Global Warming: Understanding the Forecast
Solution to Project Problems

Chapter 2

1. A joule is an amount of energy, and a watt is a rate of using energy, defined as 1 W = 1 J / s. How many joules of energy are required to run a 100 W light bulb for one day? Burning coal yields about $30 \cdot 10^6$ J of energy per kg of coal burned. Assuming that the coal power plant is 30% efficient, how much coal has to be burned to light that light bulb for one day?

8,640,000 joules per day. 0.08 kg of coal.

2. This is one of those job-interview questions to see how creative you are, analogous to one I heard, "How many airplanes are over Chicago at any given time". You need to make stuff up to get an estimate, demonstrate your management potential. The question is: What is the efficiency of energy production from growing corn?

Assume that sunlight deposits 250 W/m^2 of energy on a corn field, averaging over the day/night cycle. There are 4.186 joules per calorie. How many calories of energy are deposited on a square meter of field over the growing season? Now guess how many ears of corn grow per square meter, and guess what is the number of calories you get for eating an ear of corn. The word "calorie", when you see it on a food label, actually means "kilocalories", thousands of calories, so if you guess 100 food-label-calories, you are actually guessing 100,000 true calories or 100 kcal. Compare the sunlight energy with the corn energy to get the efficiency.

Assuming 90 days, $4.8 \cdot 10^8$ calories of sunlight. Assuming 500 calories / ear, 4 ears per plant, 400 cm^2 area per plant, I get $1.2 \cdot 10^7$ J / m^2. This would make it 2% efficient. These assumptions could be wrong, my intent is to get the student to make educated guesses.

3. Hoover Dam produces $2 \cdot 10^9$ Watts of electricity. It is composed of $7 \cdot 10^9$ kg of concrete. Concrete requires 1 MJ of energy to produce per kg. How much energy did it take to produce the dam? How long is the "energy payback time" for the dam?

about 40 days

The area of Lake Mead, formed by Hoover Dam, is 247 mi^2. Assuming 250 W/m^2 of sunlight falls on Lake Mead, how much energy could you produce if instead of the lake you installed solar cells that were 12% efficient?

$1.9 \cdot 10^{10}$, a factor of ten more than the dam produces

4. It takes approximately $2 \cdot 10^9$ J of energy to manufacture 1 square meter of crystalline-silicon photovoltaic cell. (Actually the number quoted was 600 kWhr. Can you figure out how to convert kilo-watt hours into Joules?) Assume that the solar cell is 12% efficient, and calculate how long it would take, given 250 W/m^2 of sunlight, for the solar cell to repay the energy it cost for its manufacture.

about two years

5. Infrared light has a wavelength of about 10 microns. What is its wavenumber in cm^{-1}?

1000 cm^{-1}

Visible light has a wavelength of about 0.5 microns. Whas is its frequency in Hz (cycles per second)?

$6 \cdot 10^{14}$ cycles / second

FM radio operates at a frequency of about 100 MHz. What is its wavelength?

300 cm

Chapter 3

1. The moon with no heat transport. The layer model assumes that the temperature of the body in space is all the same. This isn't really very accurate, as you know that it's colder at the poles than it is at the equator. For a bare rock with no atmosphere or ocean, like the moon, the situation is even worse, because fluids like air and water are how heat is carried around on the planet. So let's make the other extreme assumption, that there is no heat transport on a bare rock like the moon. What is the equilibrium temperature of the surface of the moon, on the equator, at local noon, when the sun is directly overhead? What is the equilibrium temperature on the dark side of the moon?

Assuming an albedo of 0.3, 360 K. On the dark side, 0 K.

2. A two-layer model. Insert another atmospheric layer into the model, just like the first one. The layer is transparent to visible light but a blackbody for infrared.

a) Write the energy budgets for both atmospheric layers, for the ground, and for the earth as a whole, just like we did for the one-layer model.

b) Manipulate the budget for the earth as a whole to obtain the temperature T_2 of the top atmospheric layer, labeled Atmospheric Layer 2 in Figure 3-5. Does this part of the exercise seem familiar in any way? Does the term skin temperature ring any bells?

c) Insert the value you found for T_2 into the energy budget for layer 2, and solve for the temperature of layer 1 in terms of layer 2. How much bigger is T_1 than T_2?

d) Now insert the value you found for T_1 into the budget for atmospheric layer 1, to obtain the temperature of the ground, T_{ground}. Is the greenhouse effect stronger or weaker because of the second layer?

