Thursday, January 21, 2021

“The Earth as a System”

Announcements

I will announce asynchronous material each Thursday – it will be posted on the calendar entry for the following Tuesday.

Reminder – Quizzes will all be due by Wednesday evenings. There will not be quizzes on weeks with exams.

Homework 1 available – due in two weeks (Feb 4) – will be based on Chapter 3 and lectures this week and next week.

Learning Assistants are now holding sessions – see Canvas Announcements for details. They will be helping with Homework 1.

I will start copying files to http://atoc.colorado.edu/~toohey/ATOC1060-S2021.html

I'm tweaking the topics/names/dates on the syllabus to more accurately reflect the lectures and asynchronous material – please refer back often.

Big news for climate, January 20, 2021

President Biden signed an Executive Order to rejoin th Paris Climate Agreement. Can that be done with the stroke of a pen?

NY Times

Big news for climate, January 20, 2021

Keystone Pipeline suspended (again, with the stroke of a pen!).

NY Times

Quizzes will be posted by Friday a week before they are due. You will have three attempts (allowing for review and discussion of questions you aren't sure about). Your grade will be based on the best score you achieve on your attempts, but once a Quiz has closed, you will not be able to change your answers and your grade will be determined.

If you have any questions about the quizzes, please ask them in class or during office hours. Nearly all questions are from the book, but some will be based on material that is covered exclusively in class. Refer to the lectures, as needed.

Outline for Lecture

Earth as a system (land, ocean, atmosphere and biosphere)
- Couplings and feedbacks

Quick summary of key points for next Tuesday (asynchronous)
- (Refer back to this section after next Tuesday)
- Light as a wave, wavelength vs. frequency, energy of a photon
- Wein's Law, blackbody radiation

Earth's energy balance
- Albedo (iClicker question, followed by breakout discussions)
- Balancing incoming and outgoing radiation
- A first estimate for Earth's "Effective Radiating Temperature"

Introduction to feedbacks
- Ice/albedo (positive) feedback

Learning goals

- To recognize that the Earth System is complex, with multiple interactions, responses, and feedbacks
- To use basic physics of energy transfer to develop a quantitative basis for examining Earth’s temperature. This will provide the foundation for evidence that human activities play an important role in climate change
- To examine one of the most dominant positive feedback loops in the Earth System – the ice-albedo feedback.
- Asynchronous – to gain a better understanding of some of basic properties of electromagnetic radiation, heat exchange, and temperature

Earth is a system…to understand the parts requires that we understand the linkages between them and the processes that are important in determining those linkages.

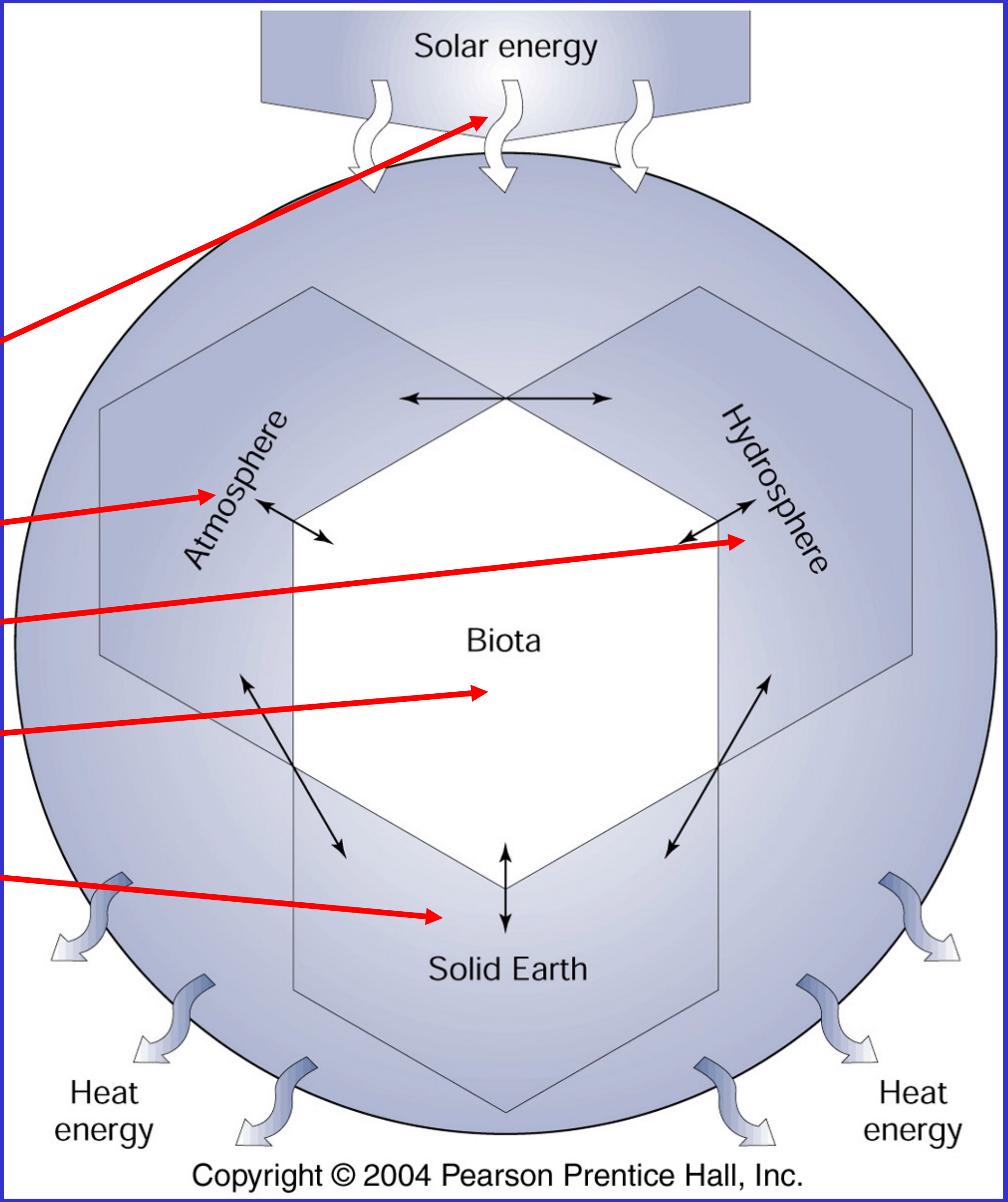
Sun

Air

Ice/water

Life

Land

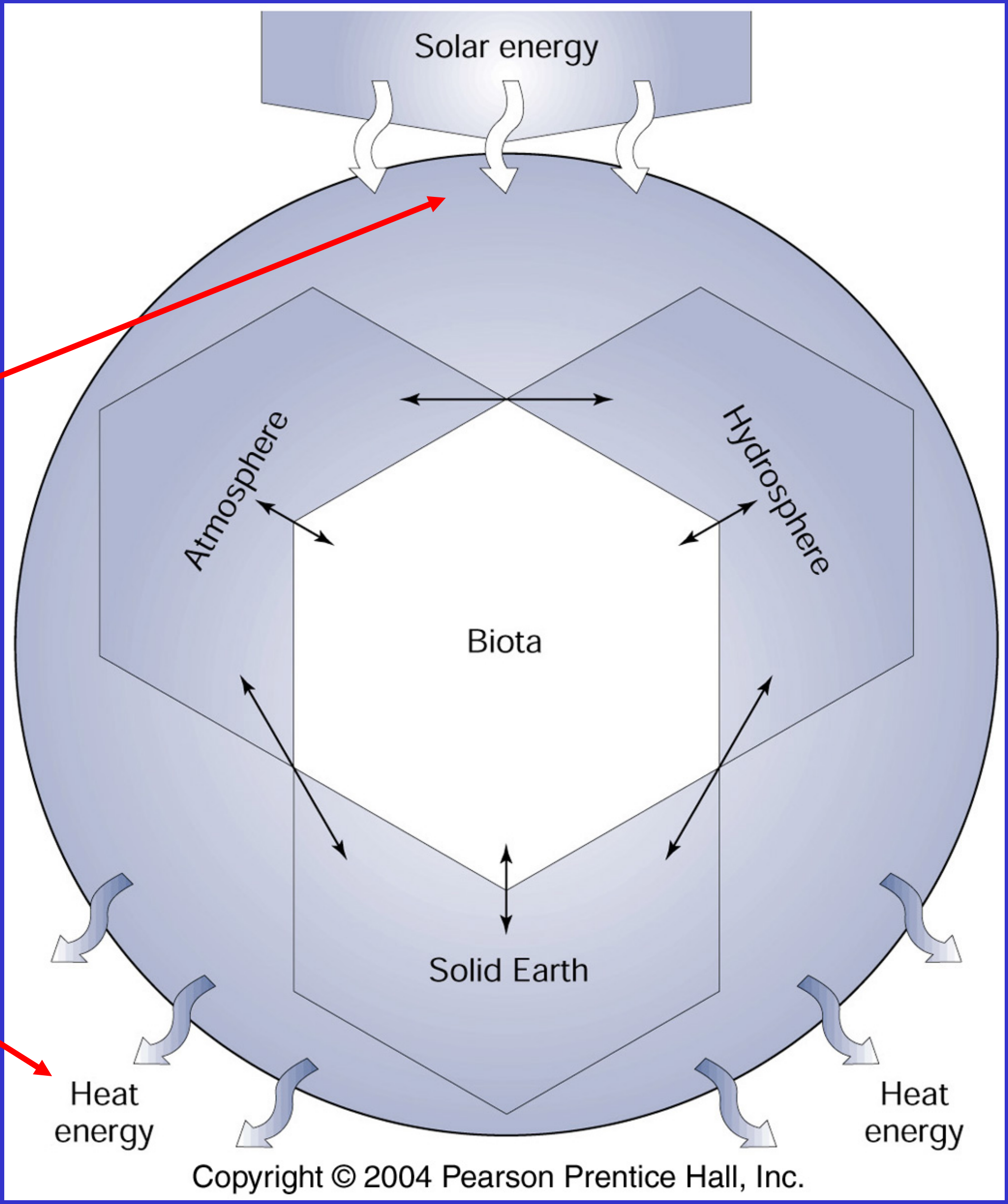


Linkages are "feedback loops" between the various elements in the system.

In this class we will examine the factors that determine Earth's climate, past and present. We will try to understand how human activities have affected these natural climate changes, and try to determine what impact these changes are having on the environment.

The first thing we will look at is the energy balance of the earth. We will see how a very simple feedback loop between the temperature and surface ice has resulted in a period of ice ages that has lasted nearly 2 million years.

Let’s start with the simplest of feedbacks.

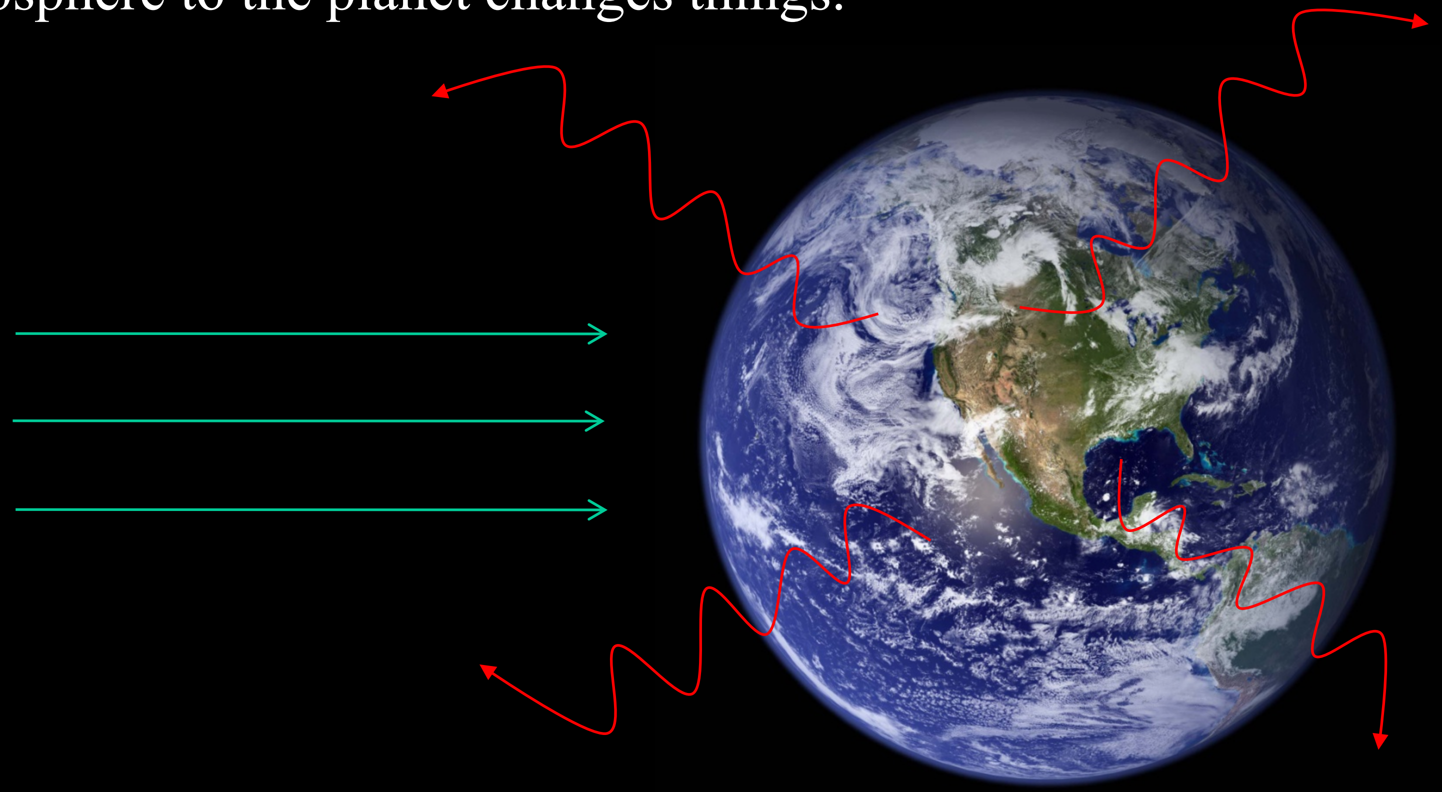


Absorption of sunlight and warming of Earth’s surface.

We can estimate Earth’s temperature by assuming Incoming (solar) energy and outgoing (heat) energy are balanced

Planetary Energy Balance

Goal – to estimate Earth's surface temperature using fundamental physics and chemistry. We'll do this in two parts – first, we'll assume Earth has no atmosphere, and use radiative balance (incoming solar = outgoing infrared) to determine the 'effective radiating temperature'. Then, we'll see how adding an atmosphere to the planet changes things.



