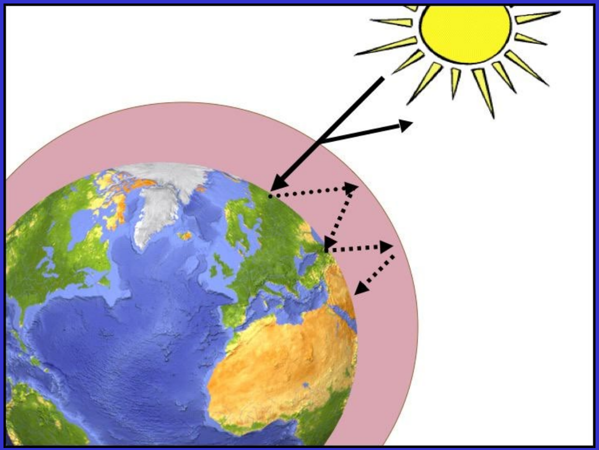
Thursday, January 28, 2021

Quick Summary of last week (Earth's surface temperature)

Atmospheric composition (p 43-46)



Temperature and pressure (p 46-47)

Molecular motion and IR (p 48-49)

An improved calculation of Earth's surface temperature (p 45)

Earth's energy budget (breakout session and intro to Asynchronous material)

For next time - But the Earth isn't flat! How do we know? Because we note differential heating which gives rise to circulation.

Announcements

Sign up for LA sessions

- I will post a rubric describing points and grades, 5% added to total grade based on LA attendance and ~6 points added to exam score based on attendance at LA sessions prior to each exam.

- Homework 1 due Thursday, February 4 (Upload files to Canvas for grading).

- Please upload whatever work you have by 8 pm, even if you are unsure, and you will receive partial to full credit.

- See my Canvas announcement describing asynchronous content.

Quick summary of last time
(see pages 36-44)

Light comes in all wavelengths, from quite long to quite short.

Wavelength is inversely proportional to frequency.

Energy is proportional to frequency – the larger the frequency (the shorter the wavelength) the higher the energy

Objects emit electromagnetic radiation ("light") depending on their temperature. The higher the temperature, the greater the amount of total radiation emitted, and the shorter the wavelength of 'peak' radiation (or "color" the object will appear)

Learning Goals for this week

What it means to be a "greenhouse gas", and why some compounds like H_2O and CO_2 are better infrared absorbers than others (like N_2 and O_2)

That Earth's temperature varies with altitude ("height") and that has important implications for energy balance

That greenhouse gases trap thermal emission from the surface, reradiating some of that back to the surface, thereby warming the surface (the "greenhouse effect")

That Earth's energy balance has many terms, and changing any one of them will cause the others to respond eventually establishing a new balance

Because the Earth isn't flat, energy is transported from the equator to the pole by circulation of water and air ("weather")

Let’s look at where we are so far.
(see pages 36-39, 40-43)

The Sun, which is at 5600 K, emits light primarily in the visible and near infrared (IR) region of the spectrum (“near” means that the IR radiation has a wavelength that is close to visible light, but not within the range of visible for the human eye)

Earth, which is at about 250-300 K emits light primarily in the middle of the infrared…around 10 micrometers in wavelength. It isn’t visible to the human eye, but we can feel it as ‘heat’ because that IR radiation is absorbed by objects, including our skin

We can estimate an average temperature for Earth by equating the incoming absorbed solar radiation with the outgoing thermal (IR) radiation.

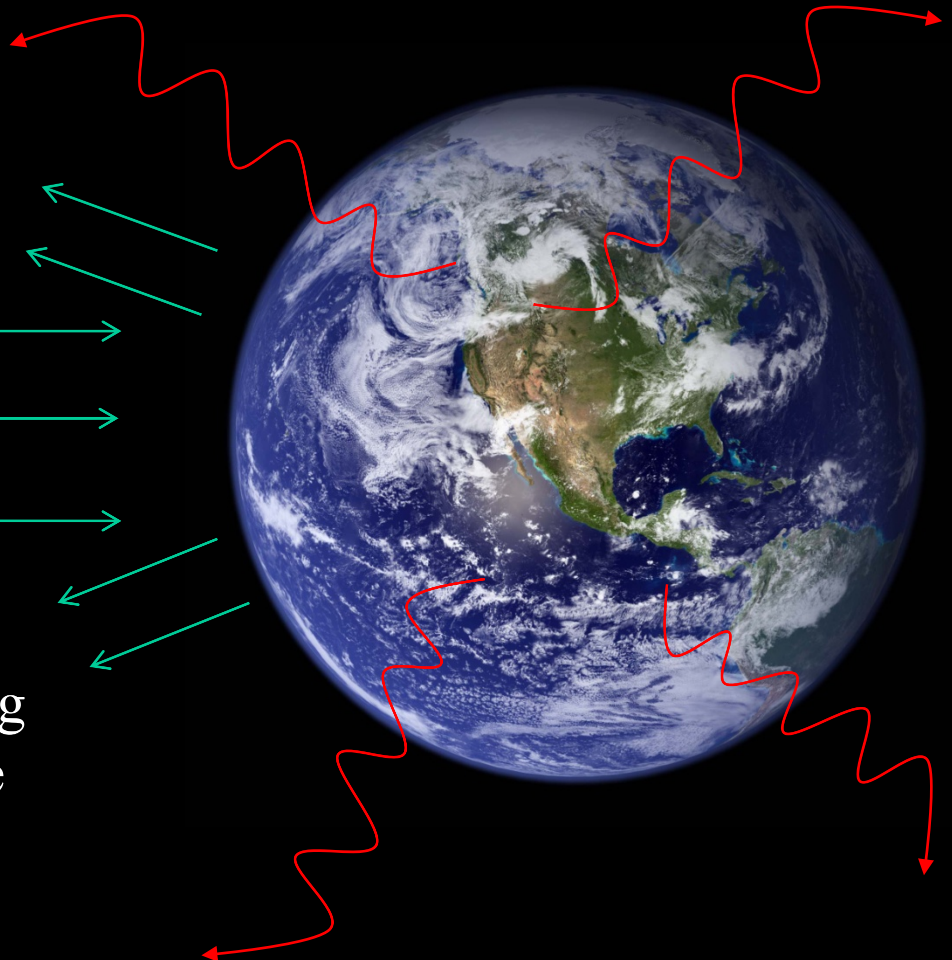
If we set incoming equal to outgoing, and solve for T, we obtain the effective radiating temperature (next slide)

Outgoing = middle and far IR

$$\sigma T^4 \text{ x } (4\pi R^2)$$

Incoming = solar visible and near IR

$$S \text{ x } (\pi R^2) \text{ x } (1 - A)$$



A = fraction of incoming light reflected to Space

Putting in numbers for Earth

$S = 1370\ W/m^2$ (watts per square meter)

$A = 0.30$ (30% of the suns incident radiation is reflected back to space)

σ (a constant) $= 5.67 \times 10^{-8}\ W/(m^2\ K^4)$

$$T = [1370\ W/m^2 \times (1 - 0.3) / (4 \times 5.67 \times 10^{-8}\ W/(m^2\ K^4))\ ]^{1/4}$$

$$= [1370 \times (0.7) / (22.68 \times 10^{-8}\ K^4)\ ]^{1/4}$$

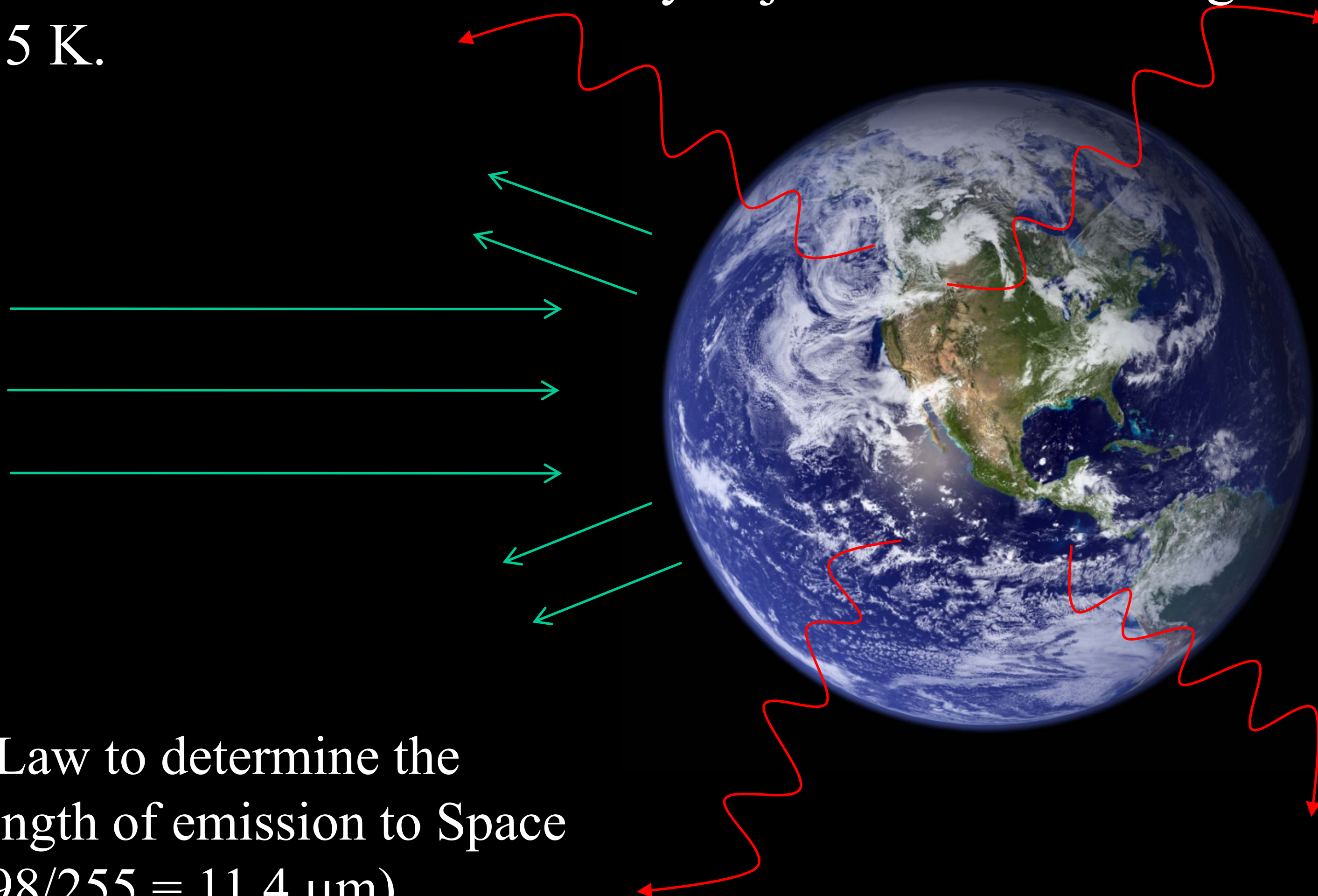
$$= [\ 959\ K^4 / (22.68 \times 10^{-8})\ ]^{1/4}$$

$$= [42.28\ x10^{8}\ K^4]^{1/4}$$

$$= 255\ K$$

(Homework 1 has a similar calculation for different values of S and A)

Summary - When we look at Earth from space, it appears as an object that has reflected 30% of the incident (visible) solar radiation back to space (e.g., the colors we can see in photos) and that acts like a blackbody object that is radiating at T = 255 K.



Use Wien's Law to determine the peak wavelength of emission to Space (answer: 2898/255 = 11.4 μm)

Clicker Question 1
So what have we missed?

We know that Earth's global mean surface temperature is warmer than –18 ^{o}C. What do you suppose the primary reason is for this?

(a) The Sun is much brighter than we think.

(b) The Earth is much darker than we think, thereby absorbing more solar radiation.

(c) Earth has an atmosphere that traps heat before it escapes back to the atmosphere, radiating that heat back toward the surface.

(d) There is a missing energy source that heats the Earth from within.