The temperature of Layer 2 is the same as the top layer of the one-layer model, or the temperature of the bare rock with no atmosphere (the skin temperature). The other temperatures are $T_1 = \sqrt[4]{2}\ T_2$ *and* $T_{ground} = \sqrt[4]{3}\ T_2$

3. Nuclear Winter. Let's go back to the 1-layer model, but let's change it so that the atmospheric layer absorbs visible light rather than allowing to pass through (Figure 3-6). This could happen if the upper atmosphere were filled with dust. For simplicity, let's assume that the albedo of the earth remains the same, even though in the real world it might change with a dusty atmosphere. What is the temperature of the ground in this case?

The temperature of the ground equals the skin temperature

Chapter 4

Answer these questions using the on-line model at http://understandingtheforecast.org/Projects/infrared_spectrum.html . The model takes CO_2 concentration and other environmental variables as input, and calculates the outgoing IR light spectrum to space, similarly to Figures 4-3, 4-5, and 4-7. The total energy flux from all IR light is listed as part of the model output, and was used to construct Figure 4-6.

Note that the model results do depend on location and clouds. The results below are for the tropical atmosphere.

1. Methane. Methane has a current concentration of 1.7 ppm in the atmosphere, and it's doubling at a faster rate than is CO_2.

a) Is ten additional ppm of methane in the atmosphere more or less important than ten additional ppm of CO_2 in the atmosphere at current concentrations?

10 ppm methane -> 2.8 W/m^2 in the tropical atmosphere. 10 ppm CO_2 gives 0.16 W/m^2. Methane is more powerful

b) Where in the spectrum does methane absorb? What concentration would it take to begin to saturate the absorption in this band? (How do you identify saturation of a band, on a spectrum plot?)

saturates at a few hundred ppm, between 1250 – 1350 cm^{-1}

c) Would a doubling of methane have as great an impact on the heat balance as a doubling of CO_2?

Doubling CO_2 gives 3.2 W/m^2. Doubling methane gives 0.8 W/m^2. Doubling CO_2 is greater

d) What is the "equivalent CO_2" of doubling atmospheric methane? That is to say, how many ppm of CO_2 would lead to the same change in outgoing IR radiation energy flux as doubling methane? What is the ratio of ppm CO_2 change to ppm methane change?

440 ppm CO_2 gives 0.8 W/m^2 of drawdown, the same as doubling methane. That's an increase by a factor of about 1.2, while methane doubles.

2. CO_2.

a) Is the direct effect of increasing CO_2 on the energy output at the top of the atmosphere larger in high latitudes or in the tropics?

It's greater in the tropics. Actually, it is proportional to the total energy outflux.

b) Set pCO_2 to an absurdly high value of 10,000 ppm. You will see a spike in the CO2 absorption band. What temperature is this light coming from? Where in the atmosphere do you think this comes from?

It's coming from the stratosphere.

3. Earth Temperature. Our theory of climate presumes that an increase in the temperature at ground level will lead to an increase in the outgoing IR energy flux at the top of the atmosphere.

a) How much extra outgoing IR would you get by raising the temperature of the ground by one degree? What effect does the ground temperature have on the shape of the outgoing IR spectrum and why?

I get 3.6 W/m^2 increase by raising the temperature 1 degree, with the water vapor set to constant pressure (no water vapor feedback). The intensity gets higher, especially in the atmospheric window region (750-950 cm^{-1})

b) More water can evaporate into warm air than cool air. By setting the model to hold the water vapor at constant relative humidity rather than constant vapor pressure (the default) calculate again the change in outgoing IR energy flux that accompanies a 1 degree temperature increase. Is it higher or lower? Does this make the earth more sensitive to CO_2 increases or less sensitive?

The change in energy flux was now only 2.1 W/m^2, rather than 3.6 with constant water pressure. The earth is more sensitive to changes in CO_2 because a larger change in temperature is required to generate a given change in IR energy.

c) Now see this effect in another way. Starting from a base case, record the total outgoing IR flux. Now increase pCO_2 by some significant amount, say 30 ppm. The IR flux goes down. Now, using the constant vapor pressure of water option, increase the Temperature Offset until you get the original IR flux back again. What is the change in T required? Now repeat the calculation but at constant relative humidity. Does the increase in CO_2 drive a bigger or smaller temperature change? This is the water vapor feedback.

