

Climate Change: The Basics

Roman Frigg

LSE

Practicalities 1



Please ask
clarificatory
questions
immediately.

Please save
critical discussion
for the end.

Practicalities 2

In the discussion at the end we use the so-called “Australian” system.



Finger: follow up
on previous question



Hand: new topic

Plan for Lecture 1

1. Blackbody Radiation
2. Energy Balance
3. Greenhouse Effect
4. Time Lag and Forcing
5. Feedback
6. Climate Sensitivity
7. Definitions of Climate and Climate Change
8. Detection and Attribution

1. Blackbody Radiation



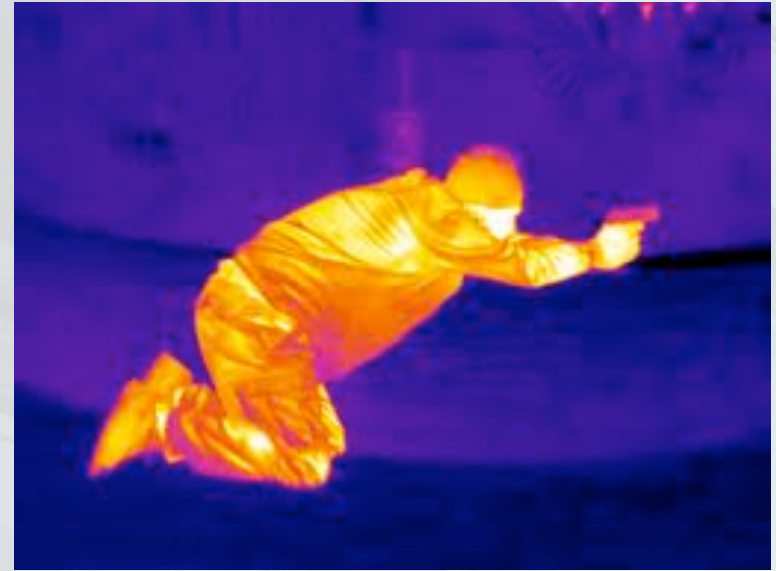
1. Blackbody Radiation



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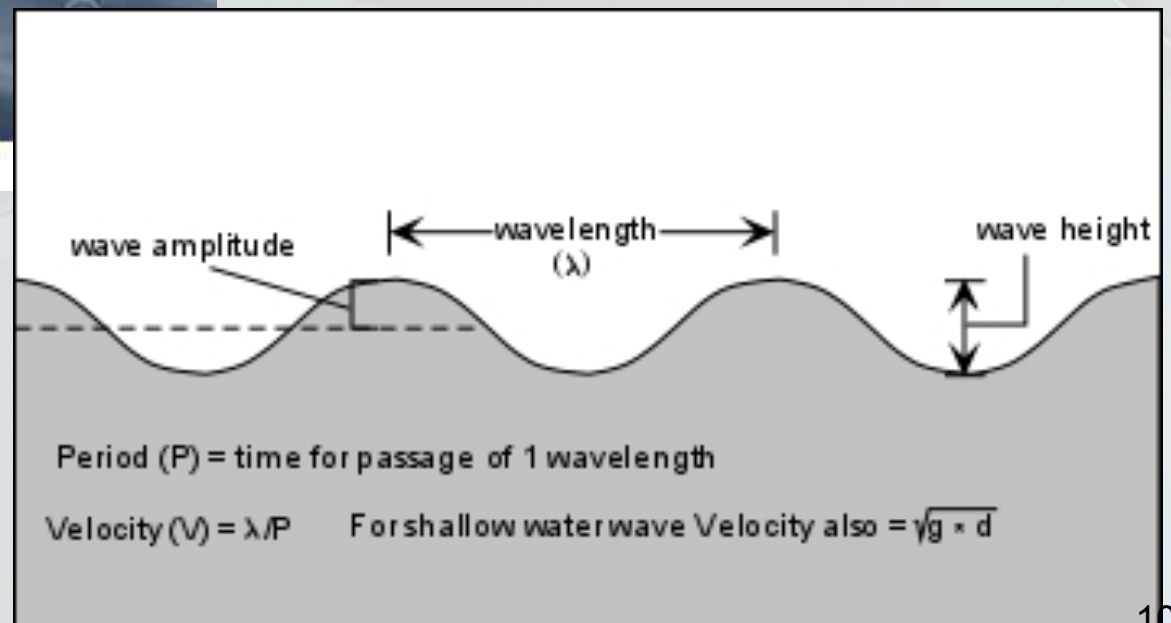
1. Blackbody Radiation



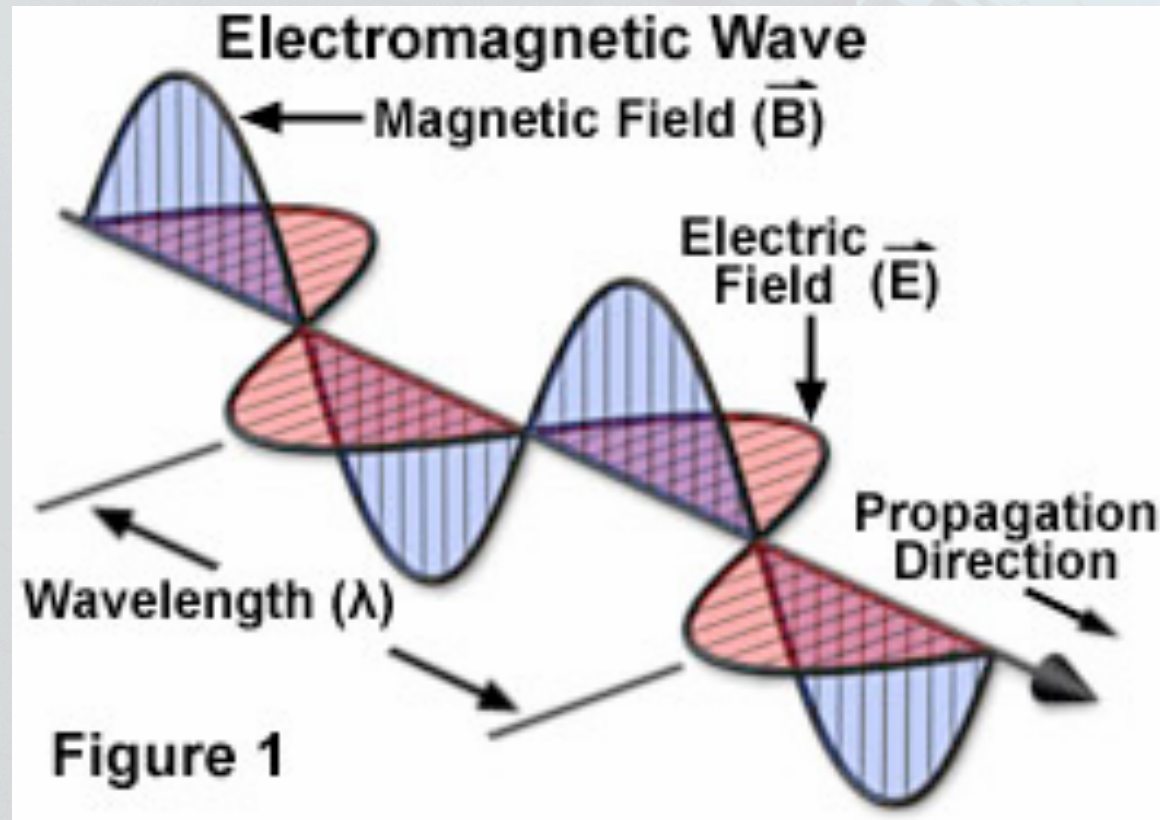
How does a thermal imager work?



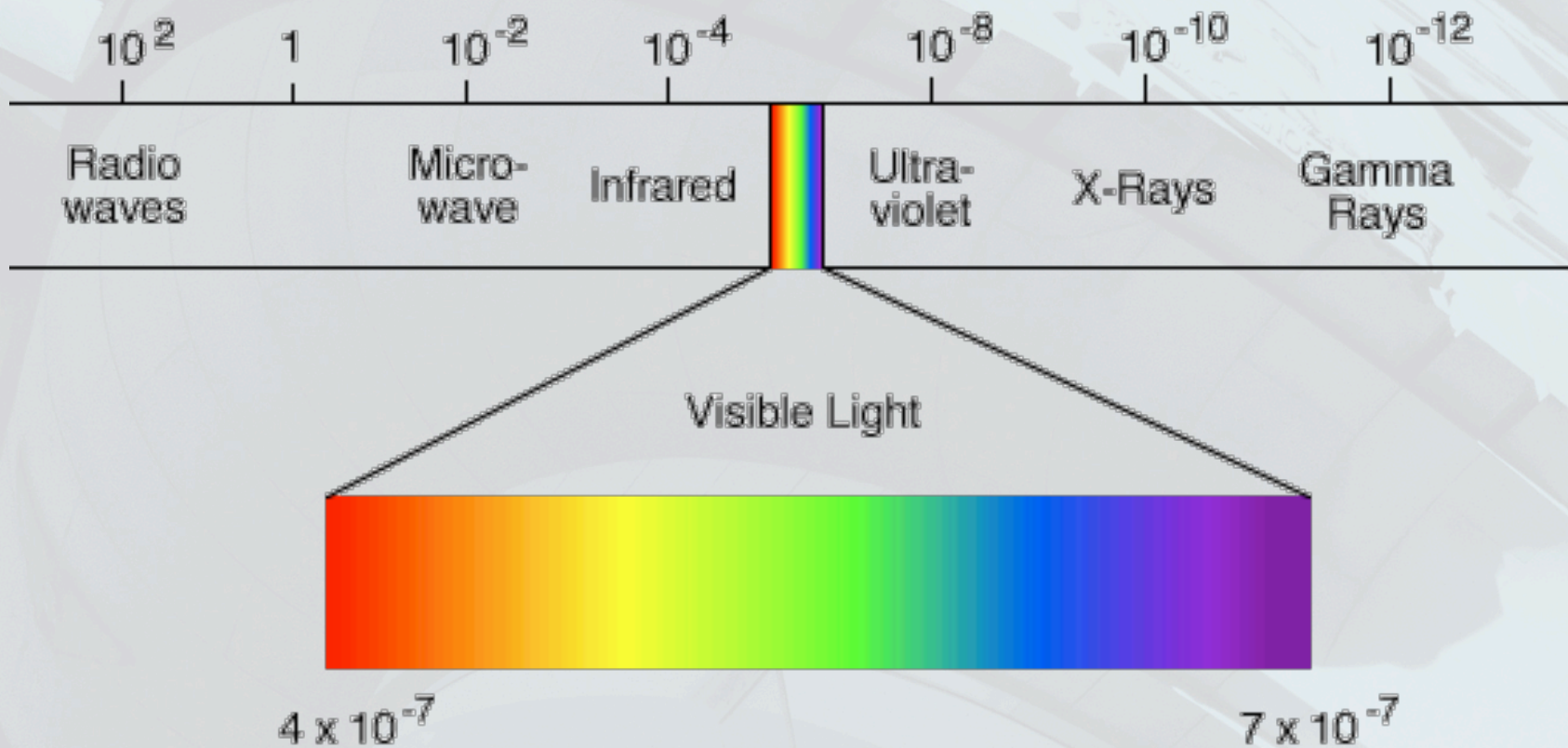
How does a thermal imager work?



How does a thermal imager work?



→ Light ... and much more!

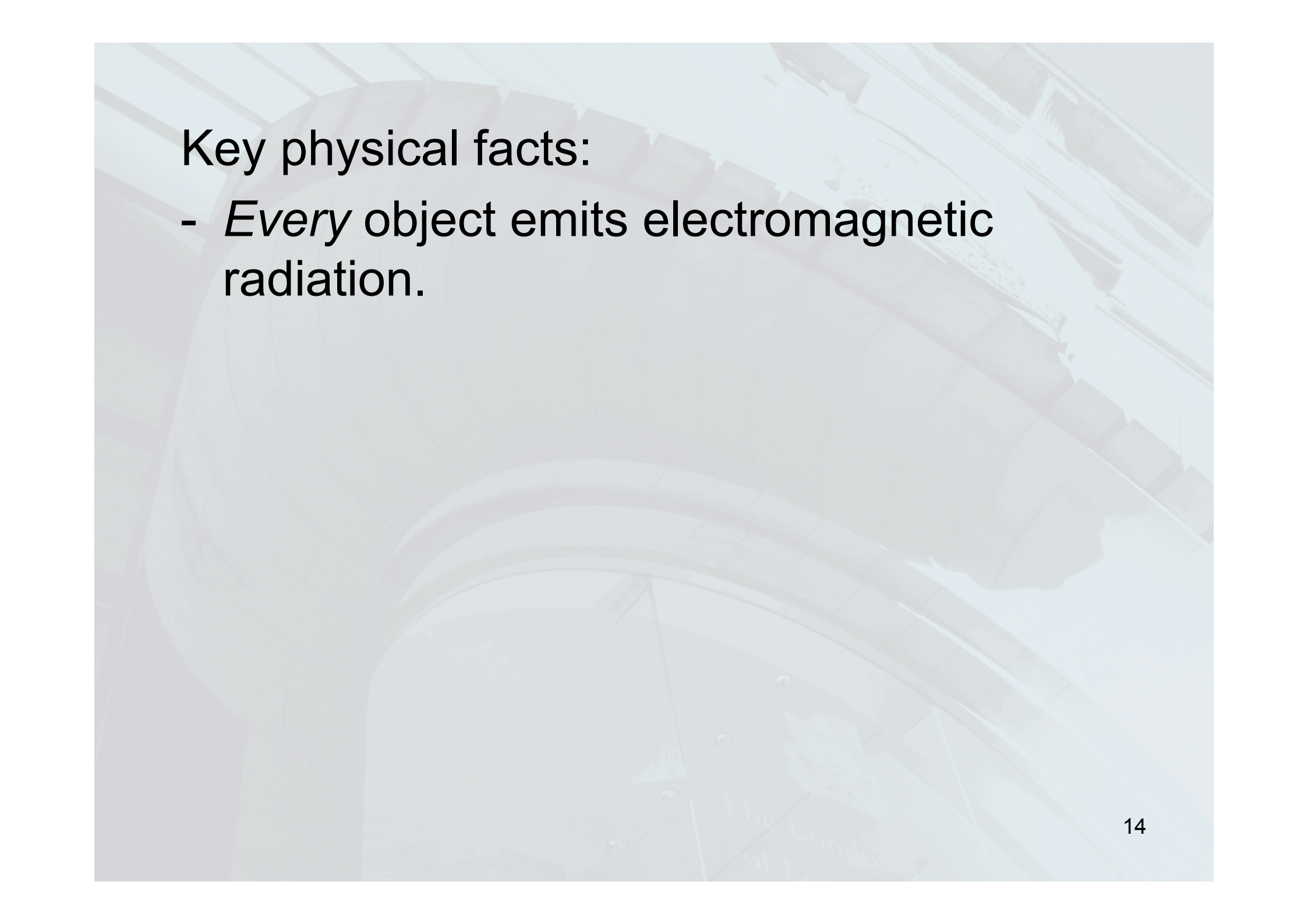


Interlude: Temperature of an object is measured in degrees:

- Normally: Celsius
- Science: Kelvin

Conversion: $K = C + 273.15$

Question: what is the physical meaning of the Kelvin scale?