If we look at Earth's atmosphere, we see that temperature is not uniform. The surface is warmest, as we'd expect, but it is much warmer than the 255 K we calculated. The average temperature of the atmosphere (vertical yellow line) is close to 255 K, but note that the temperature varies from ~290 K to < 200 K.

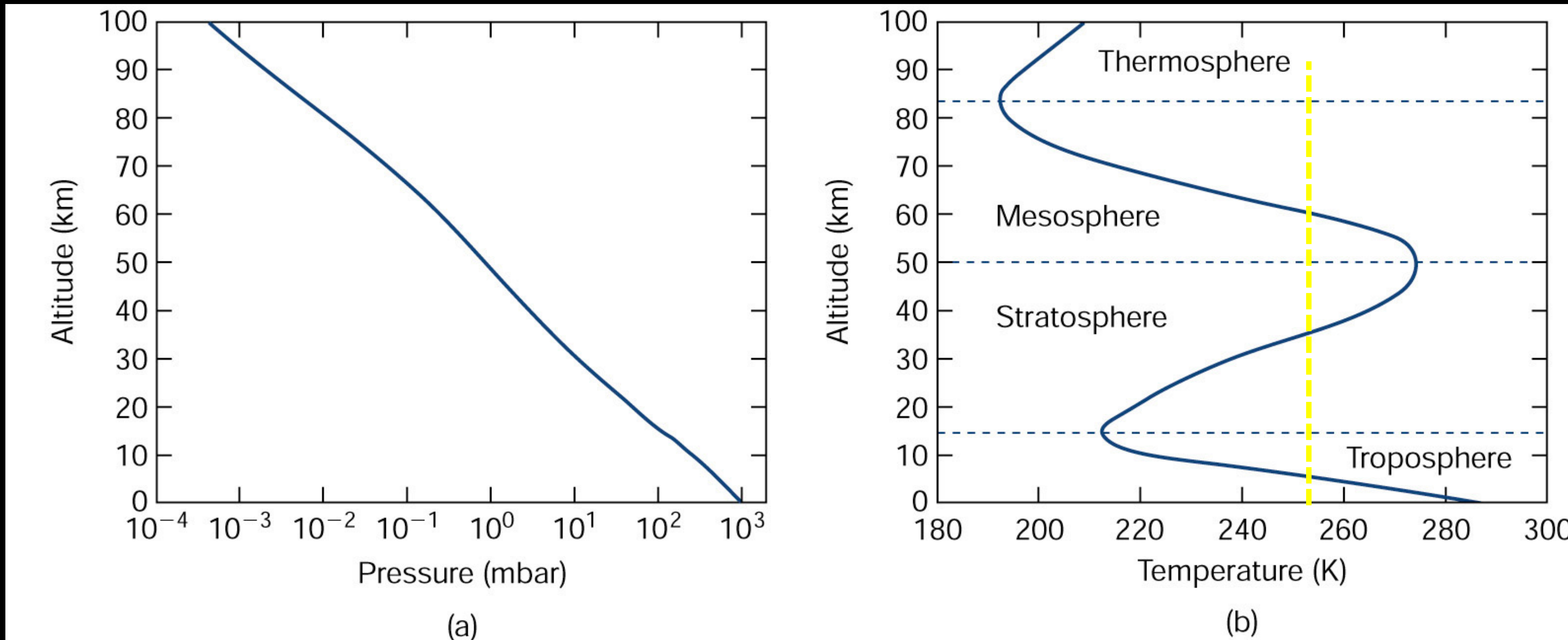


Fig. 3.9

To understand this temperature variation, we need to look at the effects of the atmosphere. Some gases will trap heat, some will condense and form precipitation, and the atmosphere as a whole can move (weather). This is redistribute heat from the surface. Some gases, like ozone (O_3) will actually absorb light from the sun (ultraviolet), thus heating the upper atmosphere.

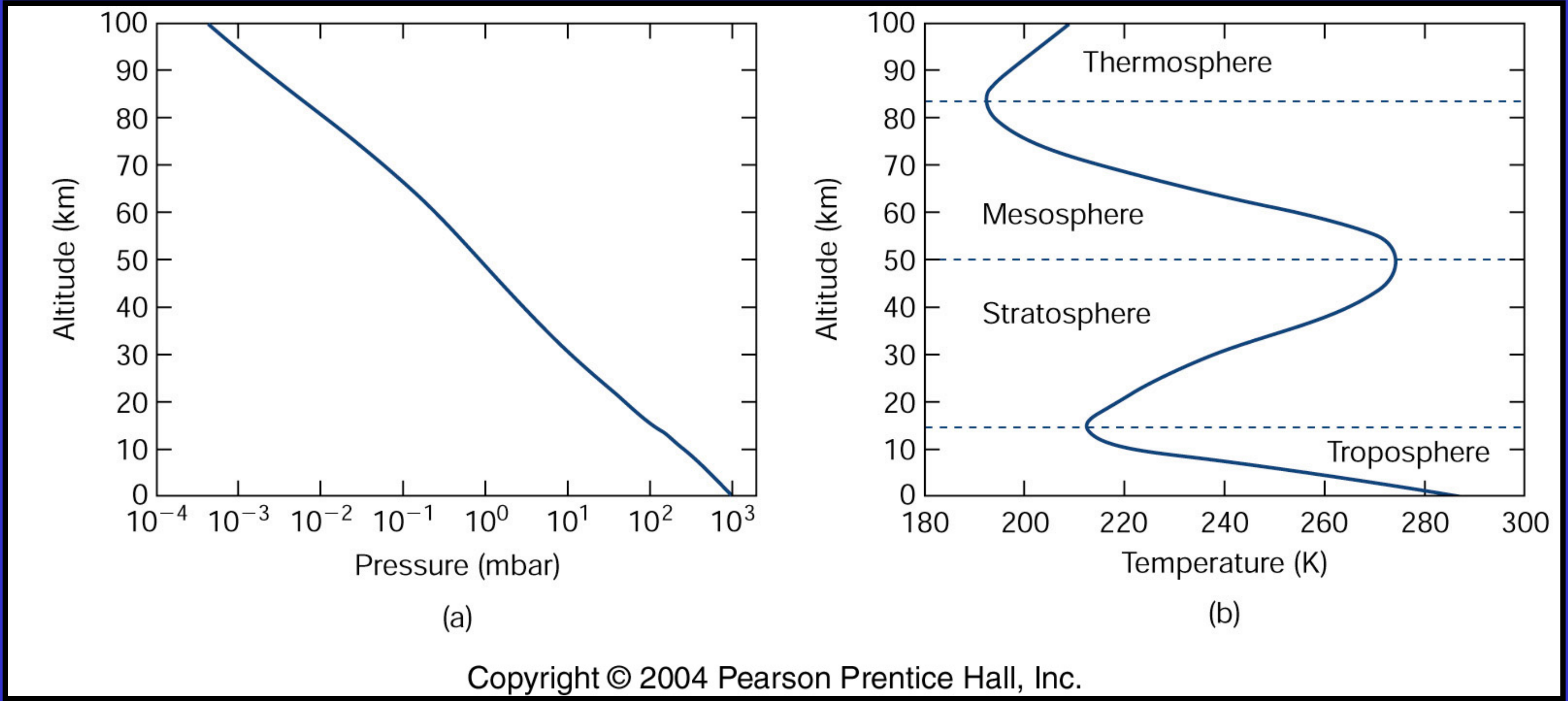


Fig. 3.9

Temperature falls off with altitude in the lower 10 km of the atmosphere. At the surface, the temperature is about 285 K, whereas at 10 km it is about 215 K. This is a drop of 7 degrees K per km (or 7 degrees C per km, since a change of 1 degree K is the same as a change of 1 degree C).

However, a 70 degree K (or C) change in temperature is a change of 126 degrees F, since a 1 degree K (or C) change is the same as a 1.8 degree F change.

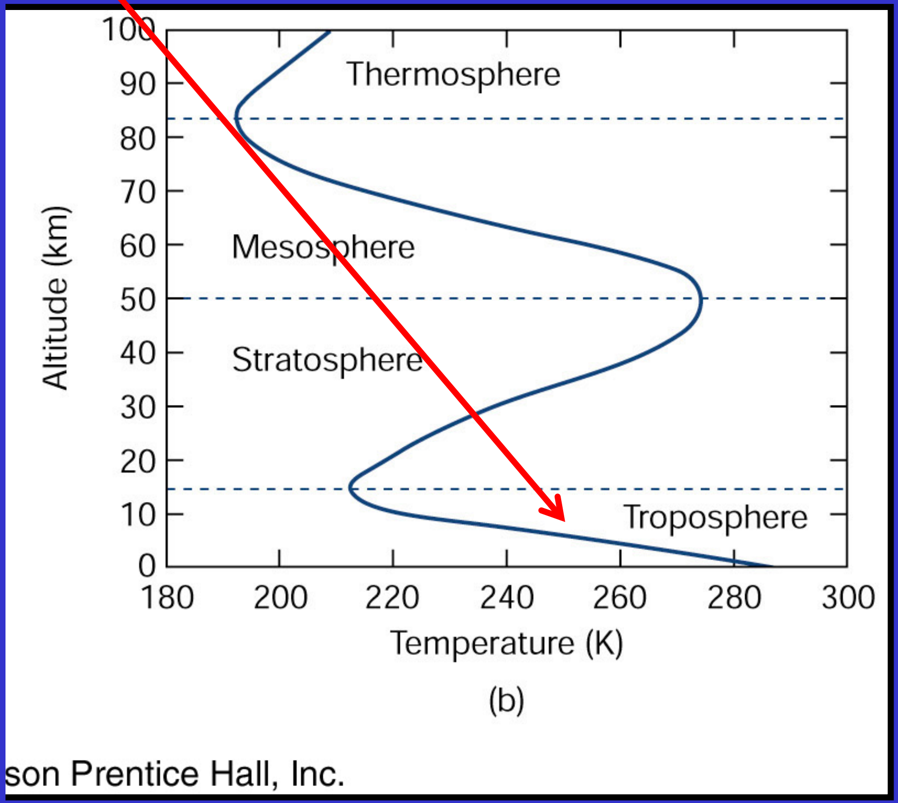
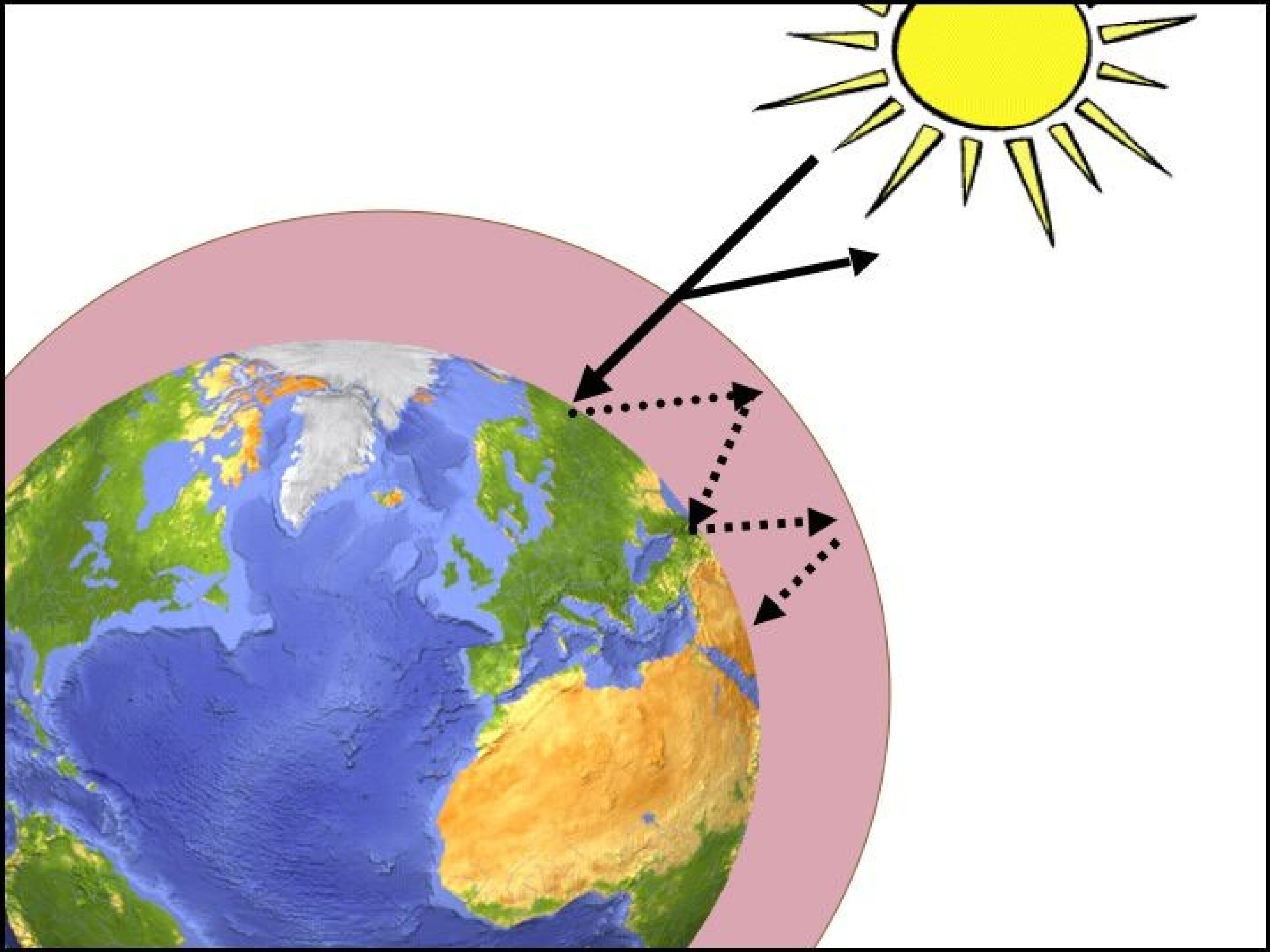