I get 0.12 degrees of warming for the constant pressure experiment, and 0.20 using constant relative humidity.

Chapter 5

1. Lapse Rate. Use the on-line full-spectrum radiation model at http://understandingtheforecast.org/full_spectrum.html . Adjust the lapse rate in the model and document its impact on the equilibrium temperature of the ground.

The temperature of the default run is 18.6° C. Setting the lapse rate to zero dropped the temperature to –11°C. Setting it to dry (-10 K/km) raised the temperature to 19.1. The steeper the lapse rate, the stronger the greenhouse effect.

2. Skin Altitude. Answer this question using the on-line IR radiation model.

a. Run the model in some configuration without clouds and with present-day pCO_2. Compute σT^4 using the ground temperature, to estimate the heat flux that you would get if there were no atmosphere. The value of σ is $5.67 \cdot 10^8$ $W/(m^2 K^4)$. Is the model heat flux at the top of the atmosphere higher or lower than the heat flux you calculated at the ground?

The potential IR flux based on the ground temperature is 457 W/m^2. The model flux is 287 W/m^2.

b. Now calculate the "apparent" temperature at the top of the atmosphere by taking the heat flux from the model and computing a temperature from it using σT^4. What is that temperature, and how does it compare with the temperatures at the ground and at the tropopause? Assuming a lapse rate of 6 K / km, and using the ground temperature from the model, what altitude would this be?

The apparent temperature based on the observed IR energy flux is 266 K. The temperature of the ground is 299 K. The temperature at the tropopause is about –75°C on the profiles plot, which is about 200 K.

The skin altitude is –32.7 K / (-6 K / km) = 5.46 km.

c. Double CO_2 and repeat the calculation. How much higher is the skin altitude with doubled CO_2?

The new skin altitude is –33.5 K / (-6 K / km) = 5.58 km, 123 meters.

d. Put CO_2 back at today's value, and add cirrus clouds. Repeat the calculation again. Does the cloud or the CO_2 have the greatest effect on the "skin altitude"?

Adding cirrus changes the skin altitude to 6.25 km, 793 meters higher.

Chapter 6

1. The Orbit and Seasons. Answer this question using an on-line model of the intensity of sunlight as a function of latitude and season at http://understandingtheforecast.org/orbit.html . The model calculates the distribution of solar heating with latitude and season depending on the orbital parameters of the earth. Enter a year A.D. and push calculate. The eccentricity is the extent to which the orbit is out-of-round; an eccentricity of 0 would be a fully circular orbit. Obliquity is the tilt of the earth's axis of rotation relative to the plane of the earth's orbit. The third number, the longitude of the vernal equinox, determines the location on the orbit (the date of the year) where Northern hemisphere is tilted closest to the sun. Using the present-day orbital configuration, reproduce Figure 6-4. Now straighten the tilt of the earth's axis of rotation by setting obliquity to 0°. What happens to the seasons?

They disappear.

2. Heat Transport. Answer these questions using an on-line full-spectrum radiation model at http://understandingtheforecast.org/Projects/full_spectrum.html .

a. The incoming solar radiation at the equator, averaged over the daily cycle, is about 420 W/m^2. What would the temperature be at the equator if there were no heat transport on earth? The default albedo in the web interface is 30%, but the real albedo in the tropics may be closer to 10%. What happens then? How much heat transport is required to get a reasonable temperature for the equator? What fraction of the solar influx is this?

Set the incoming solar to 420 W/m^2, and keep "TOA (Top of Atmosphere) Heat Imbalance" set at 0. The steady-state temperature is 44.7°C. Setting albedo to 0.1 results is a temperature of 77.4°C.

b. Repeat the same calculation for high latitudes. Estimate the annual average heat influx at 60 degrees latitude by running the orbital model from the first problem. Just eyeball the fluxes through the year to guess at what the average would be. Now plug this into the full-spectrum light model to see how cold it would be up there if there were no heat transport. If there were no transport and also no storage, how cold would it be in winter?

Let's say 200 W/m^2 annual average at 60° N. The temperature is -42.6°C. In winter, the influx is 30 W/m^2, which causes the model to blow up in a "runaway icehouse".

Chapter 7

Answer these questions using the full-spectrum radiation model at http://understandingtheforecast/Projects/full_spectrum.html.

