Homework solutions for Dessler's Introduction to Modern Climate Change

Third edition

If you find any errors, please send an e-mail to the author at adessler@tamu.edu

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Solutions to chapter 1 problems

1. White House: 38.90°N, 77.04°W, Kremlin: 55.75°N, 37.62°E, Pyramids: 29.98°N, 31.13°E. To find the location on the other side of the Earth, simply swap the hemisphere for latitude; for longitude, the opposite longitude is 180 minus longitude and change the hemisphere (thus, 30°N 70°W becomes 30°S 110°E)

2. (a) 149, 100, 21, 10, 0, -18°C

(b) 302, 212, 158, 122, 32, 14°F

3. (a) 1.8°F (b) 0.56°C (c) The reporter confused an increase in temperature (0.8°C = 0.8*9/5 = 1.4°F) with the conversion of a one absolute temperature to another (0.8°C * 9/5 + 32 = 33°F).

4. Set y = (9/5)y + 32 and solve for y to find that -40°F = -40°C

5. To calculate this, solve the equation 10x+y = (10y+x)*9/5+32 for x, which yields x = 5/41(32+17y). Then, insert y = 0 through 9 and take those solutions whose answers are 0 through 9. This yields 3 answers: 40°F (04°C), 61°F (16°C), and 82°F (28°C).

8. (a) 7% and 4% (b) 31°C and 33°C, an increase of 2°C (c) 32°C

For part (d), approximate the integrals as triangles. For the 1970s, the height is the value for 35°C, 1.5% and the base is 3°C, giving us an answer for the 1970s of 2.3%. For the 2010s, the height of the triangle is 8% and the base is 6°C. This gives an answer of 24%. These are very close to the actual values from integrating the curves, 2.4% and 22.9%.

(e) These very warm temperatures occur 22.9/2.4 or nearly 10 times more frequently in the 2010s than in the 1970s.

Solutions to chapter 2 problems

1. (a) Total growth is 3.5” (he goes from 2” below the hook to 1.5” above). (b) It took 5 years to grow, the average growth rate = 3.5”/5 years = 0.7”/year. (c) You cannot determine his absolute height from the information given.

2. From 1880 to 2012, the Earth warmed 1.3°C = 2.3°F. From Fig. 2.2, the warming from 1970 to 2020 is 0.7°C = 1.3°F.

3. No, because there is so much other evidence. The failure of a single data set would not alter my confidence in a warming Earth.

4. We are confident because we have many independent measurements that all show a consistent picture of a warming Earth. While any particular measurement could be wrong, the odds that all are wrong, and all in the same direction, is basically zero.

5. The evidence that the Earth is warming includes surface thermometer measurements, satellite temperature measurements, receding glaciers, melting sea ice, melting ice sheets, increasing ocean heat content, and rising sea level. There is virtually no evidence that goes against this conclusion.

6. A temperature anomaly is the difference between the actual temperature and a reference temperature, usually an average over a previous multidecadal period. Climatologists use anomalies rather than absolute temperature because absolute temperature can vary sharply over short distances, such as between a city and a nearby rural area. Anomalies, however, are constant over much longer distances: If it is a degree warmer than average in a city, then it is probably a degree warmer than average a few kilometers away from the city, even if the absolute temperatures are different by a few degrees. This makes the calculation of anomalies more accurate by requiring a less dense measurement network.

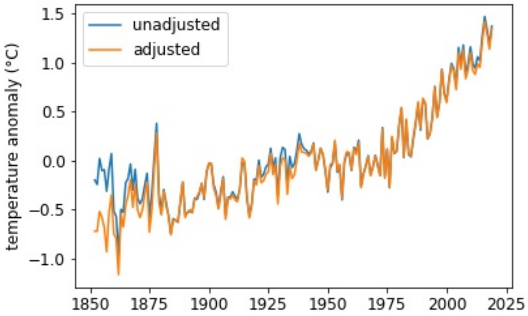
8. Trends in 10-years segments are frequently negative. Trends in 25-year or longer segments are rarely negative. That’s why one should look at several decades in order to evaluate a long-term trend.

9. Because we don’t have direct measurements of the temperature (e.g., made with a thermometer).

10. Local temperature trends may very well look completely different from the global average record. As discussed in the chapter, regional weather patterns can depart substantially from the global average. Some stations show very large adjustments. However, in the global average, those adjustments are small.

11. No, we know that the Earth has been substantially warmer than it is today.

12. As of 2020-10-03, the comparison is:



As one can clearly see, there is little difference between the adjusted and unadjusted land temperatures, except at the very beginning of the record. This tells us that skeptics do not have a point — the warming is NOT due to adjustments.

Solutions to chapter 3 problems

1. A 1-K temperature increase is equal to a 1.8°F or 1°C temperature increase

2. Power radiated by a sphere is equal to $4\pi r^2\sigma T^4 = 4\pi(1\text{ m})^2\ 5.67\text{x}10^{-8}\text{ W/m}^2/\text{K}^4\ (373\text{ K})^4 = 13{,}800\text{ W}$

3. As an object initially at room temperature warms up, it begins glowing red. As the object gets warmer and warmer, the object progresses through the rainbow: red, orange, yellow, green, blue, indigo, and finally violet. As the object heats up even more, it once again becomes black because the photons it is emitting have wavelengths too short for humans to see.

4. Star A: Most of the visible photons it is emitting are on the blue side of the spectrum, so it would appear bluish. Its characteristic emission wavelength is about 0.2 micron, which is equal to 3000/T. Thus, the characteristic temperature is 15,000 K.

Star B: Most of the visible photons it is emitting are on the red side of the spectrum, so it would appear reddish. Its characteristic emission wavelength is about 1 micron, which is equal to 3000/T. Thus, the characteristic temperature is 3000 K.

5. Power radiated by the sun is equal to $4\pi r^2\sigma T^4 = 4\pi(700{,}000\ 10^3\text{ m})^2\ 5.67\text{x}10^{-8}\text{ W/m}^2/\text{K}^4\ (6000\text{ K})^4 = 4.5\ 10^{26}\text{ W}$

6. As the filament cools, the blackbody spectrum shifts to longer wavelengths — i.e., to the red. Thus, as the bulb dims, it gets a reddish tint to it.

7. Total energy = 60 J/s (7x86400 s) = 36 million J

8. Most of the photons that incandescent bulbs emit are infrared and are therefore not visible to humans. This means that only a small fraction of the energy that is consumed by these bulbs is actually used to light the room. The rest is basically wasted.

9. a. The characteristic wavelength (in microns) is 3000/T, where T is in K. For the Sun, 3000/6000 = 0.5 microns.

b. $5.67\text{x}10^{-8}\text{ W/m}^2/\text{K}^4\ (6000\text{ K})^4 = 7.3\ 10^7\text{ W/m}^2$

c. If the radius is twice as large, then the surface area is 4 times as large. That means that each square meter must be emitting ¼ of the amount it presently is. Solving $\frac{1}{4}\ \sigma(6000\text{K})^4 = \sigma(T)^4$ for T, the new temperature, we find T = 4243 K.

10. a. E_{in} must be equal to E_{out}

b. E_{in} exceeds E_{out}

11. It is not correct. An unchanging bank balance means that money deposited equals money withdrawn; it does not mean that no money was deposited or withdrawn.

12. a. The total heat capacity = 4.18 J/g/K x 200 g = 836 J/K. The warming rate = 150 J/s / (836 J/K) = 0.18 K/s.

b. The amount of warming needed is reach boiling from room temperature is 100°C-22°C = 78°C = 78 K. The time required for this is 78 K/ (0.18 K/s) = 434 s.

c. For a blackbody at water's boiling temperature (373 K), the P/a is σT^4 = 1097 W/m^2. We need to multiply this by the surface area of the cup. Let's assume it's a cylinder that's 12-cm tall and with a radius of 3 cm. The surface area is 283 cm^2, which equals 2.83×10^{-2} m^2. Multiplying these out yields total energy radiated of 31 W.

d. Because of radiation to the room, there is less energy accumulating in the water, so it will take longer to boil.

