Homework Assignment # 2 solutions and discussion

1. a) Figure 1 shows a simplified sketch of the vertical temperature structure of the troposphere and lower stratosphere. Remember that the lapse rate is the temperature variation with height; the lapse rate is positive if the temperature increases with height, and it is negative if the temperature decreases with height. Using Figure 1, calculate the temperature lapse rate in the <u>*troposphere*</u> *(show your work).*

Using two points on the graph (namely, the top and bottom of the troposphere):

lapse rate = (change in temperature) / (change in altitude)

= [15°C - (-50°C)] / (0 km - 10 km) = (65°C) / (-10 km) = -6.5°C/km

Note that the lapse rate in the troposphere is NEGATIVE, meaning that temperature *decreases* with height. Make sure that if you subtract the temperature at the tropopause from the temperature at the ground, you also subtract the altitude at the tropopause from the altitude at the ground to get the proper sign!

b) The temperature lapse rate in the <u>*stratosphere*</u> *is +1.2°C/km (the temperature increases with height in the stratosphere). The stratopause is located at 50 km above the surface. What is the temperature at the stratopause?*

The tropopause is located at an altitude of 10 km and its temperature is about -50°C. The stratopause, located at 50 km, is 40 kilometers above this point. So at a temperature lapse rate of +1.2°C/km, we would expect the temperature change in the stratosphere to be:

change in temperature = (lapse rate) x (change in altitude)

= (+1.2°C/km) x (40 km) = +48°C

So if the tropopause is at -50°C, the stratopause will be 48°C warmer, or -2°C.

c) An infrared satellite orbiting the earth observes a cloud over Arizona and infers the temperature of the top of this cloud to be -37°C. Estimate the altitude of this cloud (using Figure 1). Would you expect this cloud to be made of liquid water or solid water?

Using Figure 1, you can estimate that the top of the cloud is located about 8 km above the surface. You could also use the lapse rate you calculated in part (a), but make sure that you don't make any sign errors:

change in altitude = (change in temperature) / (lapse rate)

= [-37°C - (+15°C)] / (-6.5°C/km) = 8.2 km

Since -37°C is far below the freezing point of water, this cloud is probably composed of solid water (typically in the form of ice crystals).

d) The same satellite observes another cloud located over Seattle with a temperature of 2°C. Estimate the altitude of this cloud. Would you expect this cloud to be made of liquid water or solid water?

Using Figure 1 or the lapse rate from part (a), you can estimate that the top of this cloud is located 2 km above the surface. Since 2°C is above the freezing point of water, this cloud is probably composed of liquid water droplets.

e) High clouds are usually made of ice crystals and are called cirrus. Low clouds are usually (although not always) composed of water droplets and are called stratus. What type of cloud was observed over Arizona? Over Seattle?

The cloud over Arizona was probably a cirrus cloud. The cloud over Seattle was probably a stratus cloud. Note that we make this inference based solely on the temperature and estimated altitude of the cloud; the fact that Arizona is drier than Seattle has nothing to do with this problem. Clouds are composed of solid or liquid condensed water, so the relative humidity inside of a cloud is always 100%.

2. a) Figure 2a shows the vertical temperature structure in Earth's atmosphere. Figure 2b shows the vertical temperature structure of the atmosphere on another planet. How might you explain the difference between the temperature structures around 50 km?

The relatively warm temperatures in the Earth's stratosphere and mesosphere are due to the absorption by ozone of ultraviolet (UV) radiation from the sun. Ozone concentration is highest in the middle to lower stratosphere. The actual temperature maximum is slightly higher (at the stratopause) because some of the UV radiation gets absorbed by higher ozone molecules before it reaches the lower stratosphere, and because the lower air density in the upper stratosphere and mesosphere means that it doesn't take as much energy absorption to increase temperature.

The atmosphere of the planet depicted in Figure 2b has no temperature maximum around 50 km. So either this planet doesn't have any ozone, the ozone is well mixed throughout the atmosphere so UV radiation gets absorbed equally at all levels, or the sun that this planet orbits does not emit much UV radiation. Another possible answer was that the atmosphere of the (giant) planet extends farther out, so that Figure 2b actually depicts only the troposphere of the planet.

Note that the layers of the Earth's atmosphere, i.e. the troposphere, stratosphere, etc., are not physical boundaries in the atmosphere but are named for their properties. The troposphere is our name for the lowest region of the atmosphere where temperature decreases with height and weather occurs, just like we call the deepest part of the swimming pool the "deep end" although it is (usually) smoothly connected to the "shallow end" of the pool without any walls or other boundaries.

Note also that "the temperature is lower at 50 km on the other planet because the temperature does not increase with height in the stratosphere" is not an explanation but a mere description of what is happening in that part of the atmosphere.

b) How might you explain the difference between the surface temperatures?