Asynchronous (Pages 37-41)

Key points:

- Light is a wave that travels at speed = 3×10^8 meters per second ($m\ s^{-1}$)
- The product of wavelength (λ) and frequency (ν) is "speed"

$$\lambda \nu = c$$

c = speed of light
Wavelength, λ (Greek "lambda" for the distance between peaks)
Frequency, ν (Greek 'nu' represents the number of waves per second)

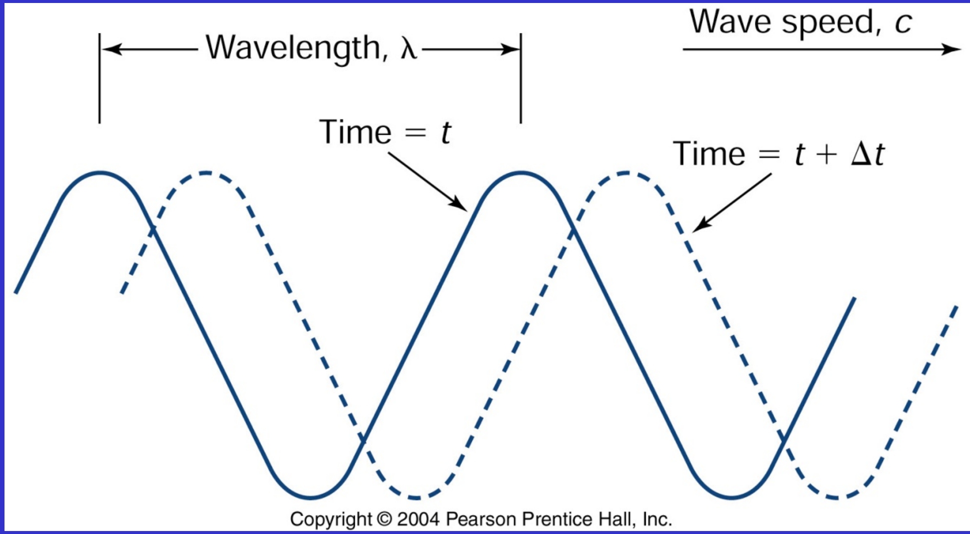


Fig 3.2

Asynchronous (Pages 37-41)

Key points:

Light exists in a wide range of "frequencies" ("colors") that represent different energies (1 nm = 0.000000001 meters = 10^{-9} m)

The Sun emits light mainly from 100 nm – 1000 nm. This spans the spectral range ultraviolet (< 350 nm) to the infrared (> 700 nm)

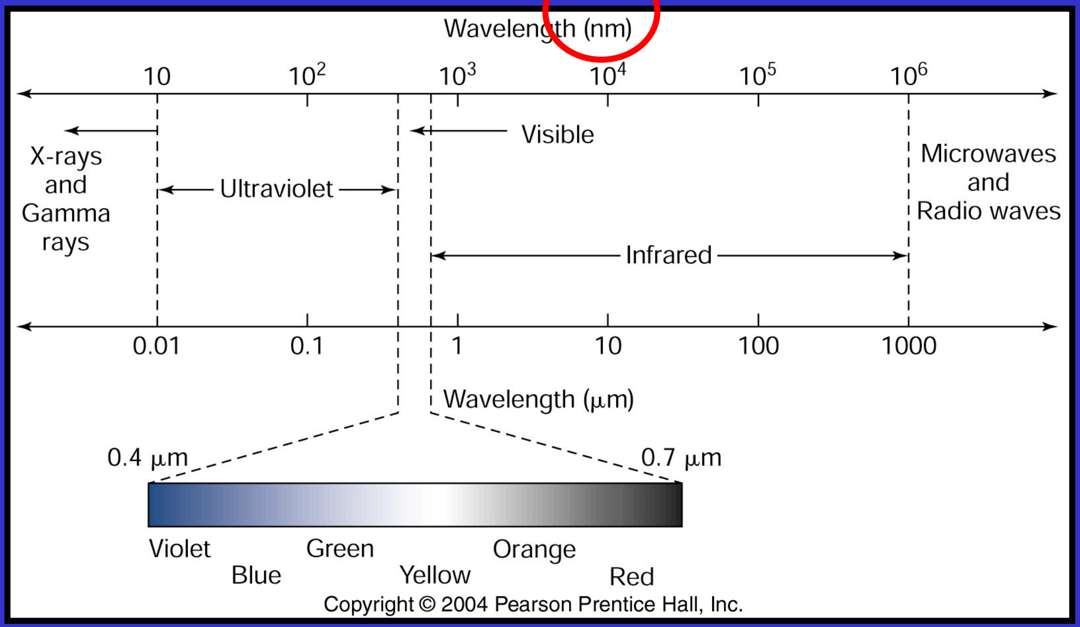


Fig 3.3

Asynchronous (Pages 37-41)

Key points:

We use various “scales” for different types of light. Don’t worry! The actual values are the same, the scaling factors are different.

1 nm = 0.000000001 meters = 10^{-9} m
1000 nm = 1 “micron” (or μm) = 10^{-6} m

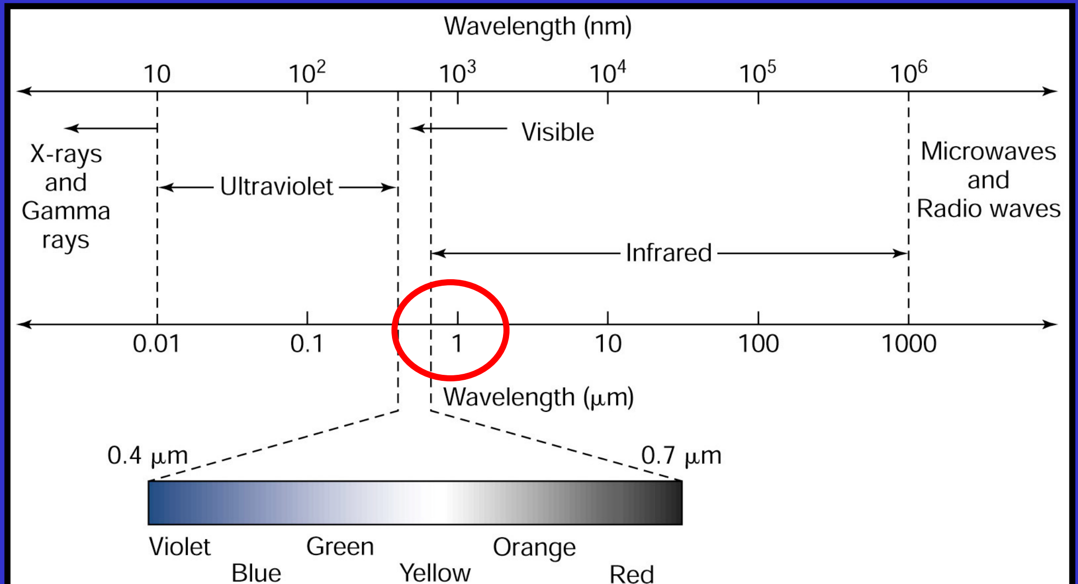


Fig 3.3

Asynchronous (Pages 41-43)

Objects emit ‘light’ based on their temperature. The amount of radiation at a given wavelength depends on temperature.

https://energyeducation.ca/encyclopedia/Wiens_Law

(See link for next Tuesday)

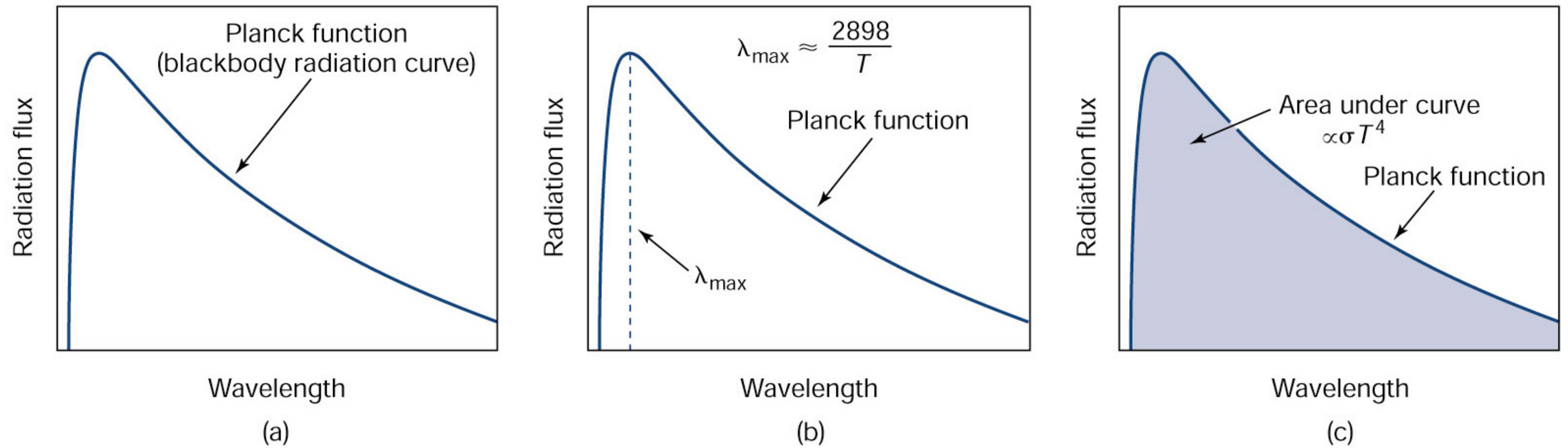


Fig 3.7

Asynchronous (Pages 41-43)

Key points:

- When we measure the light from the Sun (called the "spectrum") we find that it forms a curve that has a peak at 500 nm ("green"). It turns out this is the same curve as a "blackbody" object at T = 5600 K.
- The Earth also emits like a blackbody, but at a much lower temperature (which we will estimate)

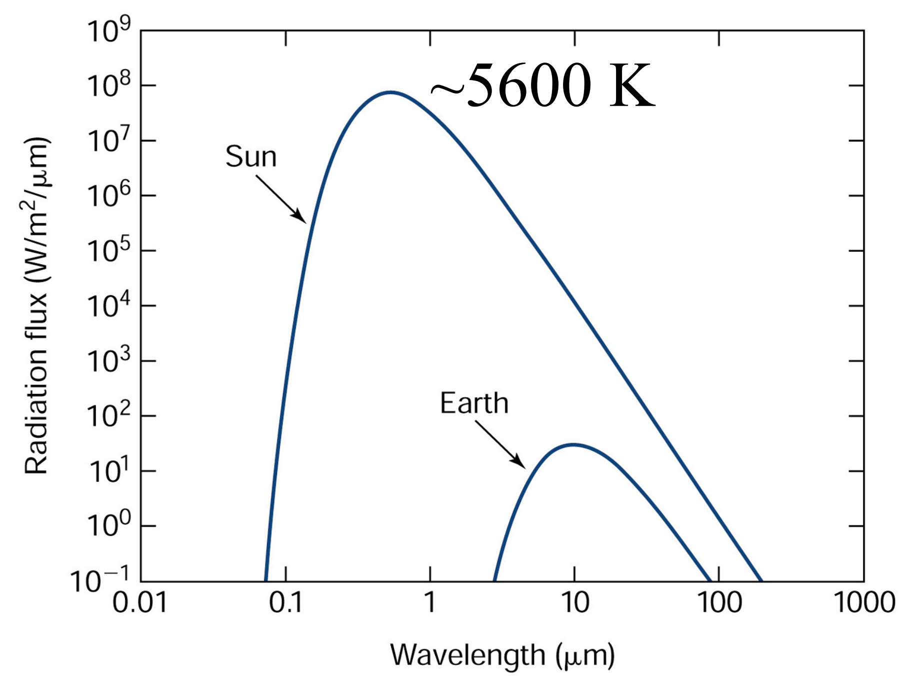


Fig 3.8

Synchronous

Note two important features of a blackbody (p42)

(1) The wavelength at which the maximum emission of electromagnetic radiation occurs can be determined from a simple equation:

$$\lambda = 2898/T \qquad \text{(Wein's Law)}$$

where wavelength is in units of micrometers (or microns, μm) and T is in Kelvin.

(2) The total amount of energy emitted by (or the 'flux' from) a blackbody object is a simple expression

$$F = \sigma T^4$$

where σ = constant (the "Stefan Boltzmann constant"). We will look at the value for this constant later when we need it.

Let’s Estimate Earth’s Temperature

Assume energy balance: Solar energy absorbed by Earth equals the energy radiated back to space.

Incoming energy = outgoing energy

What is the energy absorbed from the Sun? (incoming)

iClicker Question 1

Clicker Question 1

Which of the following best describes the amount of Sunlight absorbed by Earth?

(a) The total amount of light from the Sun that is intercepted by the Earth.

(b) The amount of light from the Sun that is reflected back to Space by the Earth.

(c) The amount of light from the Sun that is intercepted by the Earth minus the amount of light from the Sun that is reflected back to Space.

(d) The amount of light from the Sun that is “captured” by the Earth that isn’t reflected back to Space.

Clicker Question 1

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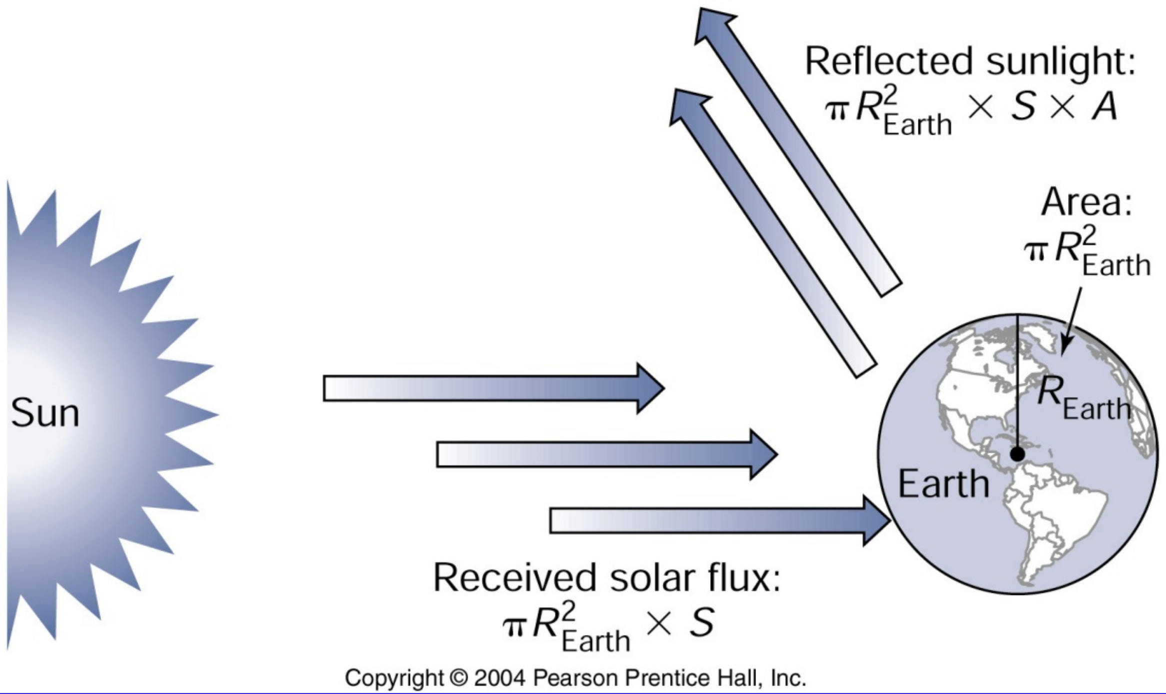
(d) The amount of light from the Sun that is “captured” by the Earth that isn’t reflected back to Space.

