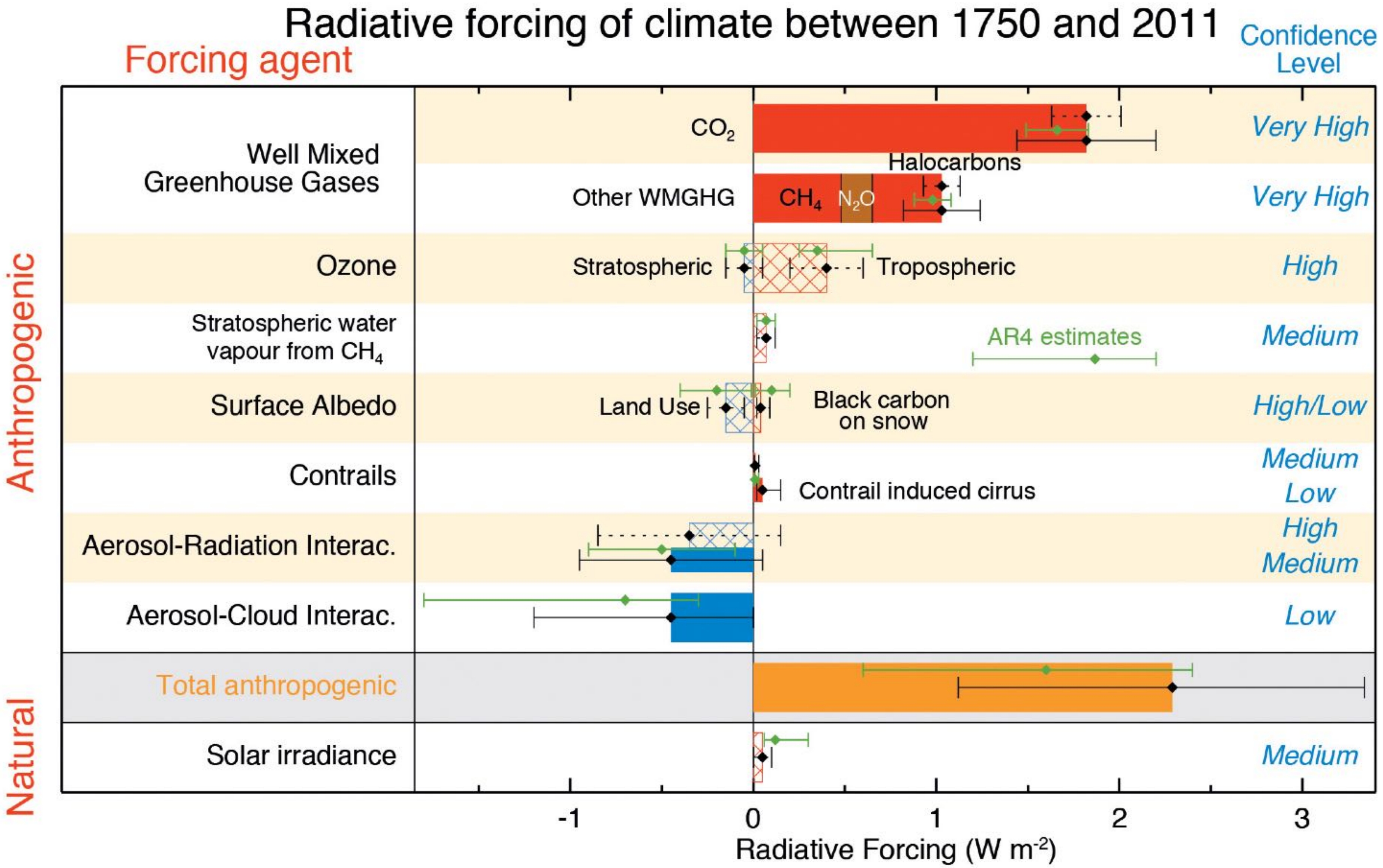


$$E_{in} = \frac{S_0(1 - 0.31)}{4} = 236.0 \ Wm^{-2}$$

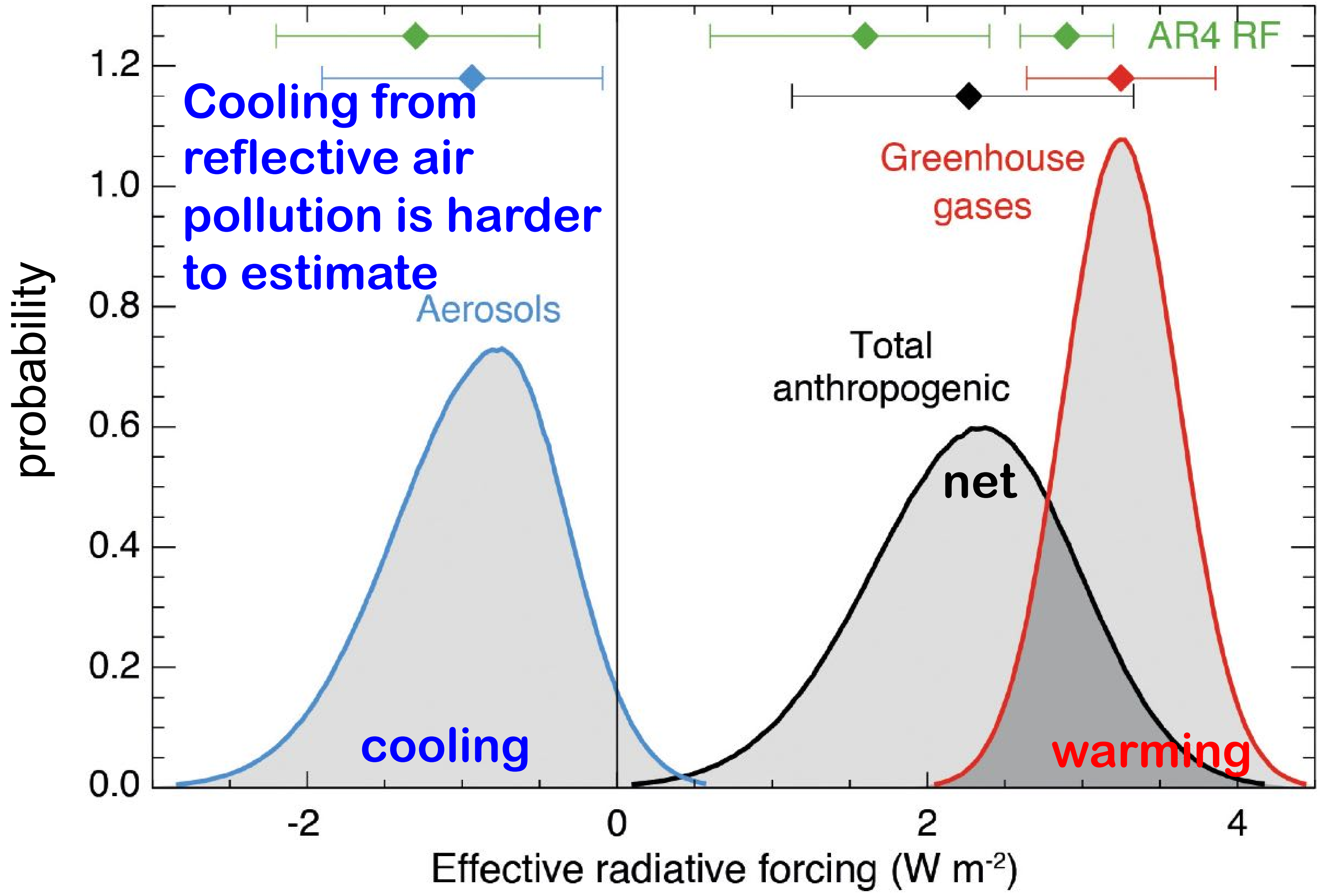
$$E_{out} = \sigma T_e^{\,4} = 239.4 \ Wm^{-2}$$

- Suppose the Earth's albedo suddenly changed from 30% to 31%
- Absorbed energy would decrease to 236 W m^{-2}
- In that instant, the outgoing energy would remain the same
- Radiative Forcing (RF) = $E_{in} - E_{out}$ = -3.4 W m^{-2}

Modern Climate Forcing



Anthropogenic Forcing



Cause and Effect

Forcing $\longrightarrow$ Response

Watts per square meter

degrees Celsius or F

$$\text{Sensitivity} = \frac{\text{Response}}{\text{Forcing}}$$

degrees per Watt m^{-2}

Earth's Climate as a "Black Box"

239.4 $W\ m^{-2}$ → **Climate System** → T_s 15 °C

Absorbed Sunshine In

Surface Temperature Out

Climate Forcing, Response, and Sensitivity

RF
+ 1
W m^{-2} → **Climate System** → ΔT_S ? ° C

Radiative Forcing (absorbed minus emitted)

Response: (Change in Surface Temperature)

Climate Forcing, Response, and Sensitivity

Forcing
(change in sunshine)

ΔF
+ 1
W m^{-2} → **Climate System** → ΔT_S
? °C

Response:
(Change in Surface Temperature)

"Let's do the math ..."

$$S_0(1-\alpha)\pi r^2 = 4\pi r^2 \sigma T^4$$

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

$$F = \frac{S_0(1-\alpha)}{4} = \sigma T^4$$

Solve for ΔF that produces a given ΔT

Baseline Climate Sensitivity

"Let's do the math ..."