If the other planet has no ozone, then more radiation will reach the surface so we would expect the surface temperature to be warmer. This planet might also be closer to the sun, or it might have a very low planetary albedo, or (probably the most likely explanation) the greenhouse effect is stronger on this planet due to higher concentrations of selective absorbers in the atmosphere.

3 a) Figure 3 is a sketch showing a simplified radiative balance on Earth. First identify the different terms in Figure 3, choosing from the following list (note that some of these are "trick" questions; some of the following processes do not appear in the figure):
(i) Emission of visible radiation by the surface not shown (very, very small in reality)
(ii) Reflection of visible radiation back to space by the cloud layer B
(iii) Emission of infrared radiation by the cloud layer F (up + down)
(iv) Emission of visible radiation by the Sun A
(v) Emission of infrared radiation by the surface E
(vi) Transmission of visible radiation through the cloud layer C
(vii) Absorption of infrared radiation by the cloud layer E
(viii) Reflection of visible radiation back to space by the surface D
(ix) Transmission of infrared radiation through the cloud layer not shown
(x) Absorption of visible radiation by the cloud layer not shown (very small in reality)

b) Assuming that A=100 units of energy, and that the albedo of the cloud layer is approximately 20%, calculate C.

C = A - B = 100 - 20 = 80 units of energy

c) If D=10 units of energy are reflected by the surface, how much energy in the form of visible radiation is absorbed by the surface of the Earth?

visible energy absorbed = visible energy received - visible energy reflected
= C - D = 80 - 10 = 70 units of energy

d) Assuming that the cloud layer is in radiative equilibrium, and that the cloud does not absorb visible radiation, we could write a radiative balance for the cloud layer, where:

input of energy = output of energy
E = F(up) + F(down)

Write a radiative balance for the surface of the earth, assuming that it is in radiative equilibrium. (Put energy inputs on one side of the equation and outputs on the other side.)

energy inputs = energy outputs
C + F(down) = E + D
(or)
(C-D) + F(down) = E

e) Again assume that the surface of the Earth is in radiative equilibrium. If F(down)=70 units of energy, calculate E using your answers from parts (b), (c), and (d). Is this consistent with the value of E given by E=F+F above, assuming that F(up)=F(down)?

E = F(down) + C - D = 70 + 80 - 10 = 140 units of energy
This is consistent with E = F(up) + F(down) = 70 + 70 = 140 units of energy

f) How would you expect terms A-F to change if you increased the number of low clouds? Would the surface of the earth be colder or warmer? Why?

A would not change (sun's emission is not affected by the number of clouds on earth).
B would increase because more low clouds means more reflected solar radiation (low clouds have a high albedo).
C would decrease because more solar radiation would be reflected back to space by the clouds, leaving less to transmit through the clouds.
D would decrease because less solar radiation reaching the surface means less is reflected by the surface once it gets there.
E would decrease because less solar radiation reaching the surface would mean less solar radiation absorbed by the surface, which would mean a lower surface temperature and thus less longwave radiation emitted by the surface to maintain radiative equilibrium. However, see F(up) and F(down)--
F(up) and F(down) are tricky, and as long as your reasoning was sound we did not subtract points. If E decreases, less longwave radiation would be received and absorbed by the clouds, so both F(up) and F(down) would decrease because the clouds re-radiate all of the longwave radiation that they receive (and this is now lower).
However, you could also argue that a higher *fraction* of the sky occupied by low clouds means that in some areas the clouds would be absorbing longwave radiation that escaped directly to space before, and since they would re-radiate this energy you would expect F(up) and F(down) to both increase. Note that this would counteract the surface temperature decrease and so you would not expect E to decrease as much, or maybe E could even increase in this situation (which would be similar to Venus's atmosphere, which has a high albedo but an extreme greenhouse effect).
We really just wanted you to assume that the clouds already absorb all of the Earth's longwave radiation, so increasing the number of low clouds would only affect the reflection of solar radiation and not the absorption of surface longwave radiation.

g) This problem is drastically simplified. Name at least one important process that was not included in Figure 3. Where would you include this process in the diagram?

Transmission of longwave radiation by clouds, convection, evaporation, etc.

4) Explain how you would expect the following changes to impact the surface temperature of the earth and why. A sentence or two is sufficient for each.

a) Snow cover increases

An increase in snow cover would increase the average albedo of the Earth's surface. Thus the Earth's surface would absorb less solar radiation, and thus the surface temperature would have to **decrease** to maintain radiative equilibrium.

b) The number of high clouds increases

High clouds warm the surface because they are poor reflectors of solar radiation (low albedo), but they are good absorbers of longwave radiation emitted by the Earth. Thus an increase in the number of high clouds would not change the amount of solar radiation received at the Earth's surface, but it would increase the amount of longwave radiation absorbed by high clouds and re-emitted back to the surface. To achieve radiative equilibrium, the surface temperature would have to **increase**.