Fig. 3.9

We know Earth's mean temperature is around 290 K

What have we missed?

We have left out the atmosphere – the emperor does have clothes!



Why does an atmosphere matter?

It insulates the surface from the extreme cold of Space!

Do we have to toss out our model (all that hard work from last time)?

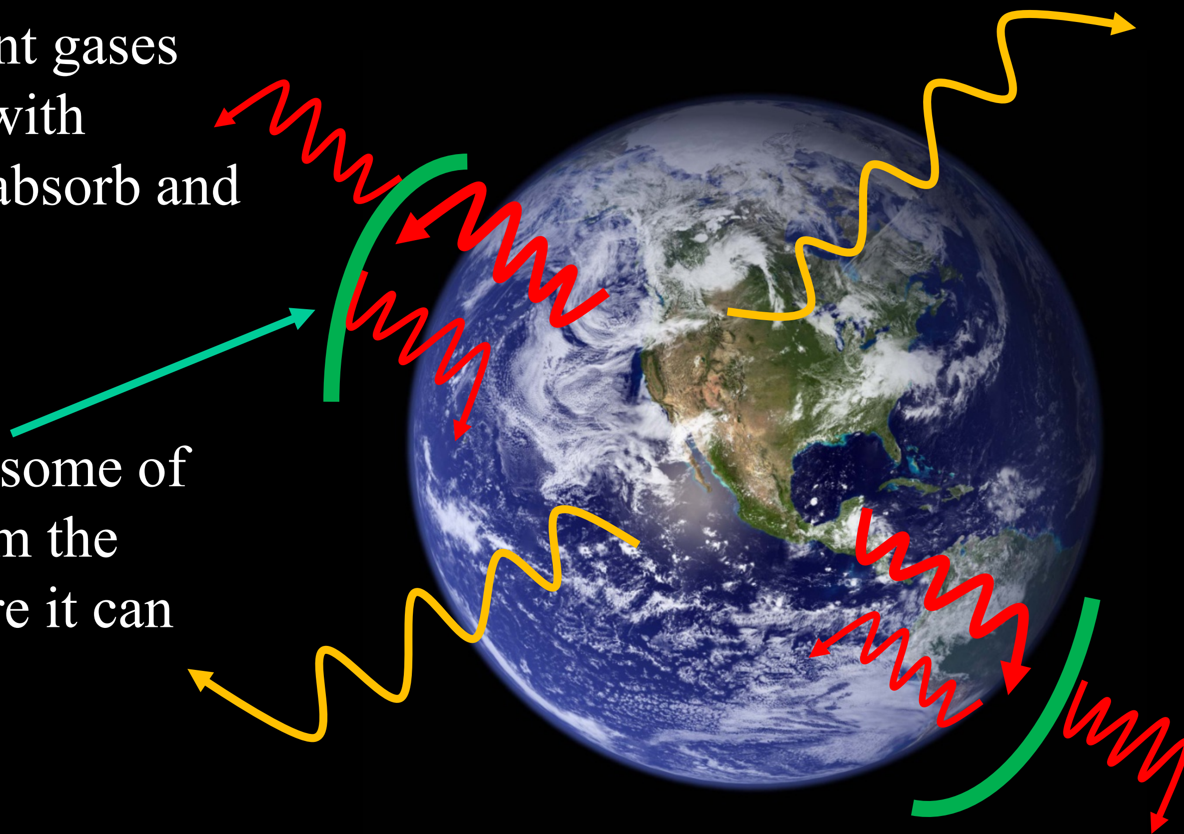
We need to improve our model!

We just need to realize that Earth doesn't have a single temperature

Most importantly, temperature varies with altitude

Infrared Trapping (the "Greenhouse Effect") will warm the surface

Let's look at the important gases that make them interact with infrared radiation – that absorb and reemit that radiation.



H_2O, CO_2, and CH_4 trap some of the thermal radiation from the surface of the earth before it can escape to space

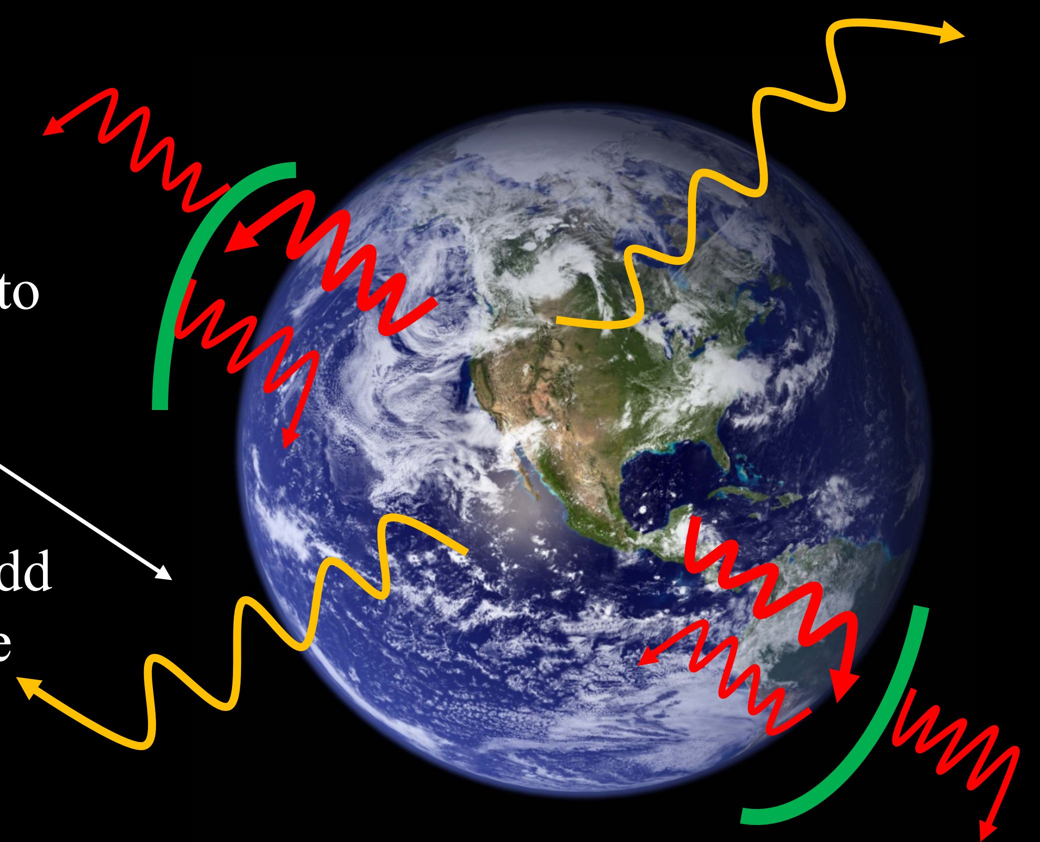
We need to improve our model!

We just need to realize that Earth doesn't have a single temperature

Most importantly, temperature varies with altitude

Infrared Trapping (the "Greenhouse Effect") will warm the surface

But some wavelengths of light aren't trapped – they still escape to Space through atmospheric "windows." This is what keeps the surface from over-heating (like Venus). But as we add more gases to the atmosphere, we increase the trapping



The Greenhouse Effect

Selective absorption by the atmosphere

Greenhouse gases are special – they are transparent to visible light, but they strongly absorb infrared light. This increases the total amount of light (or energy) that hits the surface, because the atmosphere intercepts some of the energy that is radiated by the surface and reradiates half of it back downward to Earth's surface

The other half of the energy absorbed by greenhouse gases is radiated upward toward space

Let's look at these gases first – H_2O, CO_2, and CH_4 – and then we will modify our energy balance model to determine the surface temperature in the presence of a greenhouse effect

Atmospheric Composition
The Main Constituents in Earth's atmosphere

TABLE 3-2

Major Constituents of Earth's Atmosphere Today

Name and Chemical Symbol	***Concentration (% by volume)***
Nitrogen, N_2	78
Oxygen, O_2	21
Argon, Ar	0.9
Water vapor, H_2O	0.00001 (South Pole)–4 (tropics)
Carbon dioxide, CO_2	0.037*

*In 2002

Note – CO_2 is now over 400 parts per million (400/1,000,000)

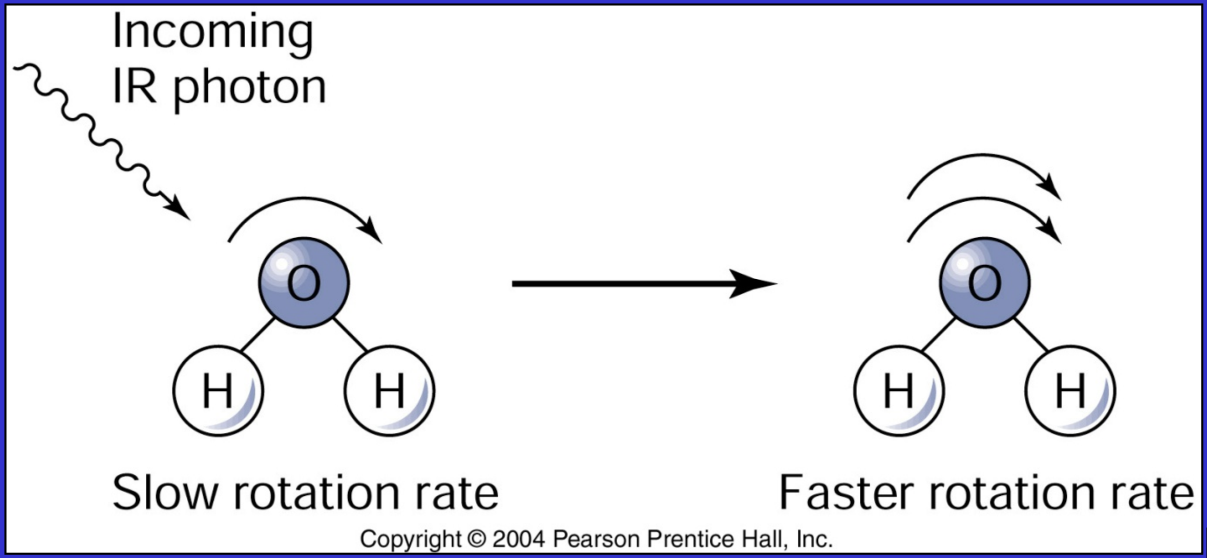
Atmospheric Composition
The Greenhouse Gases

TABLE 3-3

Important Atmospheric Greenhouse Gases

Name and Chemical Symbol	***Concentration (ppm by volume)***
Water vapor, H_2O	0.1 (South Pole)–40,000 (tropics)
Carbon dioxide, CO_2	370
Methane, CH_4	1.7
Nitrous oxide, N_2O	0.3
Ozone, O_3	0.01 (at the surface)
Freon-11, CCl_3F	0.00026
Freon-12, CCl_2F_2	0.00054

How do "greenhouse" gases interact with infrared light



By absorbing infrared light, molecules can change their states – meaning that they can shake, rattle and roll (vibrate, rotate, bend) faster. By emitting IR light, they slow down. Different molecules absorb and emit IR radiation at different frequencies depending on their atoms and bonds.