Energy Absorbed by Earth

Assume Earth is a sphere: Light hitting Earth = S x πR^2

where "S" is the "Solar Flux" at the orbit of Earth (in units of Watts per square meter). Light refected back to Space = S x πR^2 x A

We call A the "Albedo" – the fraction of incident sunlight that is reflected back to space.



Box Fig. 3.1

The albedo is defined as the fraction of incoming solar light that is reflected back to space

100% refection, “bright” object, A ~ 1
0% reflection, “dark” object, A ~ 0

Albedo = (Amount reflected to space/Total incoming solar)

Since Absorbed + Reflected = Total incoming

Absorbed = Total – Reflected = Total – Total x Albedo

Absorbed = Total (1-Albedo)

Breakout
Discussion 1

Estimate and rank the albedos of the different types of Earth surface coverage

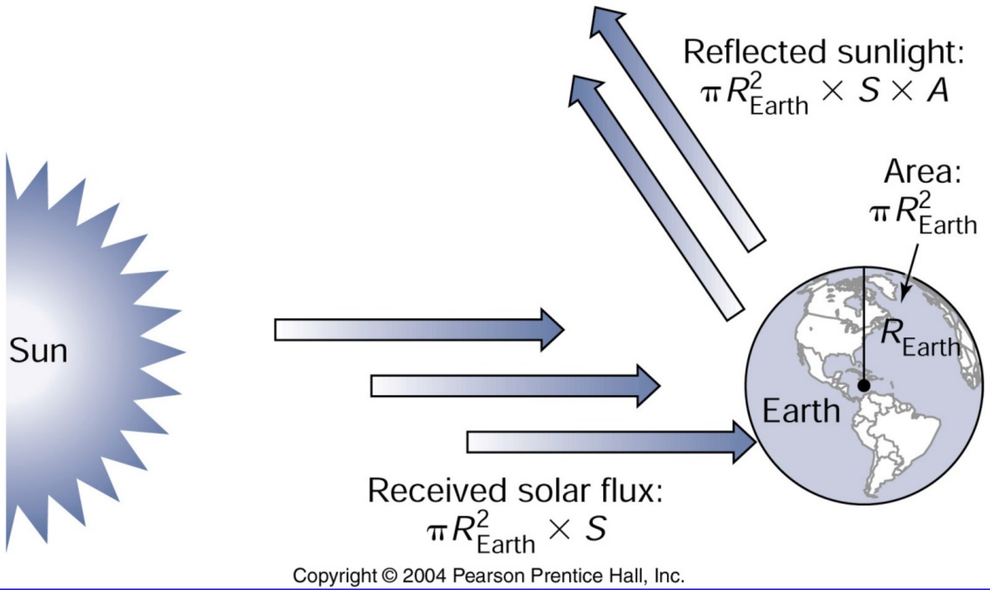
Solar Energy Absorbed by Earth

Energy Absorbed = Energy incident – Energy reflected

= (Solar flux) x (Area) – (Solar flux) x (Area) x (Albedo)

= $S \times (\pi R^2) - S \times A \times (\pi R^2)$

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



Box Fig. 3.1

Solar Energy Absorbed by Earth

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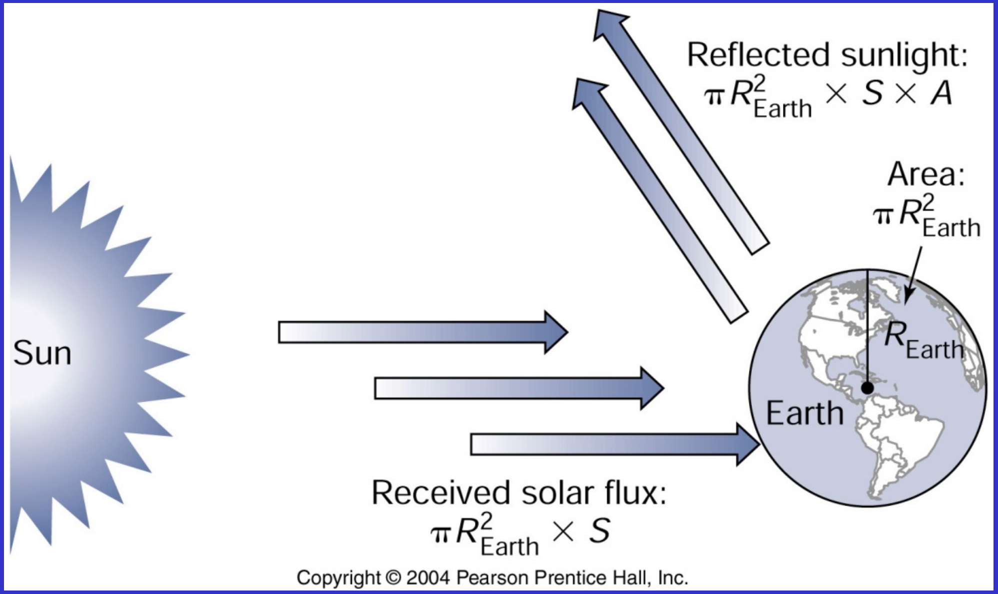
= (Solar flux) x (Area) – (Solar flux) x (Area) x (Albedo)
= $S \times (\pi R^2)$ – $S \times A \times (\pi R^2)$
= $S \times (\pi R^2) \times (1 - A)$

For absorption of sunlight, we use the shadow area of Earth (πR^2) because this is the area that intercepts sunlight by the Earth – that is, the circular shadow left by a sphere represents the light that is removed by the sphere, and that shadow area is πR^2 where R = earth's radius

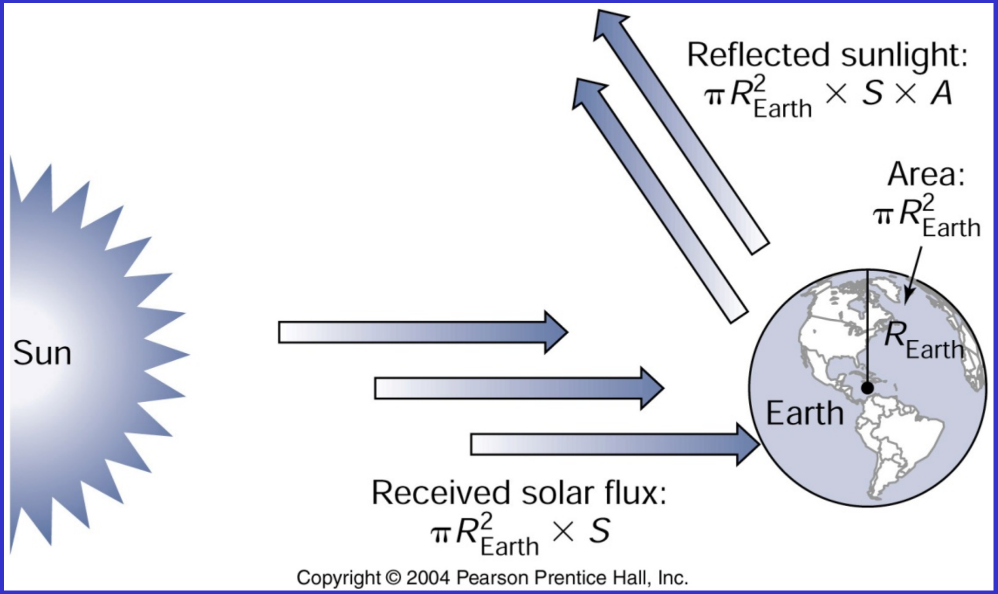


Box Fig. 3.1

Solar Energy Absorbed by Earth

Energy Absorbed = Energy incident – Energy reflected
= (Solar flux) x (Area) – (Solar flux) x (Area) x (Albedo)
= S x (πR^2) – S x A x (πR^2)
= S x (πR^2) x (1 – A)

For albedo (A) we will use an average value, because as you just discussed, Earth's surface is variable, and some things, such as ice and clouds, have high albedos and others (ocean, forests) have low albedos. We want the total energy absorbed, not just the value over a specific place.



Box Fig. 3.1

Like the Sun, the Earth emits radiation

As absorbed solar radiation heats Earth, it warms up and radiates with a flux that is given by $F = \sigma T^4$.

From Wein's Law we know that the Earth won't radiate in the visible. A blackbody with temperature ~300 K will radiate in the infrared. We call this "thermal" radiation because it is felt as "heat" rather than visible light.

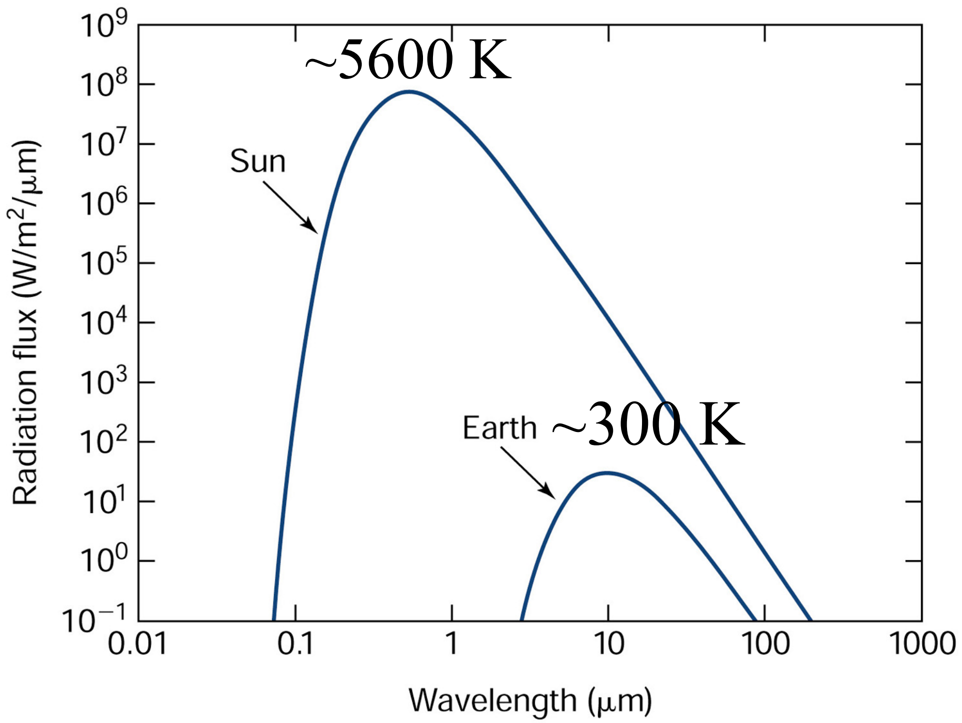


Fig 3.8

Remember the two important features of a blackbody (p42)

(1) The wavelength at which the maximum emission of electromagnetic radiation occurs can be determined from a simple equation (called “Wein’s Law”)

$$\lambda \quad = 2898/T$$

wavelength is in micrometers (or microns, μm), and T is in Kelvin.

(2) The energy emitted by (or the ‘flux’ from) a unit of area on a blackbody object is a simple expression

$$F = \sigma T^4$$

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

Outgoing "thermal" Radiation

Assume Earth is a blackbody that radiates at a temperature = T_e

$$E_{emission} = \sigma T_e^4 \text{ x (surface area of Earth)}$$

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

We call T_e the "effective radiating temperature" (or sometimes "effective temperature" for short) because it is derived from a calculation of energy balance (incoming = outgoing). It must be true, on average, or the Earth would rapidly heat up or cool down, but it isn't necessarily the observed temperature at any given time, due to factors such as slight wobbles of Earths orbit, changes in clouds or ice cover, and potential of storage of heat (such as in the oceans).

Outgoing "thermal" Radiation

$$E_{emission} = \sigma T_e^4 \text{ x (surface area of Earth)}$$

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

Note that we have used a different "area" for outgoing radiation. Atmospheric and oceanic currents move air and water around, spreading the heat, so that the Earth radiates heat back to space from all around the globe, and not just from the sunlit side. We need to use the full area of the sphere ($4\pi R^2$).

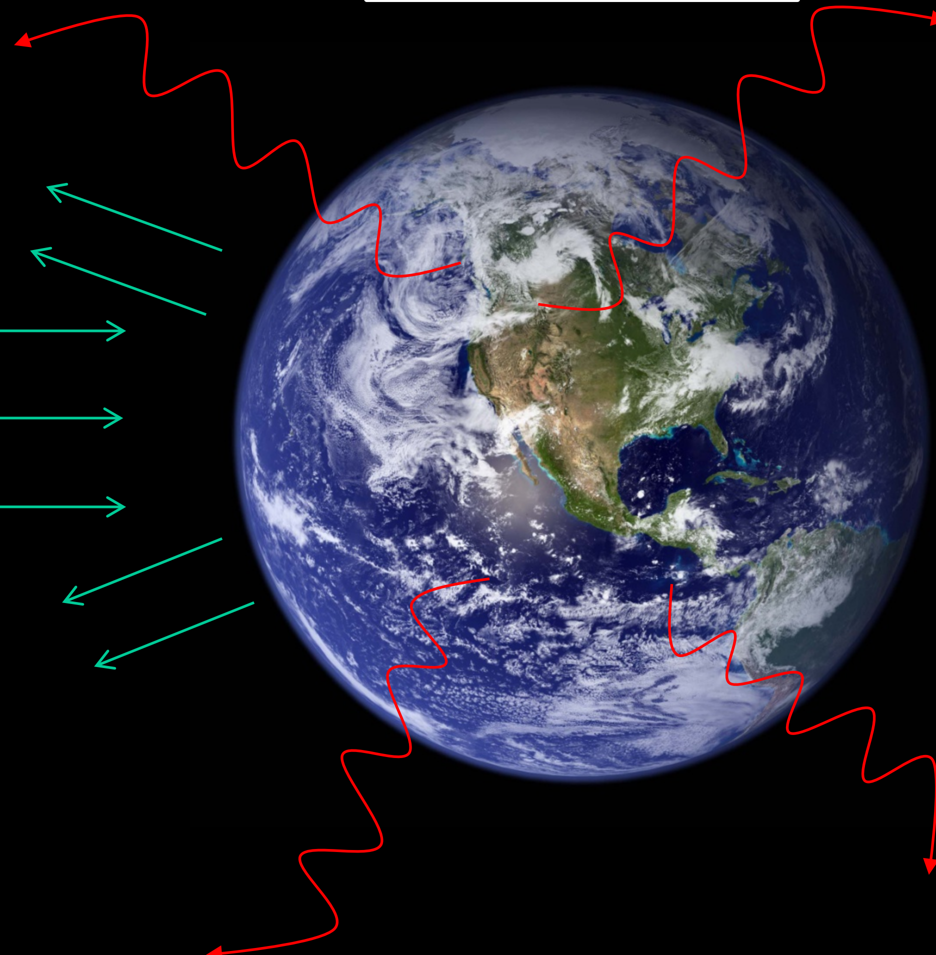
Let's equate incoming and outgoing energy

Outgoing
= middle and far IR

$$\sigma T^4 \times (4\pi R^2)$$

Incoming
= solar visible and near IR

$$S \times (\pi R^2) \times (1 - A)$$



Outgoing “thermal” Radiation

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

Interestingly, πR^2 cancels out. In other words, the effective radiating temperature DOES NOT DEPEND on the size of the object. A large object will absorb more energy from the Sun, but it will radiate more energy back to Space in the same proportion.