13. a. If you increased the temperature of the oven, you'd deliver more power to the food. b. It would not; instead, it would just burn the outside. The reason is that the speed of cooking is limited by how fast energy diffuses into the turkey. c. Photons are absorbed over a depth of about one wavelength in the food. Thus, infrared radiation from a conventional oven is absorbed in a layer a few microns deep, while microwaves are absorbed in a layer a cm or so deep. Because the absorption layer is much thicker for a microwave, you can put a lot more energy in without burning.

14. a. energy radiated by the 80°C turkey is $\sigma(273+80)^4(0.1\ m^2)$ = 88 W; energy gained by the turkey from the 3°C walls of the oven = $\sigma(273+3)^4(0.1\ m^2)$ = 33 W. Thus, the turkey is losing 55 W.

b. The rough calculation is to take the heat capacity, 30 kJ/K, and divide 55 W into it: 30×10^3 J/K divided by 55 J/s = 545 s/K. Thus, it takes 545 seconds to drop the turkey one degree. To cool the turkey 77°C will therefore take 11.7 hours. This is a reasonable 'order of magnitude' estimate.

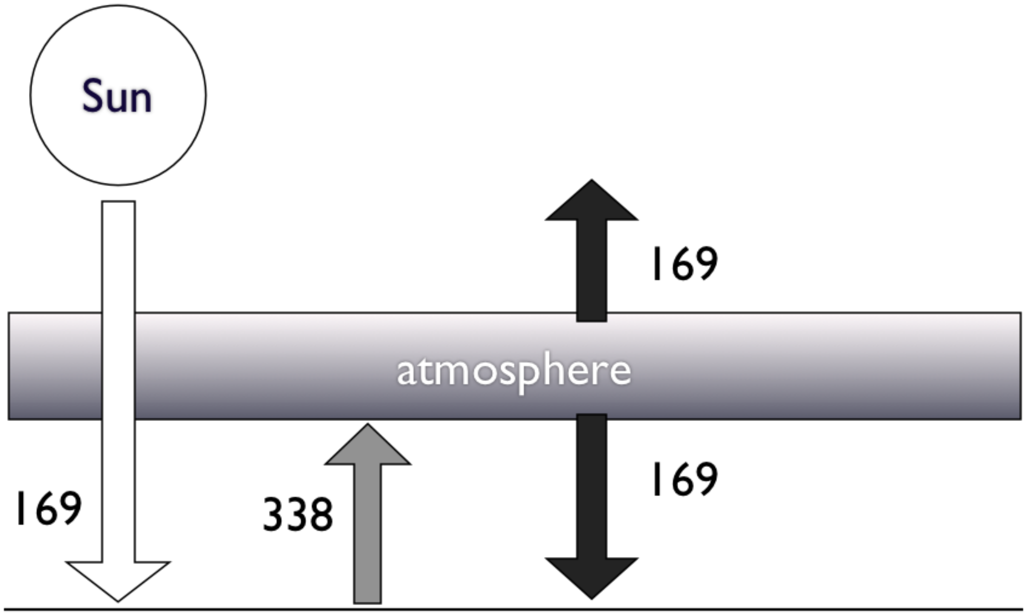
Solutions to chapter 4 problems

1. surface area of sphere = $4\pi r^2$; area of disk with radius r = πr^2; area of disk with diameter d = $\pi(d/2)^2 = \pi/4\ d^2$.

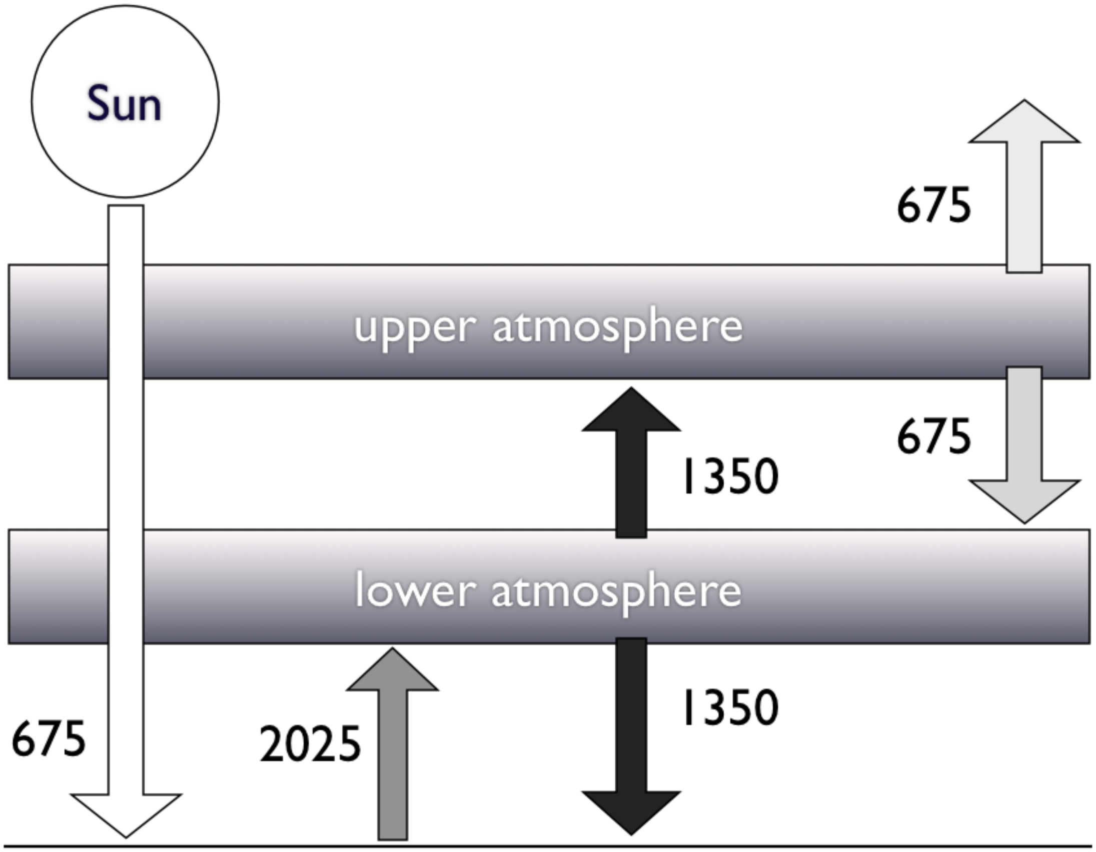
2. a. Total power output by the star = $4\pi r^2 S = 4\pi(100\text{x}10^6\text{x}10^3\ \text{m})^2(2000\ \text{W/m}^2) = 2.5\text{x}10^{26}$ W

b. The solar constant scales as $1/r^2$, so the solar constant for this planet is
$2000\ \text{W/m}^2\ (100^2)/(75^2) = 3555\ \text{W/m}^2$

3. $E_{in} = S(1-\alpha)/4 = 169\ \text{W/m}^2$. Surface temperature can be determined by solving $338\ \text{W/m}^2 = \sigma T^4$ for T. Or you can use Equation 4.5 with n=1, S=900, α=0.25. In either case, T = 278 K.



4. $E_{in} = S(1-\alpha)/4 = 675$ W/m^2. Surface temperature can be determined by solving 2025 W/m$^2 = \sigma T^4$ for T. Or you can use Equation 4.5 with n=2, S=3000, α=0.1. In either case, T = 435 K.



5. Man B is correct. While Venus is closer to the Sun, E_{in} for Venus is actually less than E_{in} for Earth (because Venus has such a large albedo). Thus, the warmth of Venus is entirely due to the greenhouse effect.

6. To do this problem, you need to assume a temperature at which the planet glows red. This will be somewhere between 1400-2000 K. The solutions below assume the surface temperature of the planet is 1600 K.