$$F = \frac{S_0(1-\alpha)}{4} = \sigma T^4$$

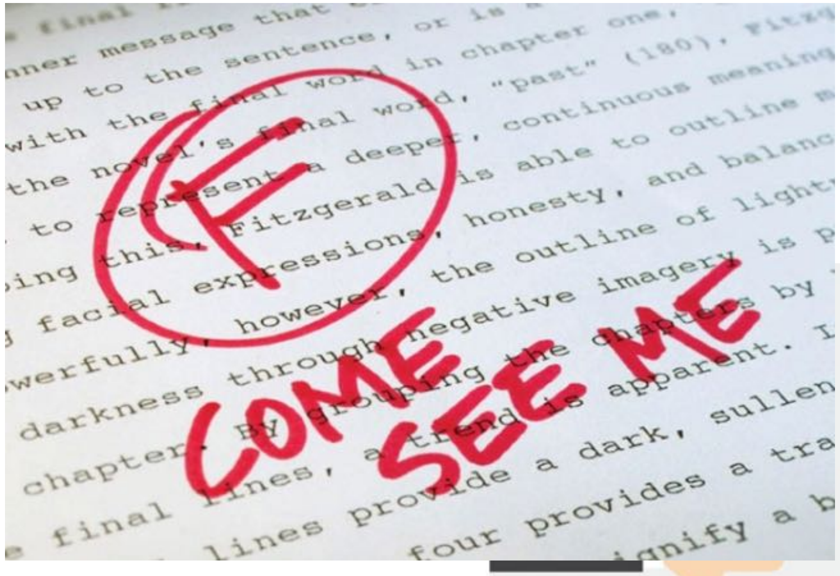
$$\frac{dF}{dT} = 4\sigma T^3 = 4\sigma(255K)^3 = 3.8W\,m^{-2}K^{-1}$$

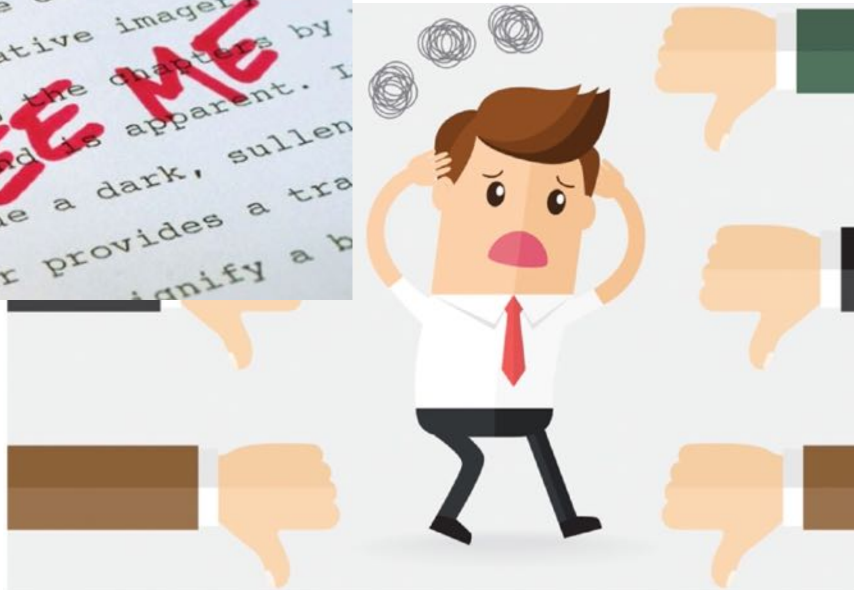
$$\Delta T = \frac{1}{3.8W\,m^{-2}K^{-1}}\Delta F = \frac{0.266\,K}{W\,m^{-2}}\Delta F$$

A 1 W m^{-2} change in absorbed sunshine produces about a 0.27 °C change in Earth's temperature

“Feedback”

in colloquial English

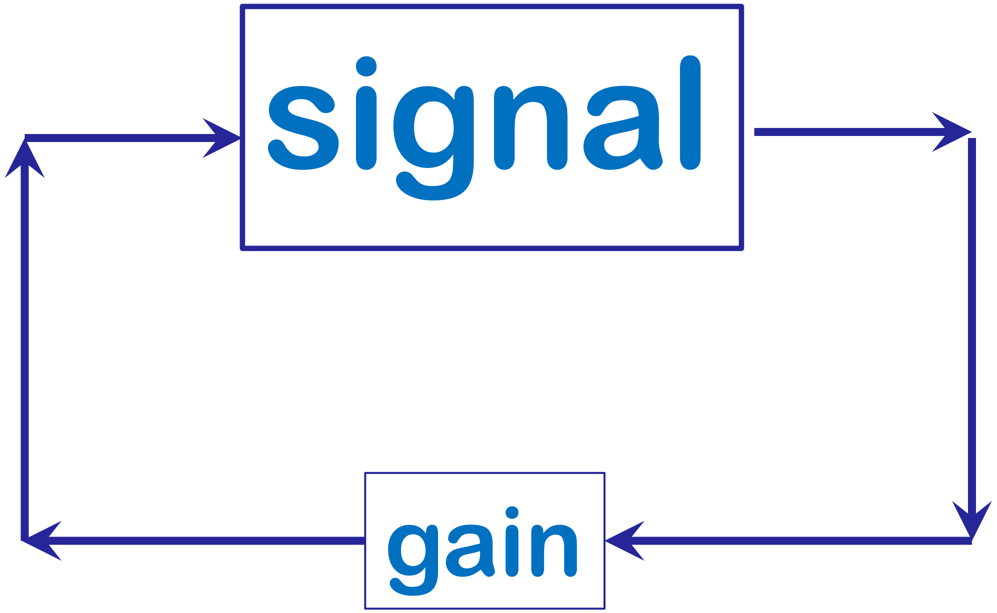




Feedback loop

as a technical concept

An input signal is modified to become stronger or weaker with each pass through the feedback loop



POSITIVE FEEDBACK

- gain > 1
- Increases signal

NEGATIVE FEEDBACK

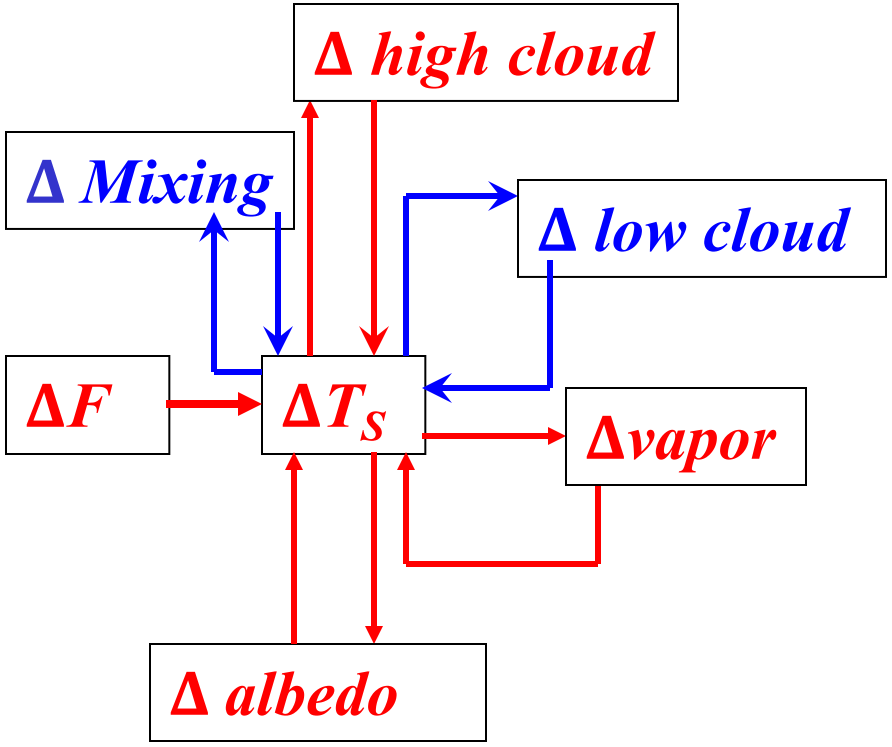
- gain < 1
- Weakens signal

No value judgements!