Key physical facts:

- *Every* object emits electromagnetic radiation.

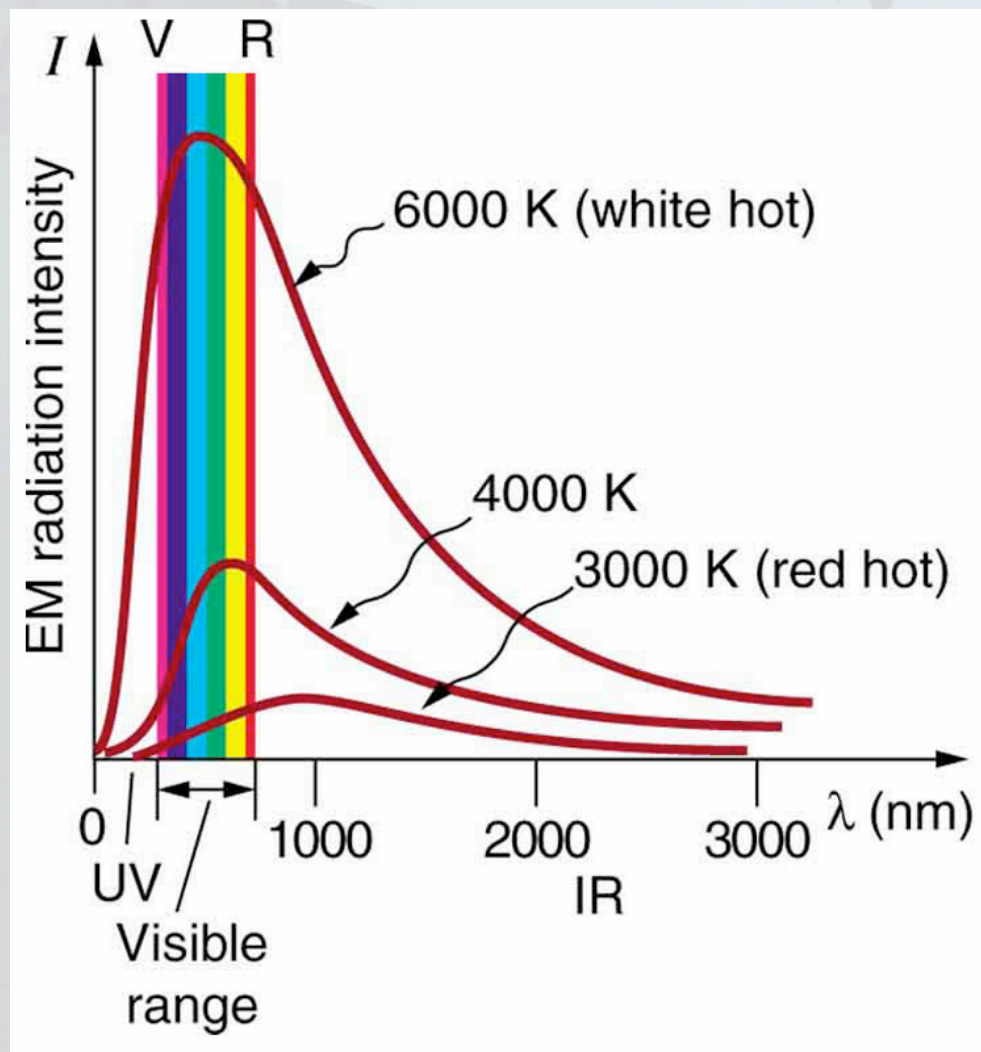


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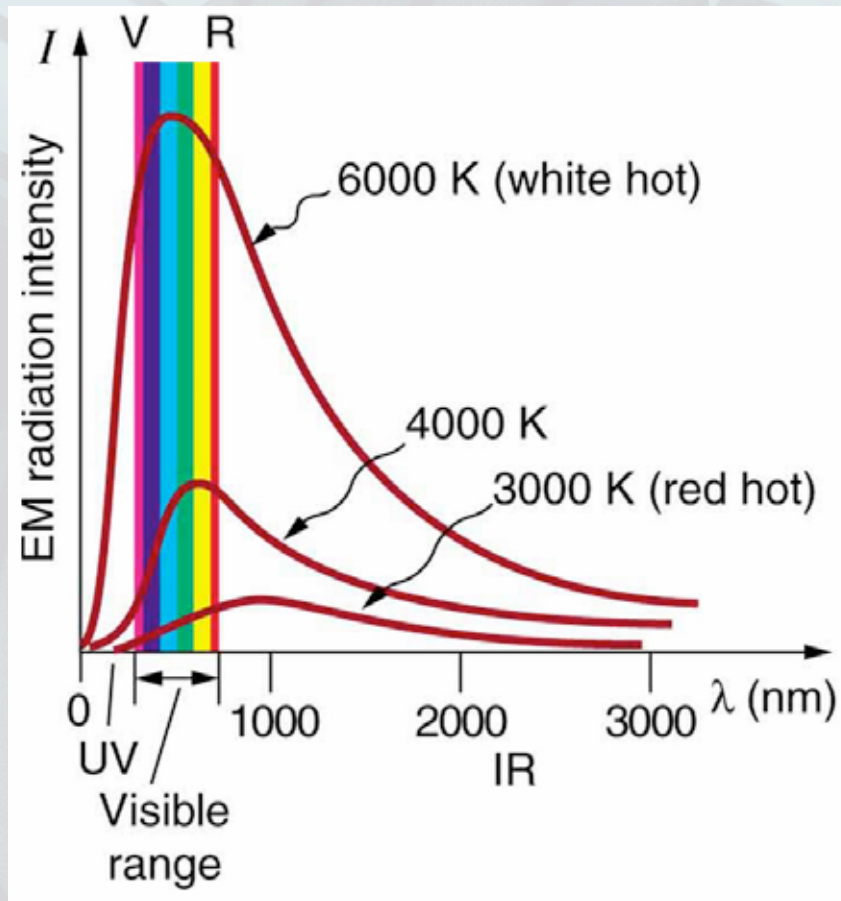
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- The wavelength of the wave depends on the object's *temperature*.

Key physical facts:

- *Every* object emits electromagnetic radiation.
- The wavelength of the wave depends on the object's *temperature*.
- There is not only one frequency emitted there is an entire spectrum, which depends on the temperature.



“Planck’s Radiation Law”

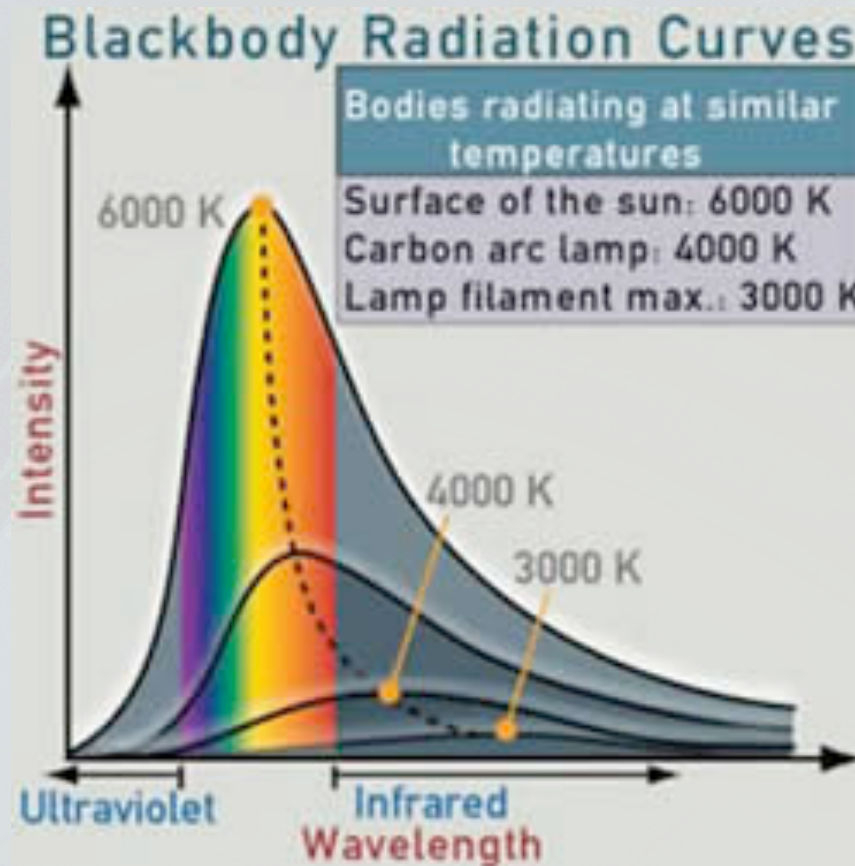


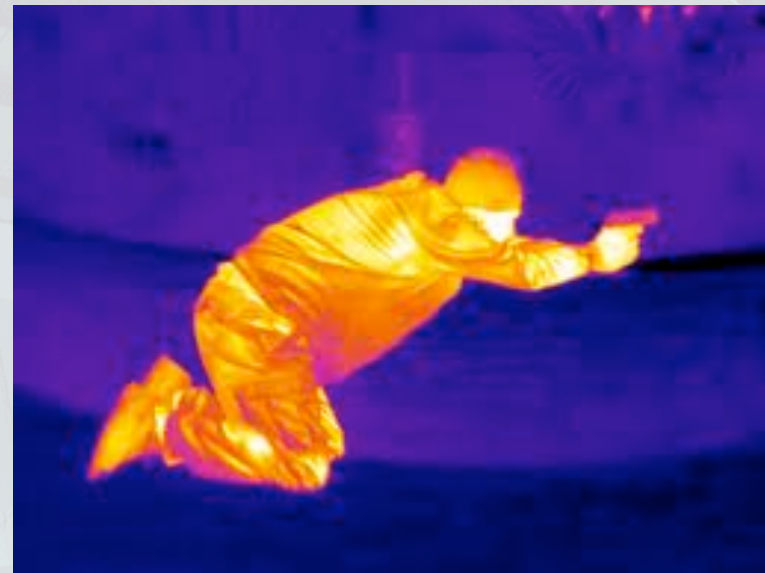
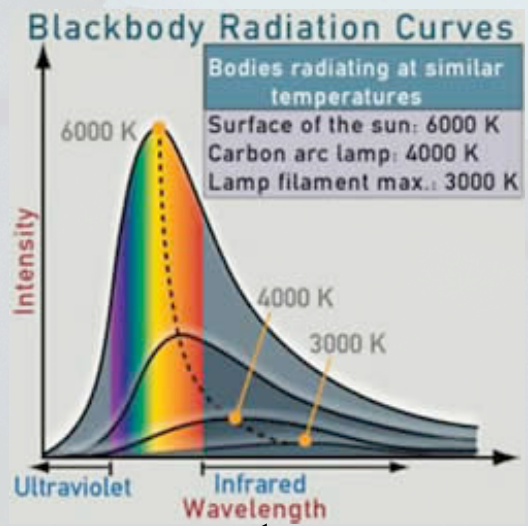
The peak of the distribution moves towards the left as the temperature increases:

$$\lambda_{\text{max}} = 3000 / T$$

“Wien’s Displacement Law”

For an object at room temperature the peak of the curve is below the visible spectrum, in the infrared spectrum (“heat”).





Incidentally ...



... and hot objects glow.

Finally, the total energy emitted per second and per square meter (of surface) by an object at temperature T is:

$$P = \sigma T^4$$

“Stefan-Boltzmann Law”, where σ is the Stefan-Boltzmann constant.

$$(\sigma = 5.67 \cdot 10^{-8} \text{ Wm}^2/\text{K}^4)$$

The S-B laws hold for a so-called **black body**: an idealized physical body that absorbs **all** incident electromagnetic radiation regardless of frequency or angle of incidence and then re-emits it.

The law is otherwise completely general: it applies to all matter. Everything around you is emitting electromagnetic waves constantly!