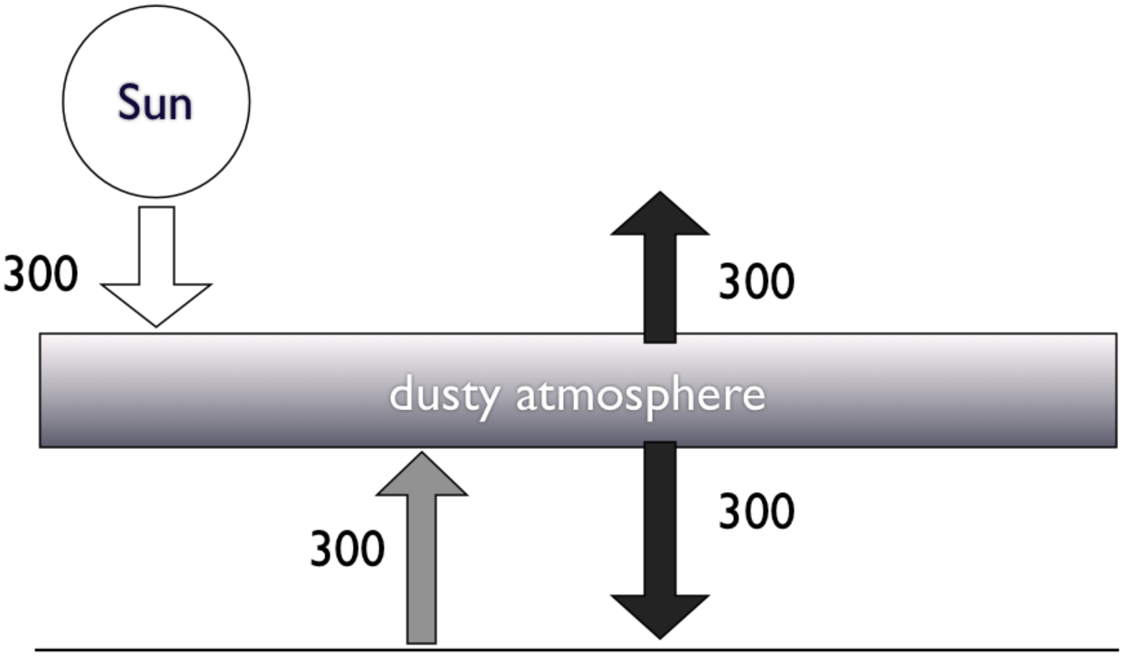
a. Solving equation 4.5 for n yields n is about 1800. That's a thick atmosphere.

b. Solving equation 4.5 for S yields a solar constant of 1.23×10^6 W/m^2

c. Remember that S scales as $1/r^2$, where r is the distance of the planet from the star. Thus, 1.23×10^6 W/m^2 r^2= 1360 W/m^2 (150 million km)^2; solving for r yields 5 million km.

7\. a. Using equation 4.5 with $n = 1$, $S = 2000$ W/m^2, and $\alpha = 0.4$, the surface temperature is 321 K.

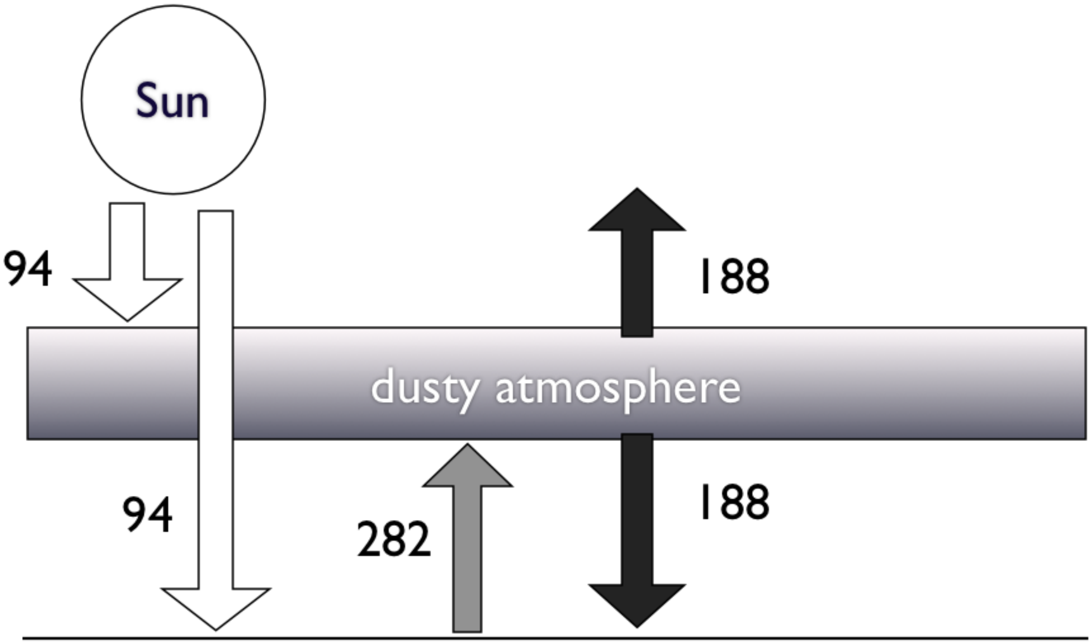
b.



You cannot use equation 4.5 to calculate the surface temperature because it was derived under the assumption that the atmosphere was transparent to sunlight, so it does not apply here. Rather, you have to draw an energy flow diagram and determine that that surface is emitting 300 W/m^2. From this, you can calculate the temperature using the equation 300 W/m^2 = σT^4. Solving for T yields T = 270 K.

c. Because the dust blocks sunlight from reaching the surface, the temperature of the surface plummets from 321 K to 270 K. This is why it's referred to as nuclear winter.

8.



You cannot use equation 4.5 to calculate the surface temperature because it was derived under the assumption that the atmosphere was transparent to sunlight, so it does not apply here. Rather, you have to recognize that 282 W/m^2 = σT^4, and solve for T, which yields T = 266 K.

9. E_{in} is the amount of energy from the Sun that is falling on the surface. The surface temperature tells us how much the surface is emitting (σT^4), and this must also be the total amount of energy falling on the surface (i.e., the sum of energy from the Sun and from the atmosphere). So $E_{in} / \sigma T^4$ is the fraction coming from the Sun. And using the fact that $E_{in} = S(1-\alpha)/4$, we can now calculate the fraction for the planets in Table 1. For Venus, Earth, and Mars, the fraction from the atmosphere is 1%, 60%, 82%.

10. To answer this question, you must consider the surface energy budget. The energy in for the surface comes from two sources: the Sun and the atmosphere. The energy from the Sun varies over the day, with large values during daytime and zero at night. The energy from the atmosphere, on the other hand, is constant throughout the day and night. For Mercury, which has no atmosphere, energy in for the surface is thousands of W/m^2 during the day and zero at night. This leads to large variations in surface temperature between day and night. For Venus, on the other hand, energy in from the atmosphere is a constant 17,000 W/m^2, while energy in from the Sun is about 400 W/m^2 during the day and zero at night. Thus, energy in for the surface is approx. 17,400 W/m^2 during the day and 17,000 W/m^2 during the night. This very small change in energy in over a day means that there is little change in temperature between over a day.

11. For a one-layer Earth-like planet ($S = 1360\ W/m^2$ and albedo = 0.3), the temperature is 302.7 K. Increasing the albedo to 0.31 reduces the temperature to 301.6 K. Thus, the answer is an increase in albedo of 0.01 will decrease the Earth's temperature by about 1 K.

12. The solar constant S varies as $1/r^2$ (e.g., if r doubles, S decreases by a factor of four). The temperature of a planet goes as the fourth root of S, which means that the temperature varies as:

$$\frac{1}{\sqrt{r}}$$

Thus, if a planet's distance from the Sun doubles, it's temperature goes down by a factor of 0.7. And if the planet's distance from the Sun is halved, it's temperature goes up by a factor of 1.4.

13. Nothing. The temperature of a planet is not a function of how big the planet is.

14. No. As Equation 4.5 shows, there is no saturation. As n gets bigger, T increases as the fourth root of (n+1). However, this does mean that each additional layer leads to a smaller increase than the previous layer.

15. The solar constant is proportional to the total energy emitted by the Sun. If total energy emitted by the Sun is equal to $4\pi R^2\ \sigma\ T^4$. Thus, if the radius R of the Sun doubles, then the solar constant will increase by a factor of 4, so the Earth's solar constant would increase to $5440\ W/m^2$. The temperature of a planet goes as the fourth root of S, so if S goes up by a factor of 4, then T will increase by a factor of $4^{0.25} = 1.4$. Thus, the Earth's temperature will increase from 288 K to 403 K.