This leaves:

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

Solving for T_e

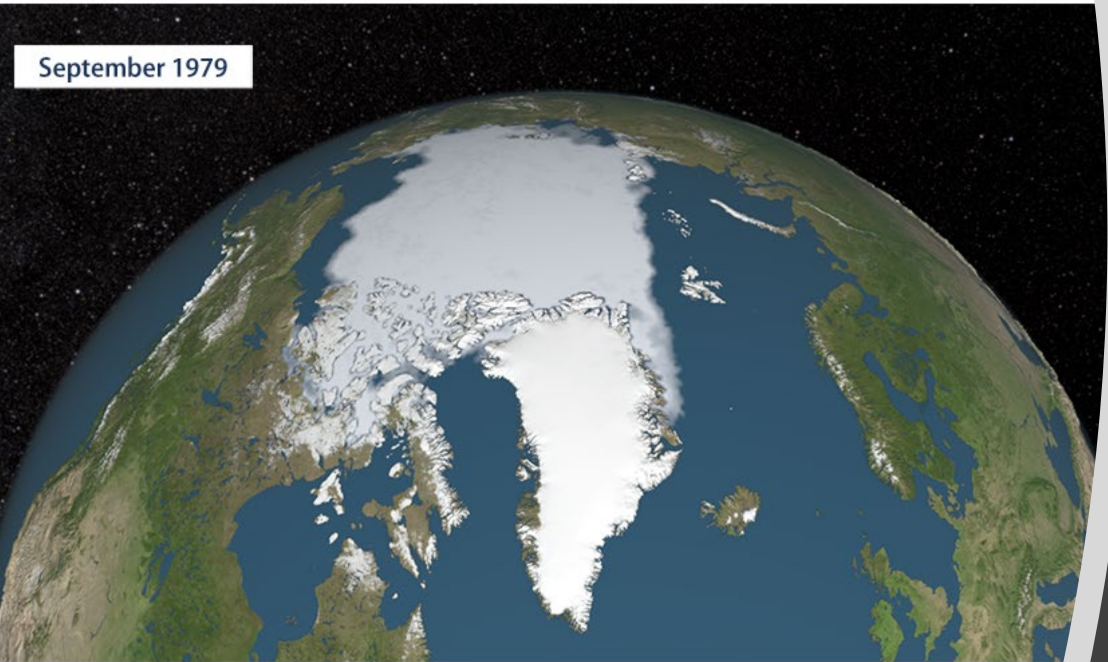
$$T_e^4 = S \times (1 - A)/4\sigma$$

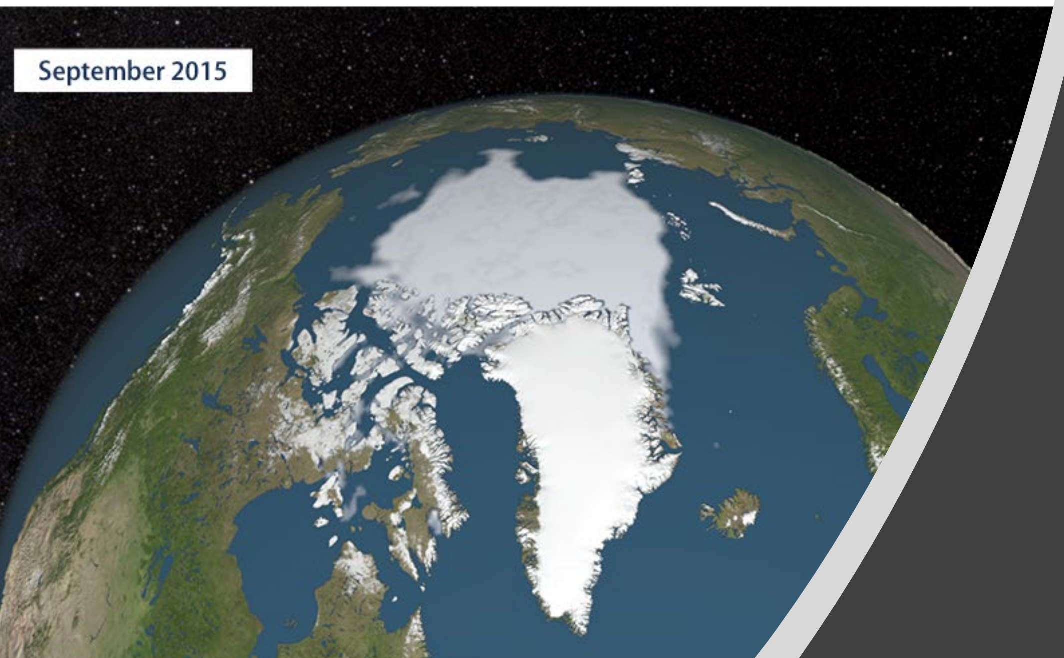
Let's stop and look at what this is telling us.

(1) If the energy from the Sun were to increase, T_e would increase.

(2) If the albedo were to decrease, T_e would increase.

(3) This gives us some important information regarding feedbacks on Earth. Before we calculate Earth's effective radiating temperature, let's look at the "ice-albedo feedback.



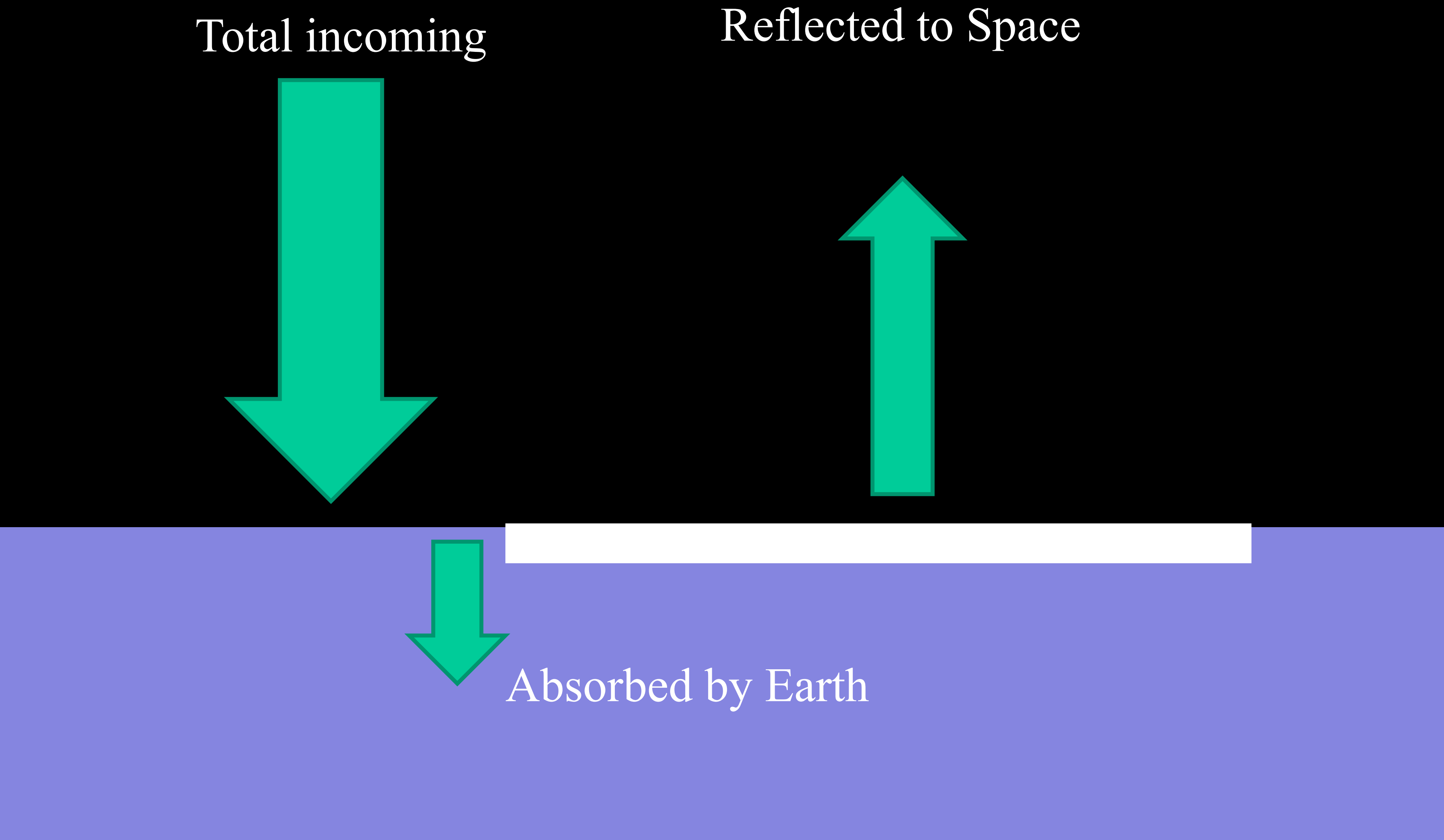


Breakout Discussion 2

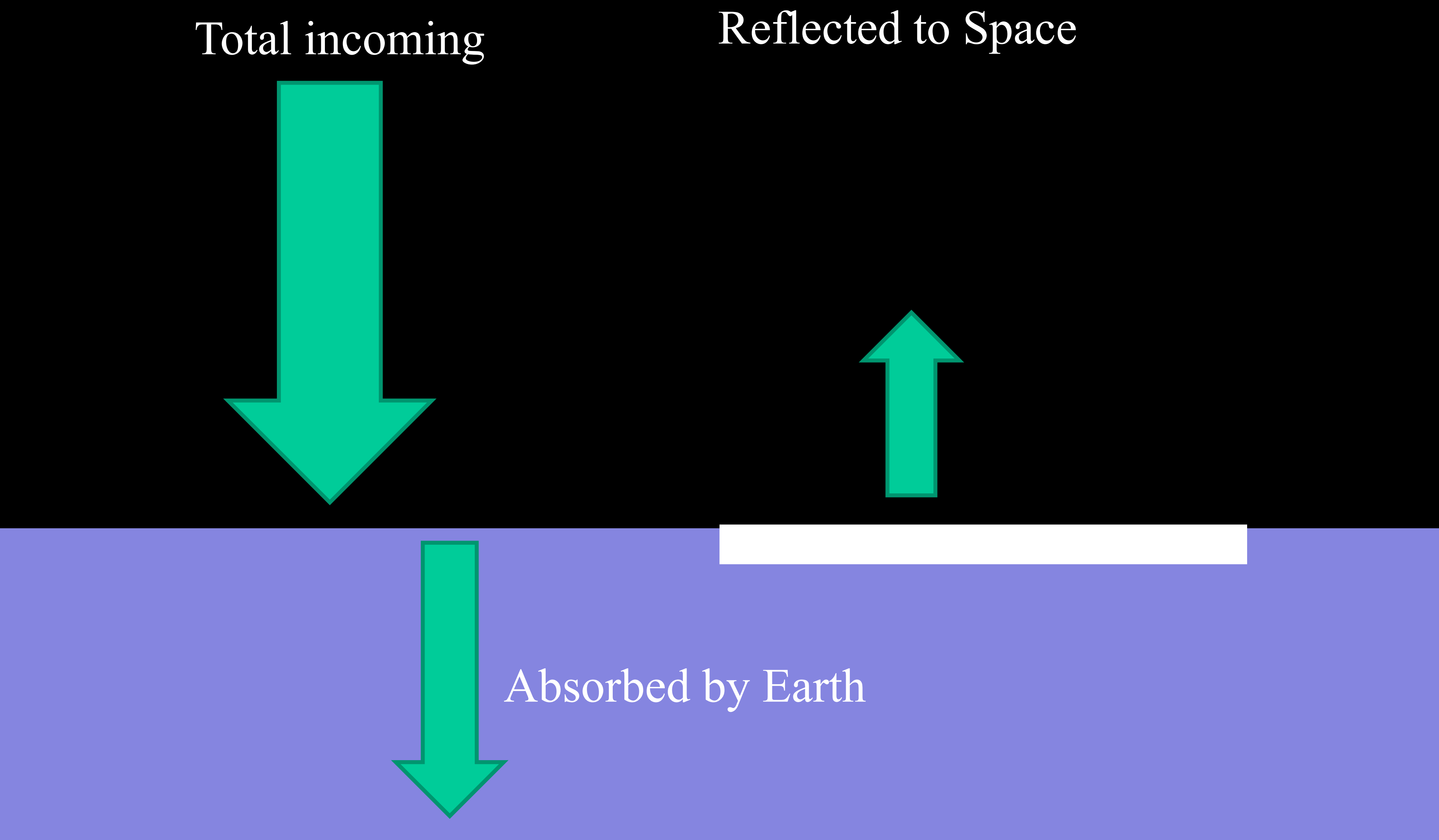
How would decline in Arctic Sea Ice affect Earth’s albedo?

Why is this positive feedback?