Positive means neither good nor bad

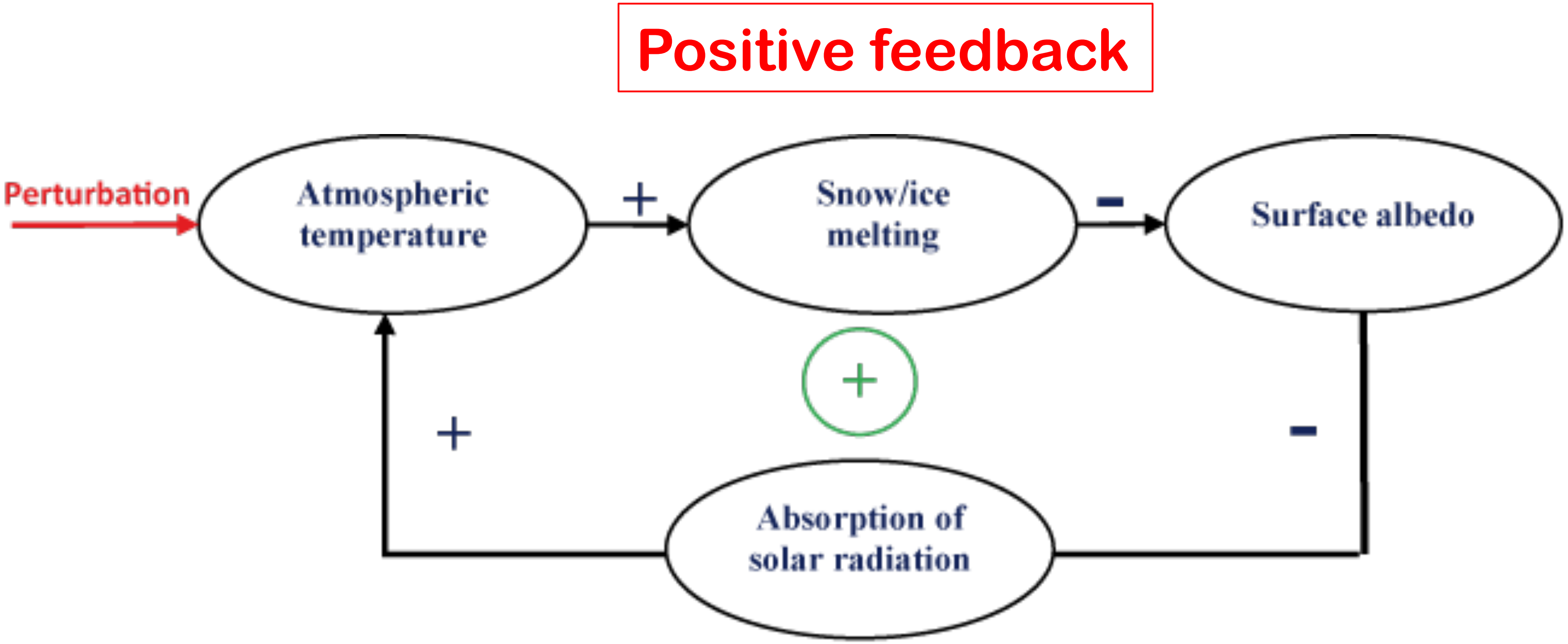
Feedback

Climate Feedback Processes



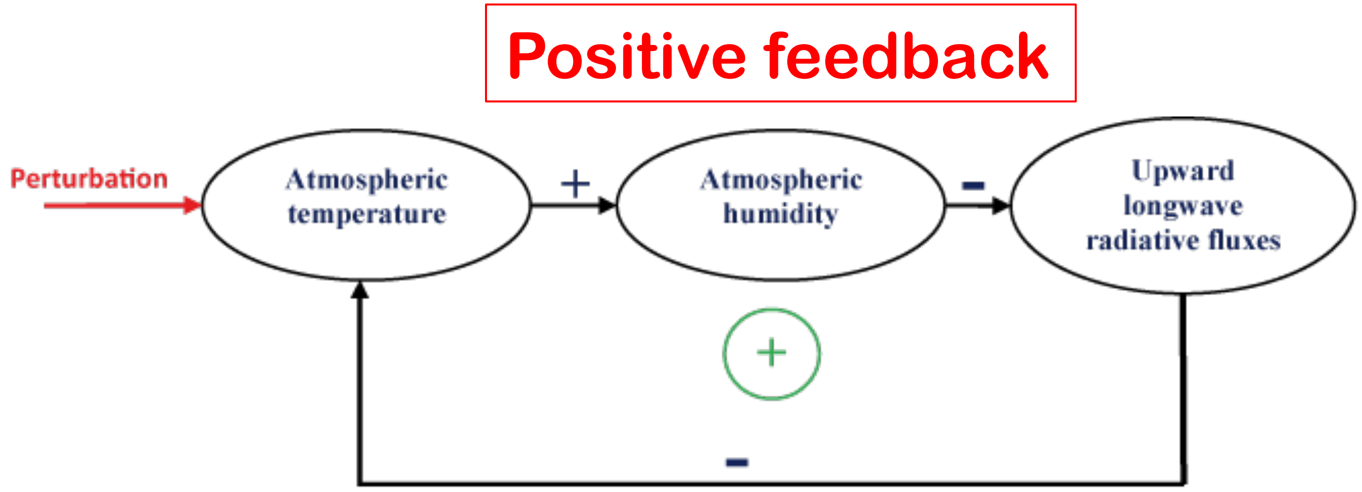
- Positive Feedbacks (amplify changes)
  - Water vapor
  - Ice-albedo
  - High clouds
- Negative feedbacks (damp changes)
  - Lapse rate
  - Low clouds

Ice Albedo Feedback



- Radiative forcing melts snow and ice
- Darker surface absorbs more radiation
- Amplifies warming or cooling

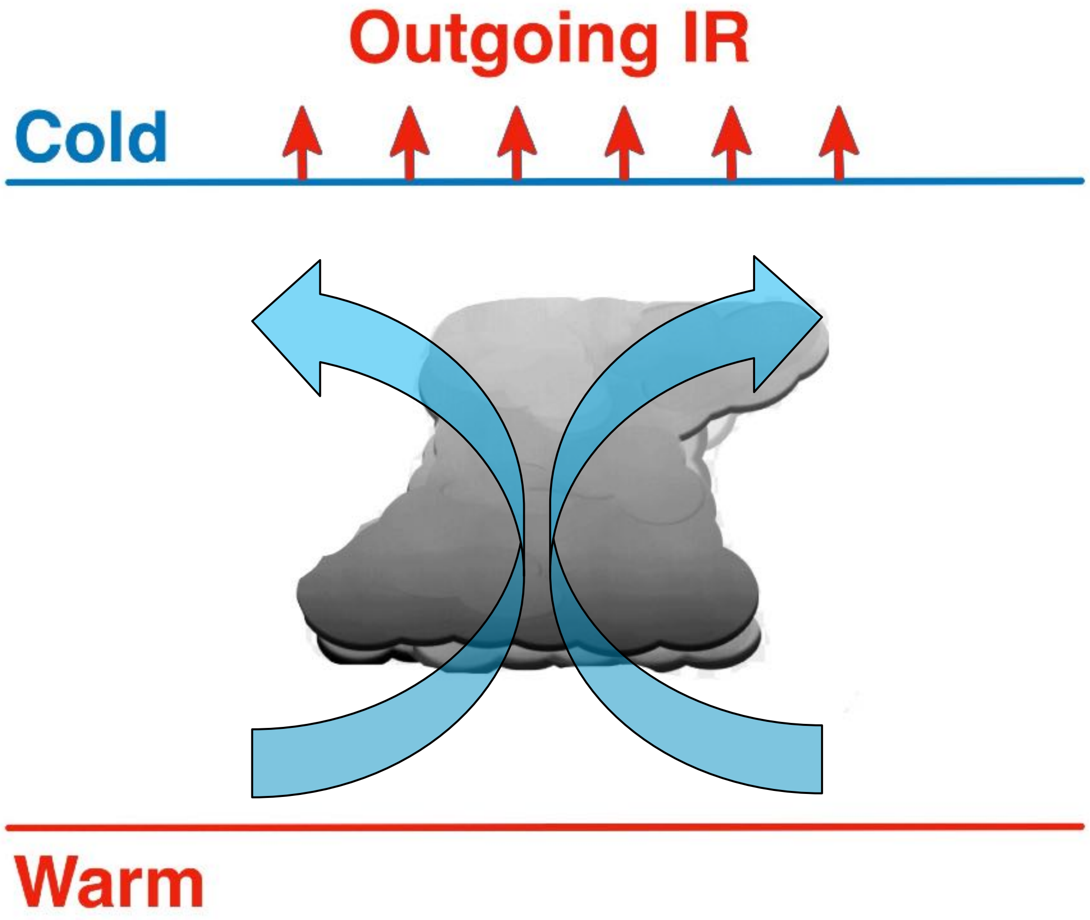
Water Vapor Feedback



- Radiative forcing warms surface
- Warmer surface evaporates more water
- Warmer air can “hold more water”
- Increased water vapor (GHG) absorbs more outgoing radiation, amplifying warming

Vertical Mixing Feedback

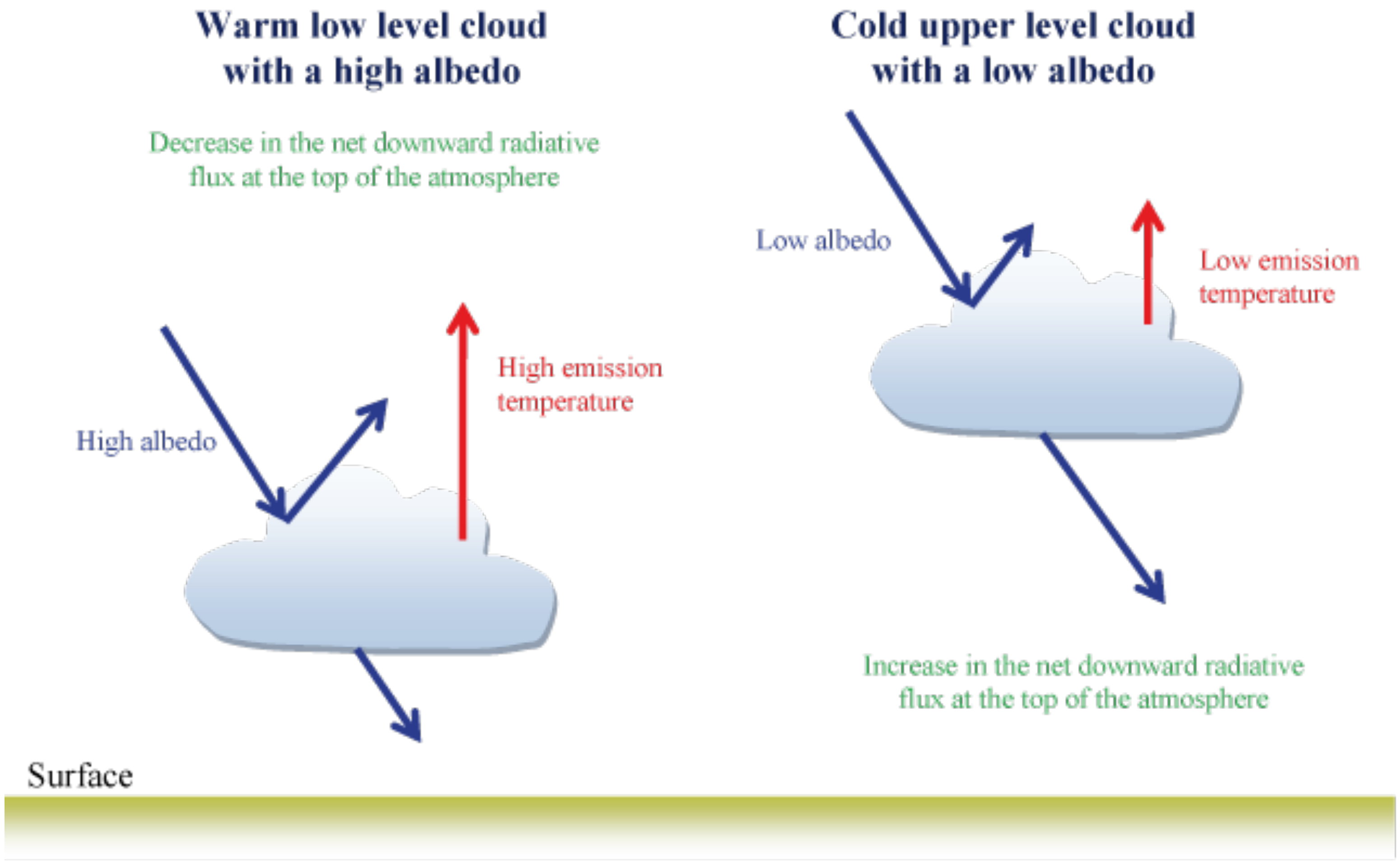
Usually negative feedback!