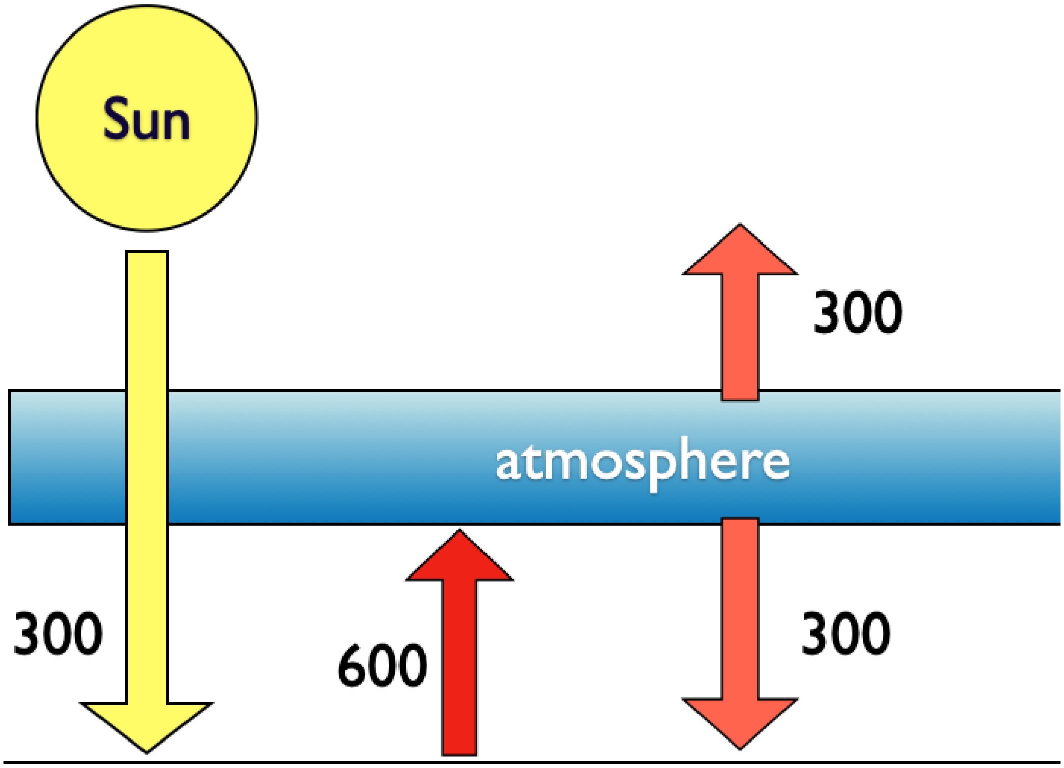
16. At night, no energy falls on the surface, so temperatures are a minimum. As the sun rises, very little solar energy falls on the surface (e.g., Fig. 4.3c); but, as the sun rises in the sky, more and more does (Figs. 4.3b and a). This causes temperatures to increase through the day. During the afternoon and into the evening, temperatures decline as the amount of solar energy falling the surface declines and, at sunset, goes to zero. This simple model would predict highest temperatures at local noon. But temperatures actually reach a maximum in the late afternoon. It turns out that the heat capacity of the surface causes a lag in the temperature response to solar heating. So while solar heating maximum occurs at noon, the temperatures will continue to increase for several hours. As discussed in Chap. 6, this same process causes the multi-decade lag in the response of the entire climate system to carbon dioxide.

17. A planet with S and α for the Earth would have E_{in} of $238\ W/m^2$. Such a planet would need to emit $238\ W/m^2$ to space to balance the E_{in}, and that means that whatever layer is emitting to space must be 255 K. And that's what the IR thermometer will so — so the answer is 255 K, regardless of how many layers the atmosphere has.

18. If the stars are Sun-like, then each one is radiating 3.8×10^{26} W (this was given in the text). The cloud has a surface area of 1.26×10^{29} m^2, which means the cloud must be emitting $50(3.8 \times 10^{26}$ W$)/(1.26 \times 10^{29}$ m$^2) = 0.15$ W/m^2 to the rest of the Universe. Converting this to temperature yields 40 K. In order to see this, you'd need a telescope capable of detecting ~3000/40 = 75 microns.

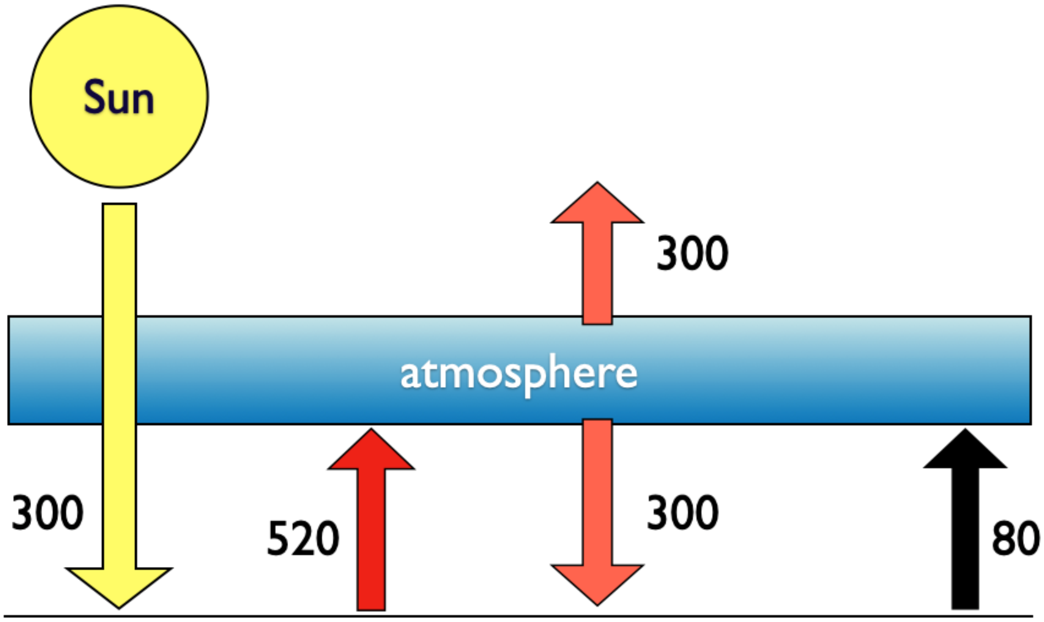
19. a. 375,000 km^2; b. 0.07%

20. a. No convection case:



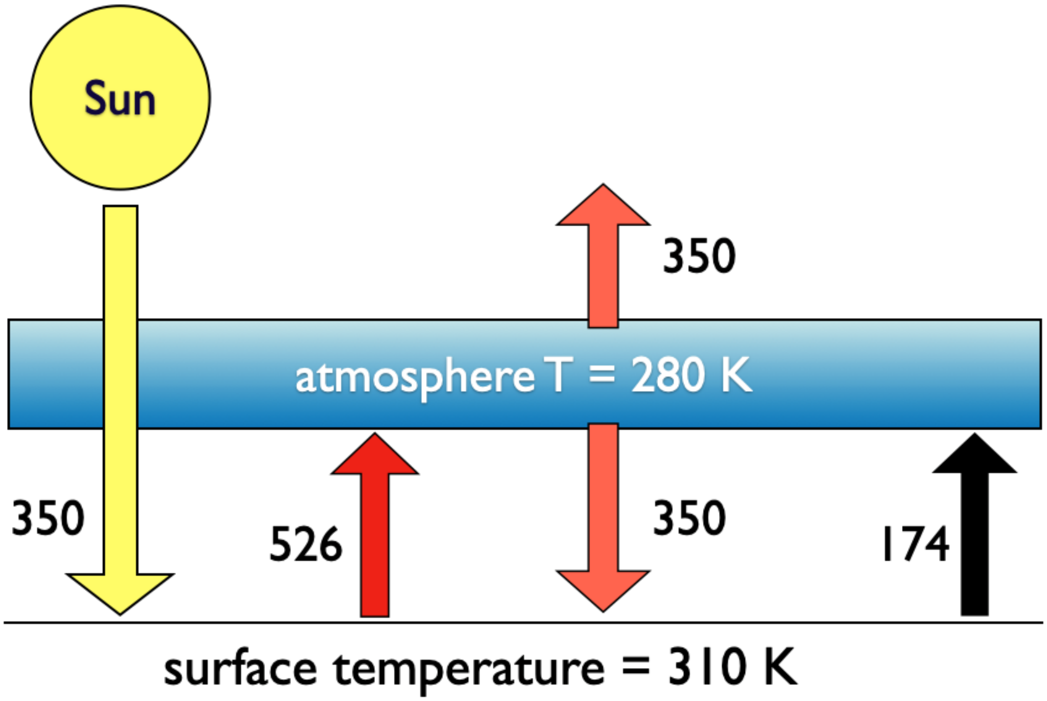
If the surface is emitting 600 W/m^2, then the surface T must be 321 K

b. With convection:



c. Temperature declines to 309 K; adding convection reduces surface temperature because it reduces the required radiative flux.