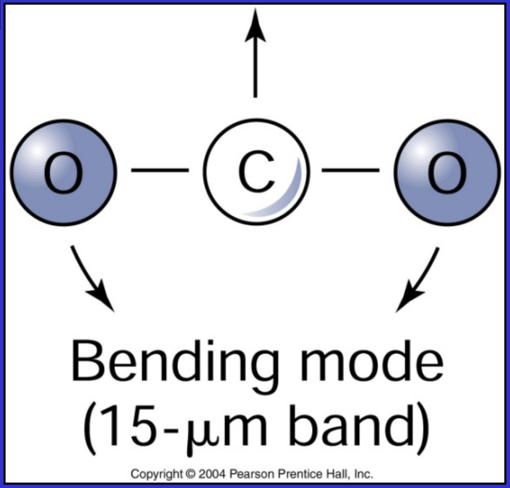


Fig. 3.12

Looking in detail at how infrared light is affected by atmospheric molecules. Note that the most important 'absorbers' (i.e., greenhouse gases) in the atmosphere are H_2O (naturally occuring gas) and CO_2 (natural and man-made sources). Detailed studies show that H_2O provides most of the thermal warming of the planet, followed by CO_2. Note that ozone (O_3) is also a greenhouse gas, but not a major one.

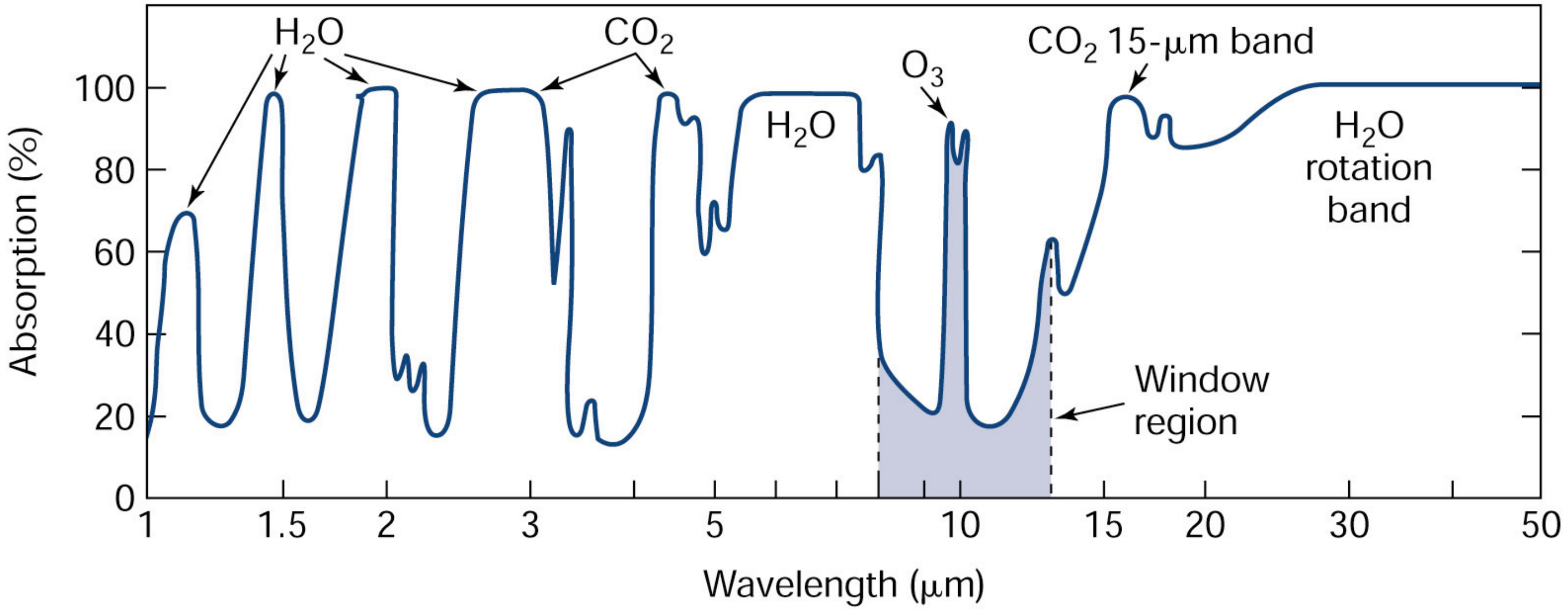
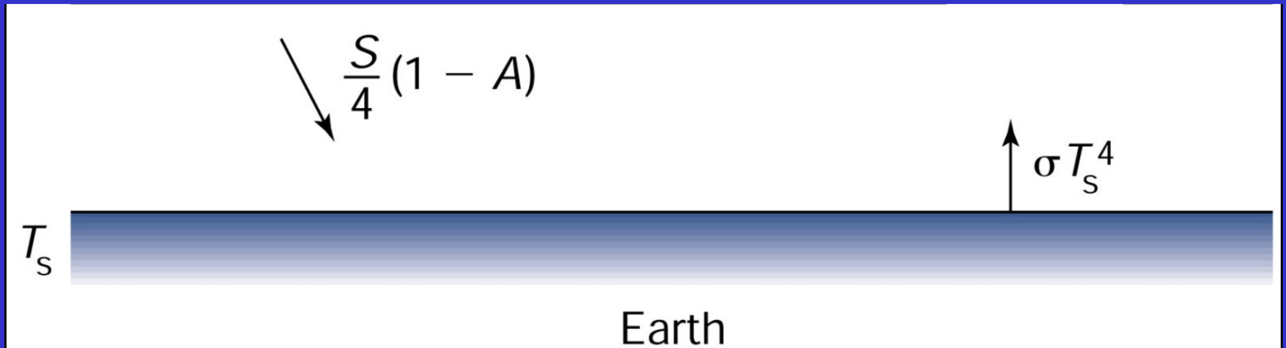


Fig. 3.13

Why does a ‘layer’ of gas above the surface make the surface warmer? Treat the layer of infrared-active gas as a ‘blackbody’, so that we can use the simple equation that relates the emission (or ‘flux’) to the temperature of the layer

Let’s return to our with surface balance with no atmosphere:

$$S/4\,(1 - A) = \sigma T_s^4$$

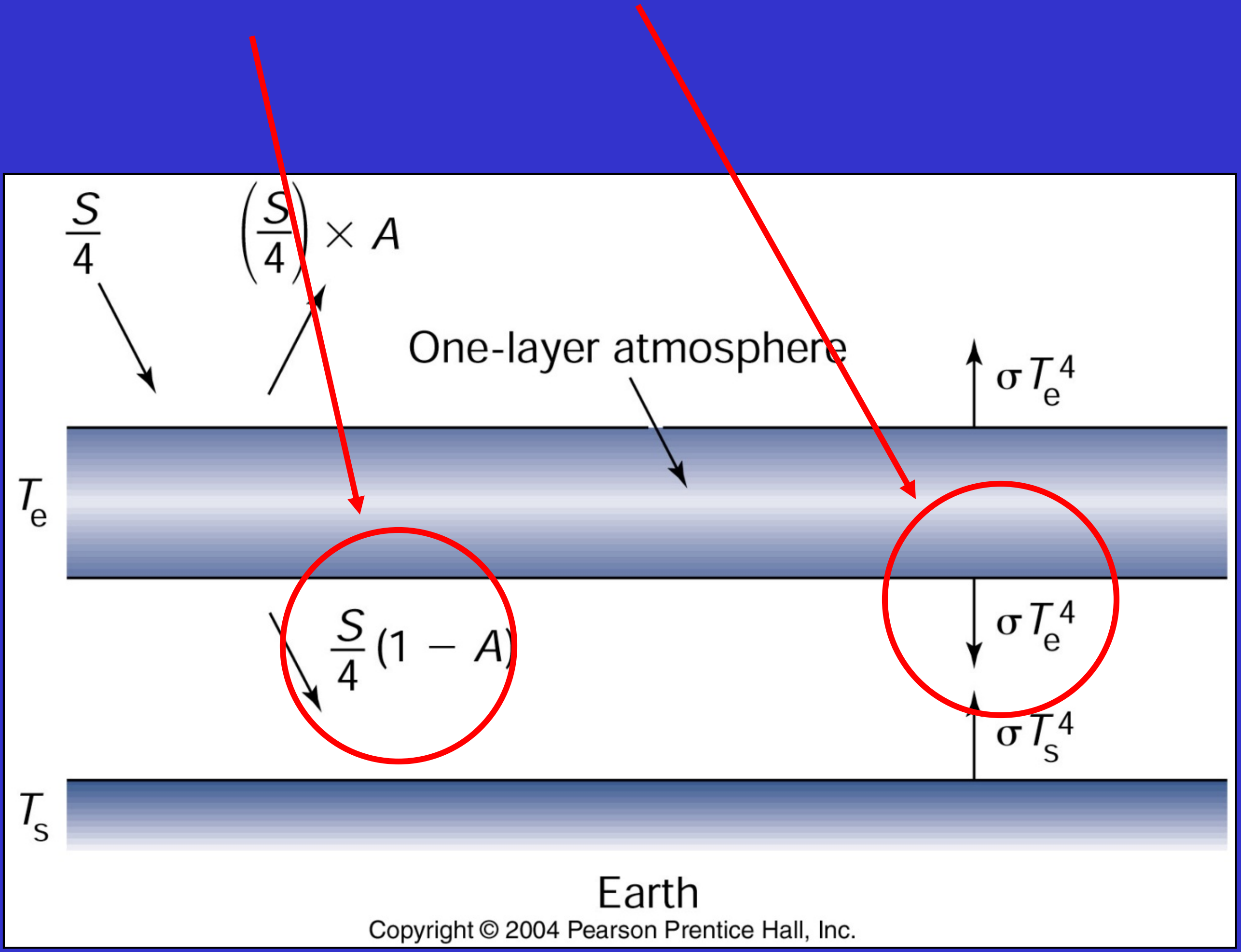


Box Fig. 3.2

Add an atmosphere

Incoming to surface:

$$S/4(1 - A) \quad + \quad \sigma T_e^4$$

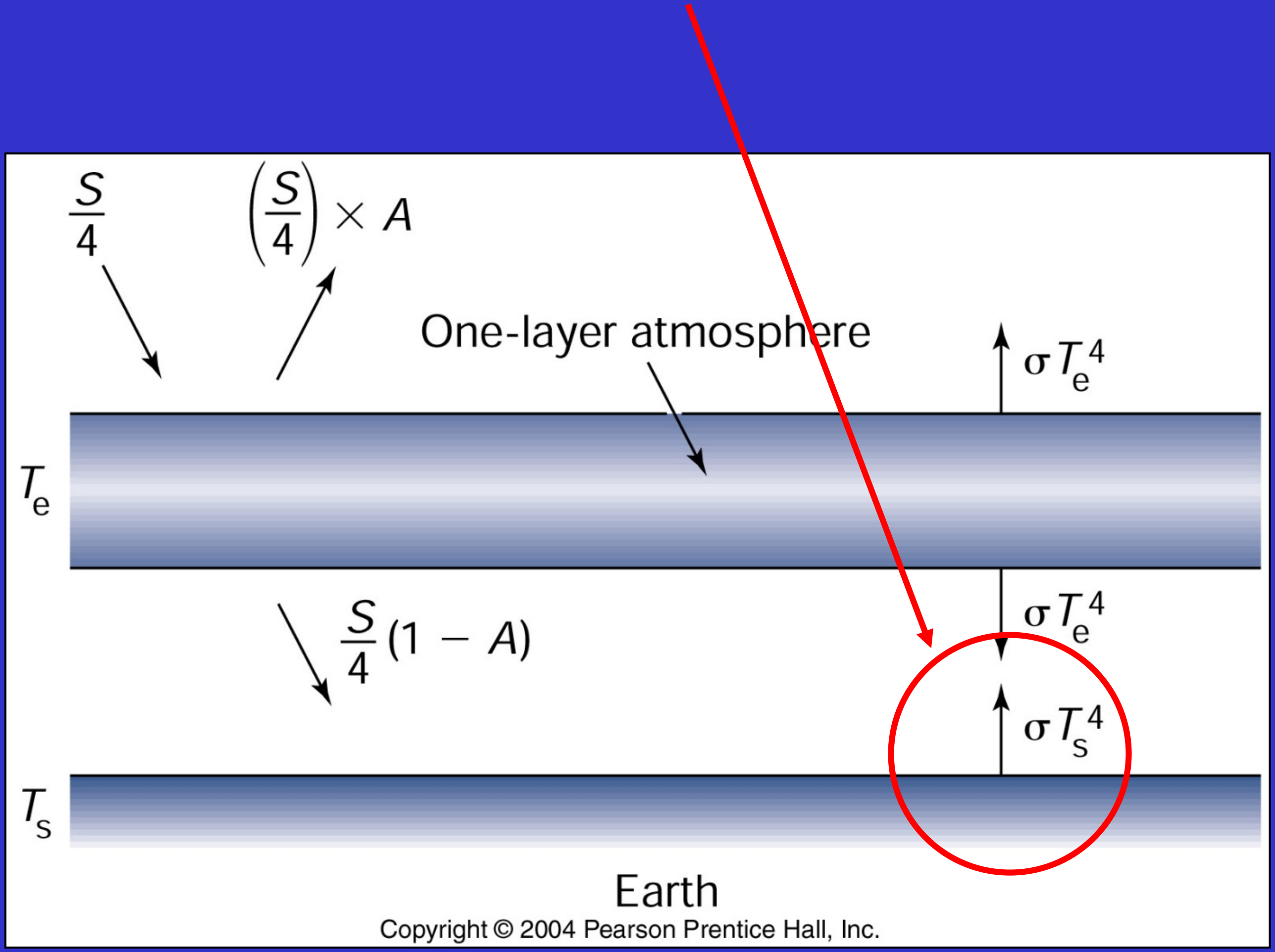


Box Fig. 3.2

Add an atmosphere

Outgoing from surface:

$$\sigma T_s^4$$

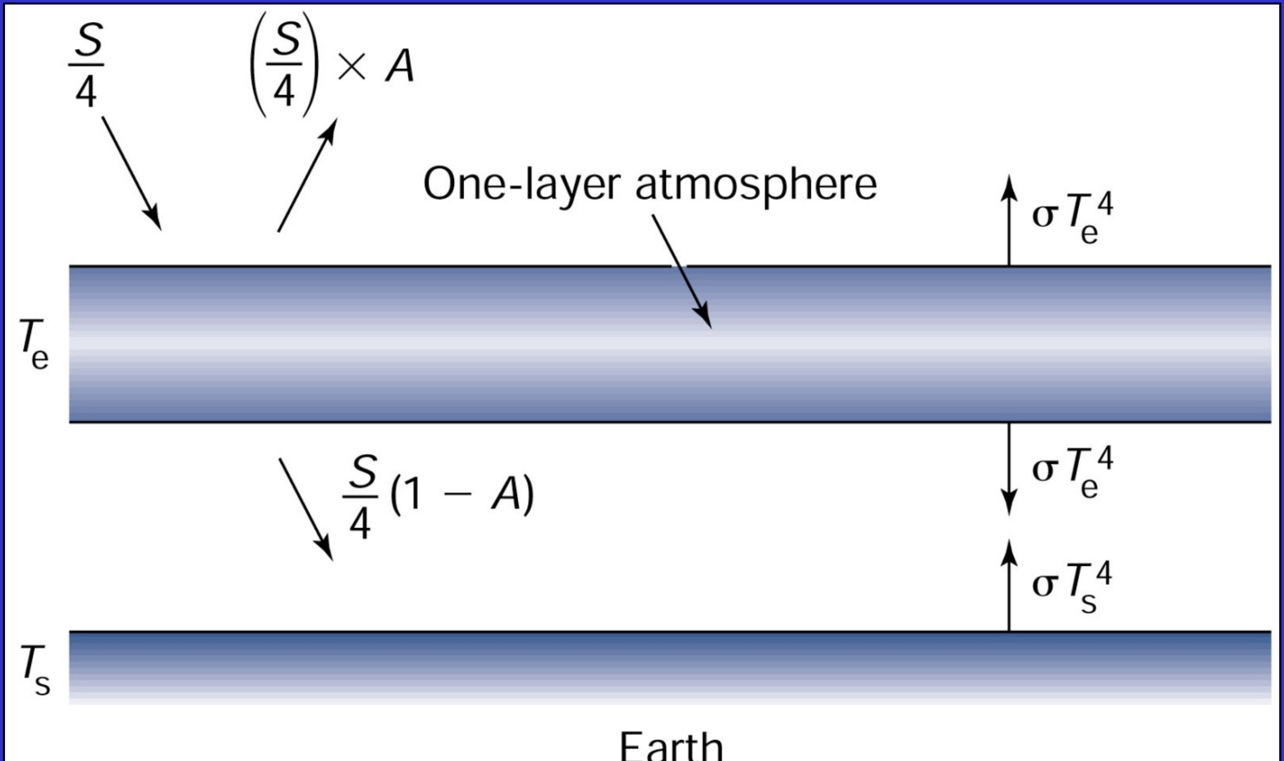


Box Fig. 3.2

New surface balance with atmosphere:

$$\sigma T_s^4 = S/4\,(1 - A) + \sigma T_e^4$$

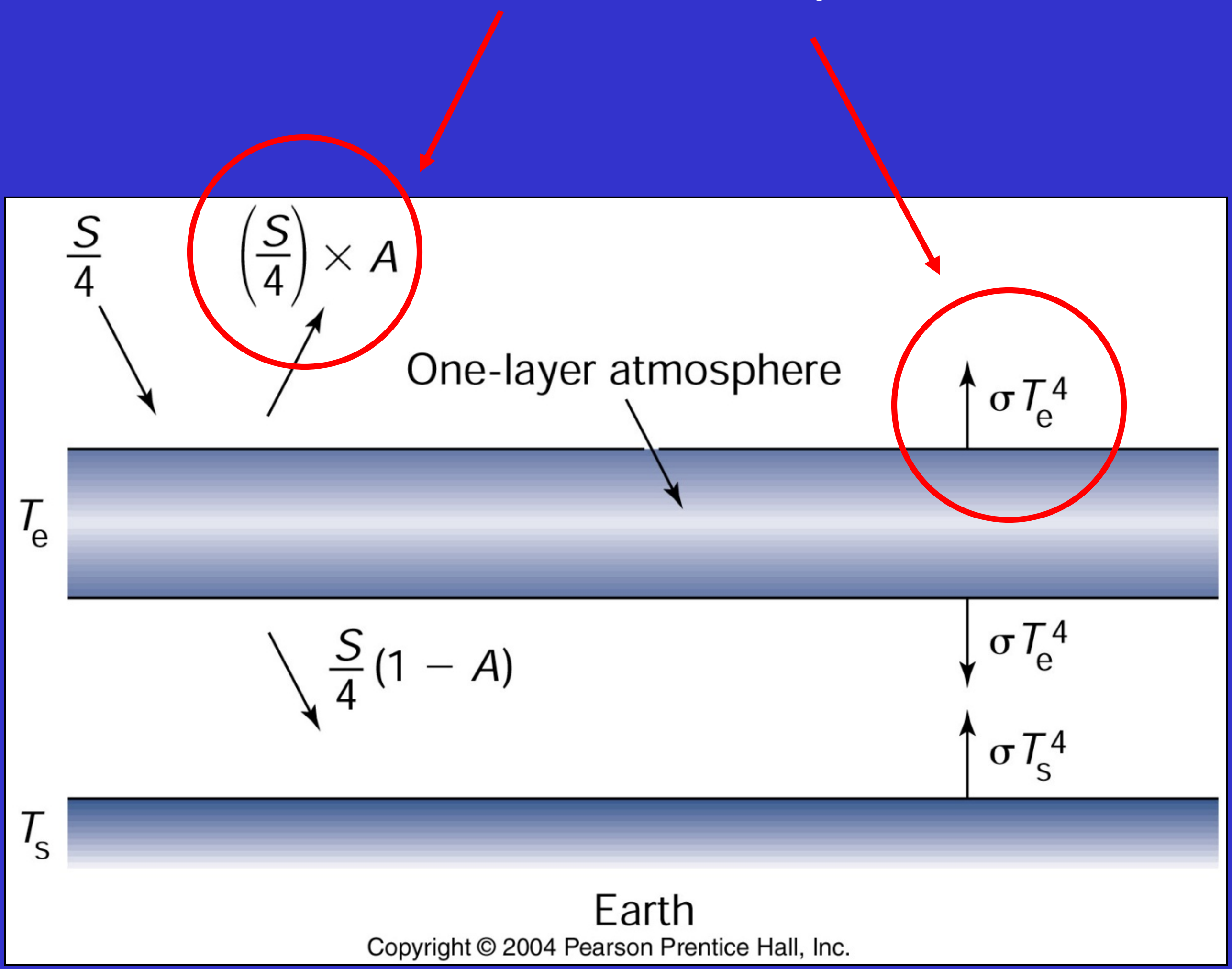
The extra term comes from insulating properties of the atmosphere - we call this the "greenhouse effect"



Box Fig. 3-2

We also know T_e - This is our original "effective radiating temperature"

$$S/4\,(1 - A) = \sigma T_e^4$$



Box Fig. 3-2

Energy transport (or 'budget') in Earth's atmosphere is a bit more complicated than just balancing incoming solar radiation with outgoing infrared. Let's take a look at what happens to "100 units" of incoming solar energy once they strike the earth.