1. Compare Two Codes. You will find that the two radiation codes give very different answers for the temperature sensitivity to CO_2 and water vapor. What is the ΔT_{2x} for each model? Is it the same for doubling from 100 to 200 ppm as it is for 350 to 700 ppm? The model includes the water vapor feedback automatically, but we can turn this off by zeroing the relative humidity. What is the ΔT_{2x} without the water vapor feedback? How comparable are the CCM3 and Chou models?

CCM3 has a ΔT_{2x} of 2.6°C, while Chou is 2.9°C.

From 100 to 200 ppm CO_2, in CCM3, the ΔT_{2x} is 2.1°C.

Without water vapor feedback, in CCM3, I get ΔT_{2x} of 1.0°C

2. Clouds and Upwelling IR Light. Use the on-line IR radiation model http://understandingtheforecast/Projects/infrared_spectrum.html. What is the effect of clouds on the outgoing IR energy flux of the atmosphere?

a) Are higher clouds or lower clouds the most significant to the outgoing IR energy balance? (Note that this calculation, in fact this entire lab, neglects incoming energy, which clouds can affect by their albedo. We'll deal with that issue in the next lab.)

I get 9 W/m^2 change for low stratus clouds, and 20 W/m^2 for cirrus clouds.

b) Can you see the effect of the clouds in the outgoing spectra? How is it that clouds change the outgoing IR flux?

The change is most apparent in the atmospheric window, which gets colder, as if the ground were at cloud level.

3. Clouds and Downwelling IR. Set the Sensor Altitude to 0 km, and choose the Looking Up option, at the bottom of the model web page. Do this with no clouds, and then again with clouds. Explain what you see. Why, at night, is it warmer when there are clouds?

In the atmospheric window part of the spectrum, when there are no clouds, you get IR from space, which is very low intensity (cold). When there is a cloud, you get IR from the temperature of the cloud bottom.

4. Clouds and Full-spectrum Light. Let's look at the effects of clouds. For each radiation code, document the effect of, say, a 100% cloud cover, for high and low clouds (run each separately). Which type of cloud has the largest effect?

There may be a bug in the model, low cloud fraction.

b. What is the effect of changing the drop size from 10 to 8 microns in the low clouds? How do these radiative effects compare with the effect of doubling CO_2?

Huge cooling for low clouds, to -28.5°C, assuming 30 g/m^2 water content. For high clouds, I get warming to 34.3° C.

c. Run a set of scenarios with high clouds, using a range of water contents, from 100 down to 2 g/m^2. Make a plot of the equilibrium temperature depend on the water content. You should get a fairly surprising-looking plot. Can you explain what you see?

g / m2 water	*Temperature*
100	*22.9*
50	*24.2*
25	*37.4*
10	*41.6*
5	*32.9*
0	*19.3*

Thin high clouds warm, but as they get thicker, they begin to reflect light, cooling back down.

Chapter 8

1. Weathering as a Function of CO_2. The rate of weathering must balance the rate of CO_2 degassing. Run a simulation where the CO_2 degassing rate increases or decreases at the transition time. Turn off the CO_2 spike (set it to zero), to make things simpler. An increase in CO_2 degassing drives atmospheric CO_2 up or down? Repeat this run with a range of final degassing rates, and make a table of the CO_2 concentration as a function of the CO_2 degassing rate. The CO_2 degassing rate is supposed to balance the CO_2 consumption rate by silicate weathering -- verify that the model achieves this. If so, make a plot of weathering as a function of atmospheric pCO_2.

pCO2	*Degassing = Weathering*
80	*5*
273	*7.5*
610	*10*
1050	*12*
2000	*15*

The weathering rate in the final equilibrium of the model balances the degassing rate, so the above is also a table of weathering as a function of pCO_2.

2. Effect of Solar Intensity. The rate of weathering is a function of CO_2 and sunlight, a positive function of both variables. By this I mean that an increase in CO_2 will drive an increase in weathering, as will an increase in sunlight. The sun used to be less intense than it is now. Turn back the clock 100 million years or 500 million years, to dial down the sun. Weathering has to balance CO_2 degassing, so if sunlight goes down, CO_2 must go up, to balance. Try it. What do you get for the initial steady-state CO_2, relative to what you get for today's equilibrium value?