21. All fluxes are W/m^2



Solutions to chapter 5 problems

1. (a) The reaction that transfers carbon from the atmosphere to the land is photosynthesis, and it is Equation 5.1. The reaction that transfers carbon from the land back to the atmosphere is respiration, and it is Equation 5.2. (b) Most of the world's land is in the northern hemisphere, so that most photosynthesis on the Earth occurs during northern hemisphere spring and summer. At this time, photosynthesis draws carbon out of the atmosphere, leading to a decrease in atmospheric carbon dioxide. During northern hemisphere fall and winter, decay of plant material via the respiration reaction leads to release of carbon dioxide and a net increase in the atmosphere. This is the cause of the sawtooth.

2. Carbon dioxide exhaled by humans, animals, etc. is part of the fast cycle between the land-biosphere and the atmosphere. Over long periods, the cycle is in balance and leads to no net increase in atmospheric carbon dioxide. Carbon from fossil fuels, on the other hand, was safely sequestered in the rocks and would not have been released to the atmosphere for many millions or even billions of years. This does lead to a net increase in atmospheric carbon dioxide.

3. It cannot be due to volcanoes for a number of reasons. First, the isotopic abundance of carbon added to the atmosphere shows that the carbon was derived from plants (low carbon-13 to carbon-12 ratio). In addition, the amount added to the atmosphere tracks closely that amount that humans are emitting — it seems unlikely that volcanic emissions would do that. And volcanoes would not cause a decrease in oxygen, which observations show closely matches fossil fuel combustion.

4. Carbon from the biosphere has low amounts of carbon-13, but (relatively) large amounts of carbon-14. Carbon from a volcano has large amount of carbon-13 and low amounts of carbon-14. Carbon from fossil fuels has has low amounts of carbon-13, and low amounts of carbon-14. Analysis of the carbon added to the atmosphere shows that its isotopic composition matches fossil fuels.

5. Humans are adding carbon to the atmosphere by extracting and burning fossil fuels and by deforestation.

6. Chemical weathering occurs when atmospheric carbon dioxide dissolves into rainwater and this falls on rocks. The rain breaks down the rocks, both from the physical impact and from the weathering reaction:

$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$ (equation 5.5)

The carbon then runs into the ocean. In this way, the carbon is removed from the atmosphere. This process cannot play any role in the problem of modern climate change because it is slow — it takes millions of years to significantly affect atmospheric carbon dioxide.

7. Of the carbon dioxide removed from the atmosphere, about half goes into the ocean and half goes into the land-biosphere. If these sinks were to suddenly stop, then the rate of increase of atmospheric carbon dioxide would about double.

8. Acid rain refers to rain that has absorbed oxides of nitrogen and oxides of sulfur (these frequently come from power plants that have poor pollution controls or burn high-sulfur coal). Once in rainwater, these oxides make nitric acid and sulfuric acid, which are more potent acids than the carbonic acid that is produced when carbon dioxide dissolves in rainwater. Thus, rain containing nitric and sulfuric acid is much more destructive to the environment than the slightly acidic rainfall that normally occurs.

9. The annual cycle in the Arctic is much larger than in Mauna Loa because it is closer to the big land areas of the planet. And the annual cycle in the Antarctic is much smaller because it is further from the big land areas of the planet.

Solutions to chapter 6 problems

1. Calculate how much S needs to be increased to generate an E_{in} of 239 W/m^2. The answer is 5.7 W/m^2.

2. Climate sensitivity is almost always expressed as 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 then one lets the climate reach a new equilibrium, which takes a century or two. Using this definition, the accepted value is 2.0-4.5°C. Climate sensitivity can also be expressed as the warming per unit of radiative forcing. The climate sensitivity in these units is 0.5–1.1 °C/(W/m^2).

3. (a) $\frac{dT}{dE_{in}} = \frac{0.25\left(\frac{E_{in}(n+1)}{\sigma}\right)}{E_{in}}$

(b) dT/dE_{in} = 0.27 K per W/m^2, so the answer is very close

(c) 0.32 K per W/m^2

4. (a) It would take millennia. This is caused by the ocean, so it is longer than Mars or Mercury, which do not have oceans. (b) E_{in} for the Earth is 238 W/m^2. This means that an increase in the brightness of the Sun would lead to a radiative forcing of +2.38 W/m^2. (c) Using a sensitivity of 0.75°C/(W/m^2) gives us a warming of 1.8°C. (d) Radiative forcing is calculated assuming the change is instantaneous, so the radiative-forcing value is the same regardless of how long it actually takes to impose the change.

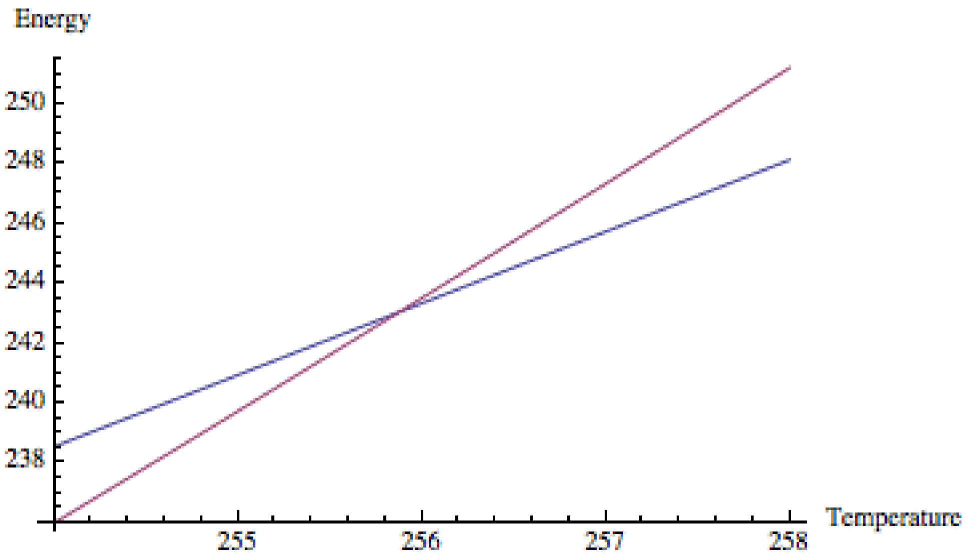
5. Forcings are imposed changes in planetary energy balance, while feedbacks are driven by changes in surface temperature. The amount of ice on the atmosphere is set by the surface temperature of the planet, which makes it a feedback.

6. $E_{in} = S(1-\alpha)/4$. For this problem, E_{in} changes from 238 W/m^2 to 234.6 W/m^2 as albedo increases from 0.30 to 0.31. Thus, the radiative forcing is -3.4 W/m^2 (it's negative, meaning that this change cools the planet).

7. a) total energy trapped: 2.3 W/m^2 $(4\pi(6000\ 10^3)^2)$ = 1.2 10^{15} W. Rate of temperature increase = 1.2 10^{15} W/(6 10^{24} J/K) = 1.97 10^{-10} K/s; convert to 0.62 K/century

b) The actual rate of warming is larger (1°C over the last 150 years), but the agreement is actually pretty good.

8. (a) $T_s = (S(1-\alpha)/4\sigma)^{0.25}$ = 254.5 K; (b) 255.0 K; (c) There are several different ways to solve this. One way is to plot energy in $((n(T)+1)S(1-\alpha)/4)$ and energy out (σT^4) for the surface and find their intersection.