- Greenhouse effect depends on emission to space from higher (colder) levels of the atmosphere
- If surface warming produces increased vertical mixing by convection, then more heat is mixed to higher levels
- Warm air aloft emits more radiation to space, compensating for original forcing

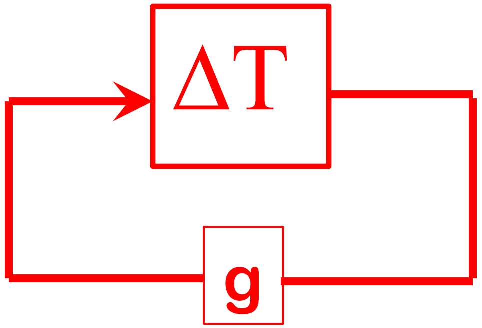
Cloud Feedbacks

Positive OR negative feedback!



- Additional water vapor makes more clouds
- Low clouds cool, but high clouds warm

Feedback Arithmetic



- Initial temperature change ΔT
- Strength of feedback indicated by *gain* g
- Feedback converts change to g ΔT
- Feedback converts g ΔT to $g(g\Delta T) = g^2\Delta T$, etc

- Overall effect of feedback is

$$\Delta T_f = \Delta T_i + g\Delta T_i + g^2\Delta T_i + g^3\Delta T_i + \ldots$$

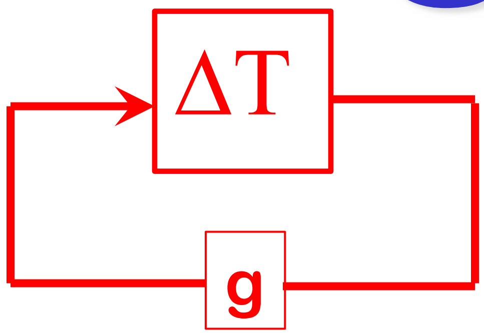
$$\Delta T_f = \Delta T_i \sum_{k=0}^{\infty} g^k$$

- Can write this more simply as

$$\boxed{\Delta T_f = \frac{\Delta T_i}{(1-g)}}$$

[see Dessler pp 51-55]

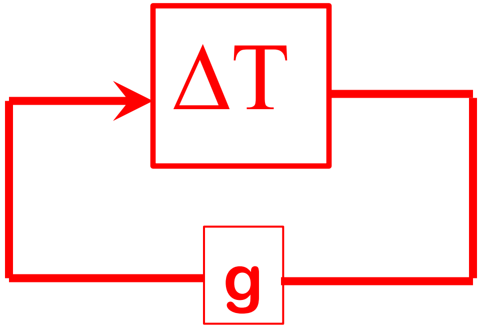
Warming vs Cooling



BEWARE!

- Positive vs Negative Feedback
  DOES NOT mean “warming” vs “cooling”
- Positive feedback INCREASES
  either warming or cooling
- Negative feedback REDUCES
  either warming or cooling

More Arithmetic



$$\boxed{\Delta T_f = \frac{\Delta T_i}{(1-g)}}$$

[see Dessler pp 51-55]

- Gains are additive:

$$g_{TOTAL} = g_{albedo} + g_{vapor} + g_{cloud} + g_{mixing} + \ldots$$

- If $g_T > 0$, overall feedback is positive (amplifies)
- If $g_T < 0$, overall feedback is negative (damps)
- Real world g's for climate are hard to measure!

Process-Level Gains

Feedback Process	Notes	Estimated Gain
Water vapor	Strongly positive!	+0.6
Ice-Albedo	Weakly positive	+0.1
Vertical Mixing (“lapse rate”)	Opposes water vapor	-0.3
Clouds (sum of low < 0 and high > 0)	Very dicey cancelation	+0.1
TOTAL	**Well-Constrained**	**+0.6**

Gains are additive:

$$g_{TOTAL} = g_{albedo} + g_{vapor} + g_{cloud} + g_{mixing} + \ldots$$

Ultimately, We're Sure

- There is positive feedback in the climate system because climate has changed A LOT over geologic time
- There is negative feedback in the climate system because climate has never "run away" to permanently freeze or evaporate the oceans

Total Climate Sensitivity & Feedback

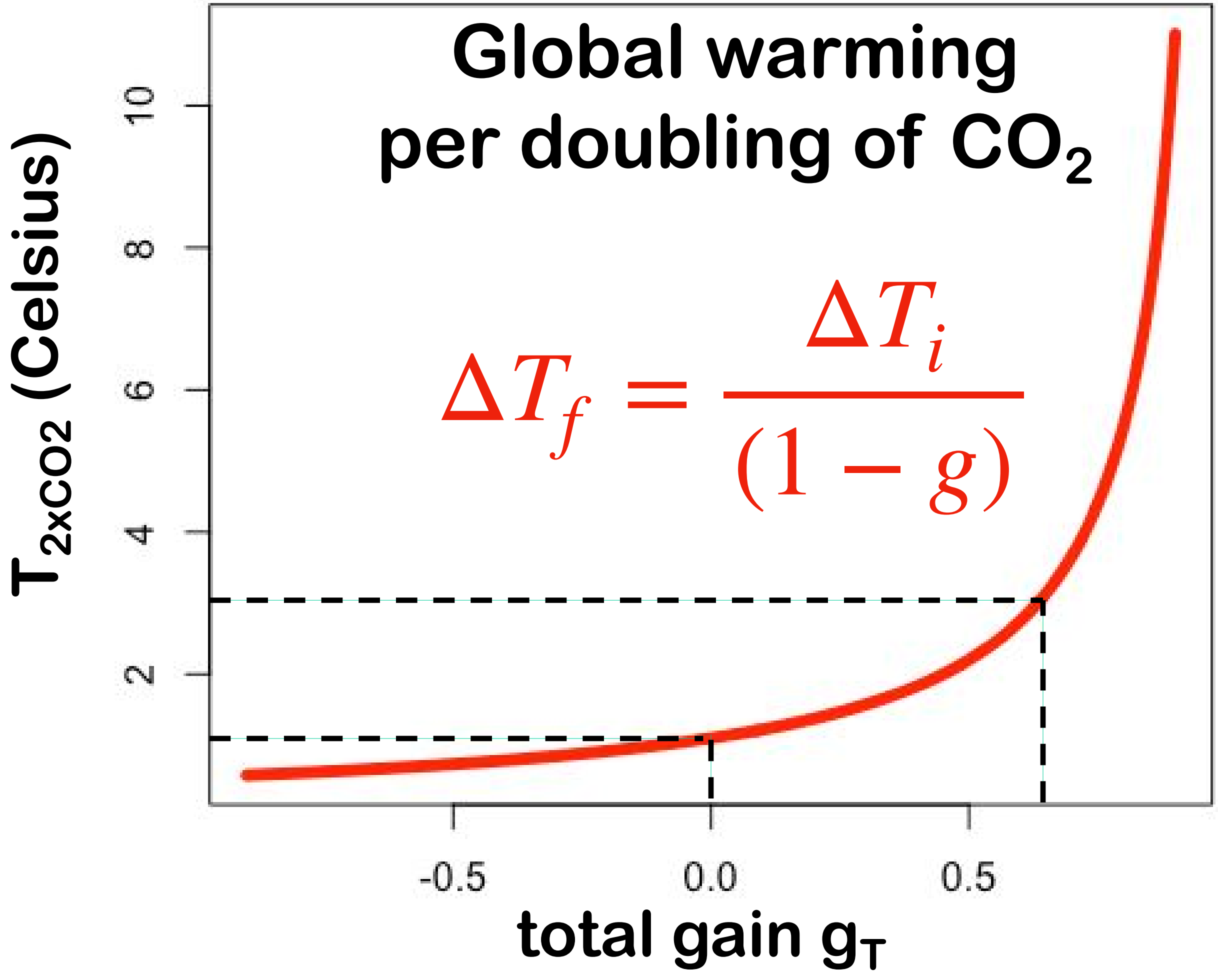
- **Without feedbacks**

  $g_T = 0$, $T_{2xCO2} \sim 1.1$°C

- **With feedbacks**

  $g_T \sim 0.6$, $T_{2xCO2} \sim 3$°C

  (our best estimate)



Estimating Total Climate Sensitivity

1. **Paleoclimate analogs**: how much has climate changed in the past when forcing of known strength was applied?
   - Advantage: all feedbacks included
   - Disadvantage: hard to quantify radiative forcing & global temperature response

2. **Calculation from physical principles** including feedback processes (complex global climate models)
   - Advantage: Physical insight
   - Disadvantage: Models likely wrong!

