Homework #11 Pt2 Solutions
Energy Flow through the Atmosphere and the Greenhouse Effect

Section 1: The solar spectrum

Objects give off different amounts of light depending upon their temperature. Figure 1 below shows the energy spectrum for our Sun along with the percent of energy given off by the Sun in the ultraviolet (UV), visible (VIS), and infrared (IR) portions of the electromagnetic spectrum.

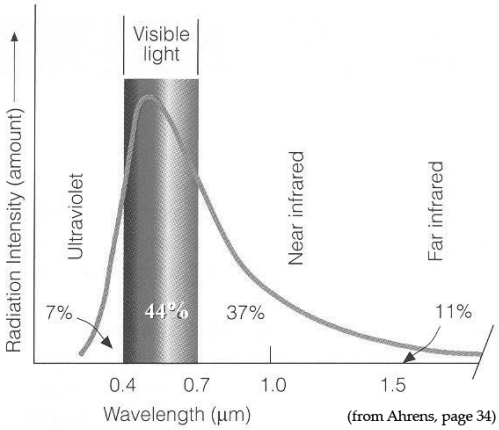


Figure 1

1) Which TWO forms of light account for the majority of energy coming from the sun: ultraviolet, visible, or infrared? Which of the three accounts for the least energy? Provide numbers to back up your answer.

   Visible and infrared light account for the majority of energy coming from the sun (92% all together!). Ultraviolet light contributes the least, only 7%.

2) Based upon Figure 1, why is ultraviolet light NOT an important energy source for heating the surface of the Earth?

   The sun doesn't radiate as much energy at ultraviolet energies as it does at visible and infrared energies. Thus, it does not contribute as much energy for heating the planet.

3) Consider the following debate between two students regarding the energy given off by the Sun.

   Student #1 – I think that the Sun gives off most of its energy at ultraviolet wavelengths because ultraviolet light is more intense than visible light and you always hear about ultraviolet light causing sunburns.

   Student #2 – Even though UV photons are more energetic than visible photons, the Sun simply gives off less ultraviolet photons and gives off way more visible and infrared photons. So I think that these longer wavelength photons account for most of the energy coming from the Sun.

   Do you agree and/or disagree with either of these students? Explain your reasoning.

   Student #1 is incorrect that the Sun gives off mostly ultraviolet light (see Figure 1). While UV causes sunburns, most of the light/energy from the sun is in the form of infrared and visible light.
   Student #2 correctly points out that just because an individual photon of UV may be more energetic, the sun gives off much more visible and infrared energy (see Figure 1).

Section #2: Atmospheric absorption of light

Earth's surface temperature is affected by energy that is absorbed at the surface. However, a photon's ability to travel through our atmosphere and reach the ground depends upon its wavelength. Figure 2 below shows that certain energies of light are absorbed in our atmosphere more than others. The figure also lists the primary gas molecules responsible for the absorption.

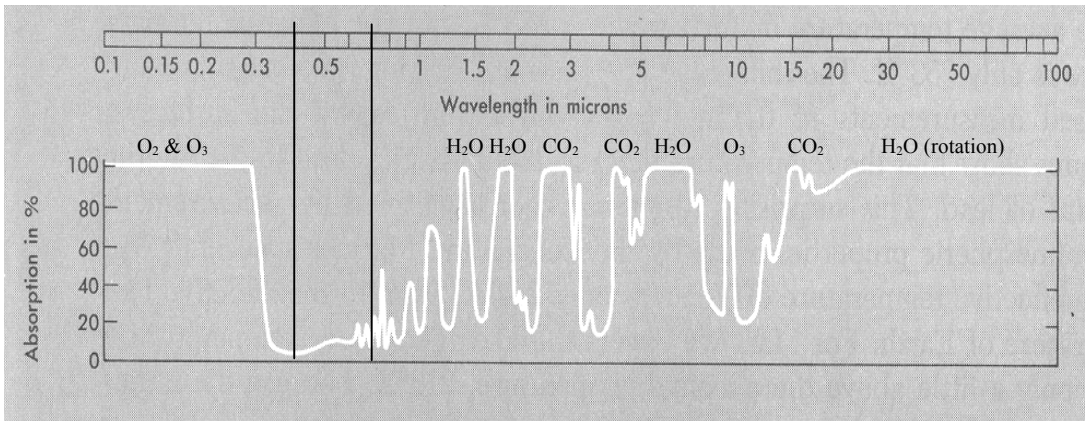


Figure 2

4) What gas molecules are primarily responsible for the absorption of each of the following forms of light in our atmosphere?