Solution = 255.9 K. You can also solve this numerically.

d) ΔT_i = 0.5 K (this is the difference between parts a and b); ΔT_f = 1.4 K (this is the difference between parts a and c; so solving eq. 6.7 for g yields a value of 0.6.

9. An increase in albedo from 0.30 to 0.312 would reduce E_{in} from 238 W/m^2 to 234 W/m^2, which is a radiative forcing of -4 W/m^2.

10. Without the fast flower feedback, the sum of feedbacks g = 0.4 to 0.7. Adding in the new feedback changes this range to 0.1 to 0.4. And since $\Delta T_f = \Delta T_i/(1\text{-g})$, this corresponds to ΔT_f = 1.1 to 1.6 ΔT_i. If the initial temperature change for doubling CO_2 is 1.2 K, then climate sensitivity is 1.3-1.9 K.

Alternatively, you can estimate this using the fact that the climate sensitivity is 2.5-4 K. If the no-feedback warming ΔT_i is 1.2 K, then g values must be 0.52-0.7. Adding in the new negative feedback yields g values of 0.22-0.4, which in turn suggest the climate sensitivity is 1.5 to 2 K.

11. (a) 5°C/(6.7 W/m^2) = 0.75°C/(W/m^2) (b) doubled carbon dioxide has a forcing of 4 W/m^2, so 0.75°C/(W/m^2) * 4 W/m^2 = 3°C

12. The Gulf of Mexico heats slowly because of it's large mass of water. The GoM reaches maximum temperature a few months after the maximum in E_{in}, and this is what sets the maximum in air temperature along the Gulf Coast.

13. To answer this, you have to calculate the radiative forcing of the two perturbations. The one with the larger RF will cause more warming. You don't need to know what the climate sensitivity is. For this problem, the RF from the change in solar constant is +1.5 W/m^2, while the RF for the change in albedo is +3.75 W/m^2. So the change in albedo will change the planet's temperature more.

14. (a) First, estimate the change in solar constant that gives you a 1 W/m^2 change in E_{in}; the new value of S is 3520 W/m^2. The change in surface temperature as the planet's solar constant goes from 3500 to 3520 W/m^2 gives us the climate sensitivity: 0.34 K per W/m^2, (b) a 10% decrease in S gives us a RF of -17.5 W/m^2; multiplying this by the climate sensitivity gives us a temperature change of -6 K.

15. Aerosol radiative forcing is presently -1.1 W/m^2, so stopping emissions of aerosols would add +1.1 W/m^2 of radiative forcing in a few months. Our planet's climate sensitivity is 0.75 K per W/m^2, so this will warm the climate by 1.1*0.75 = 0.83 K.

Solutions to chapter 7 problems

1. (a) Continental motions, changes in the Sun's brightness, orbital changes, internal variability of the climate system, and changes in atmospheric abundances of greenhouse gases. (b) The continents and orbital variations are too slow; we have observations of the Sun that show it is not getting brighter; while hard to eliminate, there is no evidence that internal variations are responsible. (c) We know that greenhouse gases are accumulating in the atmosphere and that this is expected to warm the planet; the geologic record shows that changes in atmospheric carbon dioxide has been connected with large climate changes over the past few hundred million years; particular events, such as the PETM and the Ice Ages also suggest that greenhouse gases can drive the climate; climate models cannot reproduce the warming of the 20th century without the inclusion of greenhouse gases.

2. The first one is that we are 100% certain that humans are changing the climate. The second is that it is extremely likely that humans are the dominant driver of recent warming (extremely likely = 95% certainty, recent = since 1950s). The third is that it is likely that humans are responsible for all of the recent warming (likely = 67% certainty).

3. Feedbacks react to initial changes in surface temperature and amplify or ameliorate them. Feedbacks cannot be the ultimate cause of climate change.

4. The Ice Ages begin with a small perturbation to temperature caused by changes in the Earth's orbit. These small temperature changes are amplified by a carbon dioxide feedback: as the planet warms, carbon dioxide is released into the atmosphere, providing further warming. Because carbon is acting like a feedback, it lags the temperature change.

5. The case that greenhouse gases are responsible for the Earth's present warming trend is not based on today's temperatures being unprecedented. In fact, we know that there have been many times in the past when the Earth has been much warmer than today. Rather, the case is built on an assessment of all of the possible explanations for today's warmth, which leads to the conclusion that it is very likely mostly due to greenhouse gases. We cannot evaluate the implications of a warmer MWP because we don't know what the climate forcings were then (e.g., how bright the sun was).

6. The Earth's orbital eccentricity, obliquity and the procession of the equinoxes all can modify the climate. The changes in eccentricity can change the total amount of sunlight falling on the planet, with obvious climatic implications. Changes in obliquity and the procession of the equinoxes change the distribution of sunlight in latitude and the timing of maximum and minimum sunlight during the year. These can also change the climate in important ways.

7. During the PETM, an enormous release of greenhouse gases into the atmosphere occurred (comparable to the amount that will be released if we burn all fossil fuels) over a few thousand years. At the same time, temperatures rose significantly. This

provides strong evidence that large changes in the atmosphere's greenhouse gas abundance can indeed lead to large changes in the climate.

8. The movement of the continents can modify the climate through several mechanisms. First, the location of the continents determines whether large ice sheets form. It also determines ocean circulation, which changes the transport of heat around the planet. Finally, it regulates atmospheric carbon dioxide by regulating the chemical weathering thermostat.

Solutions to chapter 8 problems

1. (a) By the end of the century, temperatures 1-4°C warmer than today (2-5°C warmer than pre-industrial). (b) The answer will depend on how the world's societies evolve (i.e., which SSP storyline we follow).

2. I = CO_2 emissions (CO_2 emitted), P = population (number of people), A = affluence ($/person), T = greenhouse gas intensity (CO_2 emitted/$)

3. (a) energy intensity (J/$) and carbon intensity ($CO_2$ emitted/J), (b) carbon intensity decreases, (c) energy intensity decreases, (d) carbon intensity increases

4. This is incorrect. Predictions of the weather are predictions of the exact state of the atmosphere at a particular time, and it is correct that these are only possible for a few days in advance. But predictions of climate are predictions of the average state of the atmosphere, and we can predict these much further in advance. For example, we can predict with great certainty that August in College Station, Texas will be warmer than January. And we can make that prediction years in advance.

5. For many thousands of years.

6. (a) For P and A growth rates of 2%/yr and 3%/yr, the product PA is growing at 4.8%/yr. That means that the T term must decrease at 4.8%/yr to have flat emissions. (b) If emissions decrease by 20% in 20 years, that means that the product of PAT must decrease by about 20%/20 years = 1%/year (calculating it exactly yields a rate of decrease of 1.11%,/yr). If the product of PA is increasing at 5%/yr, this means that T must decrease at around 6%/yr (the exact answer is 5.9%).

7. The richer you are, the more you consume. And the more you consume, the higher the emissions you're responsible for are.

8. Greenhouse gas intensity is the T term in IPAT. Historically, T has declined at 1-2%/year, so we would expect a decrease over 10 years of 10-20%. Thus, setting a goal of decreasing T by 18% is not particularly ambitious. Everything else the same, reducing T by 18% will reduce emissions by 18%. But changes in the P and A terms tend to be positive, offsetting the impact of the T reduction. In fact, increases in P and A can be large enough that emissions increase even as T is decreasing. Thus, reducing T doesn't tell you much about the trend in emissions — it doesn't even tell you the sign.

Solutions to chapter 9 problems

1. We have adapted ourselves to this climate. As a result, almost any change (warmer or colder, more rain or less rain, etc.) will result in us being worse off.

2. In the future, we expect increases in overall precipitation, but the rain will fall in fewer, heavier events. This means that the length of time between rain events is going to increase—and this is going to cause an increase in the incidence of drought. When it does rain, it's going to rain hard and lead to flooding. Thus, increased chances of both drought and flooding can occur.

3. (a) the ice-albedo feedback will preferentially heat the polar regions, (b) land has a lower heat capacity than ocean, (c) because a larger fraction of surface heating is coming from the atmosphere, which has no day-night difference (for more on this, see Chapter 4, question 10).