Setting the clock back to 500 mya and setting the spike to 0, I get pCO_2 *of 941, compared with 278 today.*

3. Plants. Plants pump CO_2 down into the soil gas, possibly accelerating weathering. They also stabilize soils, perhaps decreasing weathering. Run a simulation with a transition from no plants to a world with plants, with no carbon spike on the transition. Figure out if plants in the model, overall, increase or decrease weathering.

pCO_2 *drops from about 510 with no plants, to 280 with plants.*

Chapter 9

1. Hubbert's Peak. Point your web browser to http://understandingtheforecast.org/Projects/hubbert.html.

a. You will see two different data sets to plot against, along with the three parameters (knobs) that control the shape of the Hubbert curve. Nothing fancy here, we're just matching the curve to the data by eye. First start out with the U.S. oil production. The page comes up with some values for the curve that look pretty good to me, but you should try varying the numbers in the box to see how tightly those values are constrained. In particular, there may be combinations of values that could be changed together to fit the data nearly nearly as well, but with different values. How much wiggle room is there for U.S. oil production?

The peak looks to be definitely between 1970 and 1980.

b. Now switch to global oil production with the pull-down menu. When do you forecast the peak of oil extraction? How does it depend on your assumption of how much oil will eventually be extractable. How much wiggle-room is there for the year of the peak in global oil extraction?

If there were 500 Gton of C in oil, and if it were 40 years duration, maybe the peak comes as late as 2020.

2. The Kaya Identity. Point your web browser to http://understandingtheforecast.org/Projects/kaya.html.

a. Find the plots for GDP per capita, energy intensity, and carbon efficiency, and compare the model hind-cast (the solid line) with the data (plusses). How well constrained are the growth rates by the past data? Of course, the future may not follow the dictates of the past; this is not a mechanistic prediction but just a blind extrapolation. Using the past as a fallible guide, however, take a guess at what the range of possibilities is for each of the input values.

GDP could grow from say 1-3%/yr. Energy intensity -0.5 to -2%/yr. Carbon efficiency -0.2 to -0.5.

b. How much carbon is mankind predicted to emit by the end of the century? Using the uncertainty ranges you made in 2a, what is the highest and lowest plausible carbon emission for 2100?

Base case is 18 Gton C / yr in 2100. Highest is 120 Gton C / yr using highest numbers from 2a. Lowest is 4 using lowest combination from 2a.

3. IPCC CO_2 Emission Scenarios. Open a new browser window for the ISAM carbon cycle model, at http://understandingtheforecast.org/Projects/isam.html. This page shows the results of IPCC carbon emission scenarios made by more sophisticated crystal balls than our simple Kaya identity (and then offers to run the results of the scenarios through a carbon cycle model). On the Kaya page, try to reproduce the year-2100 carbon emissions from scenarios A (Business-as-usual), B (BAU with carbon stabilization), C (slow growth) and F (gonzo emissions). What input parameters are required?

A - defaults but with 13 billion people

B - as A but with carbon efficiency changing by -0.4%/yr instead of 0.3%/yr.

C - as A but with GDP / yr growing at only 0.6%

F - as A but with GDP 1.8%/yr would do it.

Chapter 10

1. Long-Term Fate of Fossil Fuel CO_2. Use the on-line geologic carbon cycle model at http://understandingtheforecast.org/Projects/geocarb.html. Use the default setup of the model, and notice that the CO_2 weathering rates etc. for the transient state are the same as for the spinup state. So if there were no CO_2 spike at all, there would be no change in anything at year 0. (Go ahead, make sure I'm not lying about this.) Release some CO_2 in a transition spike, 1000 Gton or more or less, and see how long it takes for the CO_2 to decrease to a plateau. There are two CO_2 plots in the output, one covering 100 thousand years and one covering 2.5 million years. How long does it take for CO_2 to level out after the spike, according to both plots?

There is a leveling out at about 20 kyr visible in the shorter-duration plot, and another leveling out at about 0.5 myr visible in the longer plot.

2. Effect of Cutting Carbon Emissions. Look at the on-line ISAM global warming model at http://understandingtheforecast.org/Projects/isam.html.

a. Run the model for the "Business-as-usual" case (Scenario A), note the pCO_2 concentration of the atmosphere in the year 2100.

b. Estimate the decrease in fossil fuel CO_2 emission that would be required to halt the increase in atmospheric CO_2, based on the present-day CO_2 fluxes into the ocean and into the terrestrial biosphere. Test your prediction by imposing these fluxes from the present-day onward to the year 2100.