Type of Light	Molecule(s) Responsible for Absorption
Ultraviolet	***O_2 and O_3***
Visible	***None***
Infrared	***H_2O, CO_2, O_3***

5) Comparing the visible and the infrared parts of the spectrum, which would you say has an easier time getting through our atmosphere? Which experiences more absorption?

Visible light has an easier time getting through our atmosphere while infrared light experiences more absorption. Figure 2 shows that only ~10% of visible energy gets absorbed while the remaining 90% makes it through the atmosphere easily.

Section 3: Spectrum from Earth's surface

Once visible light from the Sun reaches the surface of Earth, it can either be reflected back towards space as visible light or be absorbed by the ground. Reflected light does not change the temperature of the surface, while absorbed light causes the temperature of the surface to increase. Ground that is heated then gives off infrared light based upon its increased temperature. As an example, black asphalt absorbs more visible light and gives off more infrared light than a white sidewalk on a hot day.

6) The Sun is approximately 6000K at the surface and gives off most of its energy as visible light; the Earth's surface is much cooler at about 288K. What type of light do you think the Earth's surface gives off: ultraviolet, visible, or infrared light? Explain your reasoning.

   Earth's surface radiates infrared light. Cooler objects give off longer wavelengths of energy while warmer objects give off shorter wavelengths. The Sun, which is much hotter, radiates the most at visible wavelengths. Earth's surface, which is cooler, radiates at infrared wavelengths.

7) Does Earth's surface give off light at night? If so, what type? If not, why not?

   Yes, Earth's surface gives off infrared light during both day and night. Objects with temperatures around 288K give off infrared energy all the time, including the human body (you!).

8) Based upon your answer to Question 5 and 7, will the light given off by Earth's surface easily travel back through the atmosphere to space or will it be absorbed by molecules in the atmosphere? Explain your reasoning.

   Visible light reflected by the surface will travel easily back through the atmosphere, but the light radiated by Earth's surface (infrared light) will be absorbed by molecules in the atmosphere (see Figure 2).

Section 4: Energy flow and the greenhouse effect

Figure 3 below shows the flow of energy originally from the Sun through the Earth system (surface and atmosphere). The numbers listed describe the rate of energy flow through system (units of watts per square meter). A larger number indicates that more energy is flowing through that labeled pathway.

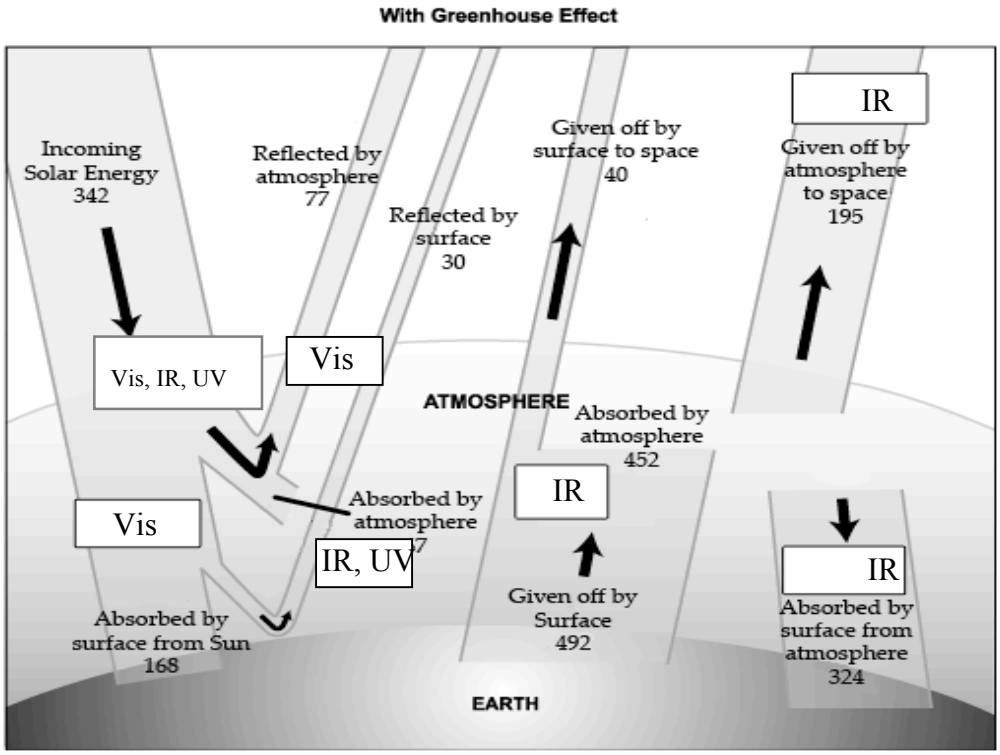


Figure 3

9) In Figure 3, fill in the empty boxes with the type of light involved: UV, visible, or IR.