4. (a) Globally, we expect precipitation to increase. We also expect the rain to fall in fewer, heavier events. The spatial distribution will also change, with precipitation increasing in the high latitudes and decreasing in most subtropical land regions as well as some parts of the tropics. (b) When precipitation falls as rain, it runs off immediately. Snow, on the other hand, stays in the mountains and runs off when the snow melts. Thus, the form of precipitation affects the timing of the runoff, which has important implications in some regions for freshwater availability.

5. a) Changes in temperature, in particular extreme heat waves, will produce negative health consequences for humans. Changes in precipitation can lead to a host of negative health effects, such as malnutrition associated with reductions in food availability and other health impacts associated with decreases in the availability of clean fresh water. We also expect warmer, more humid days to enhance the photochemical reactions that cause air pollution, leading to more smoggy days as the climate warms, along with the associated health impacts of air pollution. Warming temperatures also increase disease risk as a result of expansions in ranges of animals that transmit the diseases (e.g., mosquitoes), shortening of the diseases' incubation periods, lack of very cold temperatures that can kill the transmitters, and disruption and relocation of large human populations. Moreover, increases in water temperature, precipitation frequency, and other factors could increase the incidence of water contamination with harmful pathogens, resulting in increased human exposure.

b) There are many worries about climate change leading to national security problems. For example, climate impacts may destabilize societies through the disruptions of economic activity, food production, and water availability, as well as other mechanisms. Such disruptions could lead to mass migrations, social destabilization, failed states, and war.

c) Changes in temperature and precipitation can reduce the yield on many crops. Warmer temperatures reduce the productivity of works in the field. Changes in the climate can also impact the occurrence of pests that can destroy crops. There are also impacts on livestock and fisheries. See, e.g., https://archive.epa.gov/epa/climate-impacts/climate-impacts-agriculture-and-food-supply.html

d) Changes in precipitation, changes in evaporation from warmer temperatures, changes in timing of runoff, amount of snowpack, and changes in demand all caused by climate change will alter the amount of water available to the population.

6. Because adaptation costs money, the ability to adapt is determined by how rich you are. And because the U.S. and Western Europe are richer than African countries, they are better able to adapt to climate change.

7. (a) An abrupt climate change is a sudden and significant shift in some aspect of the climate. They might also refer to an abrupt impact, such as the flooding of the NY subway during Superstorm Sandy (b) Examples discussed in this chapter include the PETM and the Younger Dryas.

Solutions to chapter 10 problems

1. (a) \$117, (b) 7 doubling periods, (c) \$128

2. (a) \$381, (b) 3 doubling periods, (c) \$400

3. (a) $2^n = 100\ 10^{12}/0.01$; $n = \mathrm{Log}[10^{16}]/\mathrm{Log}[2] = 53$, (b) doubling every 10 years for a total of 530 years (note: it does not matter whether the log is natural log, log base 10, or some other log base)

4. Present value of \$1 trillion in 50 years at 1, 2, 4, 6, and 8% discount rate is \$608 billion, \$372 billion, \$141 billion, \$54 billion, and \$21 billion. In all except the highest discount rate, the present value of future climate impacts is greater than the today's cost of reducing emissions (\$50 billion), so you'd rather spend money to reduce emissions than deal with the impacts of climate change. For the highest discount rate, the cost of impacts is less than reducing emissions, so you'd prefer to do nothing.

5. Assume a 3% discount rate (I picked that because you should be able to invest your money at that after-tax rate). \$1450 in one year would therefore have a present value of \$1450/1.03 = \$1408. This is more than \$1400, so I'd prefer to pay \$1400 today. However, with this discount rate the difference is small, so I wouldn't feel strongly about either option.

6. (a) 7.5% (b) take the lump sum

7. Discounting tells us that the value of money declines as it recedes into the future. Draft picks also have value, and the value of a draft pick would also decline as it recedes into the future. Thus, a first-round pick in next year's draft is worth less than a first-round pick in this year's draft. This means that a trade between a second-round pick in this year's draft for a first-year pick in next year's draft would make sense.

8. (a) 42 doublings (b) 41 doublings (c) 35 doublings

9. (a) 4.7% (b) the present value increases as a cost moves forward in time; you would therefore rather pay \$10 million today than \$1 billion in 50 years

10. 5 minutes (the depth is 10 ft after 1 minute, 20 ft after 2 minutes, 40 ft after 3 minutes, 80 ft after 4 minutes, and 160 ft after 5 minutes)

11. (a) $1.03^{100} = 19.2$ times larger, (b) GDP is 17.4 times larger, a reduction of about 10%, (c) $1.029^n = 1.03^{100}$; solve for n yields n = 103.3. Thus, after 103.3 years of growth at 2.9% you reach the same level of wealth as you do after 100 years of growth at 3%, (d) given the possible negative consequences of climate change, it seems (to me, at least) a bit ridiculous to be too concerned whether future citizens are 17 or 19 times richer than we are.

13. Solve $7.8x10^9=1,000x2^n$; yielding 22.9 doublings. At 3 days per doubling, this means it will take 68.7 days for the entire population to be infected.

14. b) 1 billion people, c) 1 million people

15. SSP3: 0.88% per year, SSP5: 3% per year

Solutions to chapter 11 problems

1. Adapatation (build a seawall to head off the impacts of a rising sea), mitigation (switch from burning coal to generate electricity to solar), solar radiation management (inject aerosols into the stratosphere to cool the planet), carbon dioxide removal (add iron to the ocean)

2. (a) solar, wind, biomass, hydroelectric, nuclear, carbon-capture and sequestration, (b) no, some carbon-free energy sources are not renewable, (c) nuclear is carbon-free, but not renewable, because Uranium is a finite resource (it is mined)

3. (a) No, relying entirely on adaptation is risky because it's not clear we can adapt to climate change. It is also morally questionable because some of the most vulnerable are also the poorest, and therefore least capable of dealing with the impacts. And these poor have also contributed the least to the problem.

(b) Because of lags in the climate system, some warming over the next few decades is unavoidable. To the extent that warming cannot be avoided, we must adapt to it.

4. Solar radiation management: Advantages: fast (temperatures respond almost immediately) and cheap (compared to mitigation). Disadvantages: focuses on temperature, but would do nothing about other impacts (ocean acidification) and could create new problems (droughts), would create governance problems, once started, abrupt cessation could cause a warming spike that would be disastrous. Carbon dioxide removal: Advantages: would truly stop all aspects of climate change. Disadvantages: we don't have the technology to do it, it might be extremely expensive, it might also be risky (depending on the approach used).

5. (a) e.g., add sulfate aerosols to the stratosphere, (b) e.g., add iron to the ocean.

6. From a political standpoint, it is generally agreed that people will never accept a policy that solves the climate change problem by either greatly reducing population or greatly reducing affluence (i.e., consumption). Thus, solutions to climate change must involve the greenhouse gas intensity term, T.

7. (a) The terms are energy intensity and carbon intensity. An example of a change that reduces energy intensity is the switch to high-efficiency lighting; an example of a change that reduces carbon intensity is a switch to solar energy.

(b) Carbon intensity; switching away from fossil fuels to carbon-free energy sources

8. Because of lags in the climate system and lags in how fast we can switch to non-emitting energy technologies, the amount of carbon dioxide in the atmosphere over the next few decades is already determined. Thus, any mitigation effort will exert little impact on the climate until the 2nd half of the 21st century.

9. If you start mitigation too late, then you will be forced to use some combination of solar radiation management and carbon dioxide removal. Carbon dioxide removal

can help get you back down to the target temperature, but may leave an overshoot. Solar radiation management can cut off the overshoot.

Solutions to chapter 12 problems

1. Emitting carbon dioxide to the atmosphere is completely free to the emitter. The costs of climate change are paid by society, not the emitter (in other words, the costs of carbon dioxide emissions are an externality). But the benefits of consuming the energy go entirely to the emitter. Thus, the rational thing to do in this situation is to emit carbon dioxide without limit.

2. In general, an externality occurs when someone takes an action, and this action imposes involuntary costs on others. Emitting carbon dioxide is a classic externality because it leads to global climate change and therefore imposes costs on everyone in the world.

3. (a) Under this policy, emitters must pay a specified fee to the government for each unit (usually a ton) of greenhouse gas released to the atmosphere.