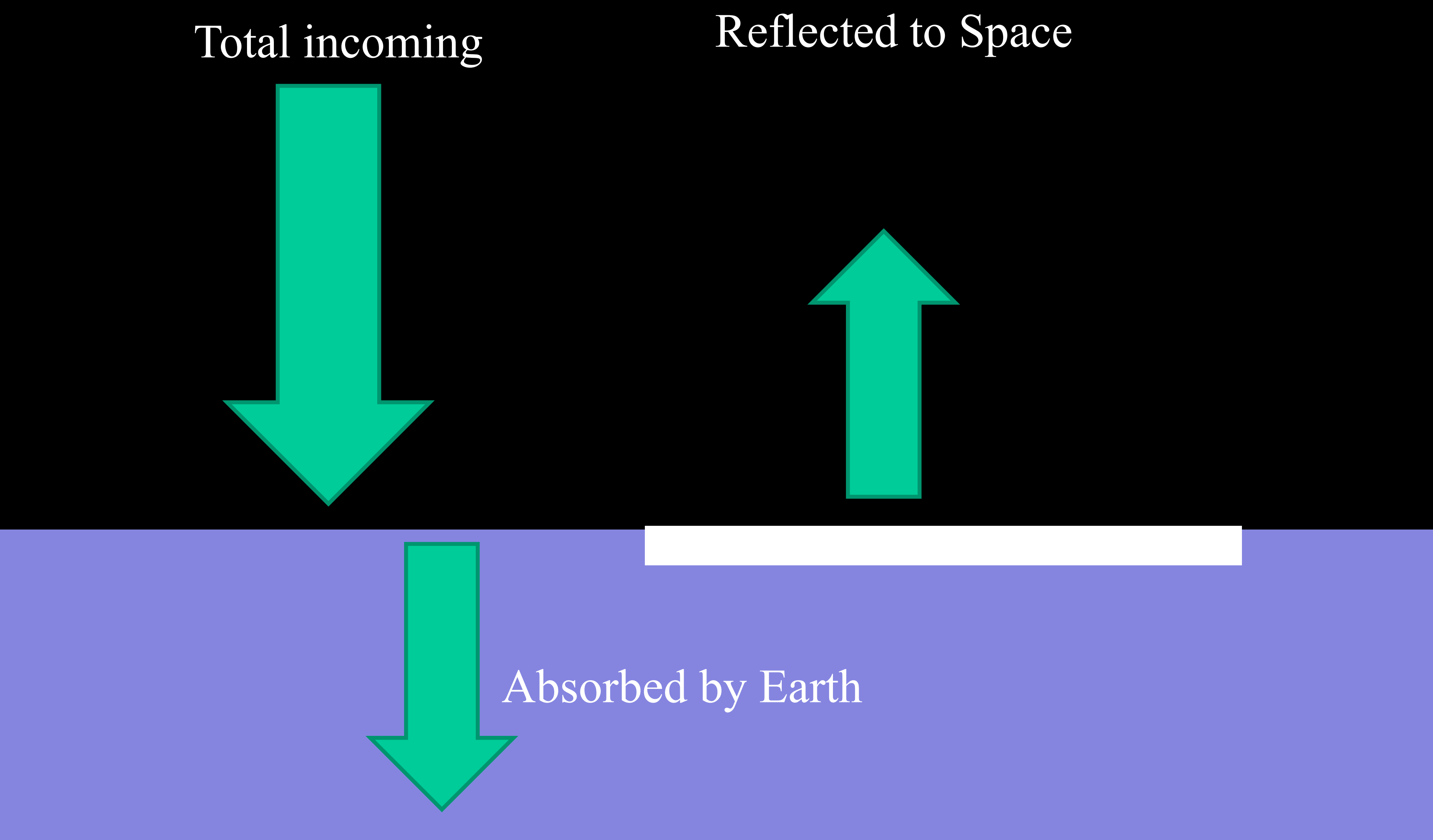
When ice melts, less light is reflected to Space



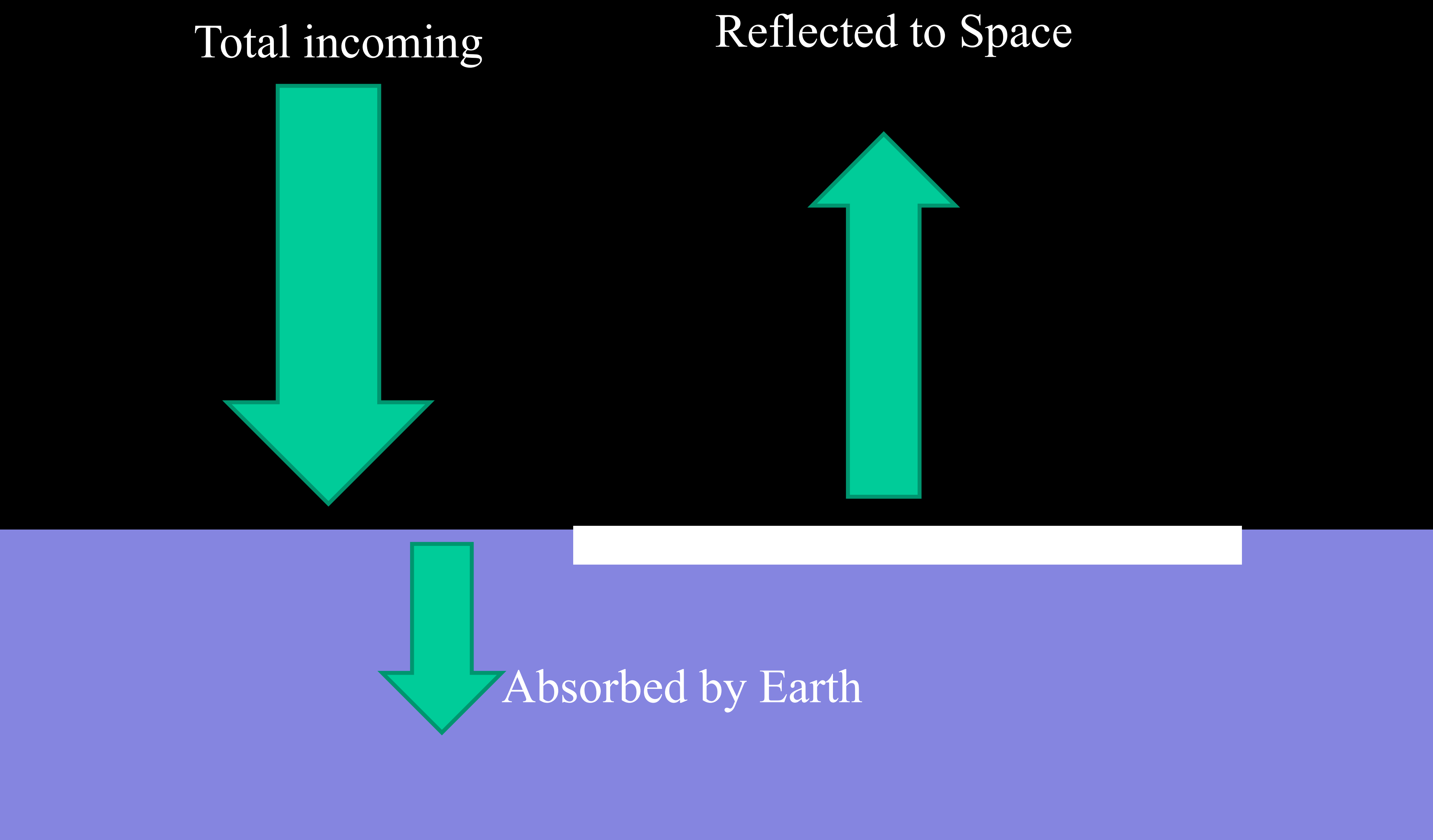
Less reflection means more is absorbed, increasing T_e
This is positive feedback



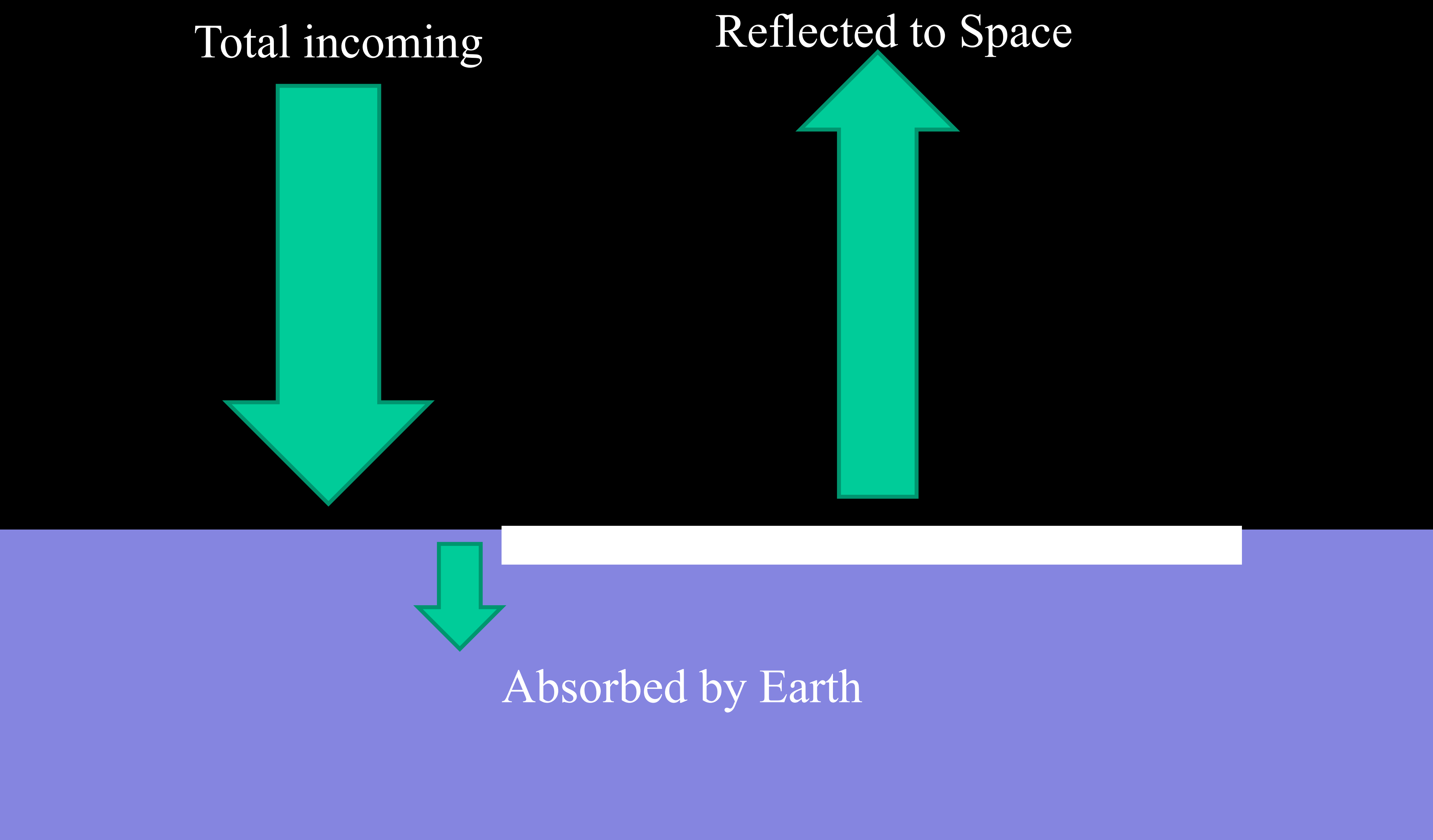
What happens if sea ice grows, and more sunlight is reflected back to Space?



If more sunlight is reflected back to Space, less will be absorbed by Earth, and T_e will decrease.



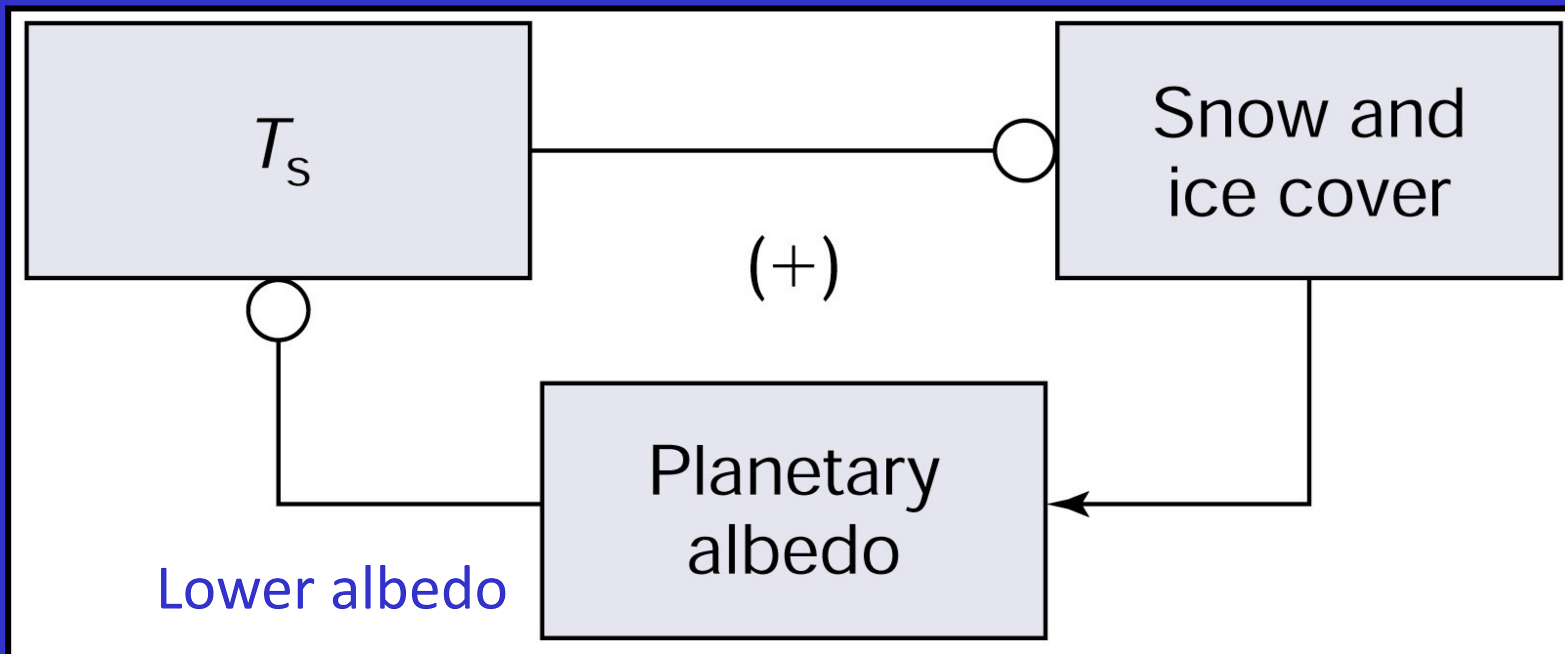
This will favor formation of more ice, which will increase the albedo – again, positive feedback!