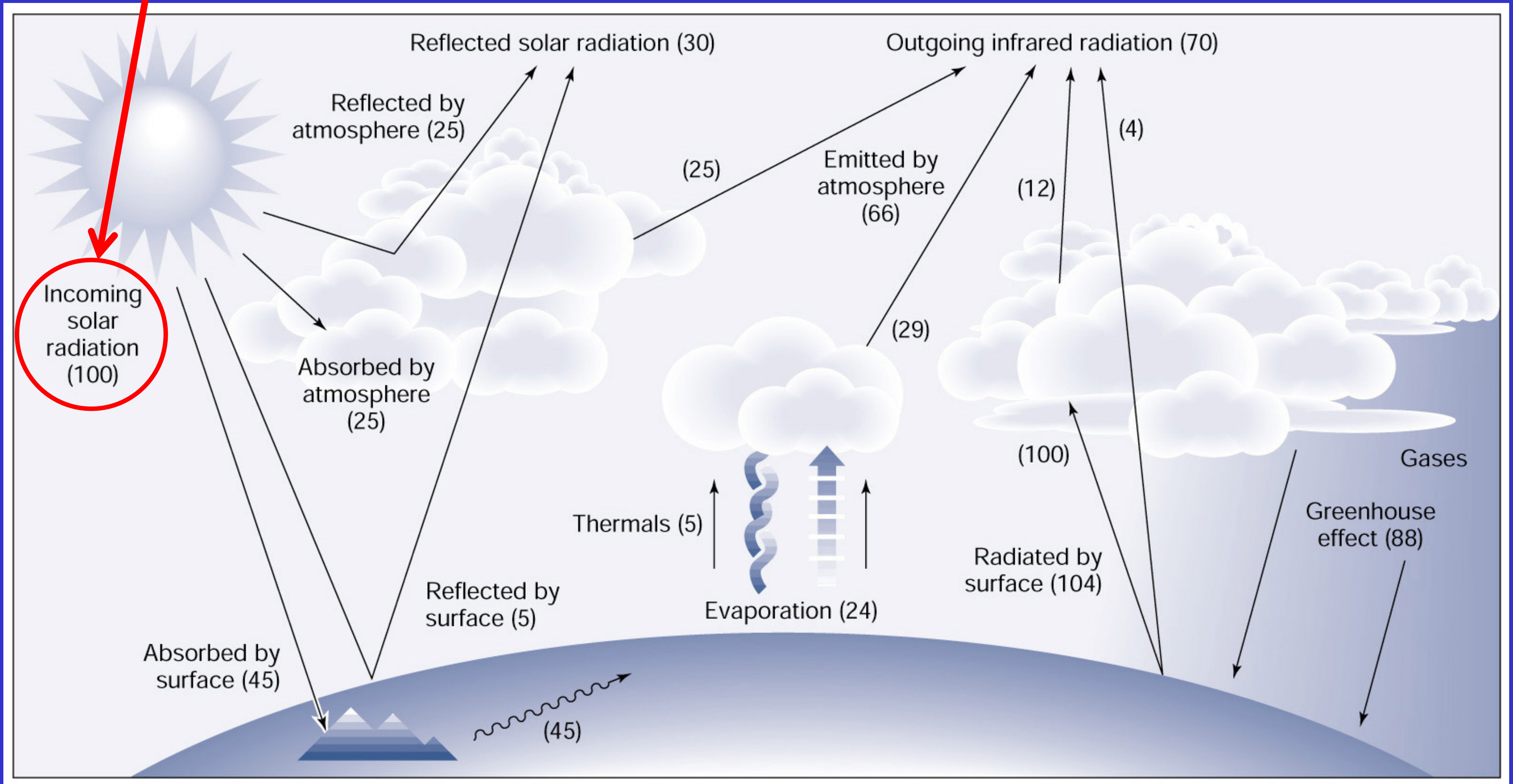


Fig. 3.19

100 units are incident on the Earth, and 30 reflect back to Space.

This means 70 are absorbed by the Earth system.

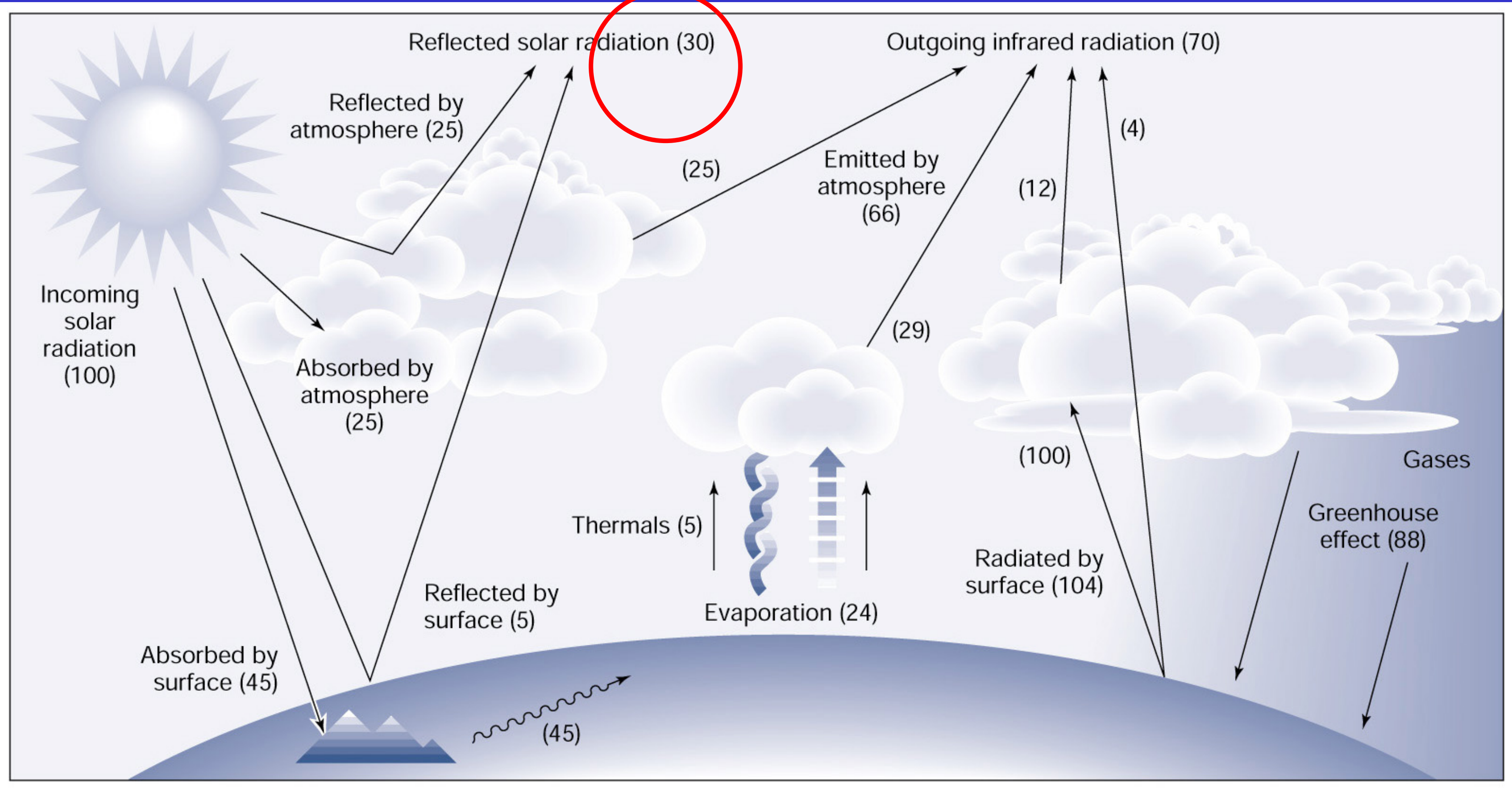


Fig. 3.19

These 70 units must eventually be reemitted back to Space or the Earth would rapidly heat up or cool down. are absorbed by the Earth system.