2. Energy Balance

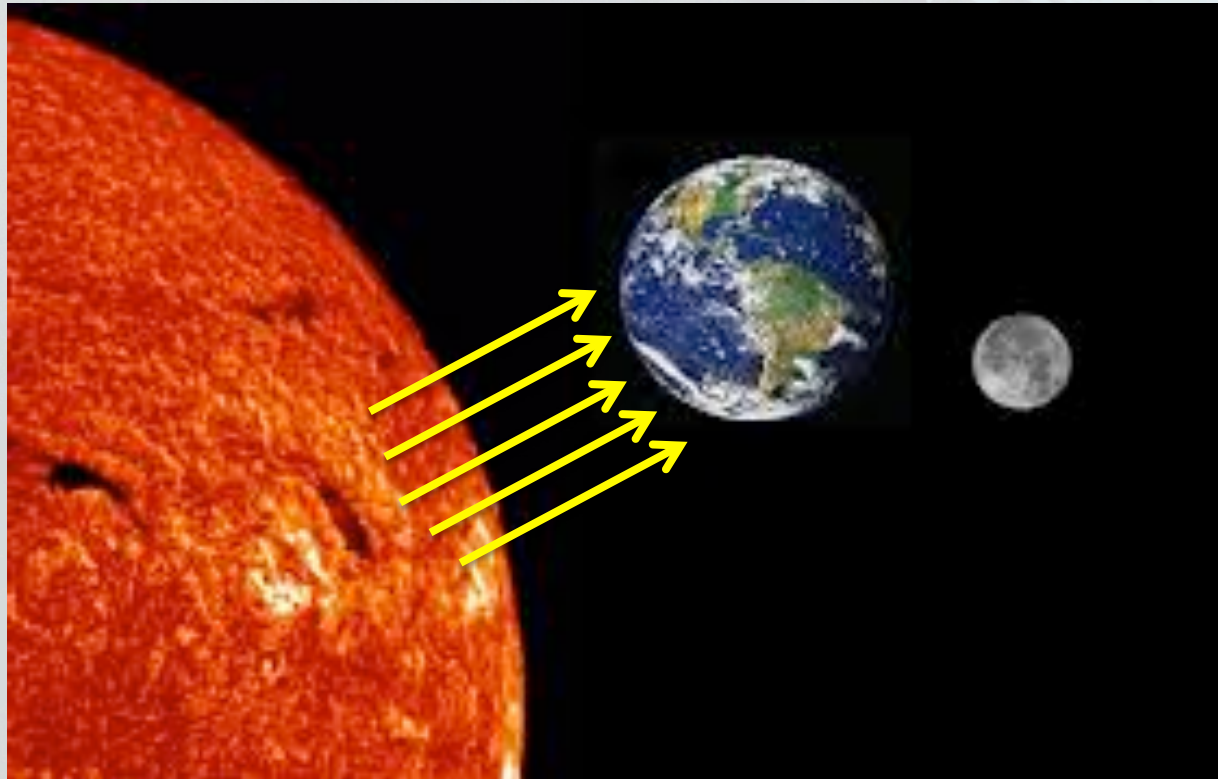
Fundamental principle of physics: Energy is conserved.

Energy can be 'moved around', but not destroyed.

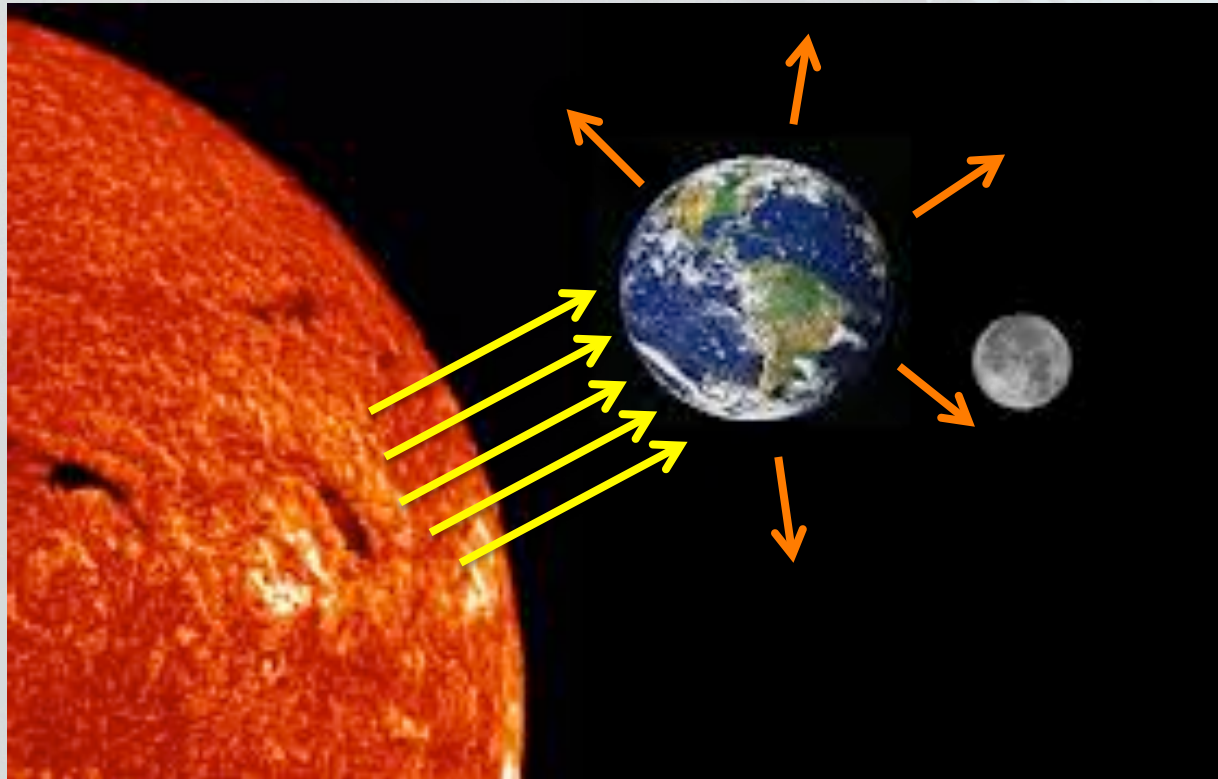
Implication for the earth:



Implication for the earth:



Implication for the earth:



For the earth at a stable temperature we must have:

Energy
coming
from the
sun to the
earth

=

Energy radiated
away from the
earth as black
body radiation

→ Basic energy balance of the earth

Now we can ask: how hot is the earth?

Total energy coming to the earth from the sun:

$$E_{\text{in}} = S \pi R^2$$

where:

S is the solar constant (1360 W/m²) and

R is the radius of the earth (6400km)

Energy *per square meter* of the surface of the earth:

$E_{\text{in}} / \text{surface of earth},$

which is $4 \pi R^2$.

Hence:

$$E_{\text{in} / \text{m}^2} = S \pi R^2 / 4 \pi R^2 = S / 4.$$



Is the earth a perfect black body?



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→ No it isn't!

A fraction of the light received from the sun is reflected back in to space by ice, etc.

→ Albedo (“whiteness”, from Latin “albus”)

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$$E_{\text{absorbed}} = (1 - \alpha) S / 4$$

For the earth: $\alpha = 0.3$

Hence: $E_{\text{absorbed}} \approx 240 \text{ W/m}^2$

The right hand side of the equation is given by the Stefan-Boltzmann law:

$$E_{\text{out}} = \sigma T^4$$

So our **energy balance equation** is:

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

The right hand side of the equation is given by the Stefan-Boltzmann law:

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So our **energy balance equation** is:

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

Doing the maths: $T = 255\text{K}$



This is -18° !!

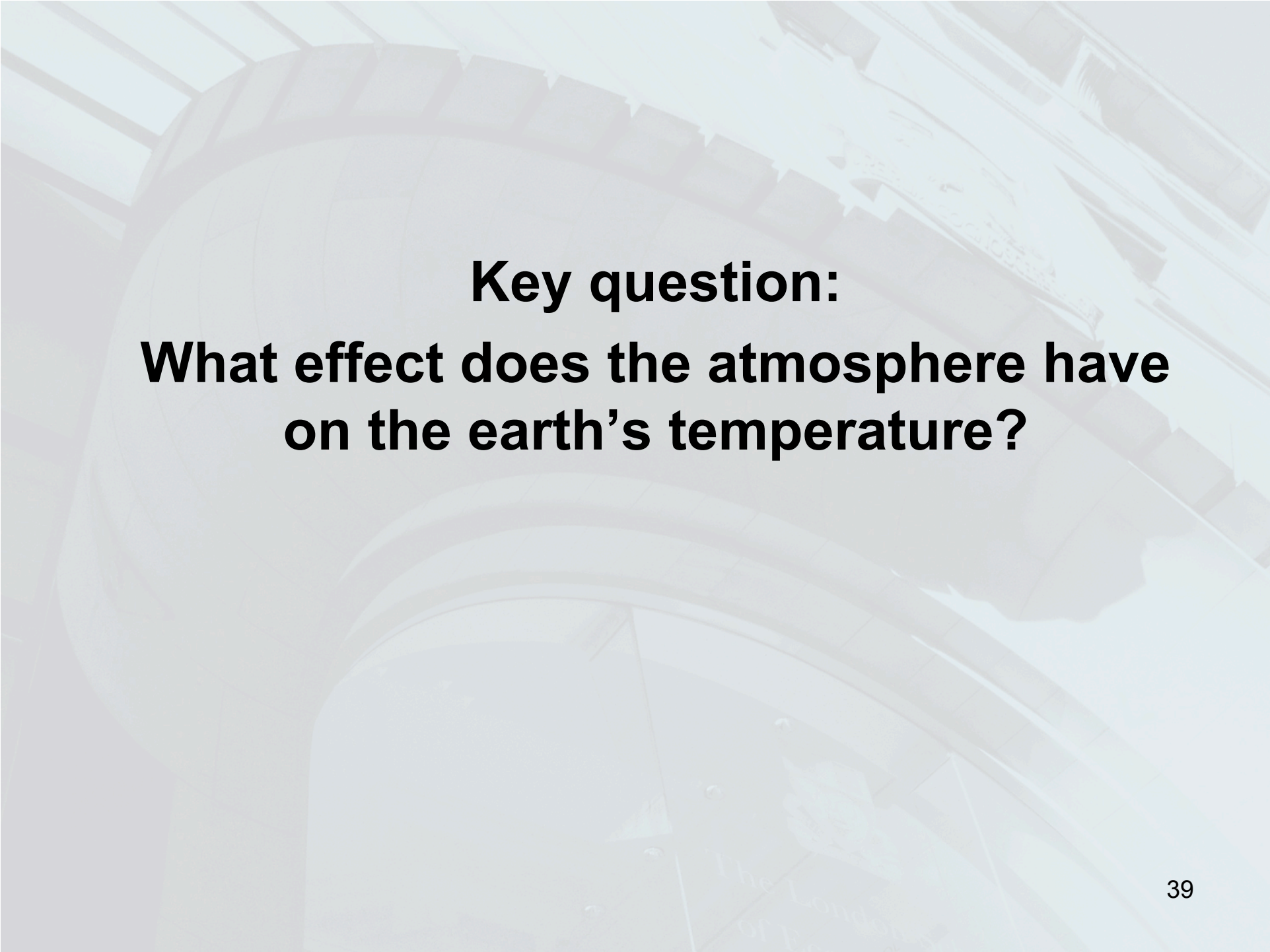
→ What has gone wrong?

This is -18° !!

→ What has gone wrong?

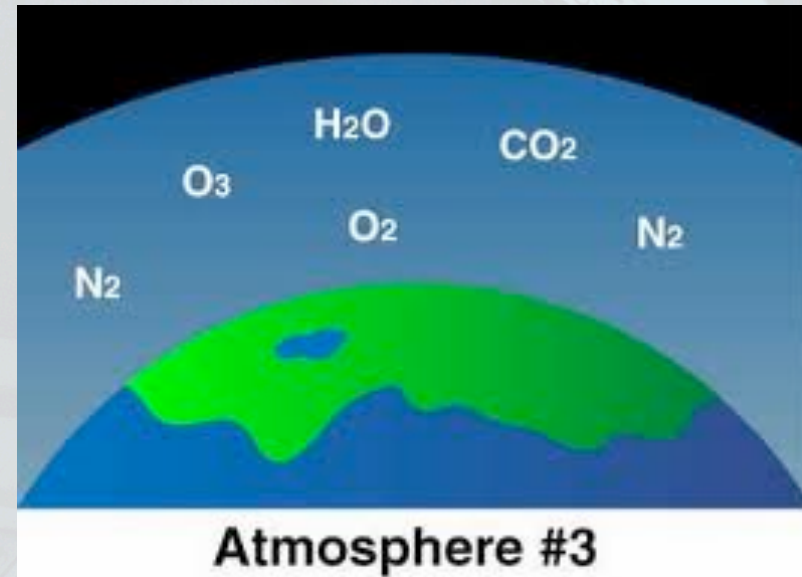
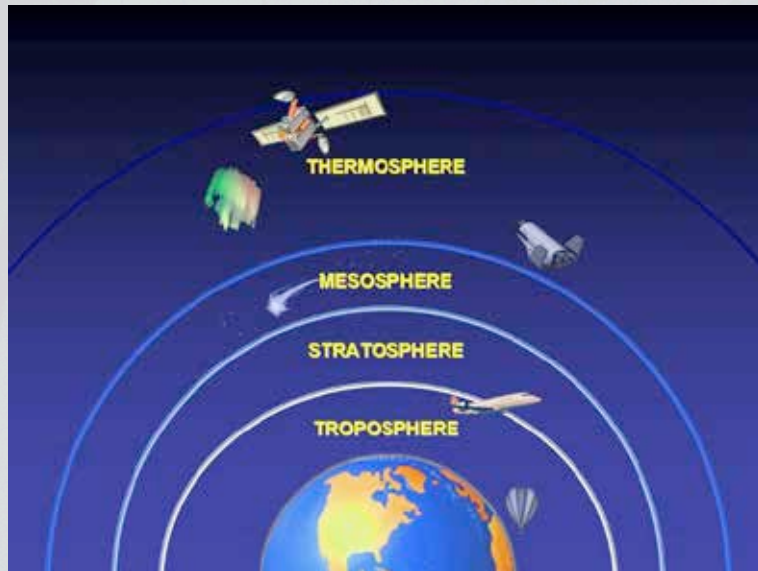
→ The earth has an atmosphere!