A Closed Loop

Temperature rises

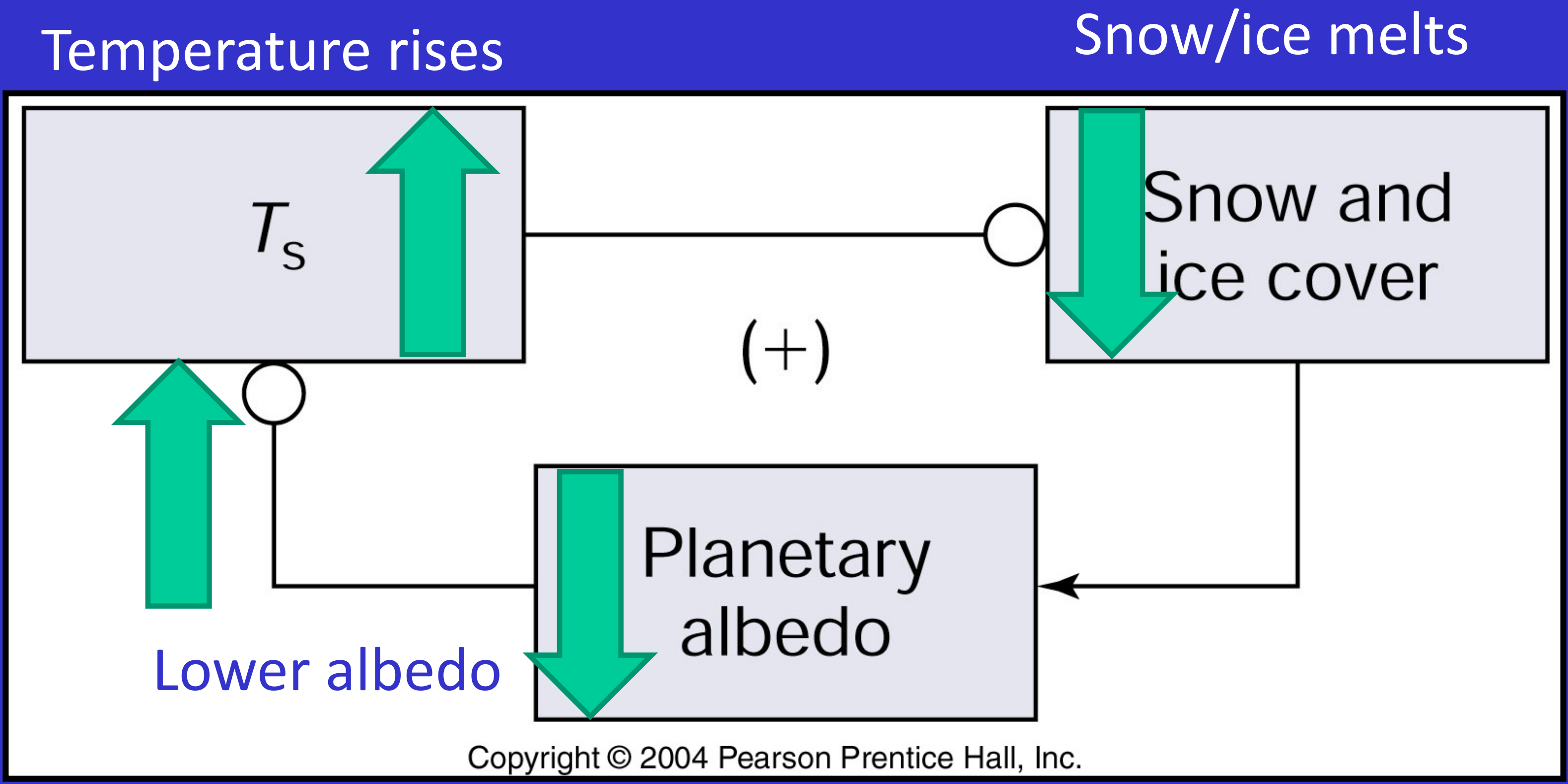
Snow/ice melts



Positive Feedback

Fig. 3.21

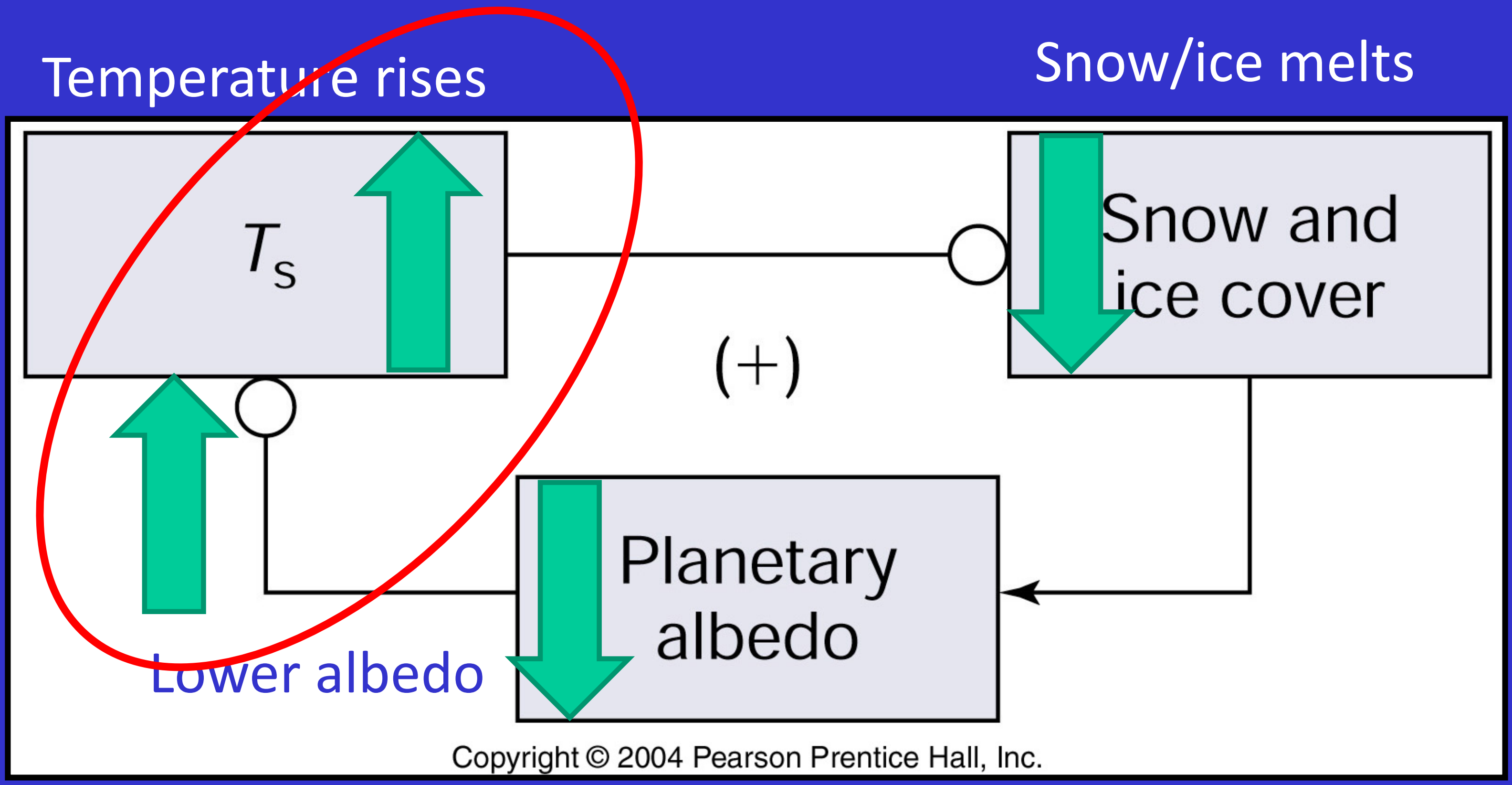
A Closed Loop



Positive Feedback

Fig. 3.21

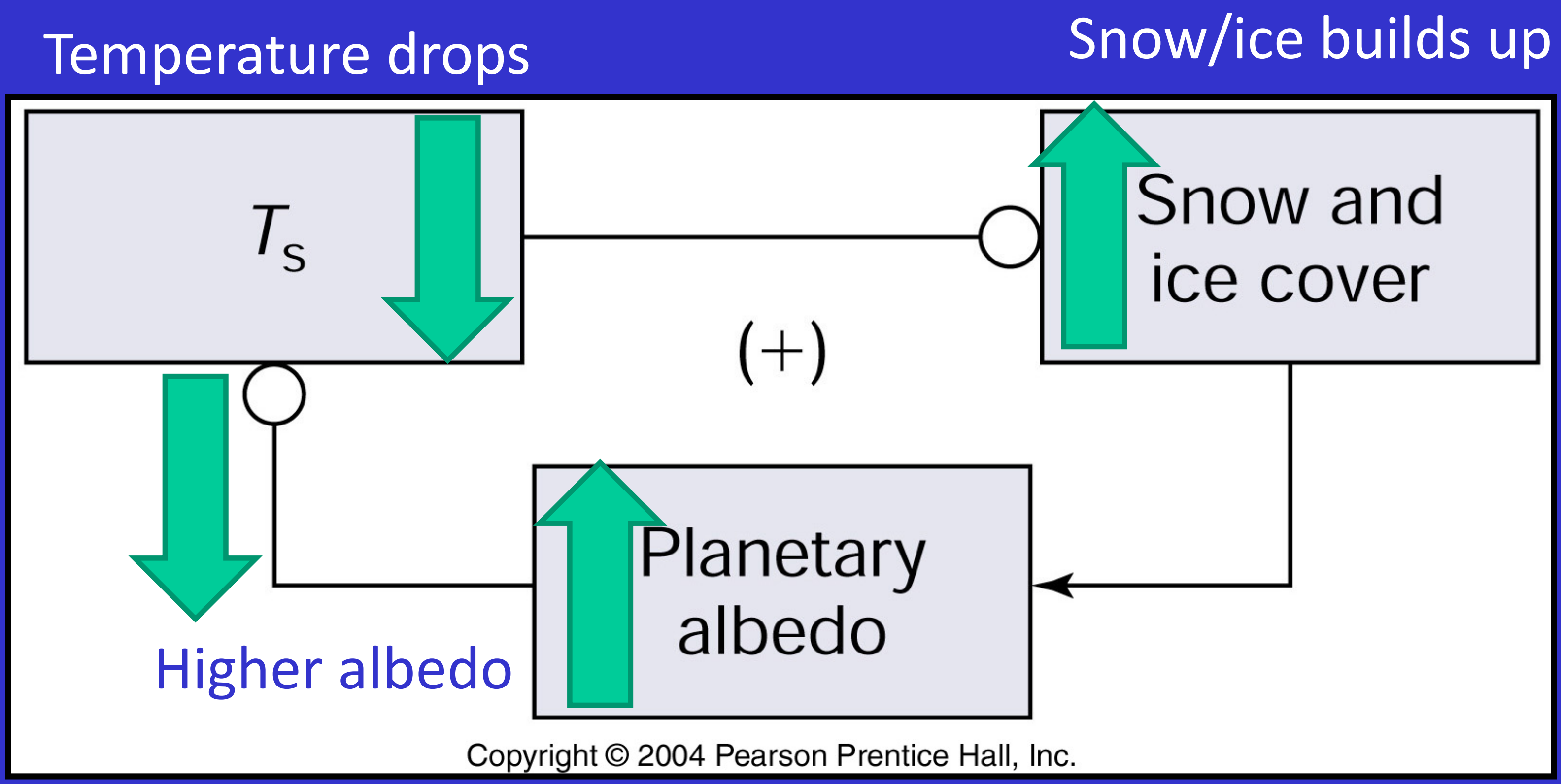
A Closed Loop



Positive Feedback

Fig. 3.21

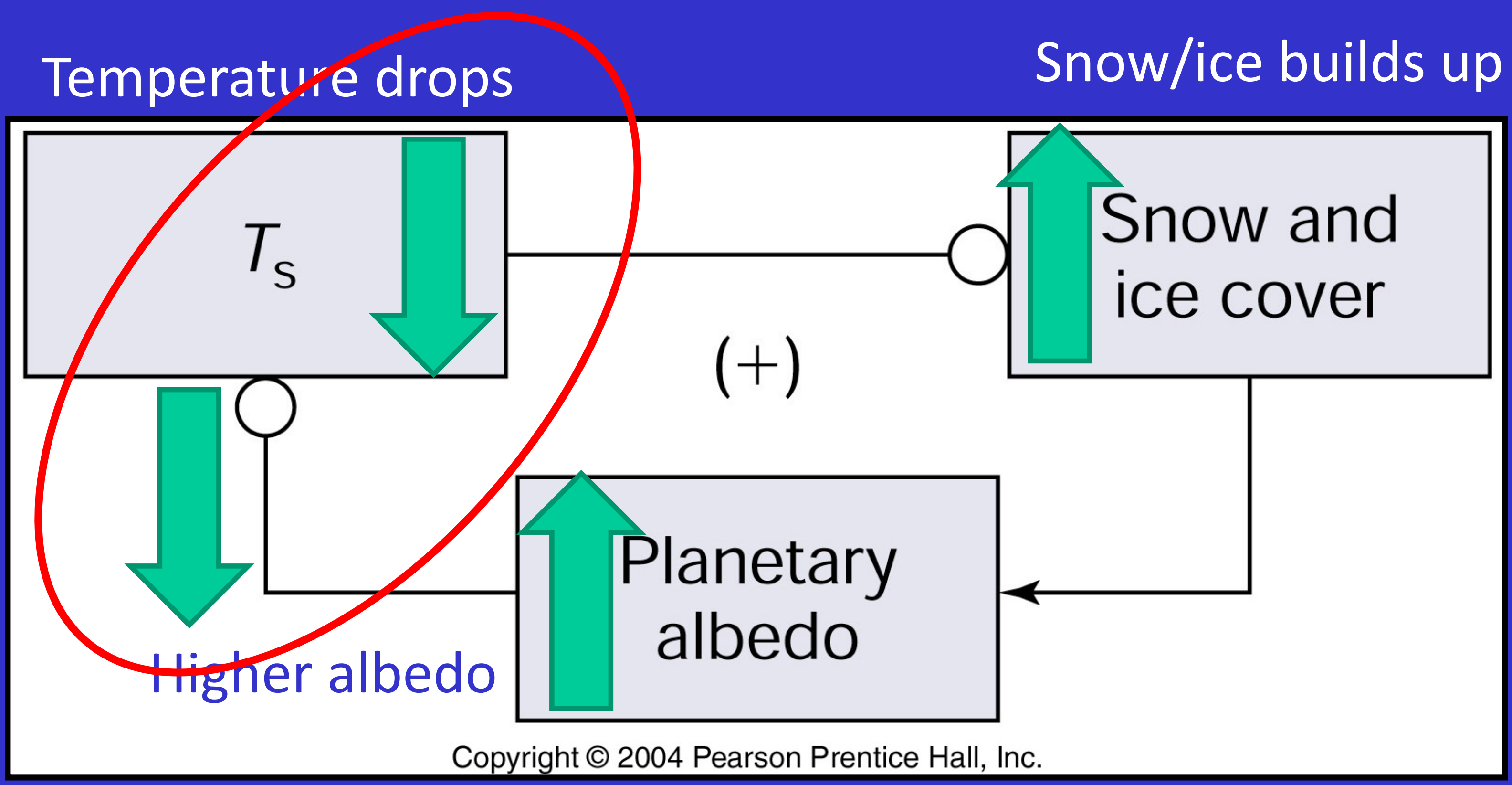
A Closed Loop



Positive Feedback

Fig. 3.21

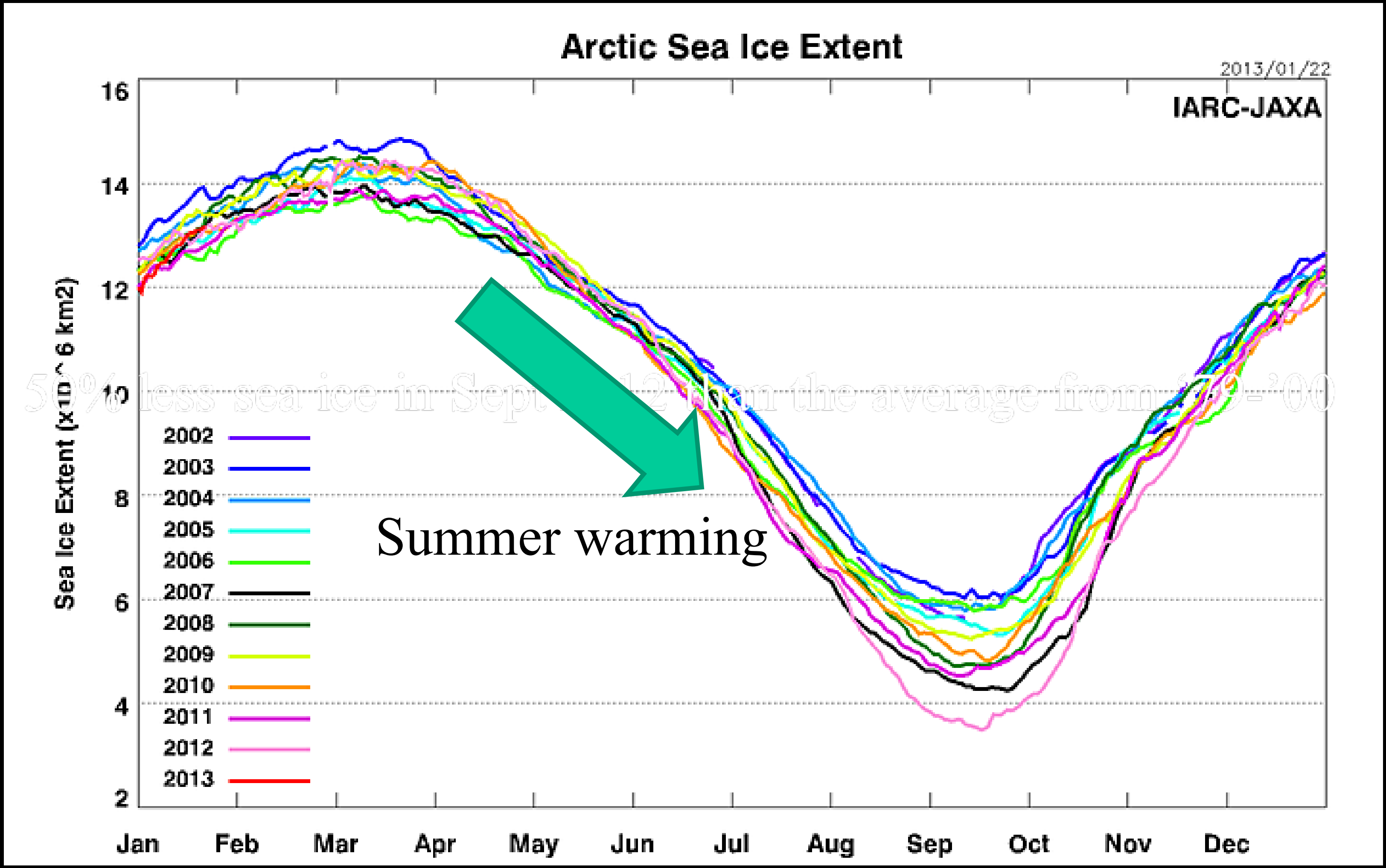
A Closed Loop



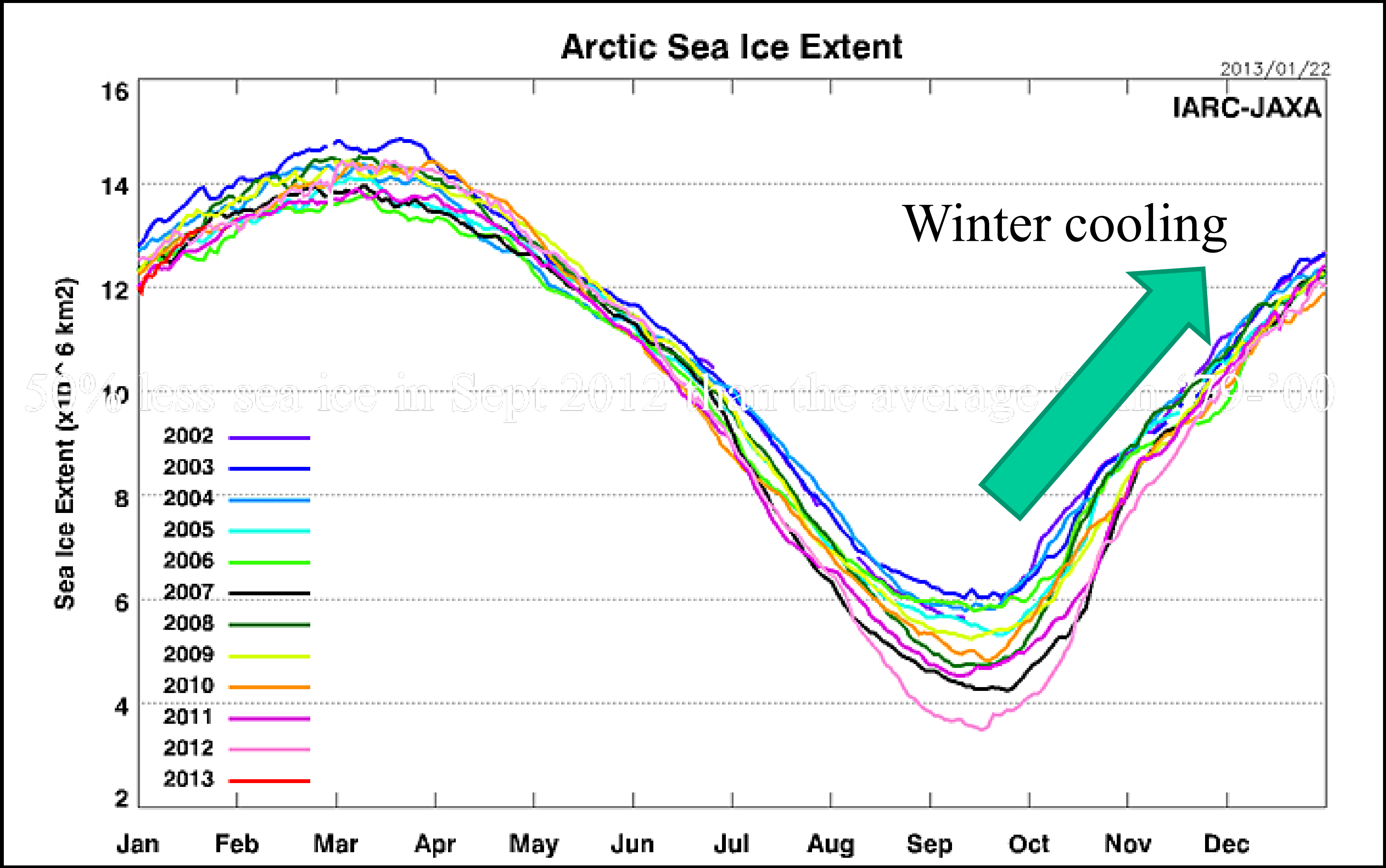
Positive Feedback

Fig. 3.21

Seasonal formation of sea ice is a very strong positive feedback



Seasonal formation of sea ice is a very strong positive feedback



Putting in numbers for Earth (like Homework 1)

$S = 1370\ W/m^2$ (watts per square meter)