10) What two types of light primarily heat Earth's surface. What one type of light primarily heats Earth's atmosphere?

Visible light arriving directly from the sun and infrared light re-radiated by the atmosphere primarily heat Earth's surface. The main type of light heating Earth's atmosphere is infrared light radiated from the surface.

11) Is more energy absorbed by the Earth's surface in the form of light from the Sun or light from the atmosphere? Provide values to justify your answer.

More infrared light is actually absorbed from the atmosphere (324 watts per square meter) than visible light from the Sun (168 watts per square meter).

12) Due to the energy absorbed by Earth's surface from the atmosphere, is the surface temperature warmer or cooler than it would be without this energy input?
The temperature of the surface is warmer than it would be because it receives a total of 492 watts per square meter (168 + 324) rather than just 168 watts per square meter.

13) How does the total rate of energy coming in from space (incoming solar energy) compare to the total rate of energy leaving out to space (all energy reflected or given off by earth and atmosphere)? Provide values to justify your answer.

They are equal to each other. 77 + 30 + 40 + 195 = 342

14) Based upon your answer to Questions 13, does the total energy in the Earth system increase, decrease, or stay the same over short time scales? Explain your reasoning.

Over short time scales, the energy leaving equals the energy arriving so the total amount of energy in the atmosphere stays the same.

The flow of energy shown in Figure 3 is the source of the natural "atmospheric greenhouse effect." Visible light penetrates the atmosphere and is absorbed by the surface. The heated surface gives off infrared light that is then absorbed by the atmosphere. The heated atmosphere gives off infrared light out to space and also back down to Earth's surface, making the surface temperature warmer than it would be without a greenhouse effect. The amount of energy entering and leaving the Earth system is balanced, but the Earth's surface temperature is warmer because the surface is heated both by visible light from the Sun and infrared light from the atmosphere.

15) In Question 4, you listed several gases. Which of these are primarily responsible for absorbing and emitting infrared light? What characteristic makes them greenhouse gases?

Water and carbon dioxide are gases that absorb and emit infrared light. These gases are transparent to visible light and absorb and give off infrared light.

16) Consider the following debate between three students regarding the greenhouse effect.

Student #1 – So the greenhouse effect is caused by infrared light being trapped in Earth's atmosphere by greenhouse gases. Visible light from the sun heats the ground, but the infrared light given off by the ground gets permanently trapped in the atmosphere and can never escape.

Student #2 – I think that's close. But based on Figure 3, all of the arrows balance and just as much energy leaves the planet as comes in. I think the greenhouse effect makes the surface hotter than it would be without greenhouse gases because the ground gets visible light from the Sun AND infrared light from the atmosphere given off back to the surface.

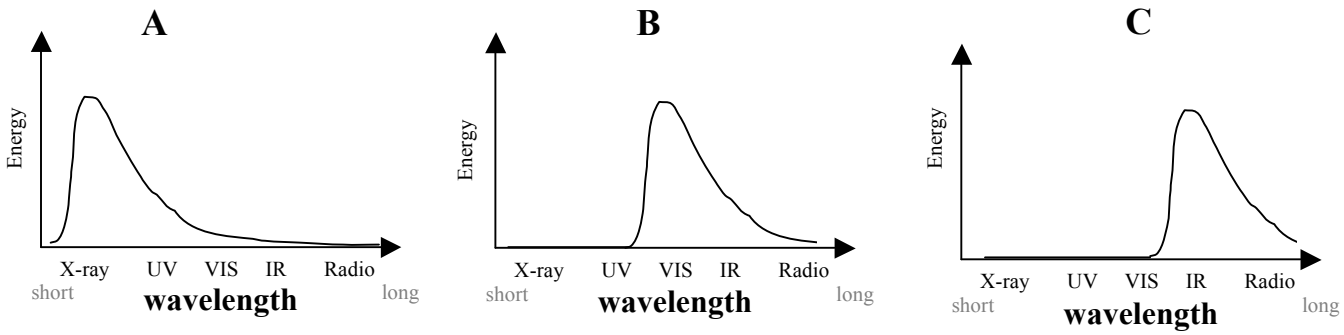
Do you agree and/or disagree with each of these students? Explain your reasoning.