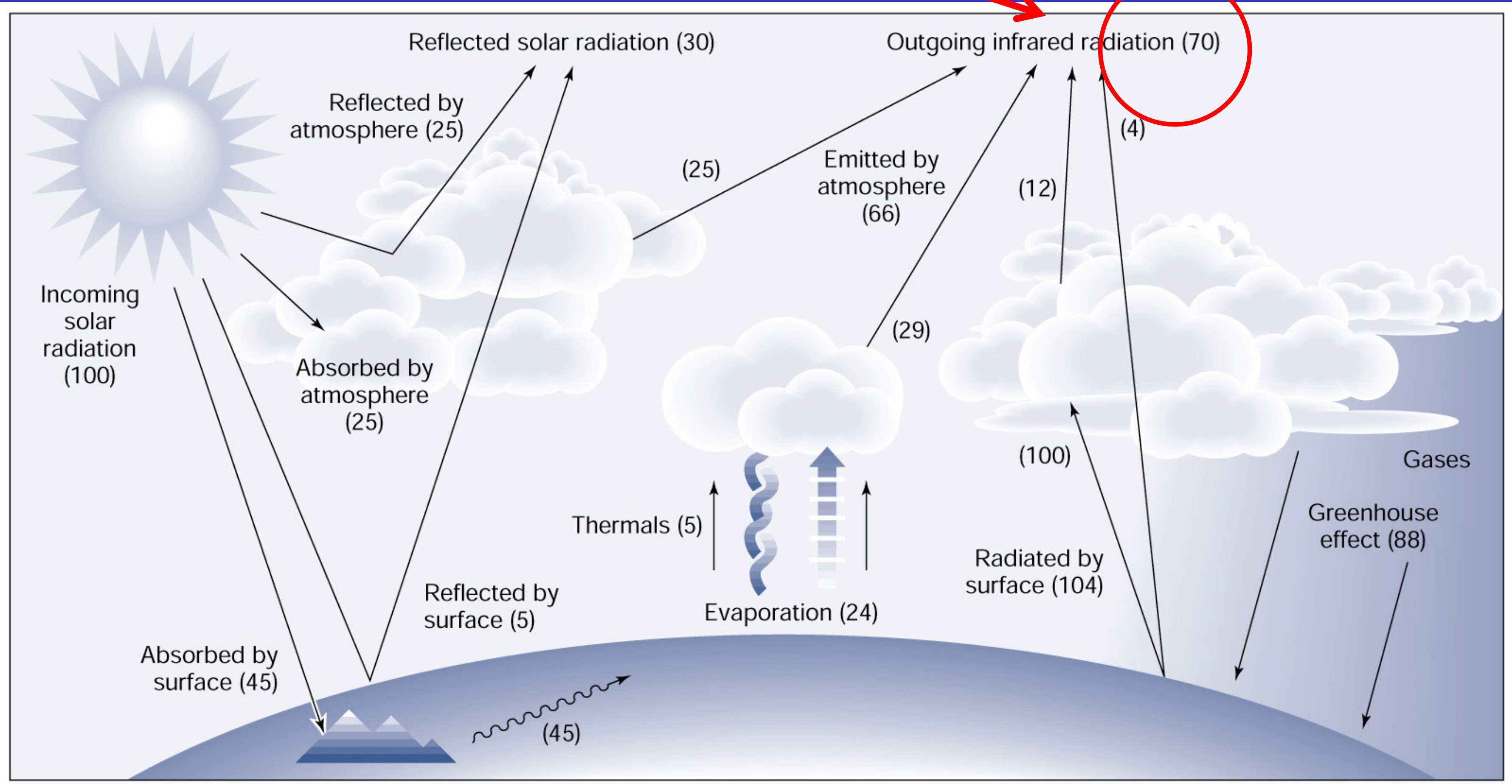


Fig. 3.19

We call this the "top of atmosphere" balance

Net incoming solar radiation = Total outgoing thermal radiation

$$S \times (\pi R^2) \times (1-A) = \sigma T_e^4 \times (4\pi R^2)$$

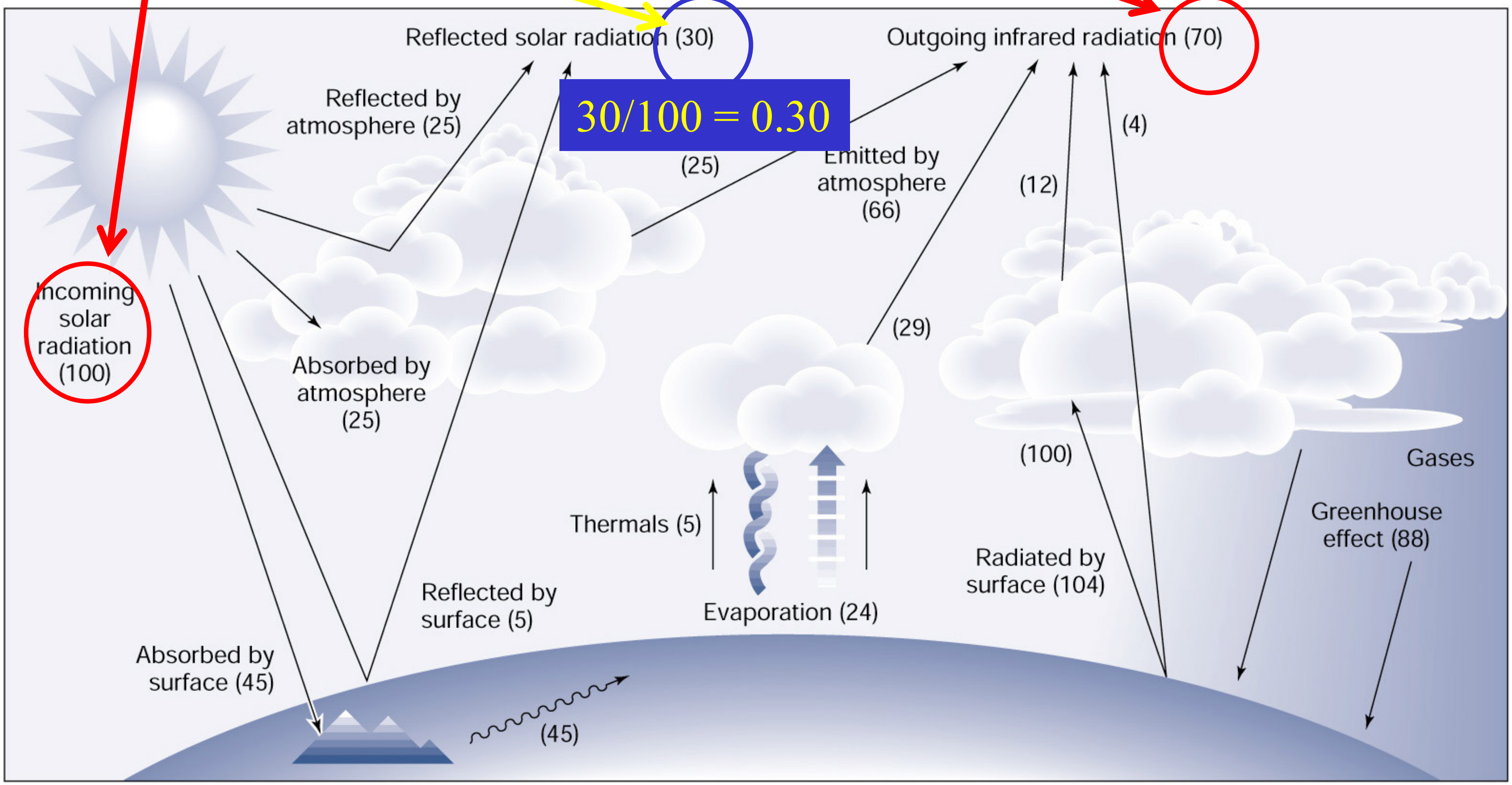


Fig. 3.19

Breakout sessions – Where, more precisely, do the 100 units of solar energy go that are absorbed by the Earth?

__________ reflected by the surface (i.e., ice, deserts)

__________ reflected by clouds and gases

__________ absorbed by surface

__________ absorbed by clouds and gases

__________ Total (must equal 100)

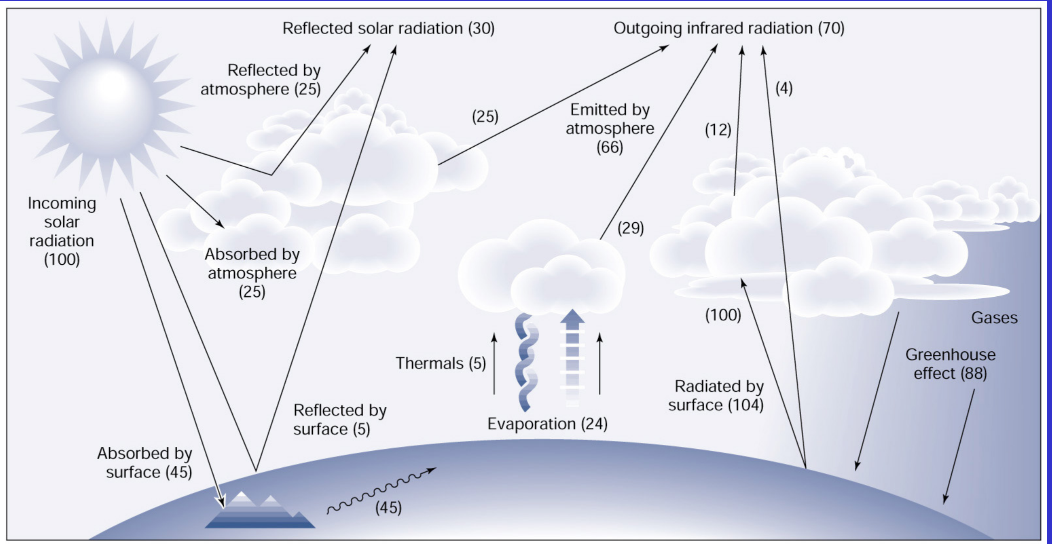
iClicker Question 2
Out of 100 units total incident on Earth, how much is absorbed at Earth's surface?

(a) 5 units

(b) 25 units

(c) 30 units

(d) 45 units



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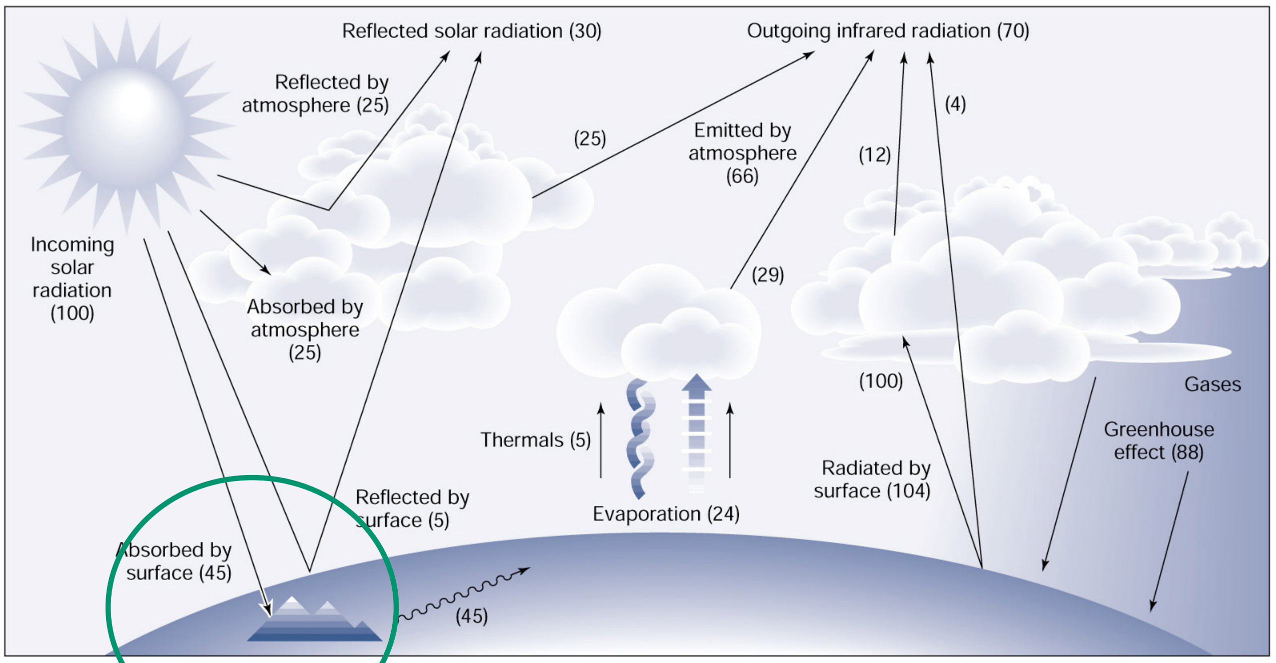

Where does the solar energy go?

100 incident = 45 (absorbed by surface)
25 (absorbed by clouds and gases)
25 (reflected by clouds and gases)
5 (reflected by surface)

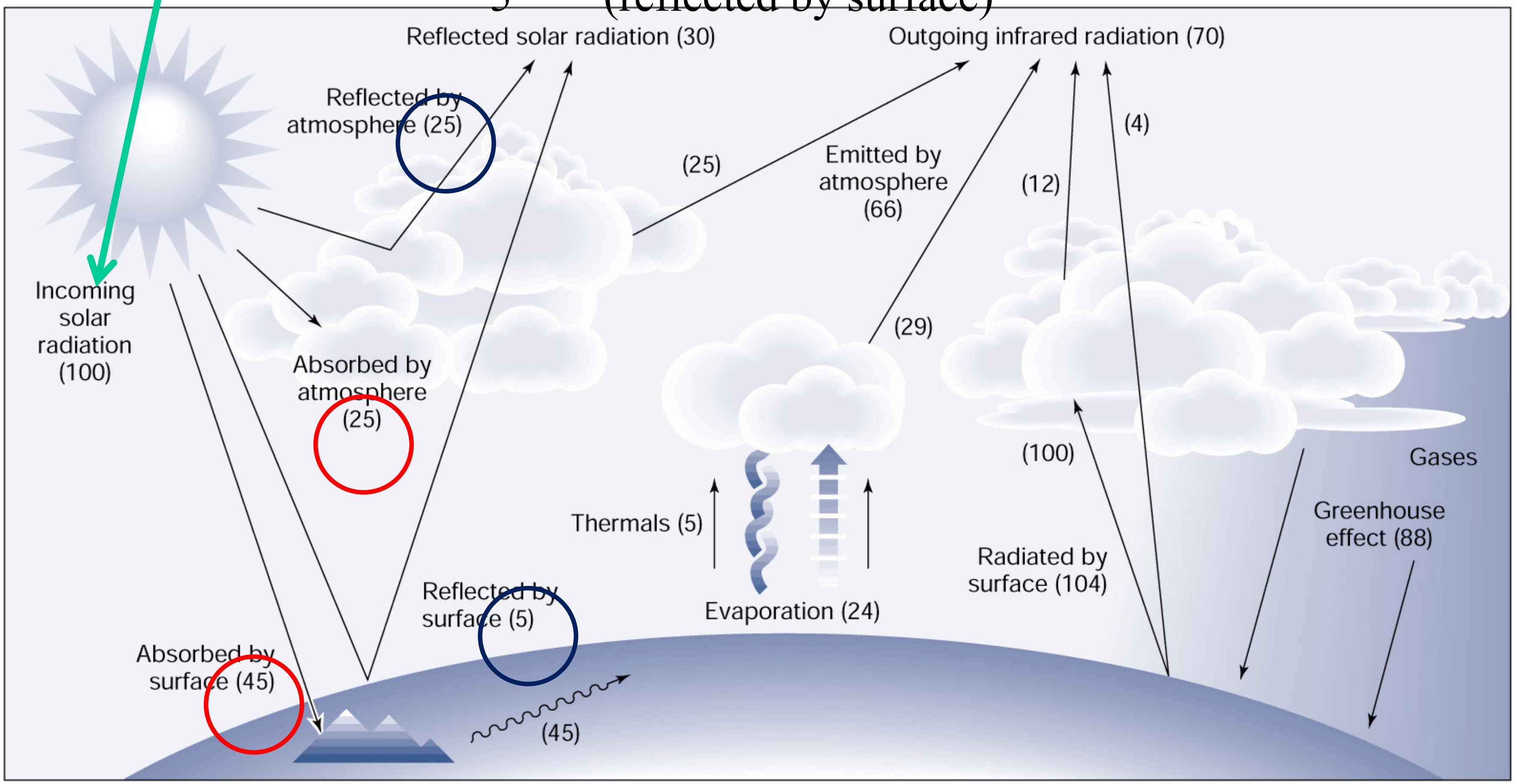

Fig. 3.19

Total input to surface = 45 (solar radiation absorbed by surface)
88 (greenhouse effect, gases and clouds)

Note – total input to surface (133) is larger than the net input (70) from the sun. This is why the surface is warmer than Earth's equilibrium radiating temperature!!