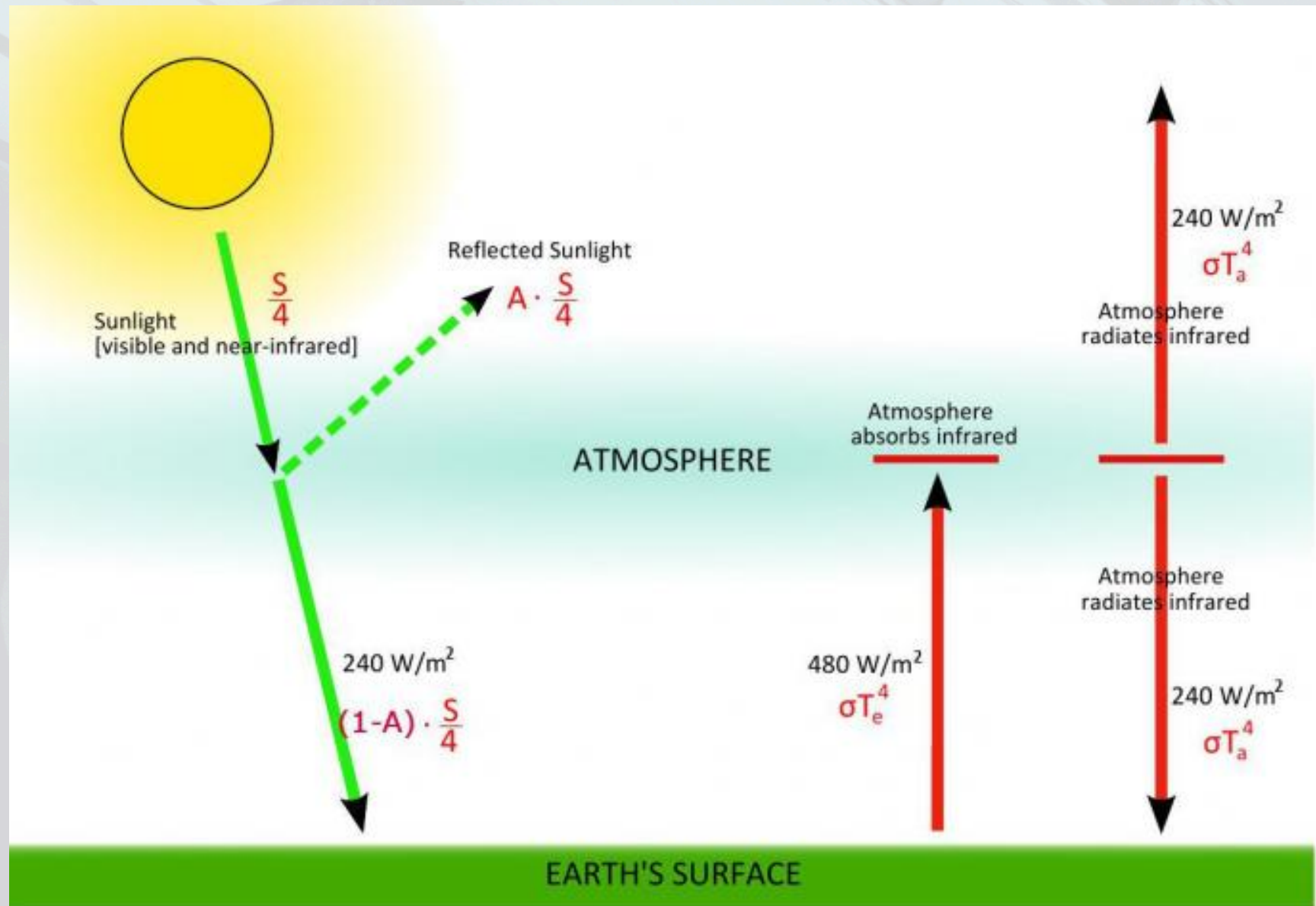
Key question:
**What effect does the atmosphere have
on the earth's temperature?**

3. The Greenhouse Effect

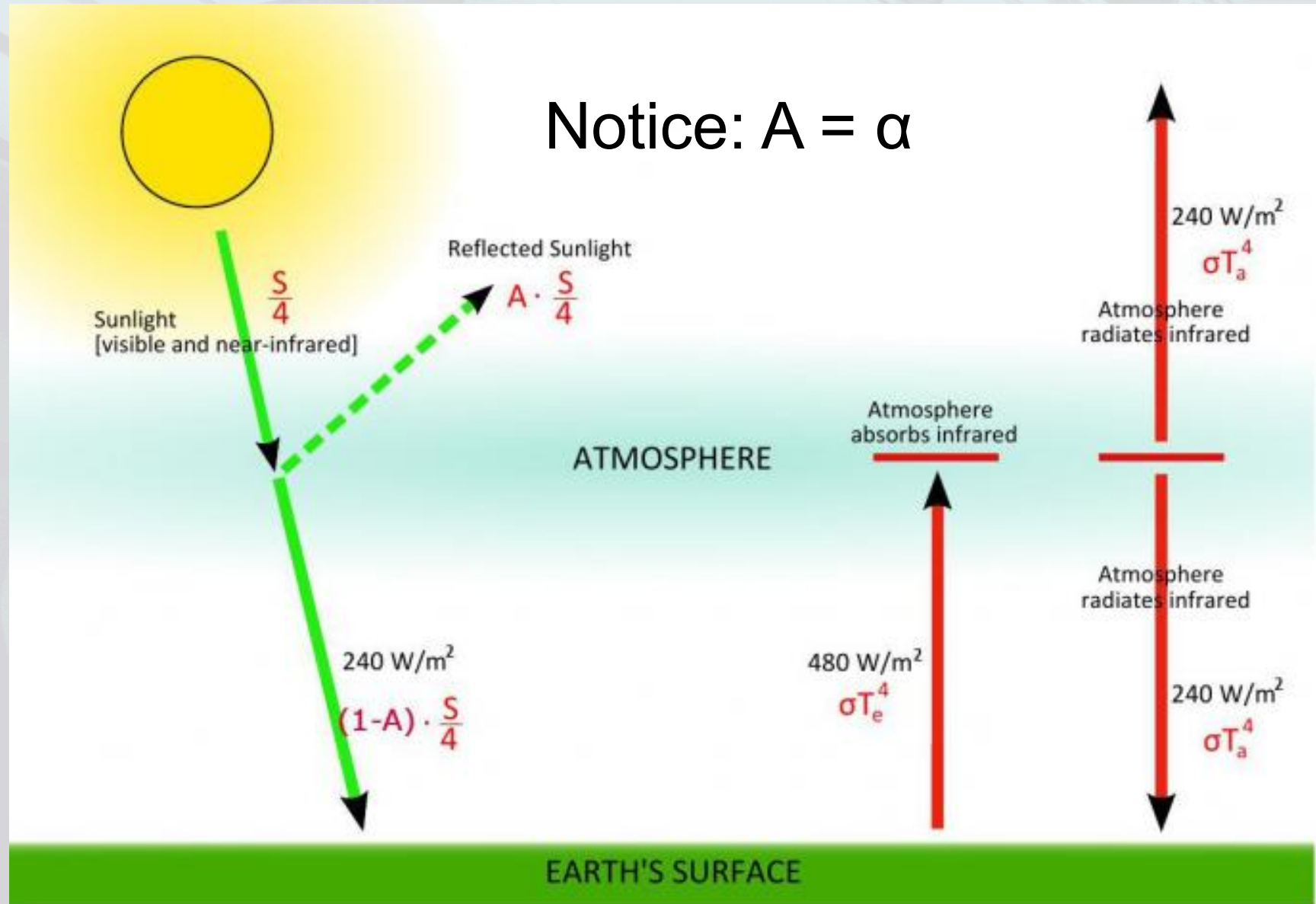


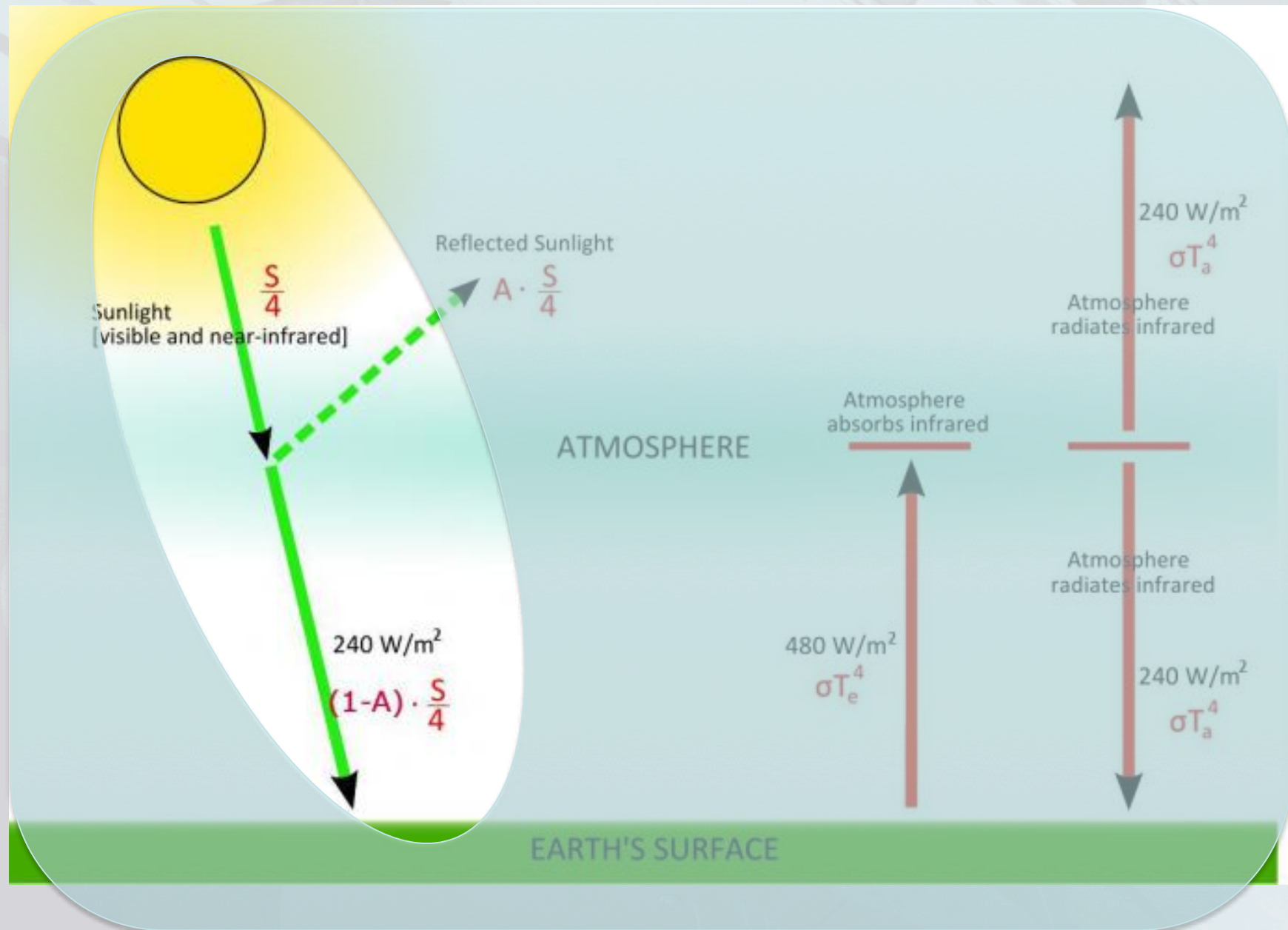
One layer model:

- Think of the atmosphere as one layer.
- Electromagnetic waves in the visible spectrum penetrate the atmosphere (that's why there is light on earth!)



Notice: $A = \alpha$

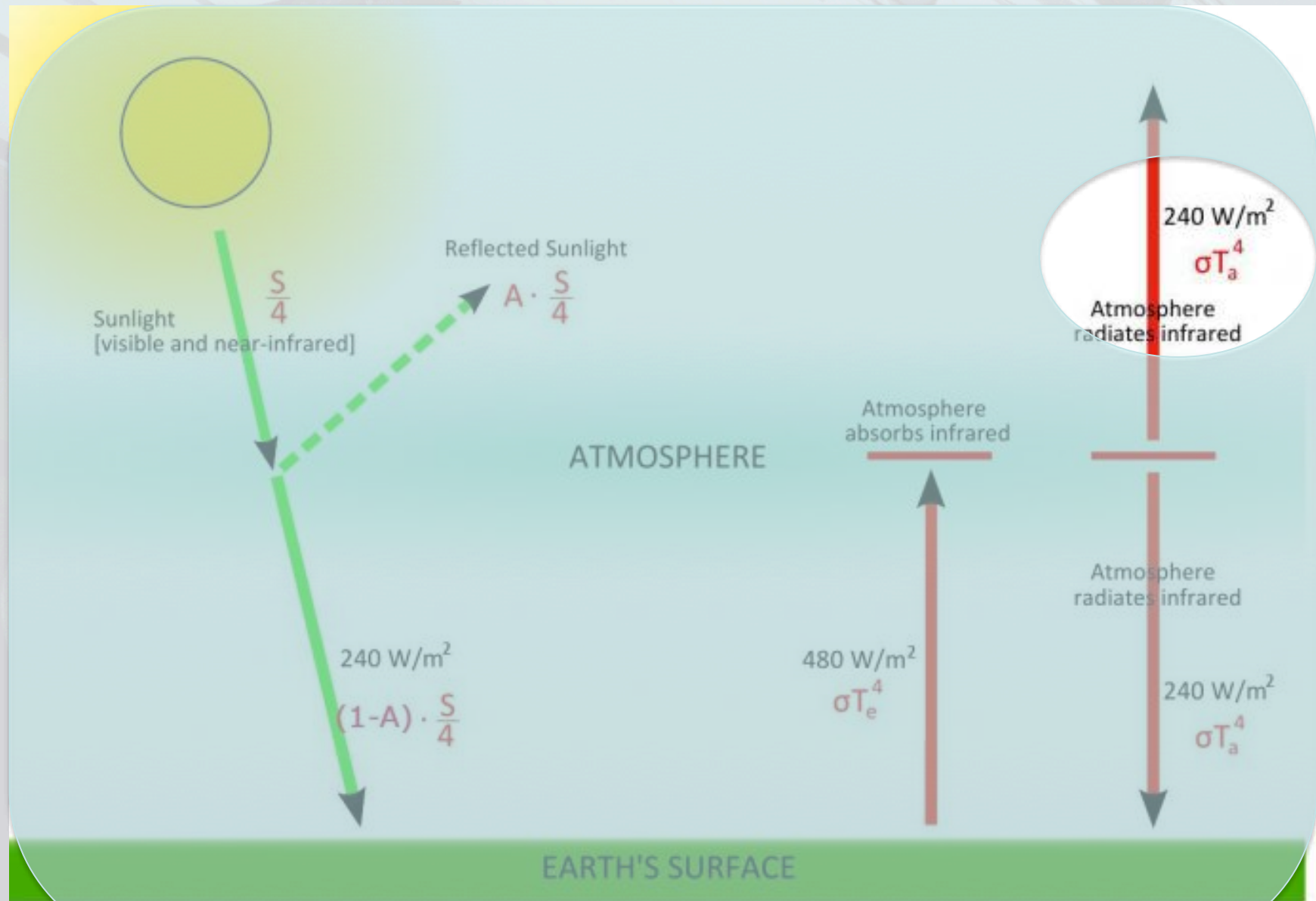




The background of the slide features a large, faint, light-blue gear on the left side, partially overlapping a map of London. The map shows the city's layout, including the River Thames and various streets. The text is overlaid on this background.