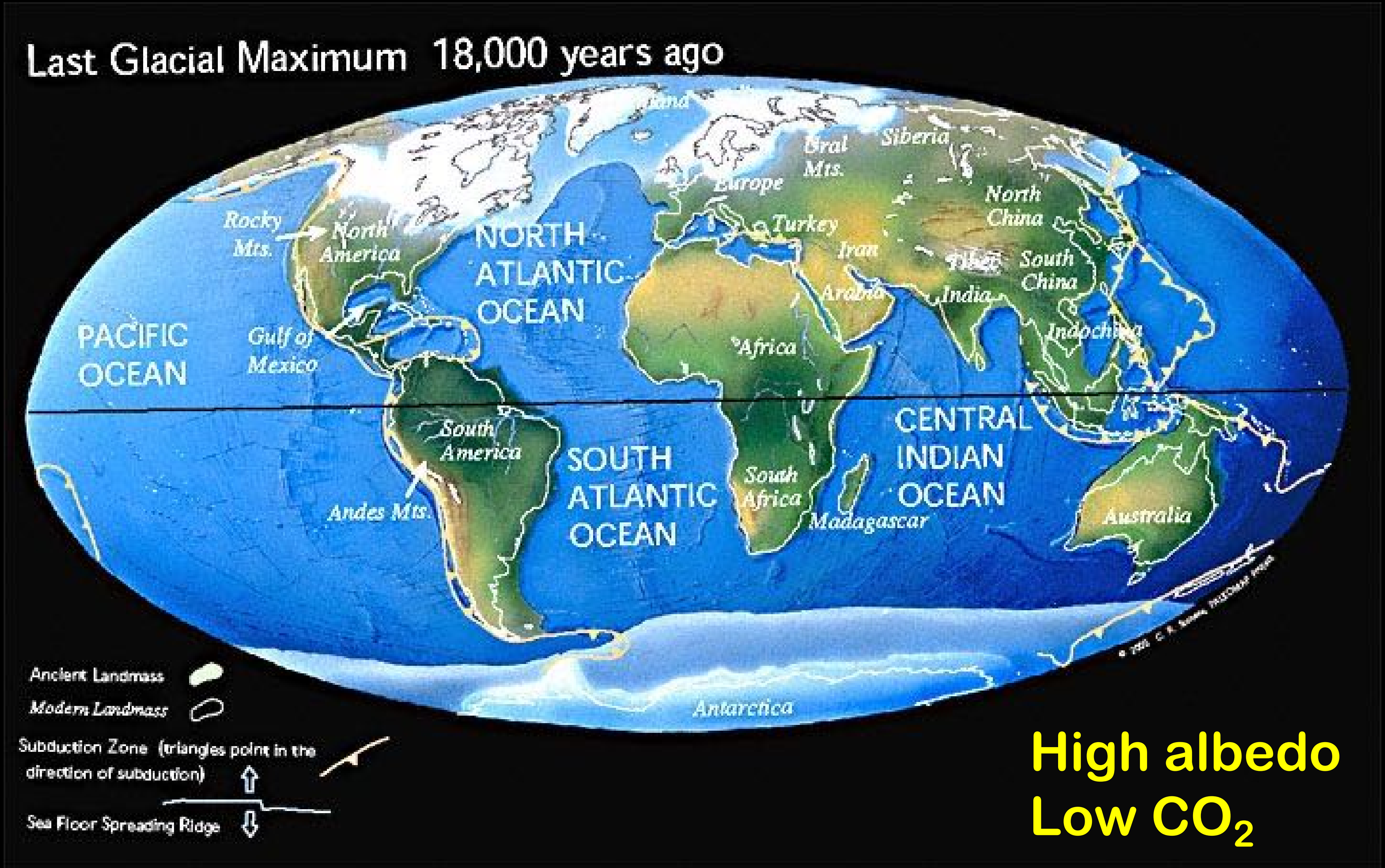
Sensitivity of Past Climates

1. Geologic past
   (100's of millions of years)
2. Deglaciation analog
   (18,000 years ago to preindustrial time)
3. Last Millennium analog
   (Medieval Warm Period to Little Ice Age)
4. Modern Climate Record
   (20^{th} Century changes)

The further back we go, the less data we have to work with.

Using modern data, we have only brief transients to study.