$A = 0.30$ (30% of the Sun's incident radiation is reflected back to space)
σ (a constant) $= 5.67 \times 10^{-8}\ W/(m^2\ K^4)$

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

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

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

$$= [42.28 \times 10^{8}\ K^4]^{1/4}$$

$$= 255\ K$$

This is minus 18 ^oC (or -18 ^oC). This is much colder than the average surface temperature of the Earth (which is about 14 ^oC).

Clicker Question 2

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.

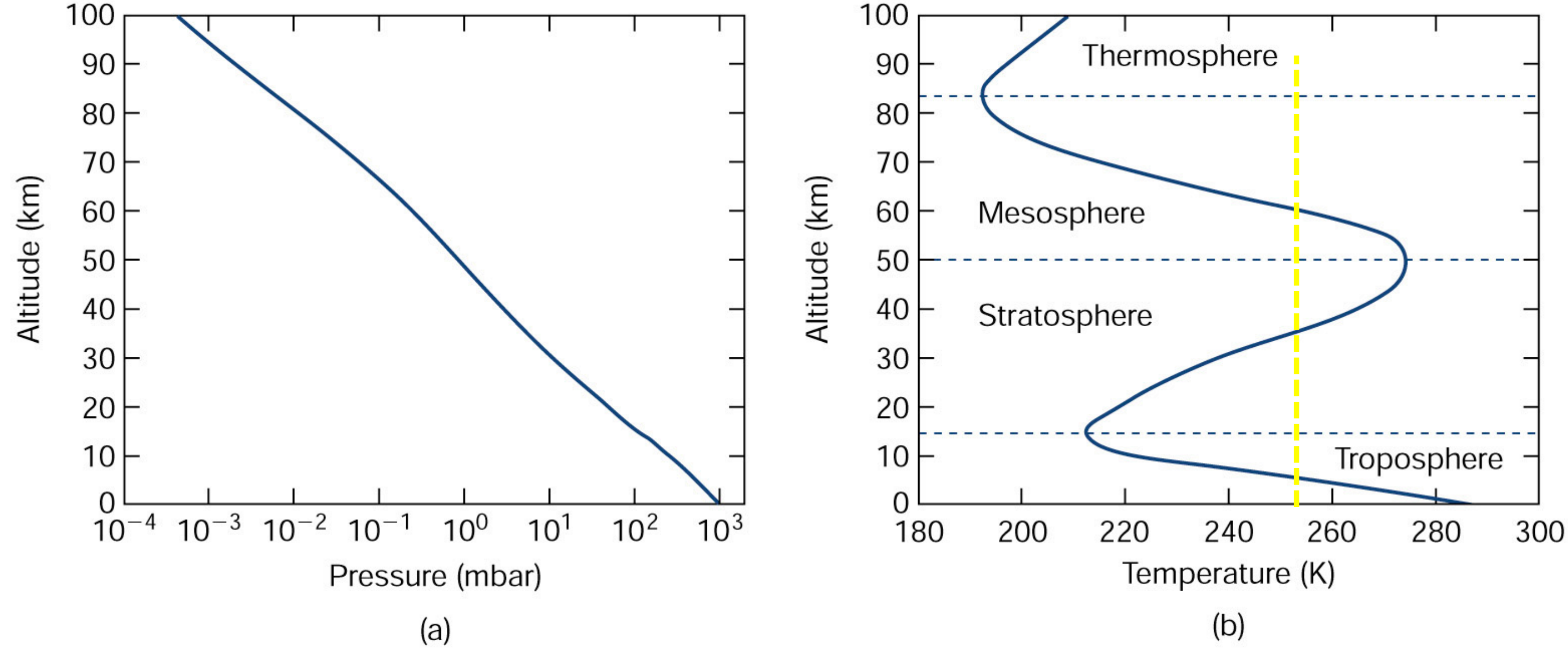


Fig. 3.9

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), and heat the upper atmosphere.

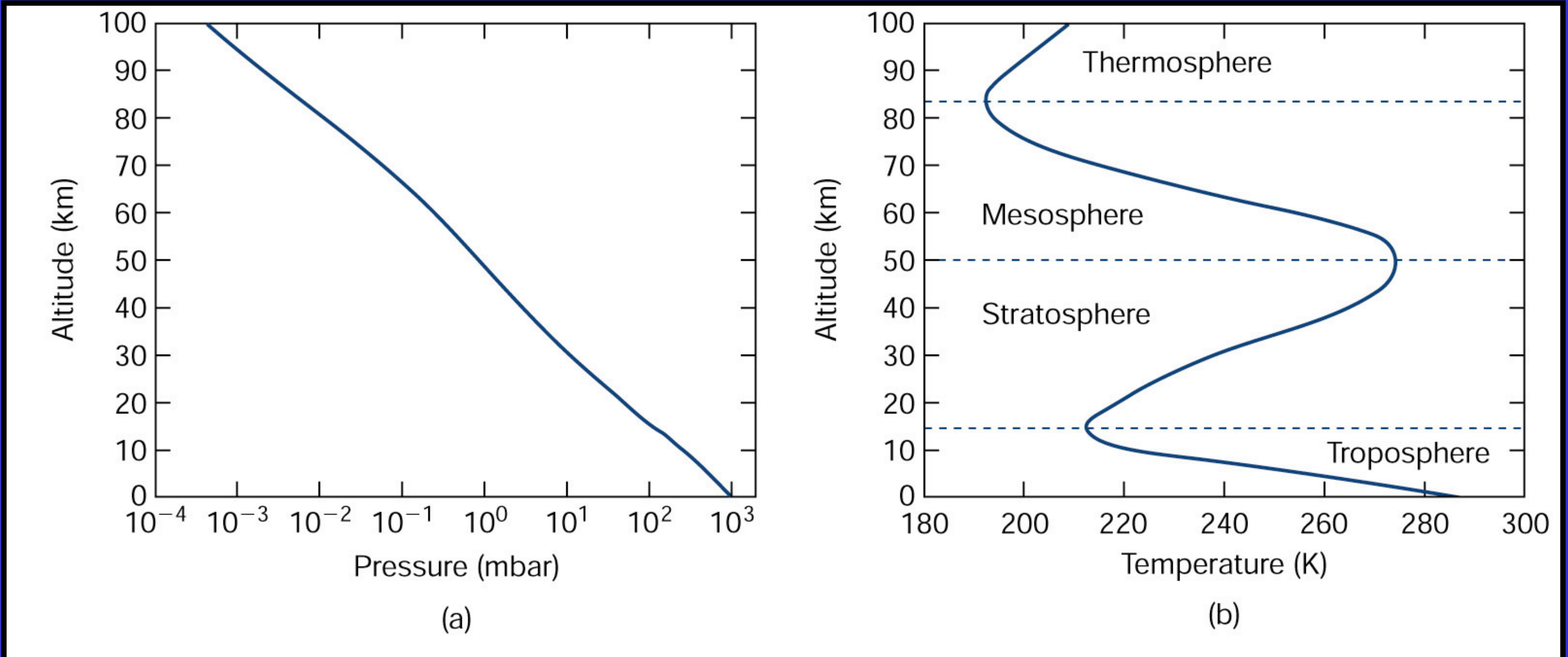


Fig. 3.9

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.