As of the year 2000, the terrestrial biosphere and ocean have taken up about half of our cumulative emissions. Using numbers from the table, Cum. Fos. + Cum. LU. = 400 Gton C, while Cum. NB and Cum. Ocean = 200 Gton C. So cutting emissions by half below 2000 levels ought to do it. Setting the fossil fuel emissions to 3.5 Gton / yr from 2000 to 2100 in the model stabilizes pCO_2 below 450 ppm.

c. Repeat experiment 2b but delaying the cuts in fossil fuel emissions to the 2050. What is the impact this time, on the maximum pCO_2 value we will see in the coming century?

pCO_2 reaches 480 ppm

3. Climate Sensitivity of this model. Deduce from the above results or new model runs, what is the climate sensitivity, ΔT_{2x}, assumed in this model?

Temperature goes up about 1.8° C while nearly doubling CO_2 in the last experiment. Temperature may not be at equilibrium, whereas ΔT_{2x} is an equilibrium measure, but neglecting that fact, ΔT_{2x} looks like about 2° C.

Chapter 11

Point your web browser tohttp://understandingtheforecast.org/Projects/bala.html.

(a) The model run begins in year 1871. Bring up this temperature map. Choose some location on the Earth's surface of interest to you, and which you can find again accurately on the map. The world is your oyster. Click on that location find the temperature there for both the rising-CO_2 and the control model runs. Record these values in a table with columns "year", "T(CO_2)" and "T(control)". Do this, for the same location, for the next 9 years, giving us 20 data points.

Choosing Chicago as a test location, I get the data

CO_2 1870	*Ctl 1870*
10.4	*9.9*
11.76	*10.84*
10.25	*9.86*
11.04	*8.69*
10.45	*10.11*
10.48	*11.97*
9.13	*12.54*
9.38	*9.7*
9.24	*10*
9.8	*9.85*

(b) Compute the mean of each temperature series using the formula

$$\frac{\Sigma T}{n}$$

where the capital sigma (Σ) means "take the sum of", in this case of all 10 temperature values, and n is 10.

The means are

10.193	*10.346*

(c) Add a pair of new columns to your table, labeled $T\text{-}T_{mean}(CO_2)$ and $T\text{-}T_{mean}$(control). Subtract the mean temperatures from the temperature each year and write this number into each row of these two new columns.
(d) Add another pair of columns and write in the squares of the deviations.
(e) Compute the mean of the squares of the deviations.
(f) Take the square root of the means of the squares of the deviations. This quantity is called the root mean square or RMS of the deviation, also called the standard deviation, abbreviated as σ. Statistically, about 2/3 of the temperatures in the table should be within $\pm 1\ \sigma$. Is this true in your case? 95% of the numbers should be within $\pm 2\ \sigma$. How many observations ought to be outside of 2 σ? How many do you find?

The RMS deviations I compute are

0.79	*1.08*

There are 5 points outside of 1 σ for the CO_2 run, and 7 for the Control run. All are with 2 σ for the CO_2 run, and 9 for the Control run.

(g) Move to the year 2000 of the simulation. Start a new table and record 10 years worth of data from the same location as before. Run through the same rigmarole to compute the mean and standard deviations of the new temperatures. If the new mean value were the same as the old mean value, you would expect 5% or 1 in 20 of the data points to be outside of 2 σ. How many of the data points actually are outside of 2 σ?

For Chicago, in the rising CO_2 run, I get

12.44
11.45
11.41
11.05
10.06
13
10.92
11
11.47
11.46

Two of these points are outside of 2 σ where σ is the CO_2 run, 1870 value of 0.79.

(h) How does the warming you have diagnosed from one location compare with the warming observed in the instrumental record (Figure 11-3)? Is the rising-CO_2 model temperature much different from the control run?

The mean in 2000 is 11.4°, up from 10.1° in 1870. This warming of 1.3° exceeds the 0.6° global mean value from the proxy records.

(i) Push the Time Series button to bring up a plot of the global average temperature from the model. The year 1871 is the beginning of the simulation, at model year 250, and the year 2000 is at model year 380. How does the global mean temperature increase compare with your spot-estimate?

The global average warming in the model was about 0.8°C during this interval.

Chapter 12

Point your web browser at http://understandingtheforecast.org/Projects/bala.html .
(a) What is the global average temperature increase from the beginning to the end of the simulation? Most climate simulations end at the year 2100, but this one goes to 2300. You may investigate either year as an "end of simulation".

The model warms about 3°C by 2100, 7°C by the year 2300.

(b) What is the predicted warming in the winter high latitude, the summer high latitude, and the tropics?