Assume further:

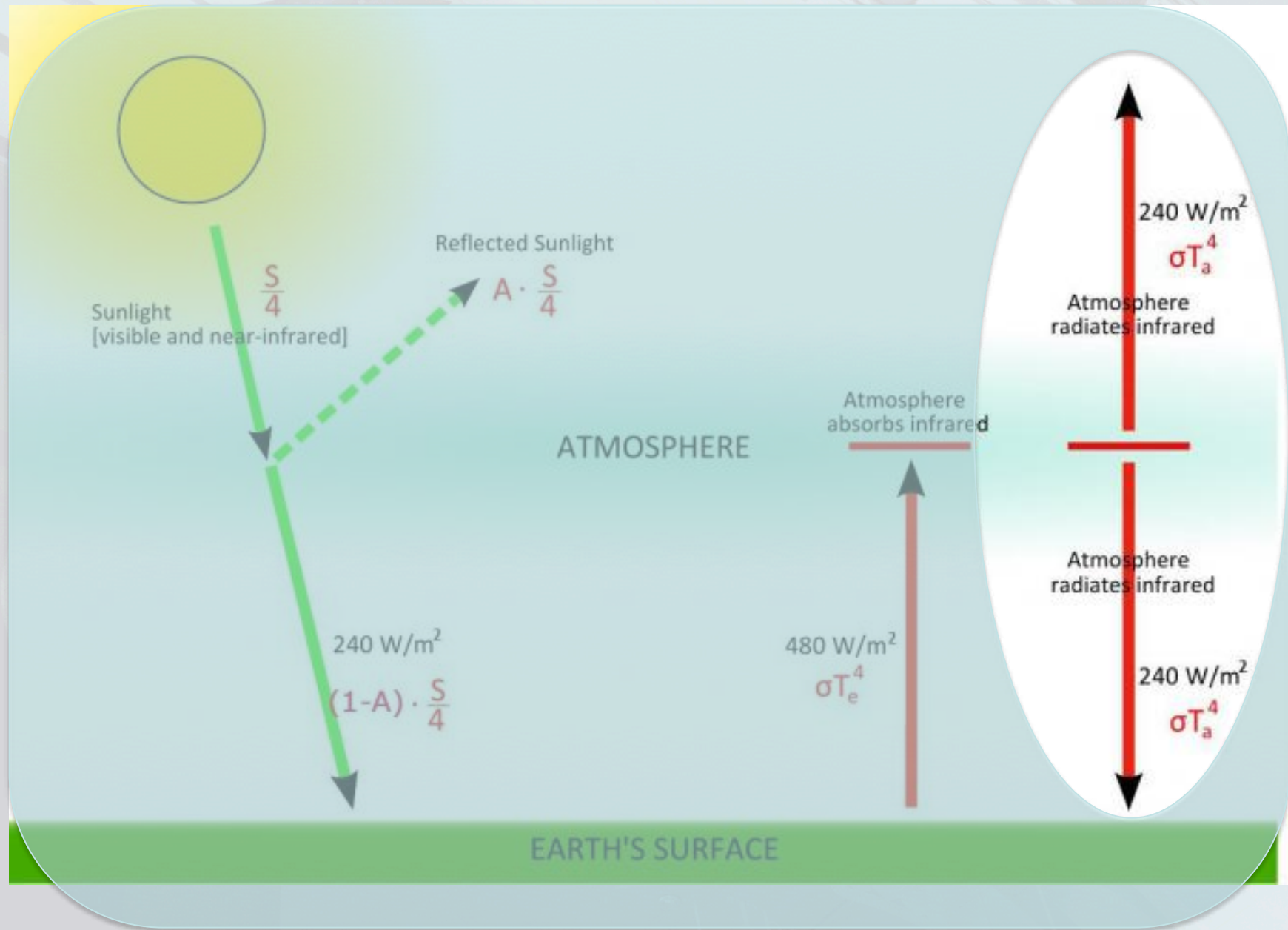
- The earth is in equilibrium, i.e. has constant temperature. This implies that the energy going in is equal to the energy going out.
- Energy going out is coming entirely from the atmosphere.





And:

- Electromagnetic waves in the infrared spectrum are absorbed by the atmosphere
- The atmosphere is a black body and hence emits radiation.
- The atmosphere radiates equally in all directions, so half of the energy goes up and half goes down.

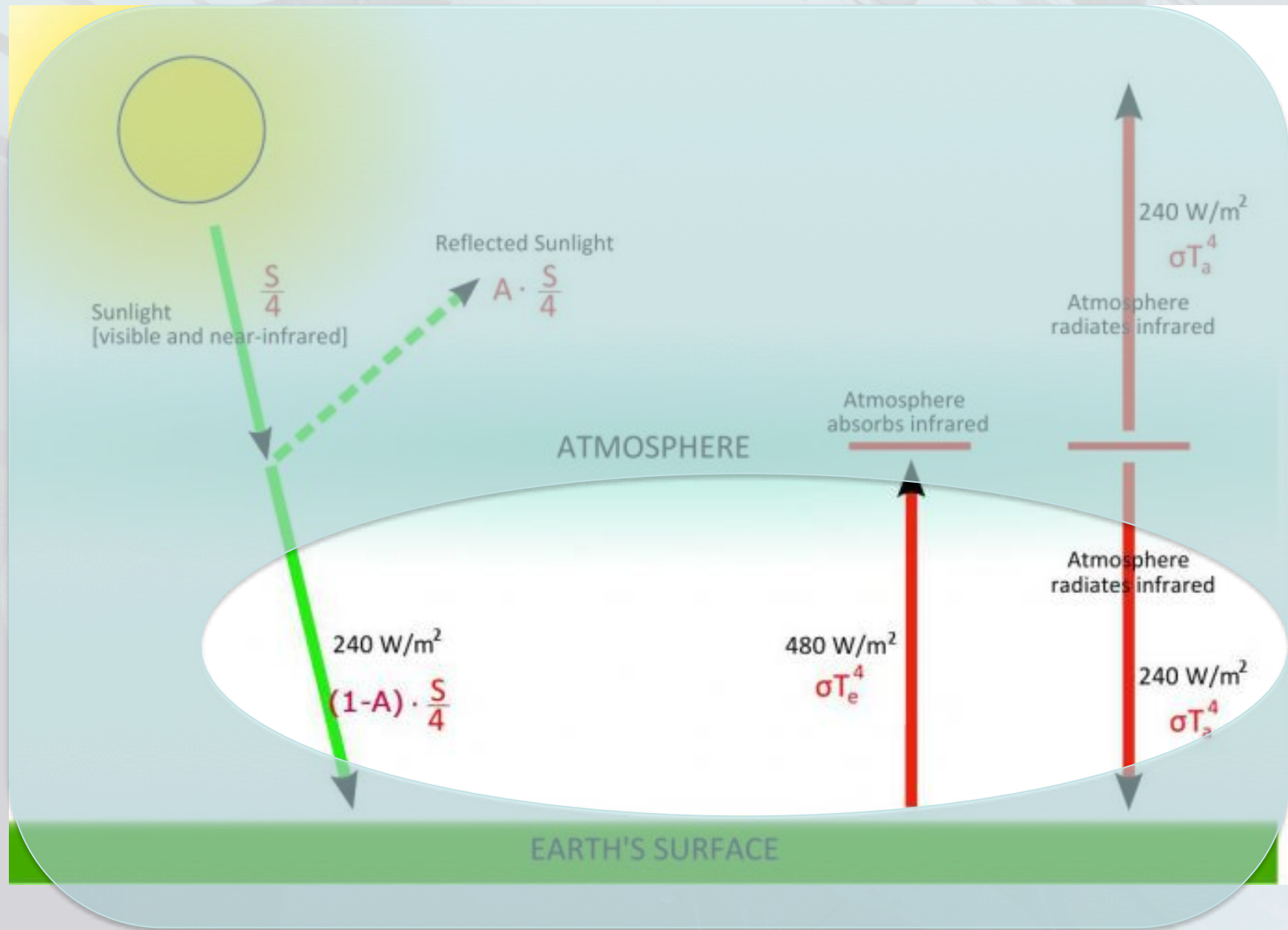


Adding up:

- 240 W/m^2 are coming in from the sun
- 240 W/m^2 are reflected back onto the earth from the atmosphere

Hence:

- 480 W/m^2 have to be radiated upwards by the earth for the earth to be in equilibrium.



So what is the temperature on the surface?

Use the Stefan-Boltzmann law ($P = \sigma T^4$):

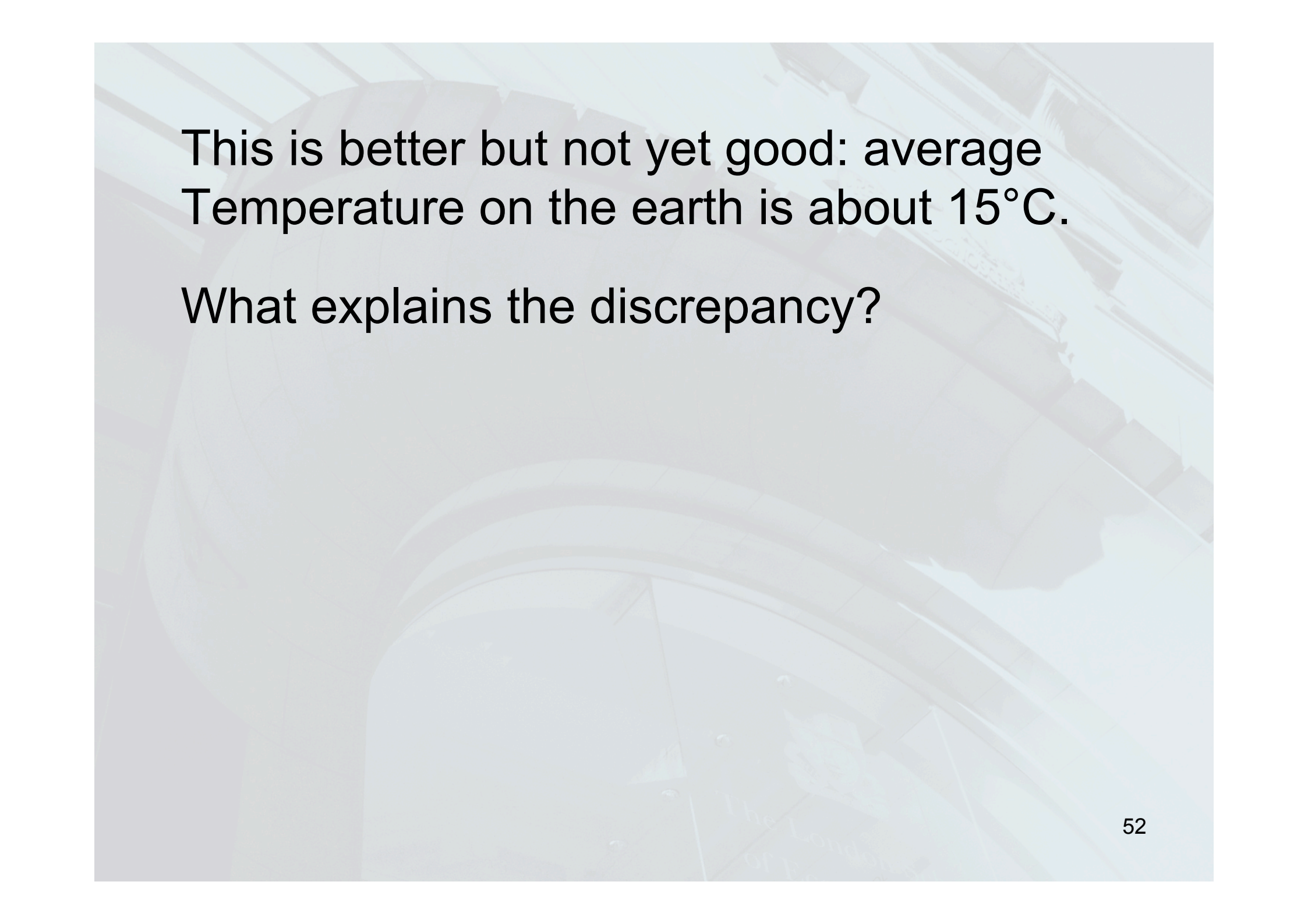
$$480 \text{ W/m}^2 = \sigma T^4$$

Plugging in the numbers yields:

$$T \approx 303\text{K},$$

This is about 30°C , which is 48°C more than for a planet without atmosphere!

→ “Greenhouse effect”.



This is better but not yet good: average
Temperature on the earth is about 15°C .

What explains the discrepancy?



→ Two layer models

...