Student #1 is correct that visible light from the sun heats the ground which then gives off infrared light which is then absorbed, but incorrect in that this energy is not trapped forever (permanently). Heated greenhouse gases re-emit infrared light back to the ground or up to space.
Student #2 correctly describes a balance of energy arriving and leaving and that the re-radiated energy from the atmosphere increases the temperature of the planet.

Section 5: Spectrum from Earth's surface

Once visible light from the Sun reaches the surface of Earth, it can either be reflected back towards space as visible light or be absorbed by the ground. This absorbed visible light causes the temperature of the surface to increase. The ground then gives off energy based upon its increased temperature.

17) The surface of the Earth is much cooler than the surface of the sun. In what wavelength region does Earth's surface give off the most energy? **IR**



18) Which of the diagrams (A, B, or C) above most accurately represents the energy given off by Earth's surface as a function of wavelength? Explain your reasoning.

C – The spectrum shown in figure C shows the most energy being given off at IR wavelengths.

19) According to your answers to Questions 17 and 18, would the surface of the Earth give off x-ray, visible, or infrared photons during the middle of the night? Correct your answers to Questions 17 and 18 to match reality if necessary.
The Earth would give off infrared photons during the middle of the night. If you incorrectly chose A as your answer, the Earth would be glowing at X-ray and UV wavelengths at night (which is not the case). If you incorrectly chose B as your answer, the Earth would be glowing most at visible wavelengths (which is also not the case because it is dark to our eyes at night).

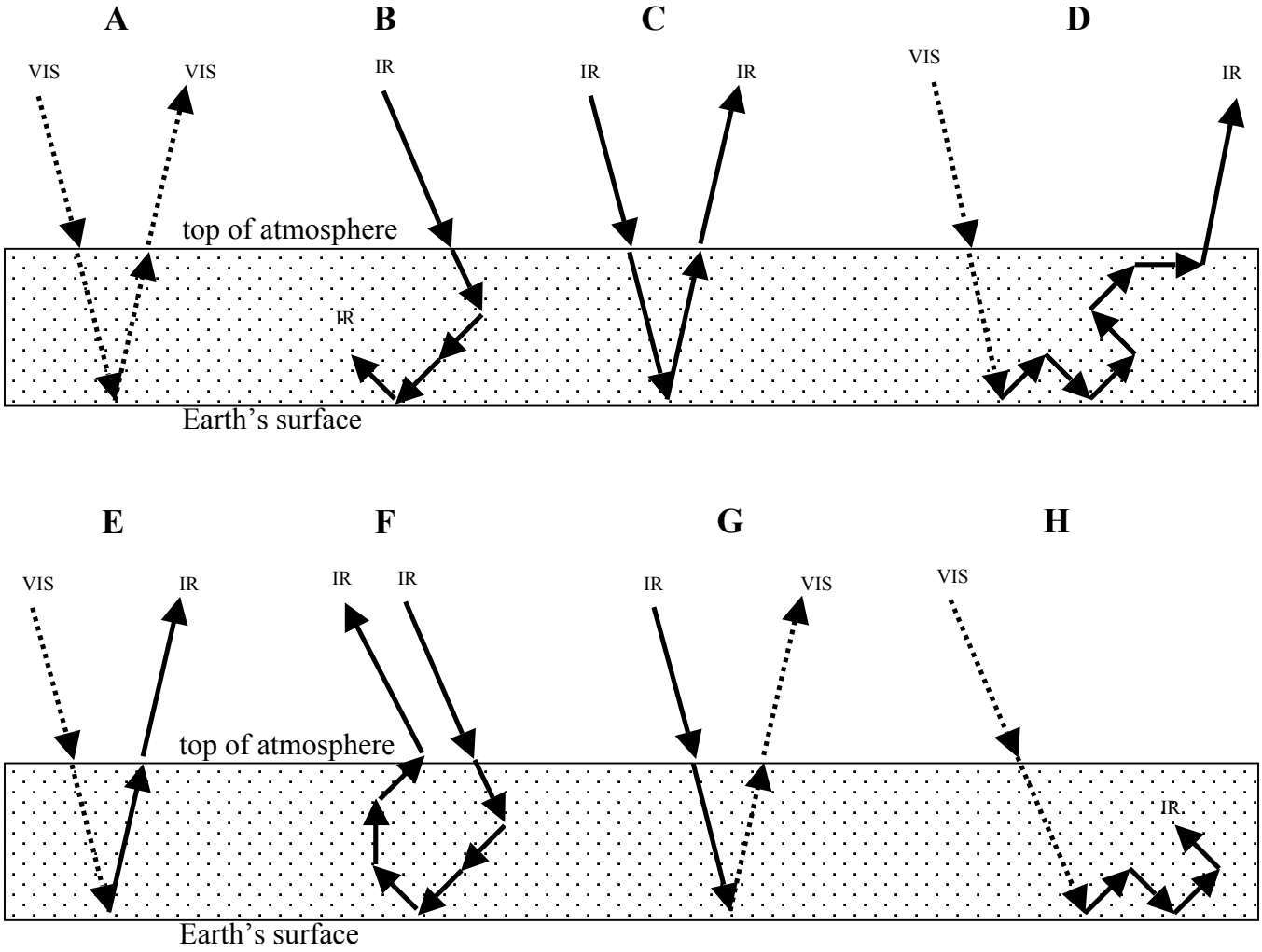
20) What happen to the temperature of the atmosphere as it absorbs light from either the Sun or from Earth's surface?