(b) Under cap and trade, the government issues a fixed number of permits each year, with each permit allowing the holder to emit a fixed amount (often 1 ton) of greenhouse gas to the atmosphere. Emitters must hold permits for the amount of greenhouse gas they emit to the atmosphere. Thus, the total number of permits issued sets a cap on total emissions. Emitters with extra permits can sell them to those needing additional permits (hence the trade part). The price of the permits is set by the market, not by the government.

(c) Under a carbon tax, the policy makers set the tax rate, which in turn sets the cost to society of the emissions reductions. But it is not exactly known what the economy's marginal cost of reduction is, so this means there is uncertainty in exactly how much of an emissions reduction will occur given a particular tax rate. Under a cap-and trade system, in contrast, the policy makers set the total number of permits issued, and therefore the total emissions from the economy. However, the uncertainty in the marginal costs means that it is not known how much it will cost to reach the specified level of emissions.

(d) They will reduce emissions until the marginal cost of reducing the next unit is equal to the tax or the cost of the permit.

4. Because the flexibility of the market-based approach means that emissions reductions are shifted to the lowest marginal-cost emitters (i.e., emissions reductions occur where they are cheapest).

5. (a) An offset is an activity that removes carbon from the atmosphere. (b) Additionality means that the offsetting action would not have taken place without the additional value given to the offsetting action by the carbon emissions regime.

6. A cap-and-trade system raises the price of energy, so by driving a small car, you save more money. Thus, driving a small car is not an altruistic action, but an

economic one — people will switch to them to save money. Those people who are willing to pay more will continue to drive SUVs. But if the price is set right, then enough people will switch that the appropriate emissions reduction will still take place.

7. Probably not. You'd have to satisfy additionality to get paid — meaning you would have to prove that that you would have gone to the store if not for the payment for the offset credit.

8. (a) Plant A = $3 + 5 + 7 = $15; Plant B = $1 + 2 + 3 = $6; total = $21

(b) Plant A reduces 2 units, Plant B reduces 4 units; total cost = $3 + 5 for Plant A + $1 + 2 + 3 + 5 for Plant B, for a total of $19

(c) The carbon tax is cheaper because the carbon tax shifts reductions to Plant A, the lowest marginal-cost emitter (i.e., where emissions cuts are cheapest).

9. (a) Plant A will sell one permit for a permit price of $5-6 (because at this price Plant A can make a profit not emitting the 5th ton), two permits for $6-7 per permit (because Plant A can profit from not emitting the 6th ton), three permits for more than $7-8 per permit.

If permits cost $9-12 then Plant B will buy one; if permits cost $6-9, then Plant B will buy two; if permits cost $3-6, then Plant B will buy three.

Thus, Plant B will buy 2 permits from plant A. The next permit would cost $7-8, but it would cost Plant B only $6 to not emit that unit.

(b) They will exchange at a cost between $6 and $9 per permit.

10. The large changes necessary for us to stabilize the climate are simply too big to be motivated simply because we've been told we *ought* to make those changes. So informational and voluntary approaches will likely form part of our response to climate change, but they can't form the fundamental basis of our emissions reduction policy.

11. The points are most valuable to students with the lowest scores in the class and those who really, really need to get a good grade. These are the students who will likely buy the points.

12. Offsets need to be 1) a mechanism that will remove carbon from the atmosphere for a long time (e.g., thousands of years, at least) and 2) satisfy additionality, 3) verifiable. The long time needed to sequester carbon makes things like planting trees a questionable way to stabilize the climate (although there are many other good reasons to do so).

13. It is true that the economy will utilize the cheapest energy source. What's incorrect about that statement is that, when comparing costs, the price of fossil fuels almost always does not include the externalities — the costs of climate impacts as

well as health impacts from air pollution. If you factor those in, it is not at all clear that fossil fuels are cheaper than renewable energy.

14. (a) a person with this card would spend money like a drunken sailor; after all, they're paying essentially none of the bill, (b) the country will go into bankruptcy because, while the cost to society from any particular person would be small, the aggregate effect of everyone possessing one of these cards would be enormous, (c) the contribution of any individual to climate change is small, but the aggregate effect on the climate of all human emissions is huge.

15. An example of a positive externality is a college education. Clearly, a college education is a benefit for the person receiving it, but college-educated citizens also benefit the rest of society. Thus, your payments to go to college are a net benefit for me. This is why education is subsidized by the government in many places.

Solutions to chapter 13 problems

1. (a) That depends, of course, on how nice you are. But most college students will say "no" to that request.

(b) You might help them in order to get them to help you out — either now or in the future. You might, for example, help them if they lent you their car for a trip you have planned next weekend. Or you might help them in order to generate general goodwill so they will help you at some later but presently undetermined point in time.

(c) The developed countries are mainly responsible for today's elevated greenhouse gases and the climate change we are experiencing. Thus, when the developed world asks developing countries to contribute to emissions reductions that is similar to the roommates asking the one who was not at the party to help clean up.

2. Louis Agassiz first discovered climate change (when he noted that ice ages had occurred); Svante Arrhenius first predicted that humans might warm the climate; Guy Stewart Callendar was the first to actually claim that humans were warming the climate. No, Trump was not correct.

4. 1) "common but differentiated responsibilities," 2) the precautionary principle, and 3) an agreement that the world should limit greenhouse-gas emissions in order to prevent "dangerous" climate change. The FCCC also included a non-binding agreement for developed countries to reduce emissions in 2000 to their levels in 1990, but that's not really a "principle"

5. We now view ourselves as a force on par with nature — and that nature needs to be protected. In the 19th century, nature was the dominant force, and humans were often fighting a battle for survival against it. The factors that caused this was 1) a recognition that humans had tremendous power to change the planet (air pollution, atomic weapons) and 2) people were getting richer, so the importance of the environment grew larger.

6. The precautionary principle says that "Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures."

7. (a) Equity means fairness, and in environmental problems it means that all must contribute, but they do not need to contribute equally.

(b) In the Montreal Protocol, developing countries were obligated to reduce production of CFCs, but they were allowed a 10-year delay. This reflected the fact that they had not contributed much to the problem and they had fewer resources to apply to the problem.

(c) In the Kyoto Protocol, the only binding emissions reductions were for the industrialized countries. The developing countries did not have any requirement to reduce emissions.

(d) Equity is implicitly included in the requirement that all countries set their own targets (the NDCs).

8. (a) 0.55 = (1+x/100)^15; solve for x = -3.9%/year

(b) total growth rate = 7%+1%-3.9% = 4.1%/year; $(1.041)^{15} = 1.82$; so emissions would increase by about 80% over this period, even though greenhouse-gas intensity was declining.

Solutions to chapter 14 problems

1. We need to reduce carbon dioxide emissions by about 50-80% by the middle of the 21st century. We also need to reduce emissions of short-lived greenhouse agents (e.g., methane, black carbon) significant — these give us a much faster reduction in radiative forcing. Aerosols are presently a negative radiative forcing, meaning that they are cooling the planet. But efforts to control air pollution will likely lead to efforts to clean up polluted air, and this will cause additional increases in net radative forcing.

2. The book argues that you look at the alternative errors (you address climate change, but it turns out to not be that serious vs. you don't address it and it turns out to be very serious). You bias your decision in order to reduce the chance of making the worse error.

3. If an action you take is irreversible, then you have to be more certain that it's the right action than if a decision is easily reversible. Put another way, you require a greater expected net benefit from an irreversible action than for a reversible action.

5. (a) In climate change policy, the choice is between paying now to reduce emissions vs. paying later to address the impacts of climate change. Discounting allows us to express these costs occurring at different times in today's dollars, so we can compare them in a meaningful way.

(b) Decrease

6. (a) 1.8-4.0 W/m^2. (b) In that case, the radative forcing limit is 1.8 W/m^2. Given that today's net radative forcing is 1.6 W/m^2, and that we cannot reduce emissions of carbon dioxide rapidly, we would have little chance of keeping radative forcing below 1.8 W/m^2.

7. The standard is that defendants must be proven guilty beyond a reasonable doubt. If the worse error were to acquit a guilty defendant, then the standard would be "defendants are guilty unless proven innocent beyond a reasonable doubt."

8. (a) for a discount rate of 0%, there is not discounting so the total present value is $1000; for a discount rate of 4%, the present value is $255.

(b) about 1.6%