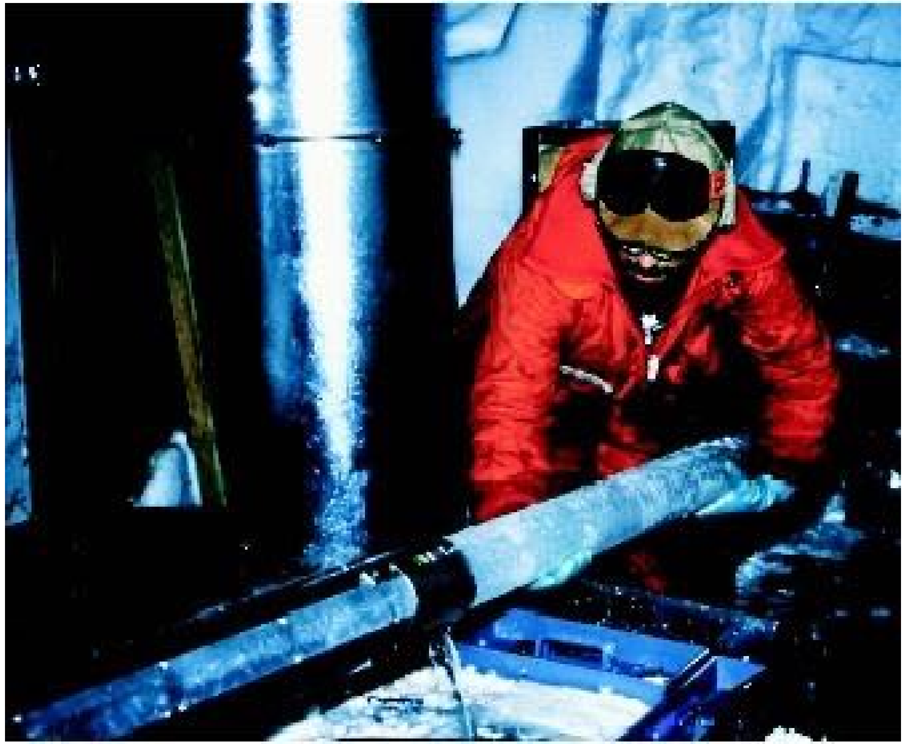
Ice Age World

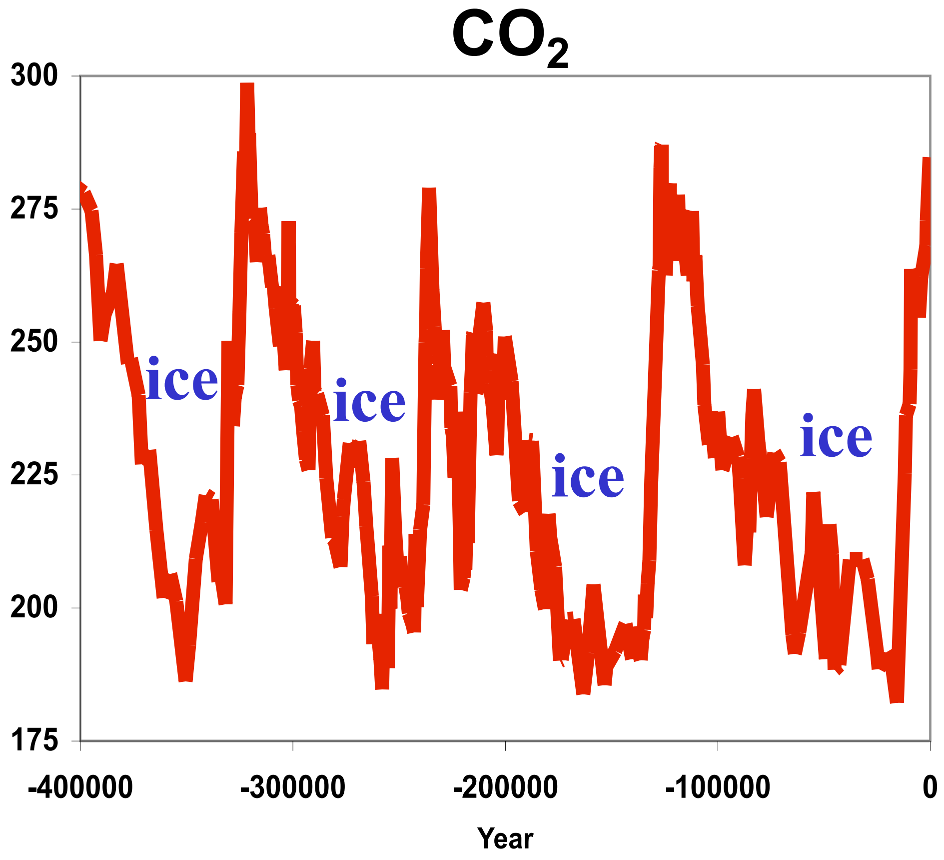


High albedo
Low CO_2

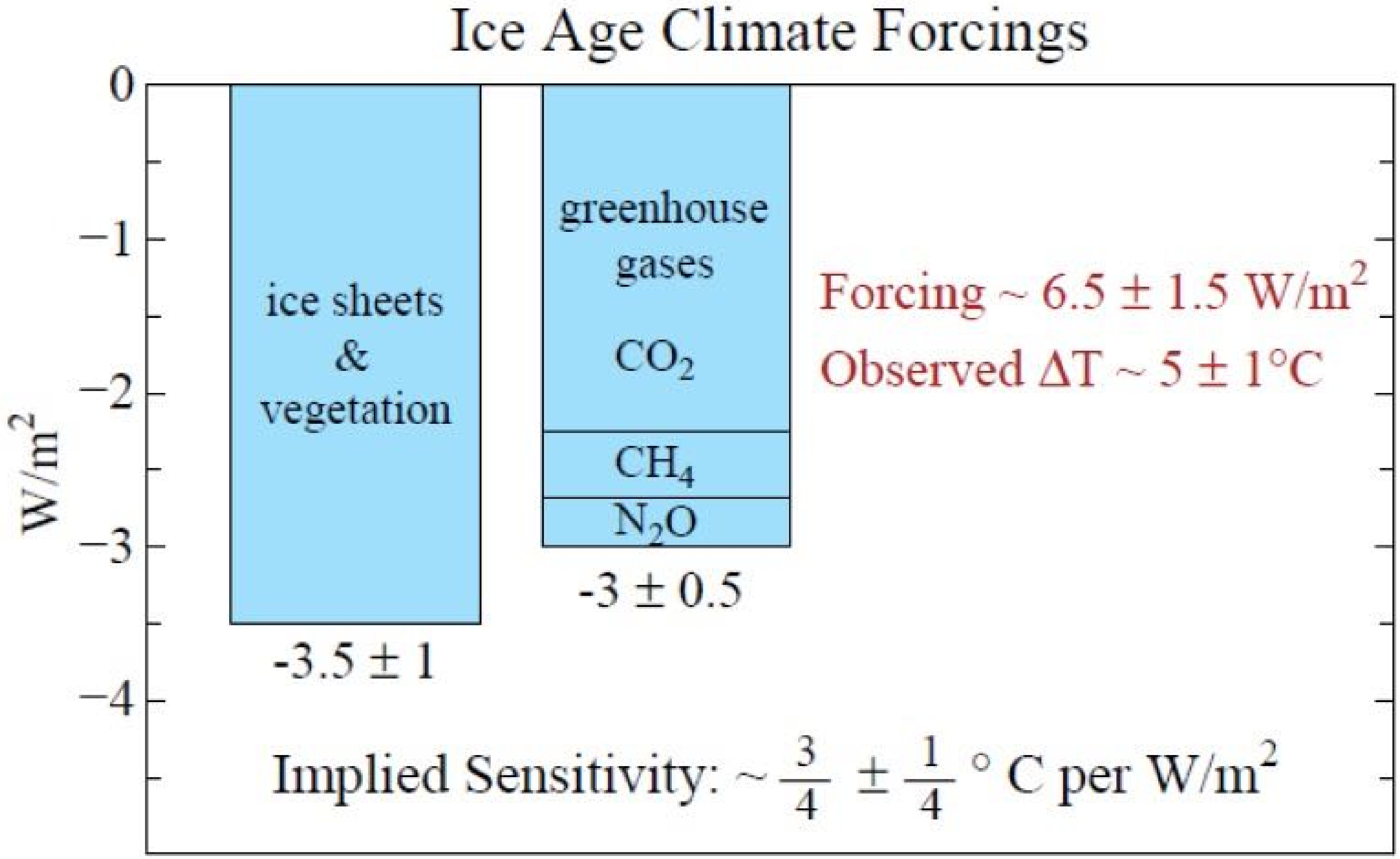
CO_2 and the Ice Ages

- Over the past 420,000 years atmospheric CO_2 has varied **between 180 and 280** ppm, beating in time with the last four glacial cycles





Climate Forcing



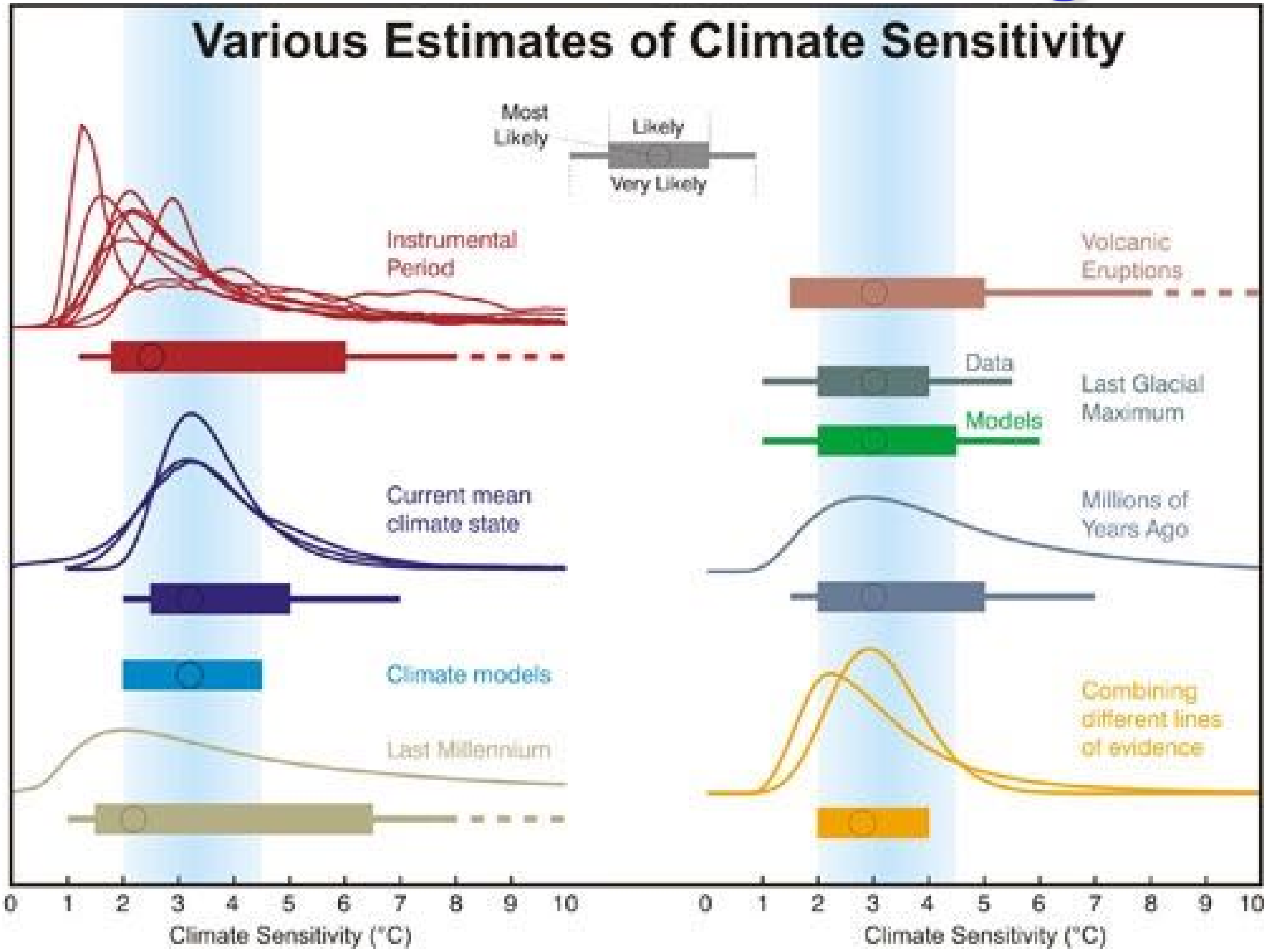
Source: Hansen and Sato (2011)

Climate Forcing & Response

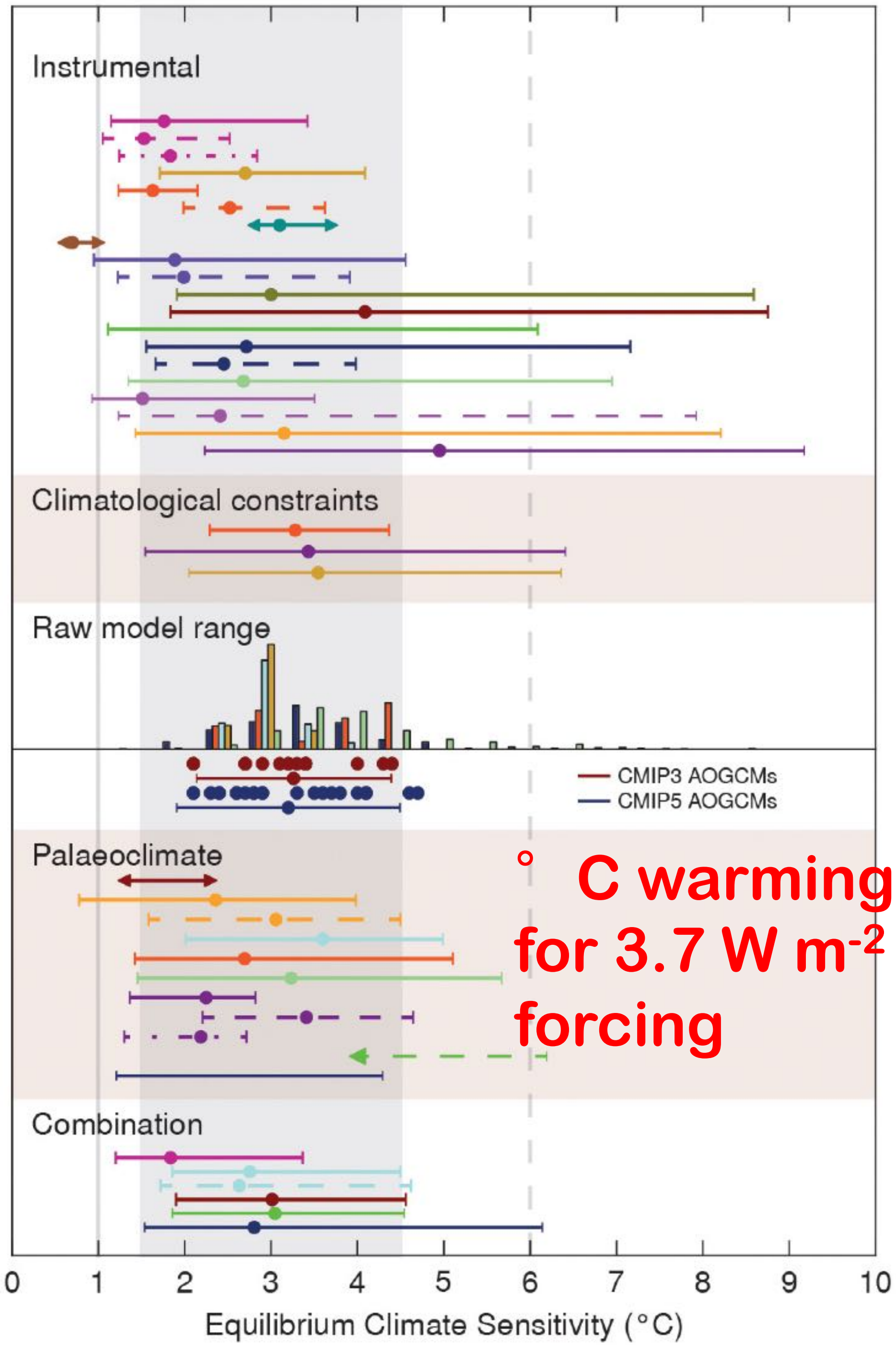
- After last ice age, Earth received about 6.5 Watts per square meter more radiation
- Temperatures warmed about 5 C over 10,000 years
- Huge ice sheets melted, seas rose hundreds of feet
- We can add 6.5 Watts / m^2 in this century!