High latitudes in winter warm by about 15-25°C in the year 2300. In summer, it's about 5-15°C. In the tropics, the annual average warming is 4-5°C.

(c) Can you see evidence for poleward migration of biome types? How far do the biomes move?

Biome 5, for example, the temperate deciduous forest, moves from 40° N to about 70° N.

(d) Can you see a systematic change in precipitation or soil moisture with climate change?

The anomaly plot shows an increase in the western tropical Pacific, a decrease in the 30° latitude bands, and an increase in higher latitudes.

Chapter 13

1. Compound Interest. The formula to compute compound interest for a bank account is

$$Balance(t) = Balance(initial) \cdot e^{k \cdot t}$$

This was first presented in Chapter 5, when we met the exponential function e^x. Assuming an interest rate of 3%/year, how much would an investment of $1.00 made today be worth in the year 2100? What if the interest rate were 5%/year?

At 3%, the investment would be worth $20. At 5%, $148.

2. ΔT_{2x}. The formula to estimate temperature response to changing CO_2 concentration is

$$\Delta T = \Delta T_{2x} \times \frac{\ln\left({new\ pCO_2} / {orig.pCO_2} \right)}{\ln(2)}$$

This formula was first introduced in Chapter 4. Calculate the temperature that would result from increasing atmospheric pCO_2 from pre-anthropogenic value of 280 ppm to 1000 and 2000 ppm. The temperature during the Cretaceous period might have been 6°C warmer than today. Using a ΔT_{2x} value of 3°C, what must the pCO_2 have been at that time? How does your answer change if ΔT_{2x} is 4°C?

Using ΔT_{2x} of 3° C, 1000 ppm of CO_2 would result in 5.5°C of warming. 2000 ppm would be 8.5°C. 6°C would be two doublings, which is 4 times 280 or 1120 ppm CO_2. Using ΔT_{2x} of 4°C, the answers are 7.3°, 11.3°, and 790 ppm.

2. Carbon-Free Energy. The Kaya Identity web page actually runs a carbon cycle model to predict the atmospheric pCO_2 response to its predicted carbon emissions. You learned about this model in Chapter 9. The Kaya web page then computes how much coal energy would have to be replaced by carbon-free energy, if we wish to stabilize atmospheric CO_2 at some concentration (choices are 350, 450, 550, 650, and 750 ppm). Using the default web page settings, which are something like a business-as-usual scenario, find from the plot the amount of energy in terawatts required to stabilize CO_2 at 450 ppm.

Stabilizing at 450 would require 20 TW of carbon-free energy by 2100.

a. If a typical nuclear reactor generates 1000 megawatts of energy, how many power plants would be required by the year 2100? (the prefix tera means 10^{12}, while mega means 10^6). How many power plants would this require?

20,000 power plants. (This is one plant every two days for 100 years).

b. A modern windmill generates about 1 megawatt of energy; let's say that future ones will generate 10 megawatts per tower. How many of these would be required to meet our energy needs by 2100? The radius of the earth is 6.4×10^6 meters. What is its surface area? Land occupies about 30% of the surface of the earth; what area of land is there? Let's assume that windmills could be placed at a density of four windmills per square kilometer. What fraction of the earth's land surface would be required to supply this much wind energy?

We would need 2 million windmills. The area of the Earth is $5.1 \cdot 10^{14}$ m^2. *Land is* $1.5 \cdot 10^{14}$ m^2. *Windmills would require 0.3% of the land surface.*

4. Carbon Stabilization and Kyoto. How much would we have to cut emissions to stop atmospheric pCO_2 from rising beyond current levels? You could just randomly plug numbers into the model, or you could do it a smarter way: Run the model for BAU (climate geekspeak for business-as-usual) and determine from the printed output below the plots what the rate of CO_2 uptake is by the ocean today (call it year 2000). You'll have to take the difference in the cumulative ocean inventory between two adjacent time points, and divide by the number of years between those two points (five), to get Gtons of C uptake per year. Plug these numbers into the model and run it, to see if that really stops pCO_2 from going up. What percentage change in emission is this? The Kyoto Protocol aimed to limit emissions to some percentage below 1990 levels. The Japanese and Europeans argued at the high end, for something like 9% reductions below 1990. The Americans and the Saudis were at the low end, say 2% below 1990. Compare this range of emission with your answer.

Cuts of about 50% would be required. These are much deeper than the Kyoto protocol mandated.