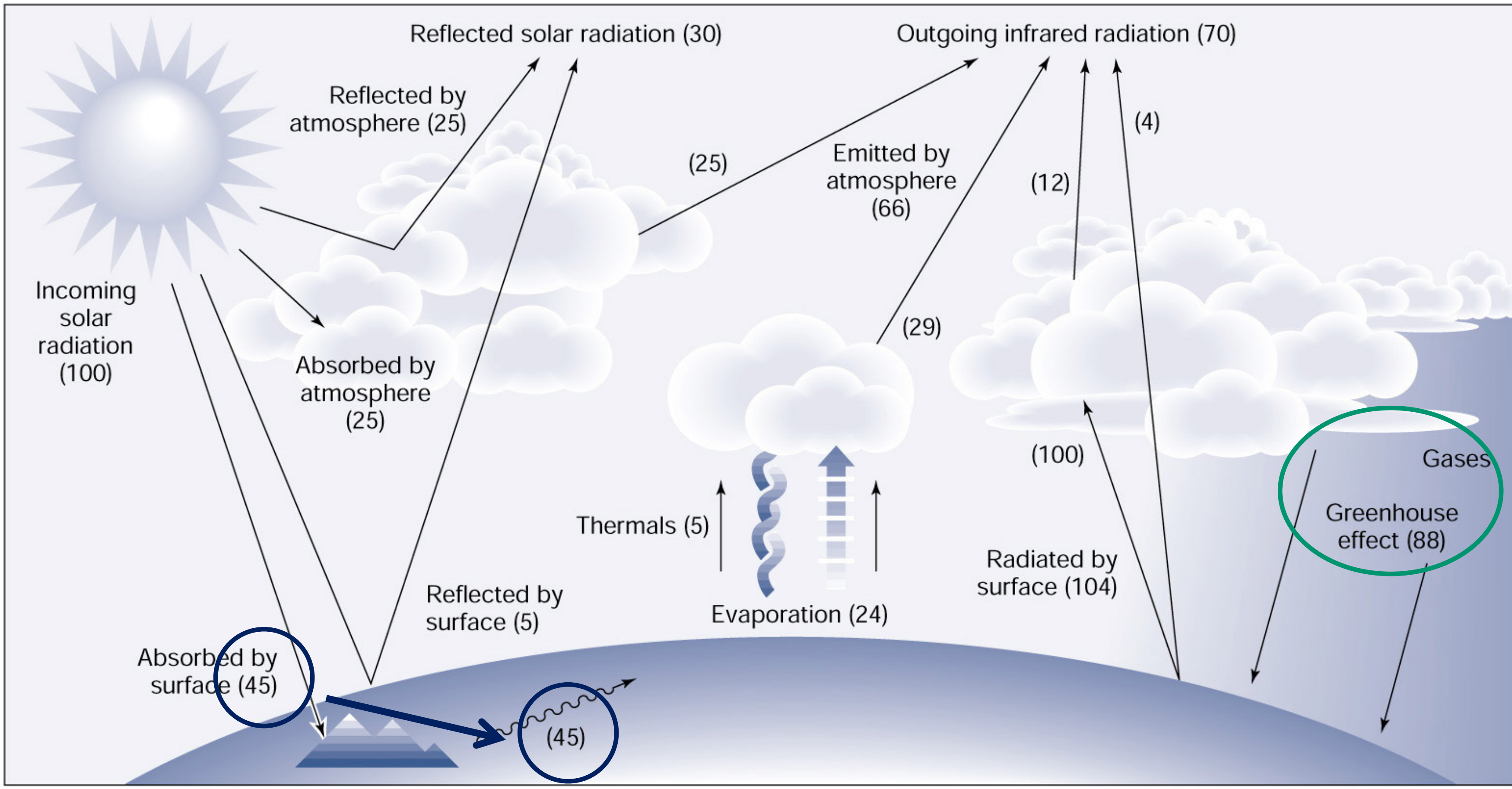

Fig. 3.19

Let's pause for a quick reality check….

Does it make sense that Earth's surface takes in 133 Units when the entire Earth system receives only 70 directly from the Sun?

We calculated the Earth's effective radiating temperature to be ~255 K based on 70 units of solar radiation absorbed by Earth.

We know that temperature varies as the fourth root of the absorbed radiation – let's call that "70 units." Let B = constant.

$$(255\ \text{K})^4 \sim B \times 70\ \text{Units}$$

$$B = (255\ \text{K})^4/70$$

$$T = (B \times 133)^{1/4} = [(255\ \text{K})^4/70]^{1/4}$$

$$T = 255\ \text{K} \times (133/70)^{1/4} \sim 300\ \text{K}$$

This is 27 ^{o}C, which is very nearly Earth's average surface temperature!

The surface doesn't just radiate heat. It is also warmed enough to evaporate water and to make air buoyant in some areas. Of 133 energy units absorbed by earth's surface, 24 evaporate water and 5 produce convection, reducing average surface temperatures from ~300 K to ~290 K.

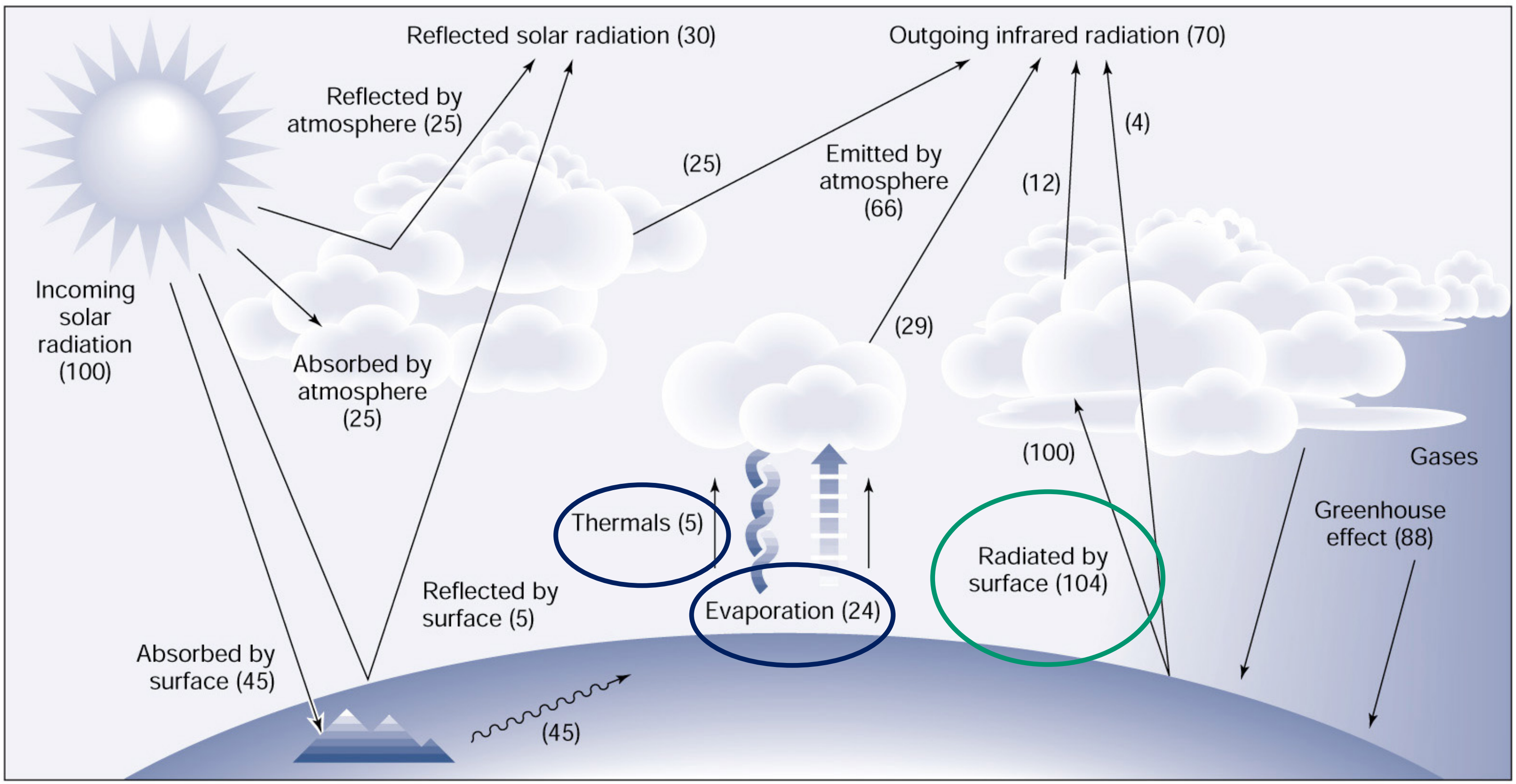

Fig. 3.19

Breakout Discussion Question

The presence of water vapor in Earth's atmosphere represents what kind of feedback on Earth's global mean temperature?

(a) Positive

(b) Negative

(c) Neither

(d) Both positive and negative

Discuss in groups for 5 minutes.

Positive feedback, because if surface temperatures were to increase, air could hold more water vapor, which would increase the greenhouse effect, thereby further heating the surface

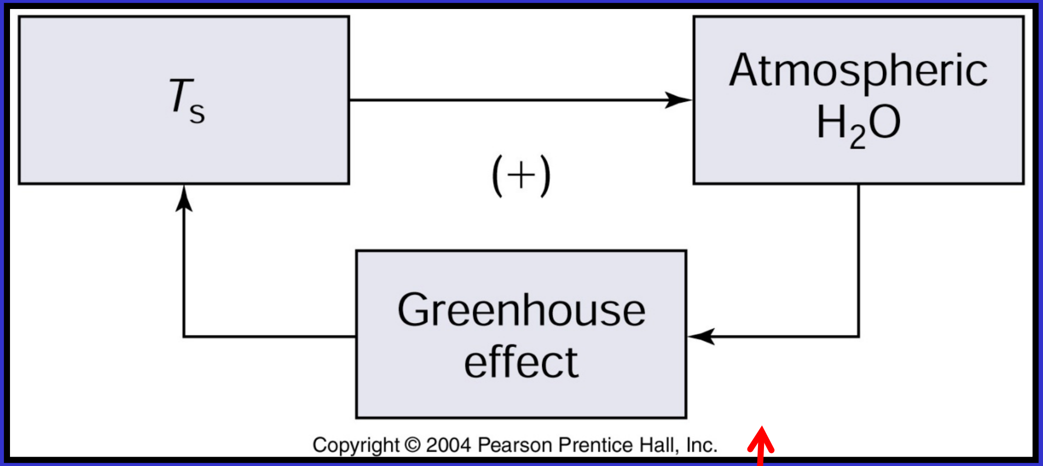

Fig. 3.20

This tells us we need to look at the properties of water!

Feedback loop

We see that water is a critical component of Earth's energy balance.

As a gas (or vapor) it is a powerful greenhouse gas.

As a liquid or solid it undergoes phase transitions that can absorb/release heat.

When it forms ice and clouds it changes the albedo.

These are all extremely important processes for maintaining Earths' climate and they create dominant feedbacks linking the hydrosphere and cryosphere to the atmosphere

We will need take a closer look at water vapor, ice, and clouds.

Summary

The Earth system receives 99% of its heat in the form of radiation from the sun primarily in the visible and near-IR

Of a total of 100 units of solar energy incident on Earth, 30% is reflected back to space by clouds and bright surface regions (ice, deserts), and 45 are absorbed by the surface. Added to these 45 units are 88 units of heat energy (thermal IR) emitted by the atmosphere (the "greenhouse effect").

Earth's surface maintains thermal balance by convection of warm, less dense, air carrying heat upward, by evaporating water ("latent heat") and by radiating the remainder upward.

Of the 104 units of energy radiated by the surface, 4 escape directly to space through "windows" in the IR spectrum of the atmosphere.

What is missing from our simple picture of global energy balance?

The Earth isn’t flat!

Asynchronous Material – February 2, 2021

Watch the first 47 minutes of the video:

Climate 101: Understanding Climate and the Redistribution of Heat, Winds, Water, and Worries

Follow along with the worksheet on Canvas – questions are labeled based on the elapsed time of the video.

Key concept is to follow the "Energy Budget Diagram" like the one we just examined here.