Climate Sensitivity

Dozens of studies using many different methods agree that climate sensitivity is about 3 C per doubling of CO_2



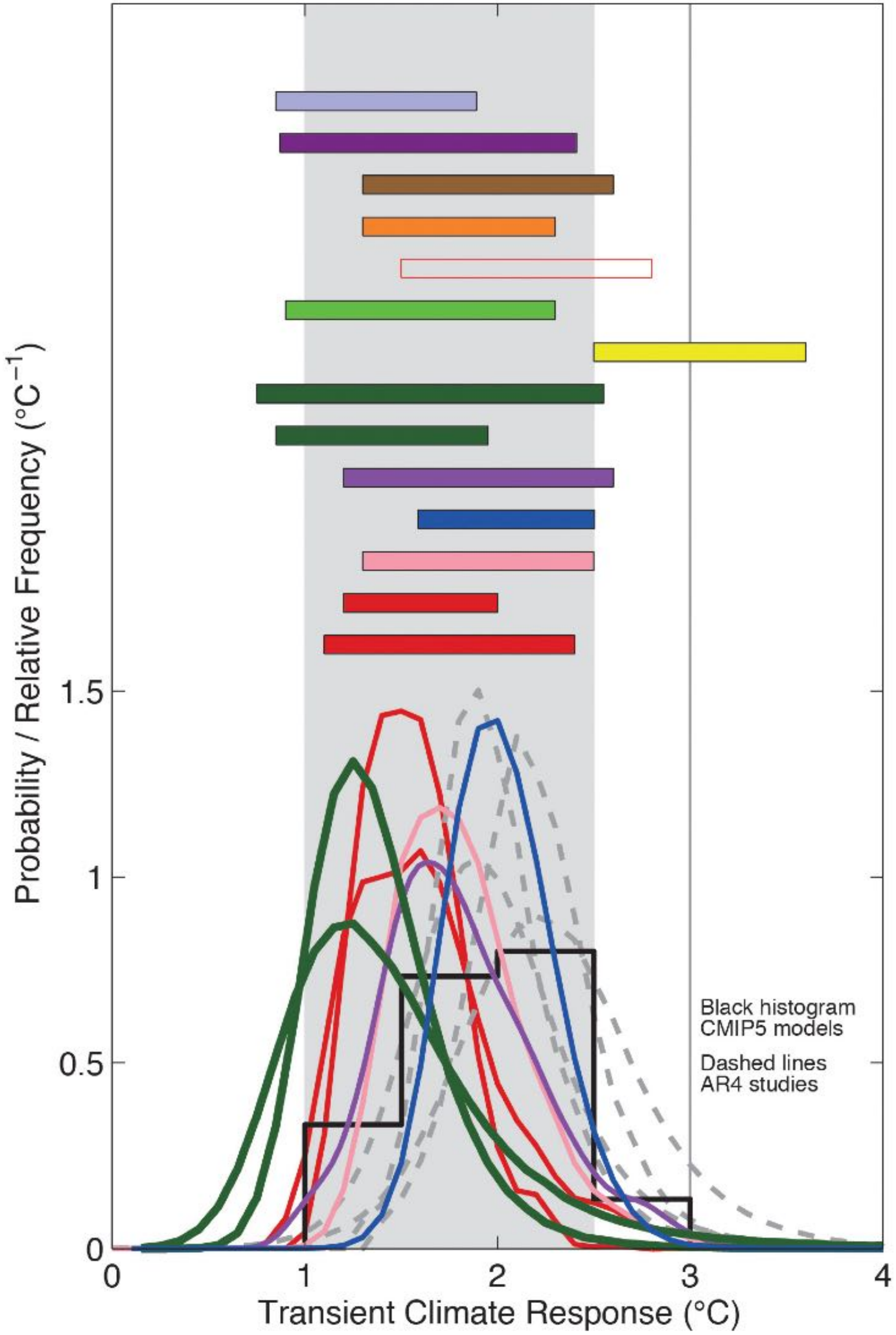
Distributions and ranges for climate sensitivity from different lines of evidence. The circle indicates the most likely value. The thin colored bars indicate very likely value (more than 90% probability). The thicker colored bars indicate likely values (more than 66% probability). Dashed lines indicate no robust constraint on an upper bound. The IPCC likely range (2 to 4.5° C) and most likely value (3° C) are indicated by the vertical grey bar and black line, respectively (Source: Knutti & Hegerl, Nature, 2008)



° C warming for 3.7 W m^{-2} forcing

Equilibrium Climate Sensitivity

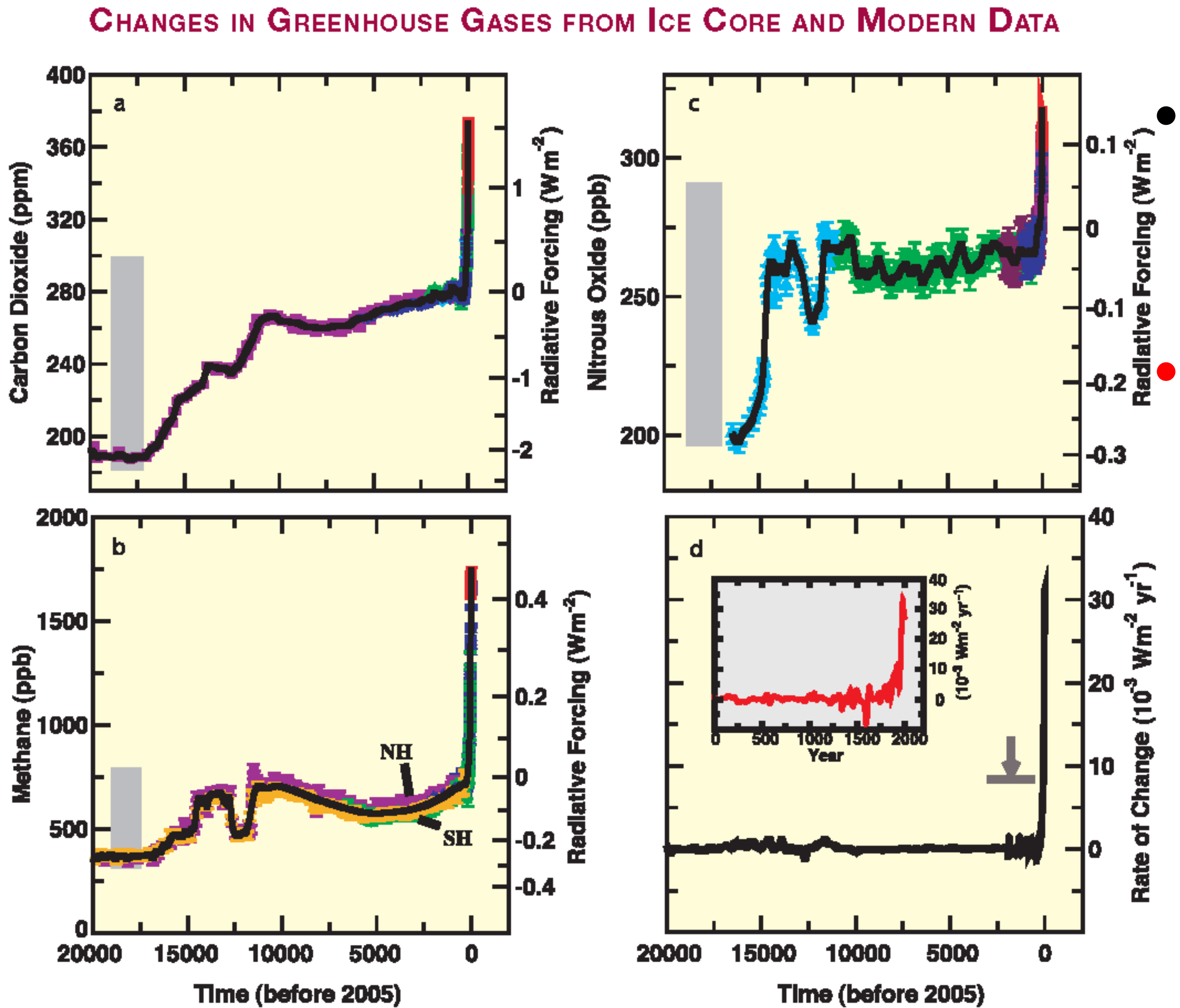
- Surface warming required to re-establish thermal equilibrium at top of atmosphere
- Many lines of paleoclimate evidence and most GCMs find about 3 °C



Transient Climate Response

- **Warming takes a long time because much of the heat is absorbed by the oceans**
- **TCR is warming at time when CO_2 reaches 560 ppm**
- **Models and obs show TCR ~ 1 to 2.5 ° C**

GHG Radiative Forcing



- Note different scales
- Modern changes comparable to postglacial, but much faster!