→ N-layer models

$$T = \sqrt[4]{S(n+1)(1-\alpha) / 4\sigma}$$

Sources or *uncertainty*:

(a) Parameters

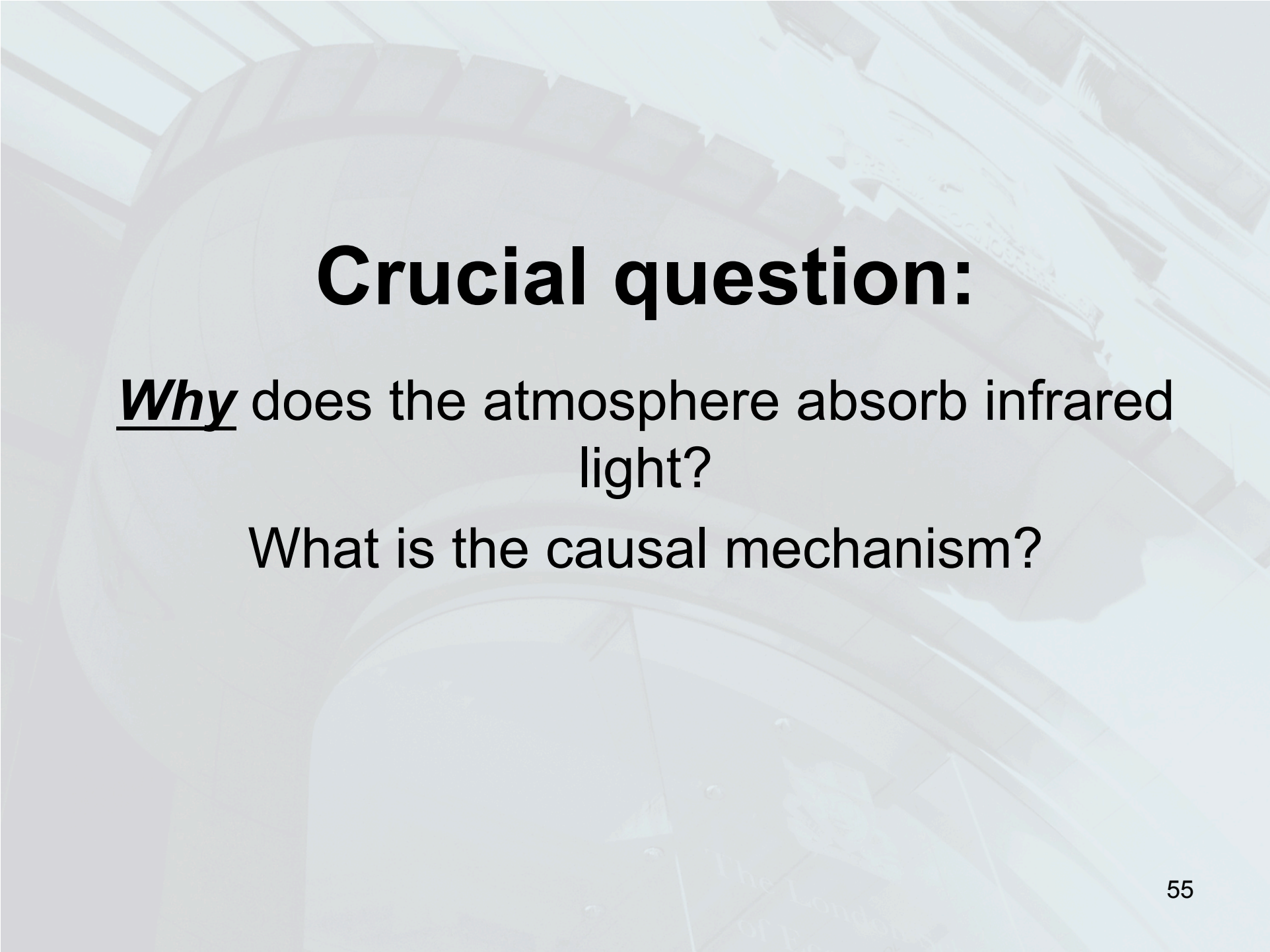
- σ : small
- S: relatively small (however: variations)
- α : considerable

(b) Structural

Immense simplifications have been made.

De-idealising this model leads to GCMs

→ Next lecture.



Crucial question:

Why does the atmosphere absorb infrared light?

What is the causal mechanism?

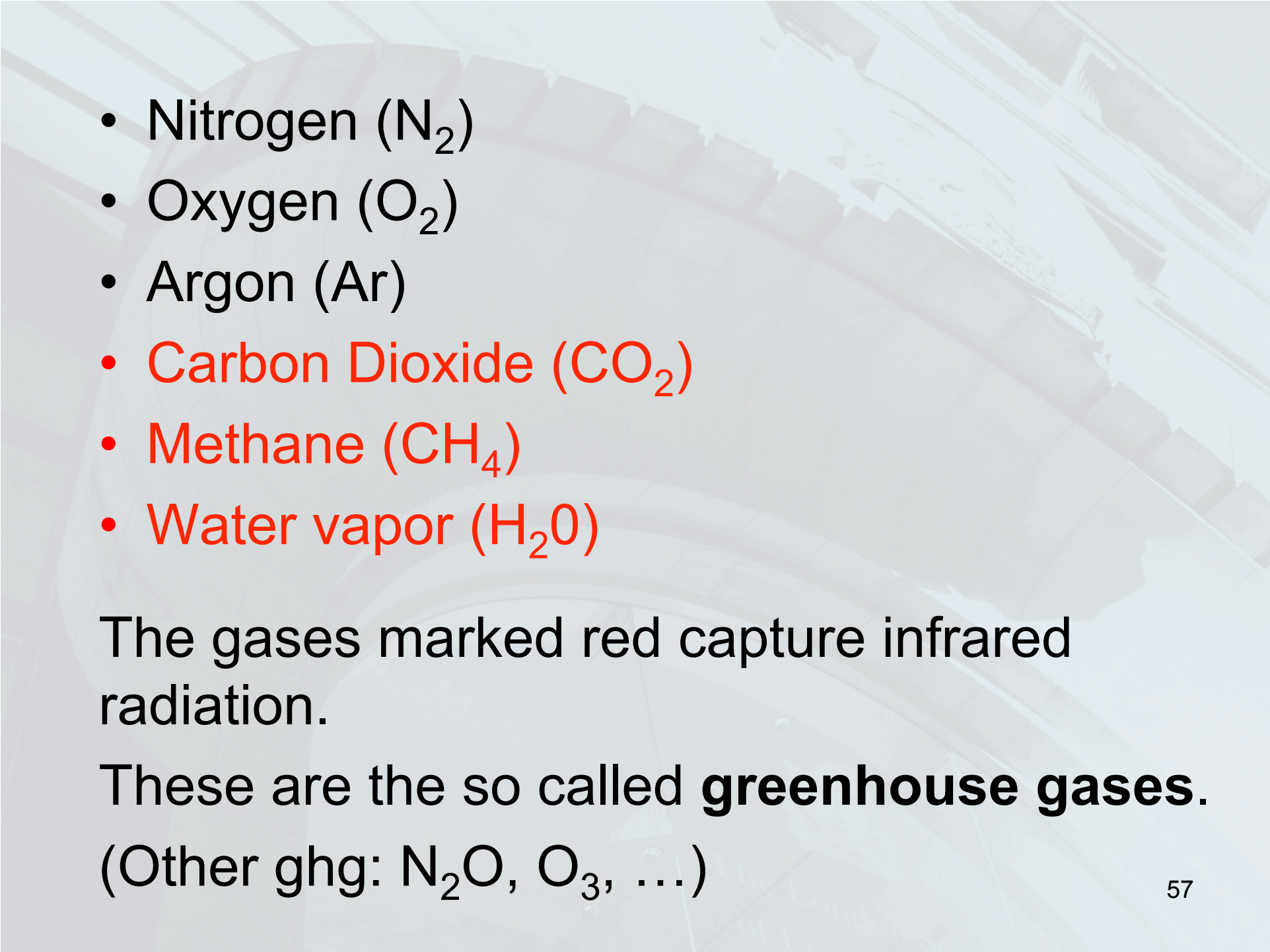
→ Composition of the atmosphere:

(a) Dry Atmosphere (no water)

- Nitrogen (N_2): 78%
- Oxygen (O_2): 21%
- Argon (Ar): 1%
- Carbon Dioxide (CO_2): 0.039% = 390 ppm
- Methane (CH_4): 1.8ppm

(b) Water:

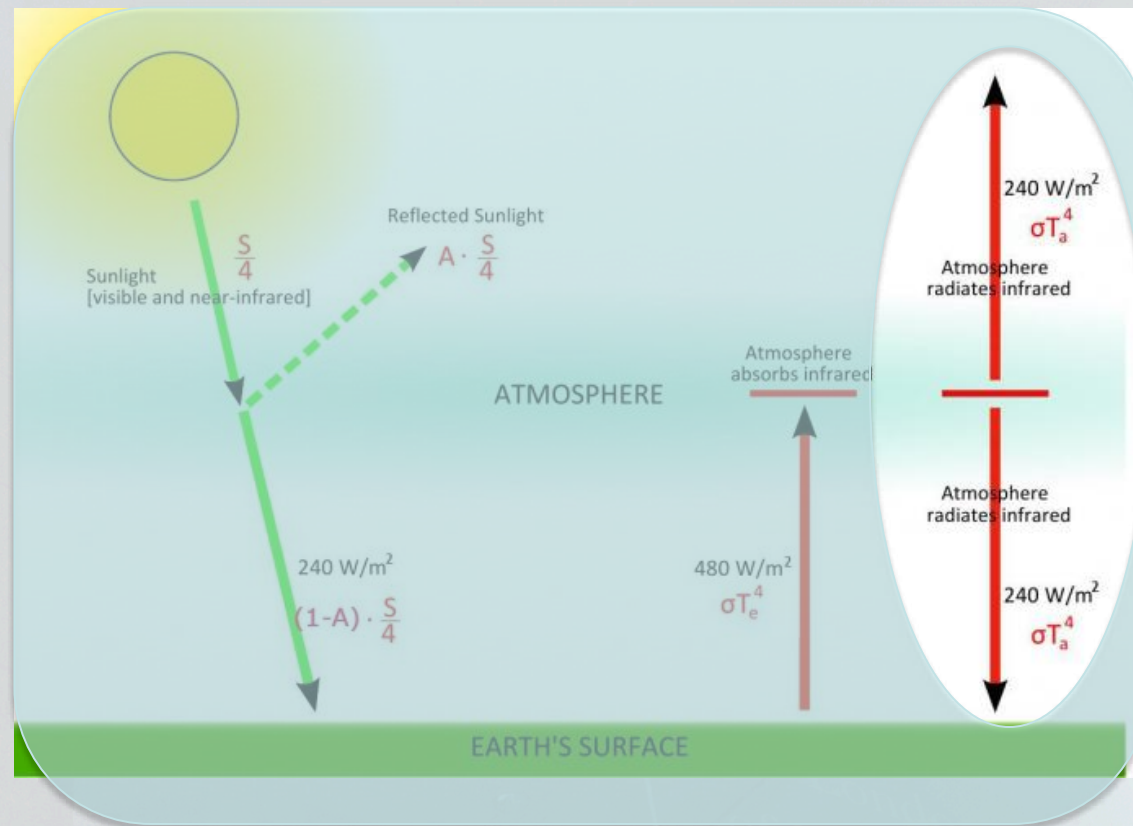
- Water vapor (H_2O): 0.2% - 4% of total.

- 
- Nitrogen (N_2)
 - Oxygen (O_2)
 - Argon (Ar)
 - Carbon Dioxide (CO_2)
 - Methane (CH_4)
 - Water vapor (H_2O)

The gases marked red capture infrared radiation.

These are the so called **greenhouse gases**.
(Other ghg: N_2O , O_3 , ...)

Greenhouse gases are responsible for the atmosphere's black body behaviour. Without them radiation would escape unhindered.



Not all greenhouse gases are equally important:

- Water vapour is the most important greenhouse gas because there is a lot of it (main source: evaporation from the oceans → feedback loop.)
- CO₂ is the second most important greenhouse gas. With only 390ppm there is little of it (→ small changes matter!)
- Methane is rare, but it's 20 times more powerful than CO₂ per molecule!

Burning fossile fuels puts CO_2 into the atmosphere, which contributes to heat capture.

Carbon Cycle: CO_2 moves between the atmosphere, oceans, land biosphere and rocks. Understanding this cycle is important. → Readings.

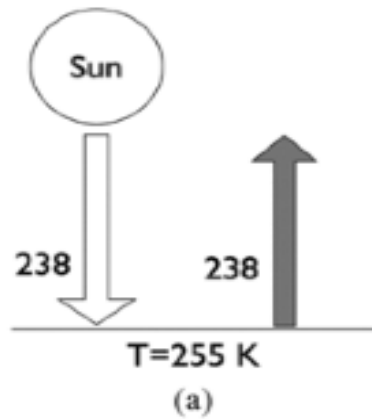
4. Time Lags and Forcing

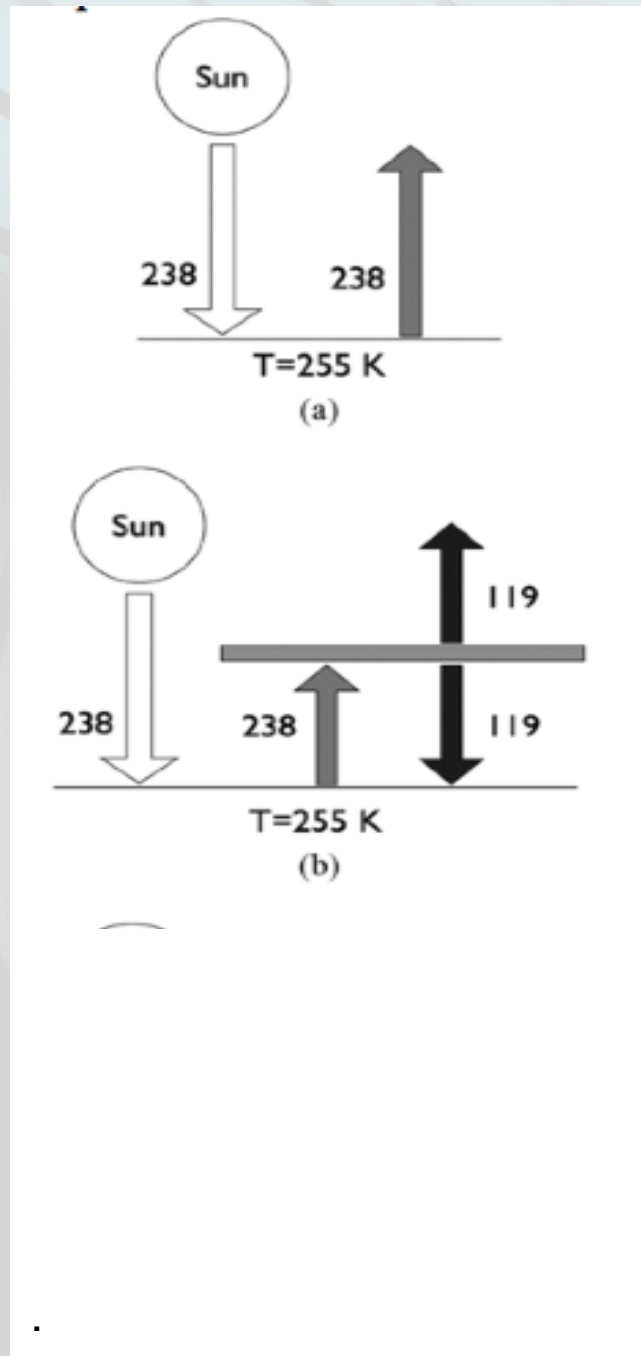
So far we have considered equilibrium situations ($E_{\text{in}} = E_{\text{out}}$). But thermal processes often take a long time to reach equilibrium.