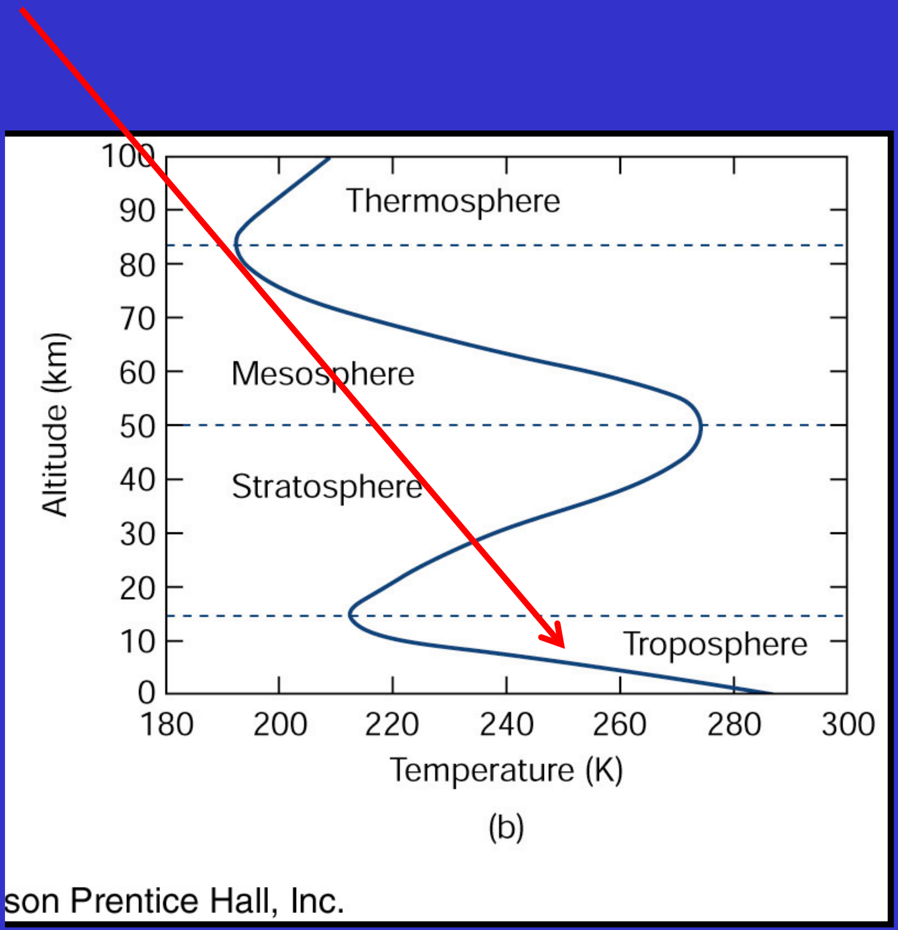


Fig. 3.9

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

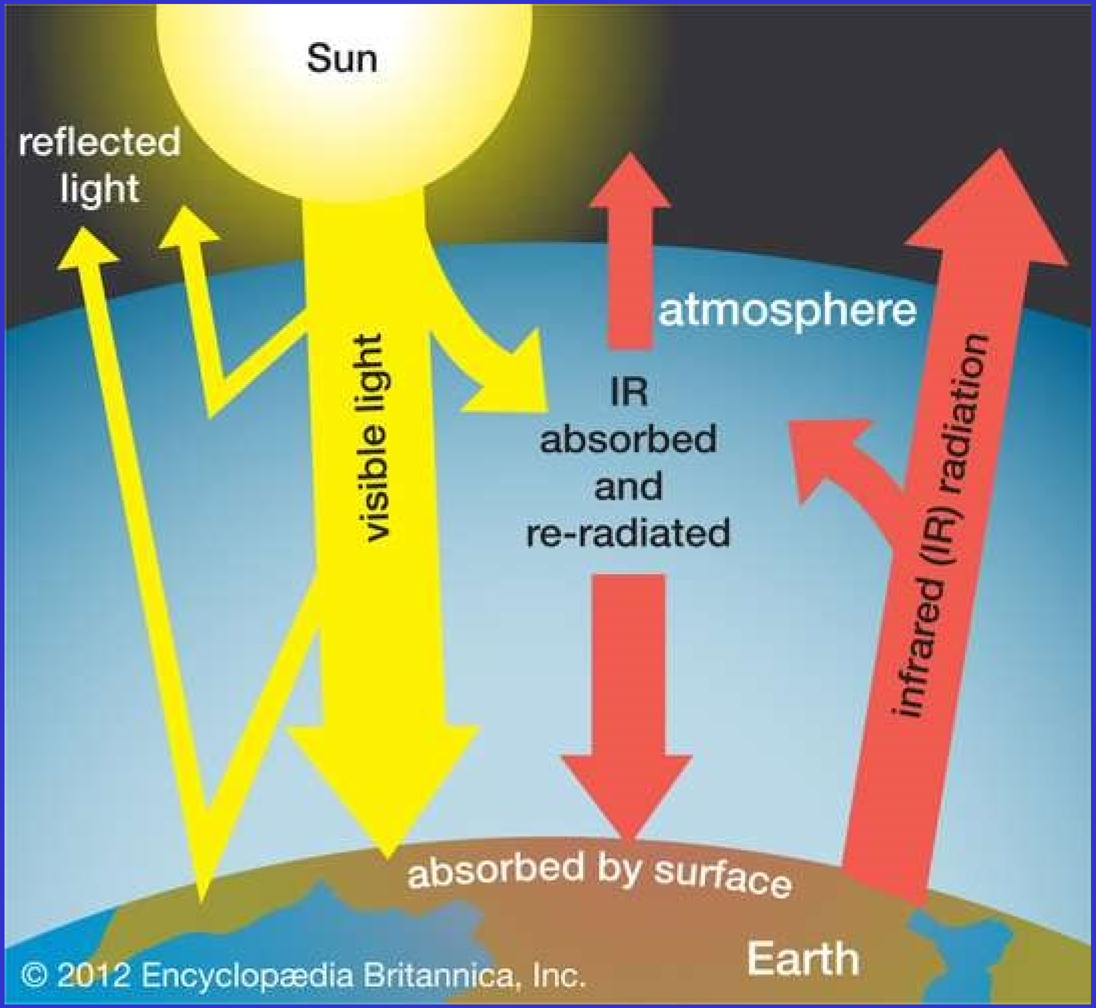
Atmospheric Composition
The Greenhouse Gases

TABLE 3-3

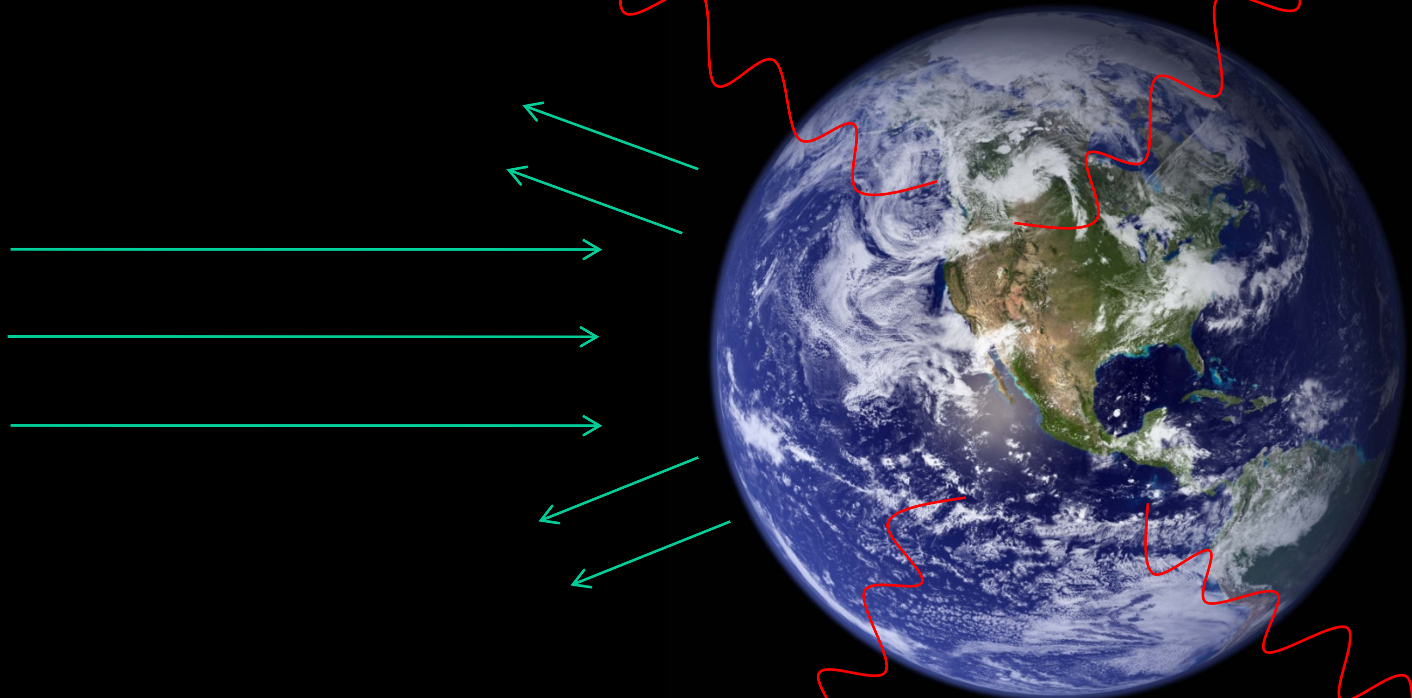
Important Atmospheric Greenhouse Gases

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

For next week – The Atmosphere and the Greenhouse Effect



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 a temperature of 255 K.



Question - If T_e is 255 K, what is λ_{max}?

Use Wien's Law (I won't answer this one for you!)

This is the T you get if you set the two boxed expressions equal to each other and solve for T

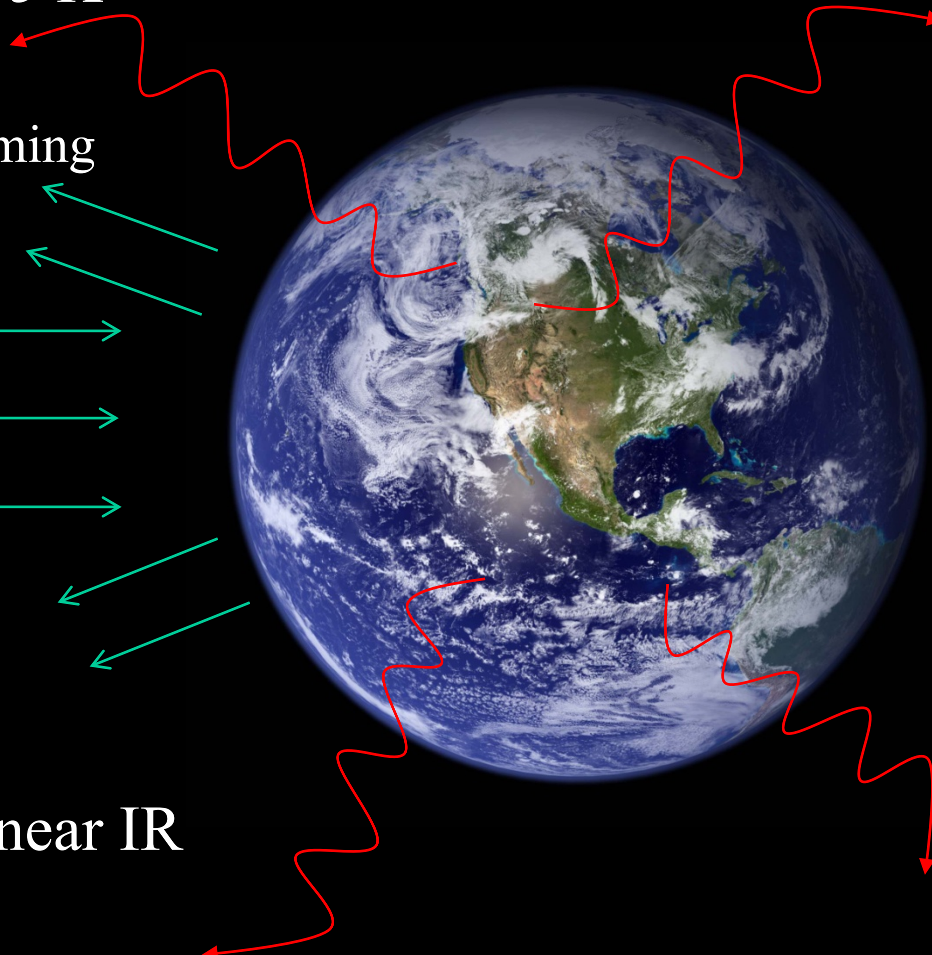
$T_e \sim 255$ K

Outgoing = middle and far IR

$\sigma T^4 \times (4\pi R^2)$

A = 0.3 (30% of incoming light reflected to space)

$S \times (\pi R^2) \times (1 - A)$



Incoming = solar visible and near IR

What we know so far:

Energy of light is inversely proportional to wavelength – shorter wavelength photons have higher energies than longer wavelengths.

A blackbody (an object that efficiently absorbs and emits electromagnetic radiation) will emit a spectrum of light that has maximum emission ("peak") at a wavelength (in microns, or μm) given by $\lambda_{max} = 2898/T$, with a long 'tail' of less emission at longer wavelengths. Thus, the apparent color of the object shifts to shorter wavelengths as the temperature of the blackbody increases.

The total amount of energy radiated from a unit of area of a blackbody increases by the fourth power of the temperature of the object (T^4 or TxTxTxT). So if the temperature of an object is doubled, the amount of energy radiating from that object is 16 times greater!

When we set the amount of solar energy absorbed by Earth equal to the amount of thermal energy it emits, we can derive an equation for the effective radiating temperature. Solving this equation using the solar flux at Earth and other constants gives us a temperature of about 255 K, which is minus 18 degrees Celsius!