Compare Ancient & Modern Forcing

- **End of Ice Age**: 6.5 W m^2

  Over 100 centuries (18k to 8k BP)

- **“Little Ice Age”**: $<$ 1 W m^2

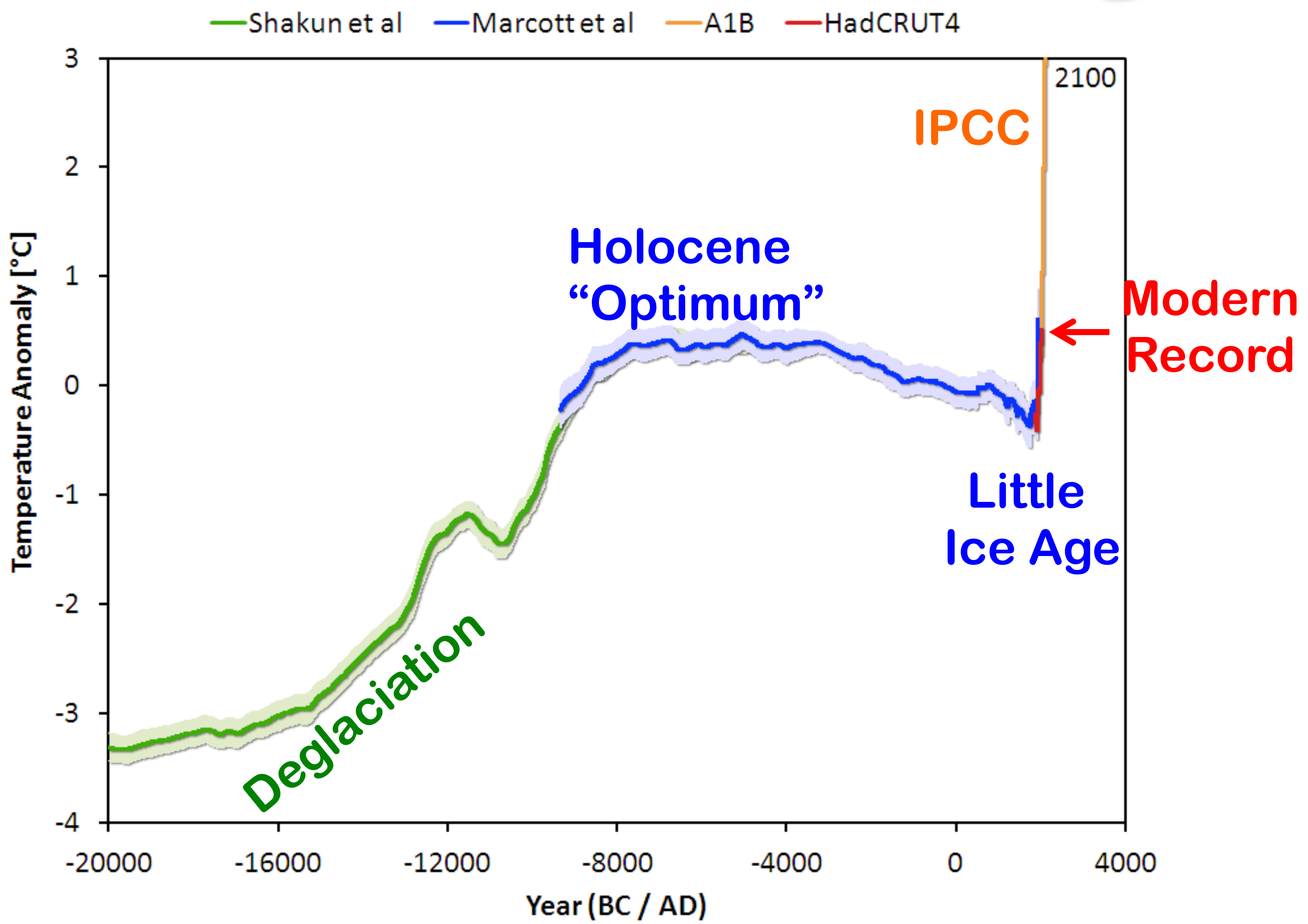
  (Roughly 1400 to 1800)

- **Since 1850**: ~ 2 W m^2

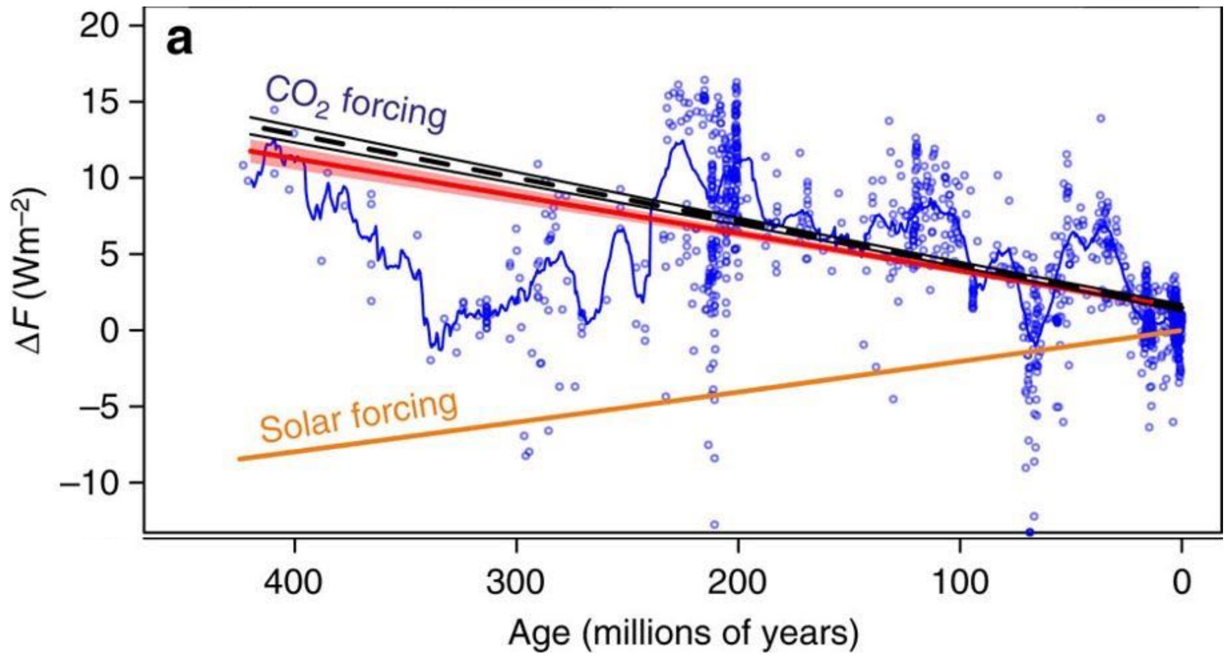
- **Burn 10x FF to date**: 12 W m^2

  (over 3 centuries if no policy)

Since Last Ice Age



Geo-Goldilocks

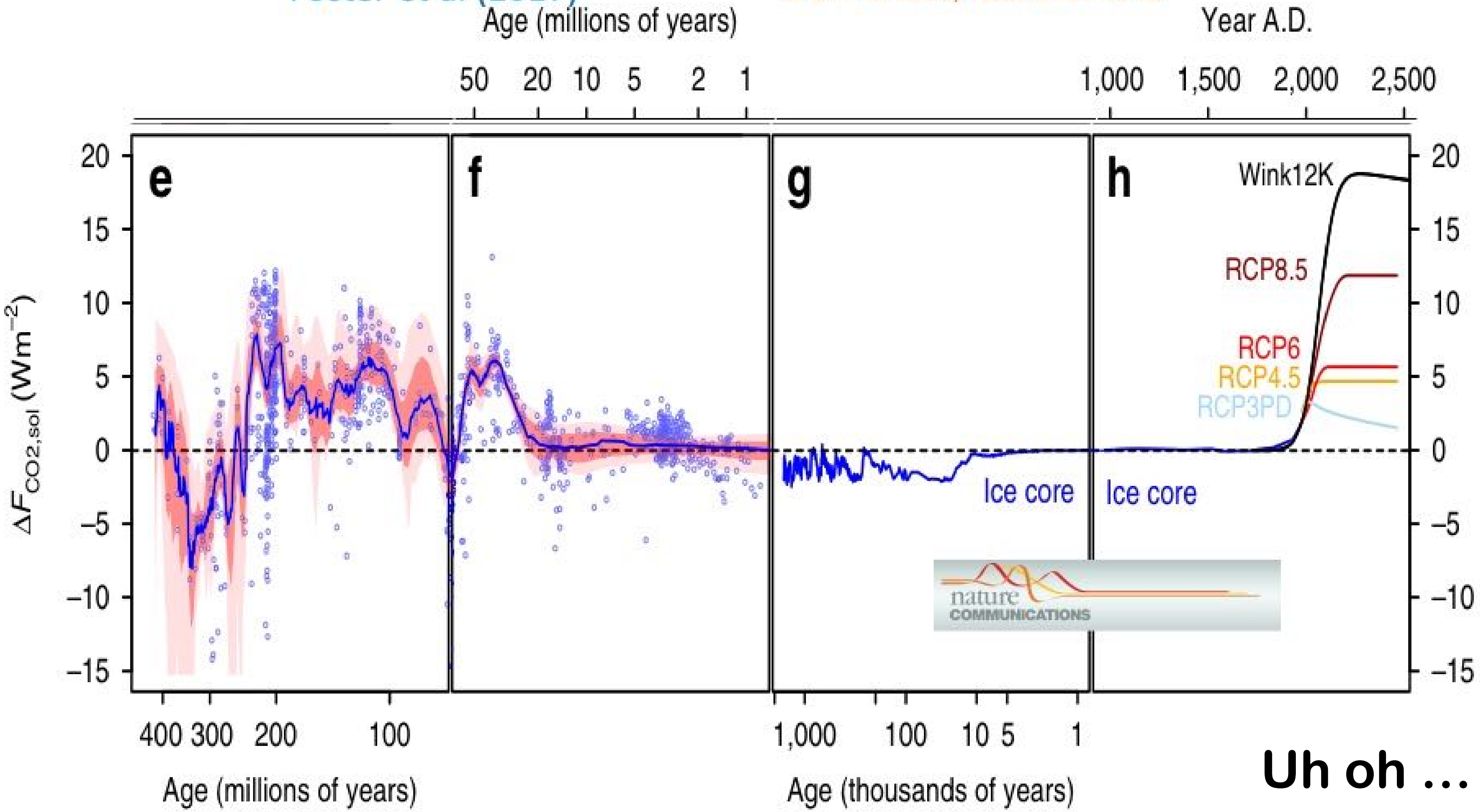


- Sun has brightened over geologic time – now 30% brighter than for early Earth
- Greenhouse forcing has mostly fallen, with some ups and downs
- Drop in GHG forcing has largely compensated for the increase in solar forcing

Climate Forcing (solar + CO_2) Over Geologic Time

Foster et al (2017)

DOI: 10.1038/ncomms14845



Uh oh …