→ Cooking pasta

Question: how does the earth react to additions of greenhouse gases to the atmosphere?

Start with a planet
without atmosphere.

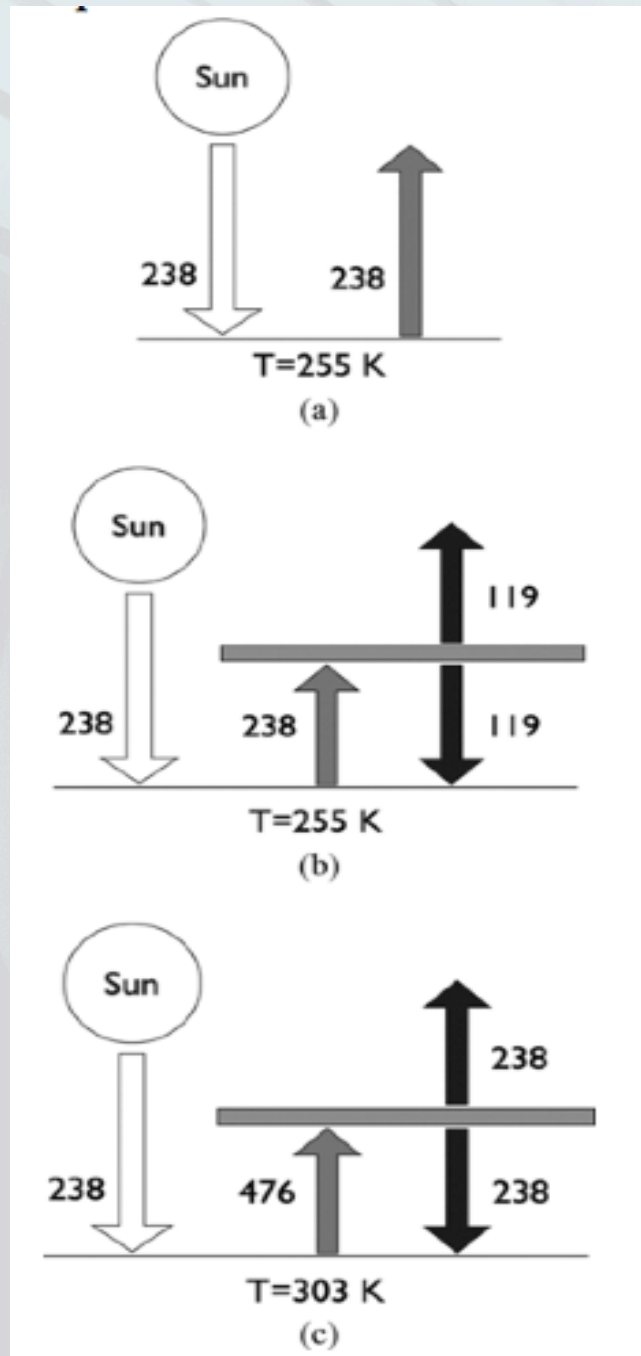




Start with a planet without atmosphere.

Suddenly add an atmosphere. This disturbs the energy balance: Outgoing energy is smaller than incoming energy.

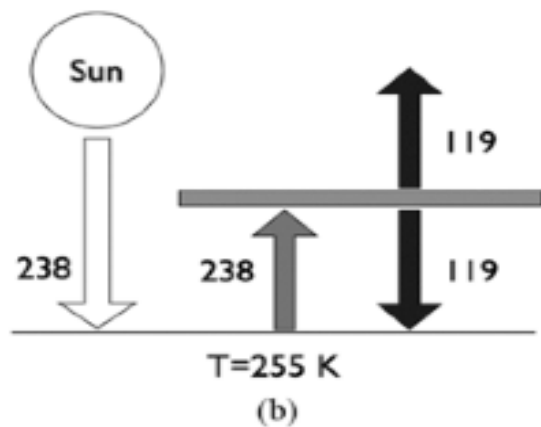
As a result the planet heats up until ...



Start with a planet without atmosphere.

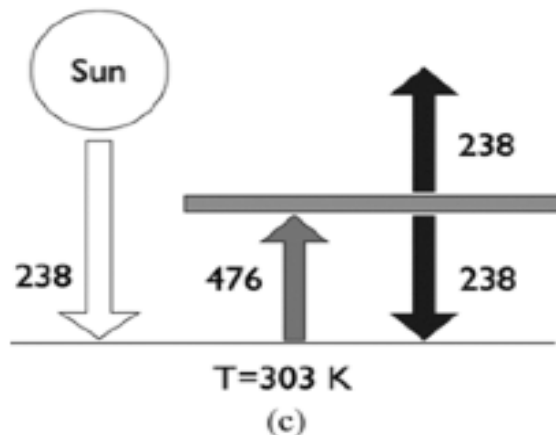
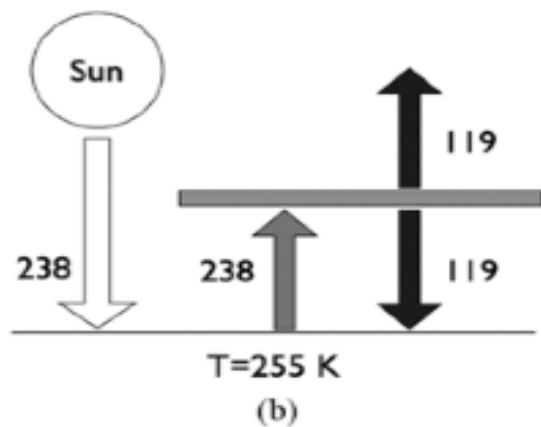
Suddenly add an atmosphere. This disturbs the energy balance: Outgoing energy is smaller than incoming energy.

As a result the planet heats up until its surface radiates enough to restore balance.



In detail:

- Energy influx remains the same.
- Energy reflected from the surface remains the same (surface temperature remains the same).
- Energy escaping is halved because of the atmosphere.
- So the surface receives extra energy.
- The surface heats up
- As the surface warms up the energy out increases.



In detail:

- Energy influx remains the same.
- Energy reflected from the surface remains the same (surface temperature remains the same).
- Energy escaping is halved because of the atmosphere.
- So the surface receives extra energy.
- The surface heats up
- As the surface warms up the energy out increases.
- Eventually the surface is warm enough to restore equilibrium.⁶⁶

This warming does not happen instantaneously. For the earth it takes a few decades to reach a new equilibrium.

→ “Time lag”.

→ Reason: oceans with large heat capacity.

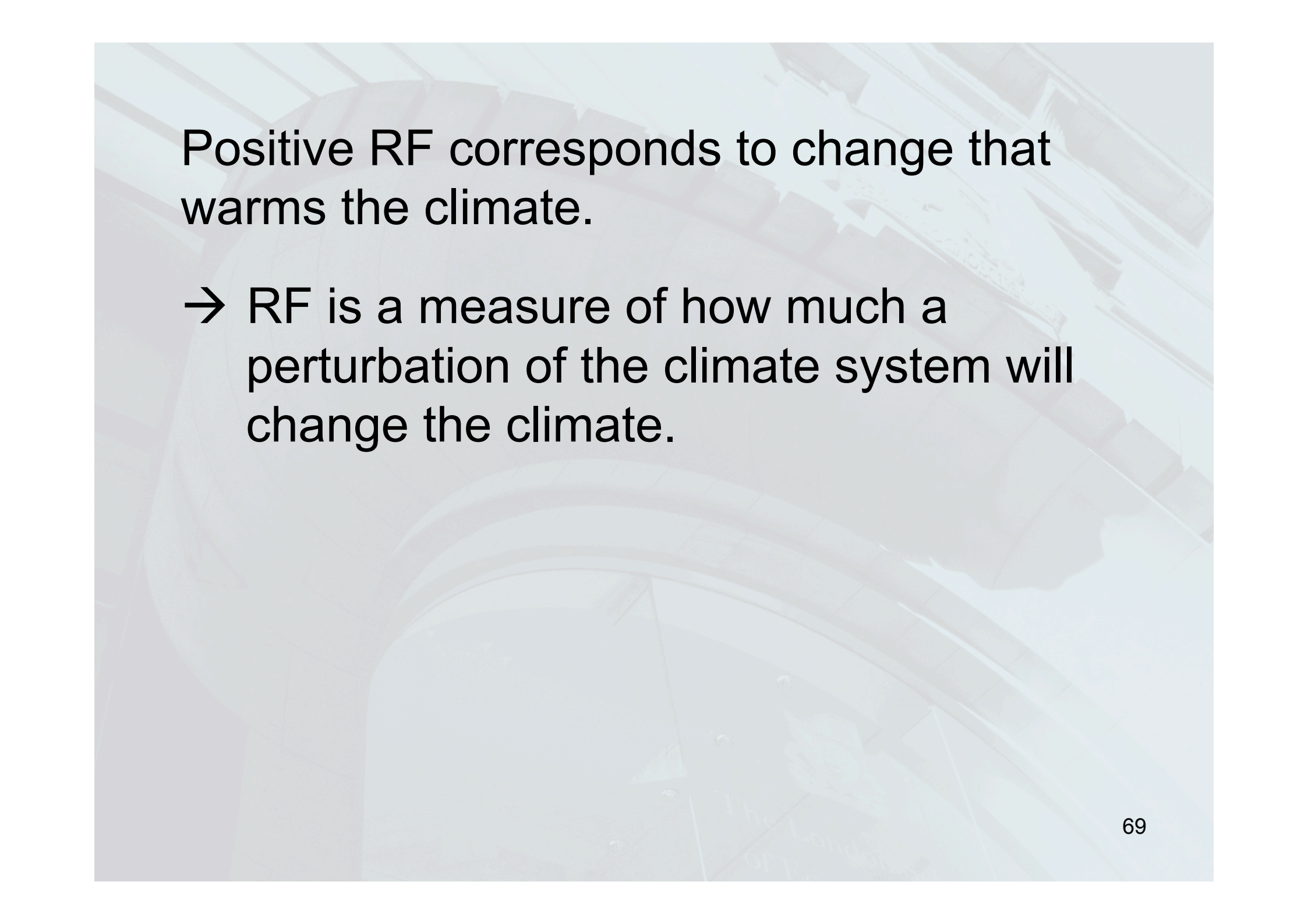
And if we keep adding greenhouse gases the earth keeps warming and no new equilibrium is reached.

→ Implications for climate policy!

Radiative forcing (RF) is the *change* in $E_{\text{in}} - E_{\text{out}}$ for the planet as a result of some change imposed on the planet before the temperature of the planet has adjusted in response

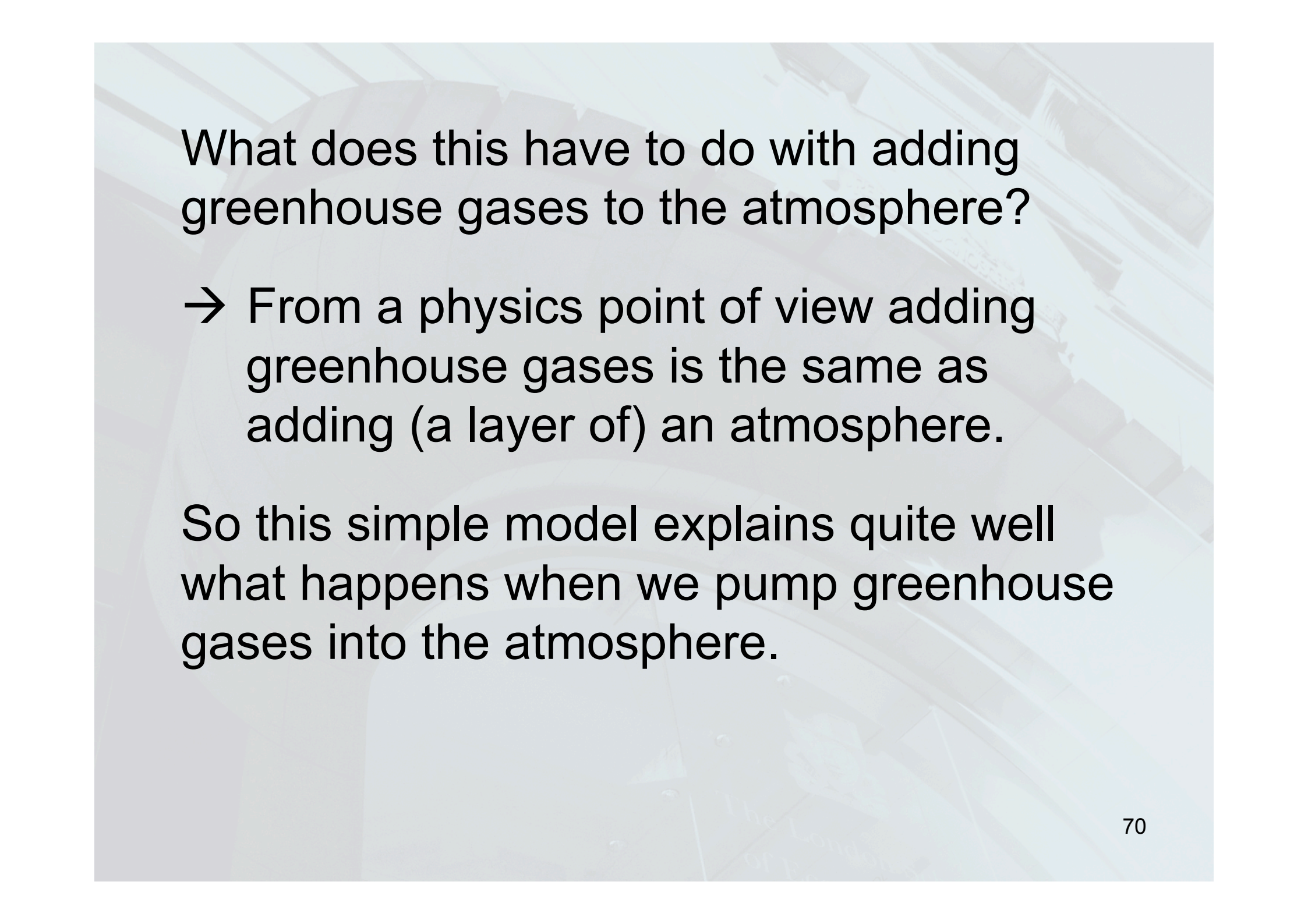
$$\text{RF} = \Delta(E_{\text{in}} - E_{\text{out}}) = \Delta E_{\text{in}} - \Delta E_{\text{out}}$$

Exercise: what is the RF for our model?