c) The number of low clouds decreases

Low clouds cool the surface because they are good reflectors of solar radiation (high albedo), although they also warm the surface because they absorb and re-radiate some of the longwave radiation emitted by the Earth. (This is why it seldom gets too warm during the day or very cold at night when there are low clouds overhead.) The *net* effect of low clouds is to cool the surface (the reflection of shortwave radiation dominates longwave trapping). So if you were to decrease the number of low clouds, you would decrease the average shortwave albedo, which would mean more radiation reaches the surface and the surface temperature would **increase**.

d) The concentration of water vapor in the atmosphere increases

Water vapor is an important greenhouse gas (in fact, the most important one). An increase in the concentration of water vapor in the atmosphere would constitute a greenhouse warming, which would mean a surface temperature **increase**. Note that we only asked what would happen if the concentration of water *vapor* increased; you did not need to consider changes in the number of clouds or precipitation due to higher water vapor concentration.

e) Anthropogenic CO_2 emissions increase

The anthropogenic increase in carbon dioxide concentration due to fossil fuel burning and other activities constitutes a large portion of greenhouse warming, which we talked about in class for several days. Surface temperature would **increase**.

e) The concentration of SO_2 aerosols decreases (consider only the direct effect)

The *direct* effect of sulfur dioxide aerosols is to scatter some of the incoming solar radiation back to space. Thus if the concentration of these aerosols was to decrease, more shortwave radiation would reach the surface and the surface temperature would **increase**. Make sure you know the difference between the *direct* effect of aerosols and the *indirect* effect of aerosols.

f) The amount of forest cover decreases (Hint : the albedo of a forest is very small)

Forests absorb almost all of the solar radiation they receive. If you were to chop down these forests, the albedo of the surface would increase (the albedo of dirt is higher than the albedo of forest), less solar radiation would be absorbed by the surface, and the surface temperature would **decrease**.

5 a) When does the longest day of the year occur in Seattle (longest duration of sunlight)? The longest night of the year? Equal hours of day and night? Explain.

The Earth's axis of rotation is tilted 23.5 degrees from the ecliptic plane (the plane of the Earth's orbit around the sun). At certain times of year the Northern Hemisphere (including Seattle) is leaning more in the direction of the sun and we receive both more intense radiation (because the zenith angle is smaller) and a longer duration of radiation (because we spend more time in the "sunlit" half of the Earth than we do on the "dark side" of the Earth as it rotates on its axis). At other times of the year we are pointed away from the sun and we receive less intense radiation and have shorter "days". Currently, our tilt into the sun is maximal on June 21st or 22nd, so this is the longest day of the year in Seattle (we call the longest day, or the day with the smallest zenith angle at noon, the summer solstice). The longest night occurs on December 21st or 22nd, when we are "pointed" away from the sun, and this is called the winter solstice. On March 21st-22nd and September 21st-22nd, the Earth's axis is oriented such than neither the Northern Hemisphere nor the Southern Hemisphere is pointed towards the sun so every point on Earth, including Seattle, receives exactly 12 hours of sunlight.

b) If the Earth's tilt suddenly shifted from 23.5 degrees to 45 degrees, how would you expect your answers in part (a) to change? Would you expect the summer to be warmer or colder in Seattle if this happened? Why?

The argument in part (a) does not depend on the exact tilt of the Earth, so the longest day of the year, shortest day of the year, and equal parts day and night would occur on the same calendar days. However, if the tilt were 45 degrees, Seattle would actually receive 24 hours of daylight during the summer solstice and also for a few days before and after the solstice (we would be above the new "arctic circle"). Also, the sun would be much more intense at noon that it is currently at that time of year (we would be very close to the new "tropic of cancer"), so we would expect the summers to be much, much warmer than they are now.

c) If you lived on the equator, when would the longest day of the year occur? The longest night? Why? When during the year would you expect the sun to be directly overhead at noon? When would it be the closest to the horizon at noon?

The equator is neither in the Southern Hemisphere nor the Northern Hemisphere, and consequently it is never pointed "at" the sun or "away" from the sun. Also, points on the equator **always** spend exactly half their time on the sunlit half of the Earth and half their time on the dark side of the Earth, so every day has 12 hours of daylight and there is no "longest day" or "longest night" of the year at the equator. However, the solar zenith angle at noon does change over the course of the year on the equator. Recall that the sun is directly overhead at noon at the tropic of cancer during the summer solstice and at the tropic of capricorn during winter solstice (in the Northern Hemisphere), so it cannot also be directly overhead at noon on the equator during those days! In fact, the sun is farthest from overhead at noon (i.e. closest to the horizon) during the solstices. During the equinoxes, neither Hemisphere is pointed "at" the sun and the sun is directly over the equator at noon. Make sure you understand the difference between length of day and the intensity of sunlight due to solar zenith angle.