Same as your answer for #13, the temperature of the atmosphere increases when it absorbs energy.

Section 6: The Greenhouse Effect

You should now have a picture of visible light traveling all the way through the atmosphere to the surface of Earth while infrared light (both from the Sun and from Earth's surface) cannot travel very far through the atmosphere without being absorbed. It is important to note that this absorbed infrared light doesn't disappear and also isn't trapped in the atmosphere forever; rather, it simply travels a shorter distance through the atmosphere before it is absorbed and then given off again in a random direction. So, while visible light can travel all the way through the atmosphere without being absorbed, infrared light is continuously absorbed and given off and absorbed and given off many times as it travels through the atmosphere and travels shorter distances.

The diagrams below show possible paths for visible and infrared light as they travel through Earth's atmosphere. Visible light is represented with dashed arrows; infrared light is shown with solid arrows. Note that three out of the eight diagrams properly depict possible paths for visible and infrared light through the atmosphere.



21) List the FIVE diagrams that incorrectly depict how visible and infrared light travel through the atmosphere? For each, describe what is wrong with the diagram.

B – The diagram correctly shows IR light being absorbed and re-emitted by the atmosphere, but it incorrectly shows the IR light being trapped forever after the last absorption event shown. In reality, infrared light eventually makes it to the top of the atmosphere and radiates to space.
C – The diagram incorrectly shows IR light traveling directly into and out of the atmosphere. Based upon the absorption properties of the atmosphere, IR light is more likely to be absorbed and re-emitted several times in the atmosphere.
E – The diagram correctly shows visible light passing through the atmosphere, heating Earth's surface and re-emitting IR light, but it incorrectly shows this IR light passing directly back through the atmosphere without being absorbed and re-emitted by greenhouse gases.
G – The diagram incorrectly show IR light passing directly through the atmosphere (rather than being absorbed and re-emitted) and also shows IR light converting into visible light at the surface. It is very uncommon for infrared light to increase in energy to visible light; rather it is more common for visible light to convert into IR light.
H – The diagram incorrectly shows the infrared light being permanently trapped after the last absorption event shown. In reality, infrared light eventually makes it to the top of the atmosphere and radiates to space.

22) Of the remaining three diagrams, which shows visible light reflecting off the surface of the earth and traveling back out to space as visible light? If this light is completely reflected, does it do any heating of the surface?

Diagram A shows visible light reflecting off the surface and traveling directly back out to space. This reflection event does not heat the surface.

23) In the space below, redraw the TWO diagrams that properly show how visible and infrared light travel through the atmosphere and lead to an enhanced surface temperature.

See diagrams for "D" and "F"

24) What is the source of visible photons that heat the surface of Earth? What are the TWO sources of infrared photons that heat the air in our atmosphere?

The sun is the source of visible photons that heat the surface of Earth. Both the sun and the heated surface of Earth are sources of IR photons that heat the air in our atmosphere.

25) If the surface of Earth immediately gave off to outer space the same amount of energy as it received from the Sun, the surface would be 255K (0°F). Where does the additional energy come from that heats the surface of Earth to its measured value of 288K (58°F)?

The fact that greenhouse gases absorb and re-emit IR photons causes these photons to spend more time in the atmosphere than they normally would if they could radiate directly out to space. The atmosphere acts like an insulator slowing down the transport of IR energy out of the atmosphere. The fact that these IR photons spend more time in the atmosphere and also reheating the surface of the earth increase the surface temperature to a value of 288K.