The background of the slide features a composite image. On the left, a portion of a globe is visible, showing latitude and longitude lines. On the right, there is a photograph of a city street, likely London, with a rainbow arching over the buildings. The text is overlaid on this background.

Positive RF corresponds to change that warms the climate.

→ RF is a measure of how much a perturbation of the climate system will change the climate.



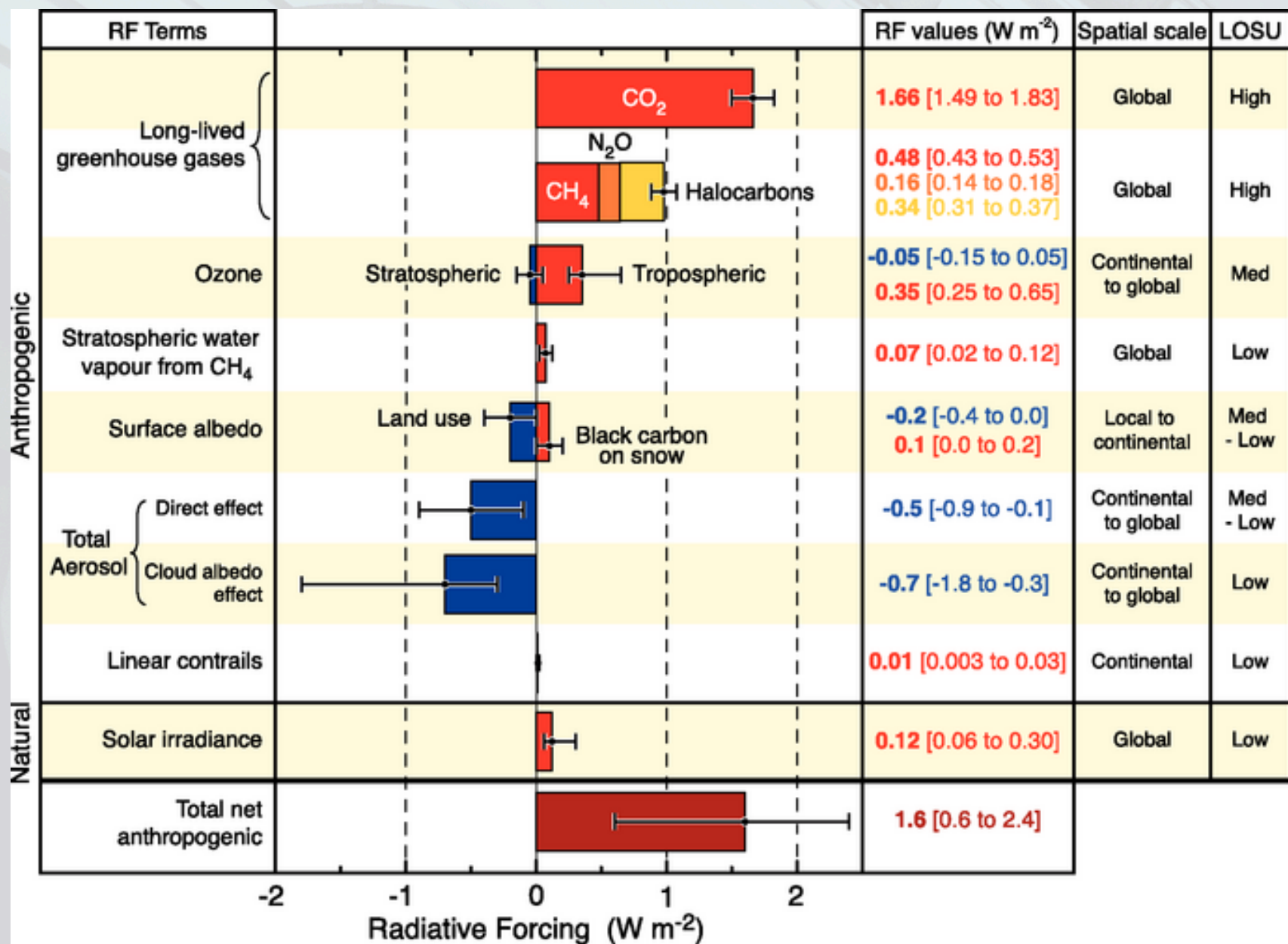
What does this have to do with adding greenhouse gases to the atmosphere?

→ From a physics point of view adding greenhouse gases is the same as adding (a layer of) an atmosphere.

So this simple model explains quite well what happens when we pump greenhouse gases into the atmosphere.

Anthropogenic Forcings:

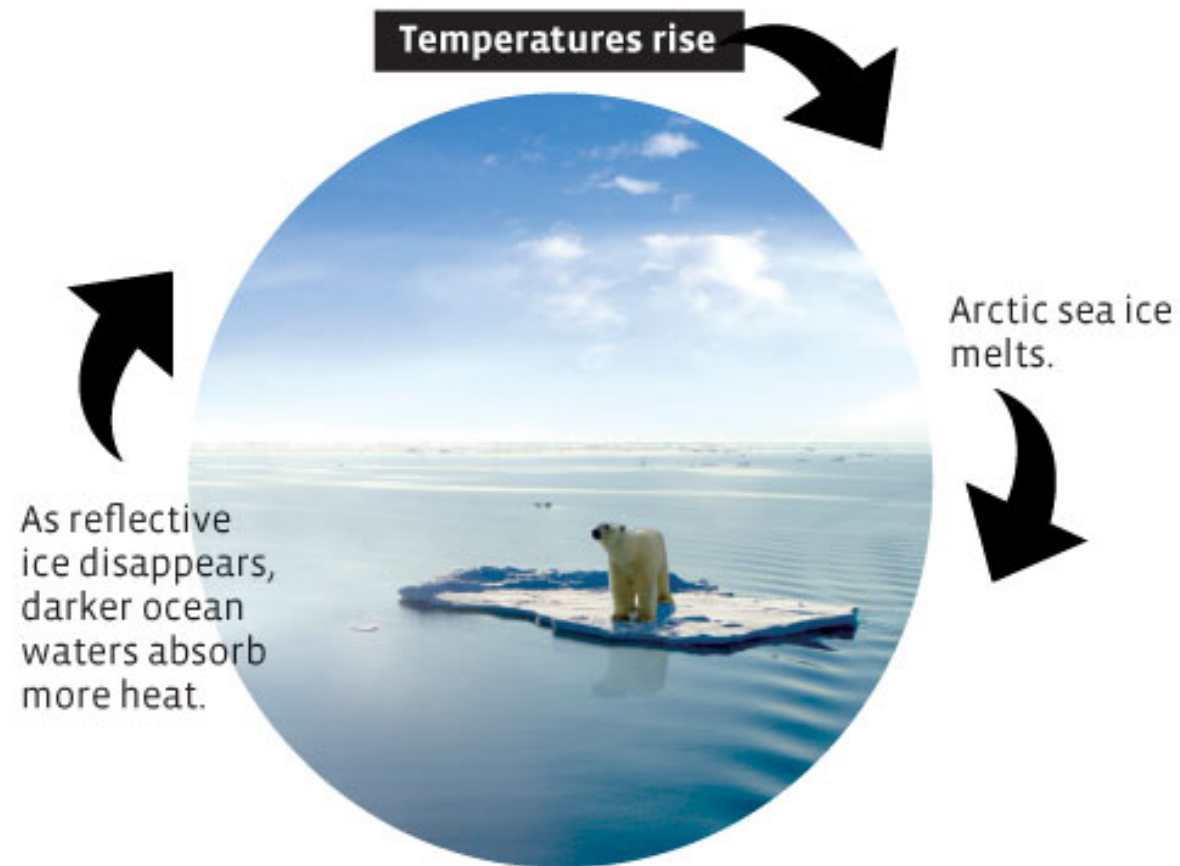
- Greenhouse gases have positive forcing
- Land use change: negative, since deforested land has higher albedo
- Aerosols:
 - Direct: negative, since they reflect sunlight
 - Indirect: negative, since they result in smaller droplets in clouds with higher reflectivity.



©IPCC 2007: WG1-AR4

5. Feedbacks

VANISHING ARCTIC ICE





Examples:

- Ice sheets
- Carbon stored in permafrost

6. Climate Sensitivity

Climate sensitivity = the warming that occurs if the carbon dioxide is instantaneously increased from 280 ppm, the pre-industrial value, to 560 ppm, twice the pre-industrial value, and one then lets the climate reach a new equilibrium.

(“response to doubling of CO₂”.)

This may take a century or two!

Calculations are not easy:

Value depends on feedbacks – if there are positive feedbacks, climate sensitivity higher.

AR5 (Summary for Policymakers):

“Equilibrium climate sensitivity is likely in the range 1.5°C to 4.5°C (high confidence), extremely unlikely less than 1°C (high confidence), and very unlikely greater than 6°C (medium confidence).”

7. Defining Climate

- Average weather in a particular place over a particular period, often 30 years.
- The totality of climate system conditions over a particular period (often 30 years), often described with statistics.
- Counterfactual statistical distribution of climate system conditions that would occur over an infinite period for a *given set of initial and boundary conditions*.

Climate Variability

Variation in climate system conditions on any time scale longer than an individual weather event.

For instance, this summer it was hotter London than last summer.

Climate variability can be due to:

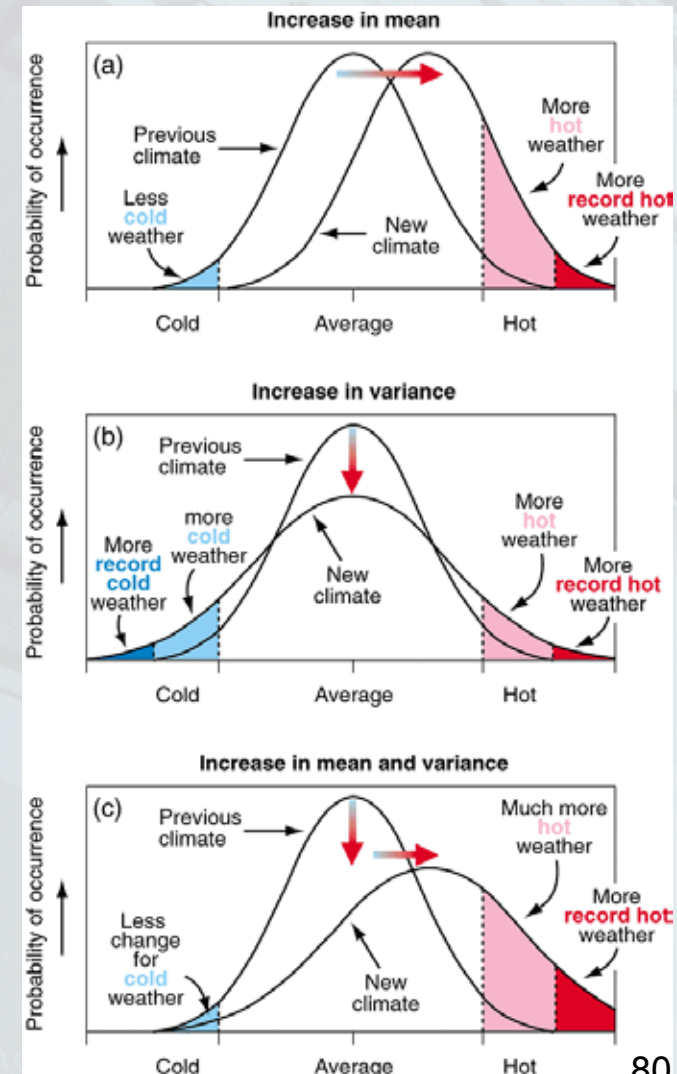
Internal variability: natural processes internal to the climate system.(e.g. El Niño); or.

External forcing: processes “external” to the climate system that perturb its energy balance:

- **natural:** volcanoes, changes in solar output
- **anthropogenic:** increased greenhouse gas or aerosol emissions.

Climate Change

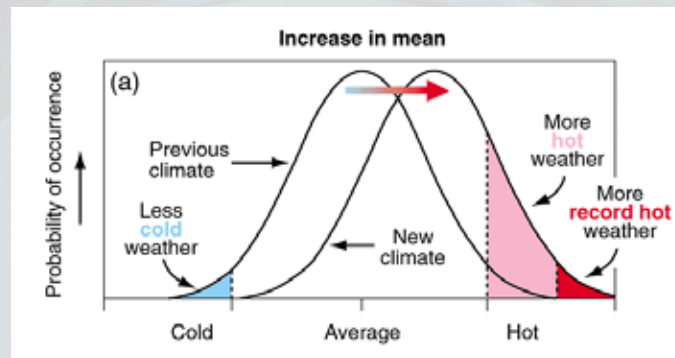
- A change in the statistics of climate system conditions that persists for an extended period of time, usually decades or more.
- can be due to *internal variability* or *external forcing*.



8. Detection and Attribution

Climate Change Detection

The process of demonstrating that climate has changed in some defined statistical sense, without giving a reason for that change.



Caveat: Often detection is understood as the process of demonstrating that observed variability is unlikely to be due to internal variability.

AR4: “An identified change is ‘detected’ in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small.”

Climate Change Attribution

The process of identifying the most likely causes of a detected climate change, with some specified level of confidence.

AR4: “Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.”

AR4: This involves demonstrating that a detected change is:

- consistent with the estimated responses to a particular combination of anthropogenic and natural external forcing, and
- not consistent with alternative, physically plausible explanations that exclude important elements of that combination of forcings.

Further reading:

Sellers, William D: A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System. *Journal of Applied Meteorology* 8, 1969, 392-400.

North, Gerald R., Robert F. Cahalan, James A. Coakley: Energy Balance Climate Models. *Reviews of Geophysics and Space Physics* 19(1), 1981, 91-121.

