Global Warming: Understanding the Forecast

Second Edition

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Preface

Global Warming: Understanding the Forecast is based on a class for undergraduate non-science majors at the University of Chicago, developed by Ray Pierrehumbert and myself. The class serves as partial fulfillment of our general education or "core" science requirements. We teach the class, and I have written the textbook, in a mechanistic way. We are aiming to achieve an intuitive understanding of the ropes and pulleys of the natural world, a fundamental scientific foundation that will serve the student for longer than would a straight presentation of the latest predictions.

The text is aiming at a single problem, that of assessing the risk of anthropogenic climate change. The story ranges from science to economics to policy, through physics, chemistry, biology, geology, and of course atmospheric science. We see the distant past and the distant future. In my opinion, by looking at one problem from many angles the student gets a pretty decent view of how a working scientist really thinks. This is as opposed to, say, taking a survey tour of some scientific discipline.

The text is suitable for students of all backgrounds. We do make some use of algebra, mostly in the form of what are known as (gasp) story problems. The student will be exposed to bits and pieces of chemistry, physics, biology, geology, atmospheric science, and economics, but no prior knowledge of any of these topics is required. One can learn something of what each field is about by learning what it is good for, within the context of the common unifying problem of global warming.

I have provided a project associated with each chapter after the first, either a computer lab or a paper and pencil exercise, suitable to do in lab sections or as homework. The first three are paper and pencil, aimed at building a foundation for understanding the computer labs that follow. The models run on our computers at the University of Chicago, and you can access them through web pages. No special setup of the student's computer is required, and the students can work equally well in a computer lab or at Starbuck's (actually, it would be interesting to see if that's true.).

This book benefited by thorough, thoughtful reviews by Andy Ridgwell, Stefan Rahmstorf, Gavin Schmidt, and a fourth anonymous reviewer. The web interface to the models benefited from input by Jeremy Archer. The visible/IR radiation model was constructed by Ray Pierrehumbert and Rodrigo Caballero. The ISAM carbon cycle model was provided by Atul Jain. The Exercises in Chapters 11 and 12 make use of model output provided by G. Bala, and is plotted using ferret, developed at NOAA PMEL.

Preface to Second Edition

The text has been revised and updated throughout, reflecting results from the fourth Intergovernmental Panel on Climate Change Scientific Assessment Report, published in 2007.

Dedicated to George Lockwood, and the spirit of curiosity.

Chapter 1. Humankind and Climate

Everyone always complains about the weather, but no one ever does anything about it. --Mark Twain.

The Glaciers are Melting, But Is It Us?

Is it really possible that human activity could alter the weather? As I write it is a crisp, clear fall day. What would be different about this day in 100 years, in a world where the chemistry of the atmosphere has been altered by human industrial activity?

There is no doubt that the Earth is warming. Mountain glaciers are disappearing. The Arctic coast is melting. Global average temperature records are broken year after year. The growing season has been getting longer. Plans are being made to abandon whole tropical islands as they sink into the Pacific Ocean. Shippers are awaiting the opening of the Northwest Passage that early explorers searched for in vain, with the melting of sea ice in the Arctic.

Of course, the natural world is has variable weather all by itself, naturally. Is it likely that some of our recent weather has been impacted by human-induced climate change, or how much of this would have happened anyway? If humans are changing climate, do we know that this is a bad thing? How does the future evolution of climate compare with the climate impacts we may be seeing today?

Weather versus Climate

We should distinguish at the outset between climate and weather. Weather is chaotic, which means that it cannot be forecast very far into the future. Small errors in the forecast grow with time, until eventually the forecast is nothing but error. The word "climate" means some kind of average of the weather, say over 10 years or more. Weather models cannot reliably predict whether it will rain or be sunny on a particular day very far into the future, but climate models can hope to forecast the average raininess of some location at some time of year. Weather is chaotic, but the average is not chaotic, and seems to be in some ways predictable (Chapter 6).

Human forcing of climate is expected to be small compared to the variability associated with the weather. Temperature in the coming century is projected to rise a by few degrees centigrade (Chapter 12). This is pretty small compared to the temperature differences between the equator and the pole, between winter and summer, or even between daytime and night. One issue this raises is that it is tricky to discern a change in the average, when the variability is so much greater than the trend. Careers are spent computing the global average temperature trend from the 100+ year thermometer record (Chapter 11).

The small change in the average, relative to the huge variability, also raises the question of whether a change in the average will even be noticeable. One way that the average weather matters is in precipitation. Groundwater tends to accumulate, reflecting rainfall over the past weeks and months. It may not matter to a farmer whether it rains on one day versus the next, but if the average rainfall in a region changes, that could spell the difference between productive farming and not. A change in the average climate would change the growing season, the frequency of extreme hot events, the distribution of snow and ice, the optimum growth localities of plants and agriculture, and the intensity of storms.

In addition to day-to-day weather, there are longer-lasting variations in climate. One past climate regime was the Little Ice Age, ~1650 – 1800, bringing variable weather to Europe. By some reconstructed temperature records it was about 1°C colder than our "natural" climate from about the year 1950. Before that was the Medieval Climate Anomaly, perhaps 0.5°C warmer over Europe, coincident with a prolonged drought in American southwest. The causes of these climate changes will be discussed in Chapter 11, but for now it is enough to observe that relatively small-sounding average-temperature shifts produced noticeable changes in human welfare and the evolution of history. The climate of the Last Glacial Maximum, 20,000 years ago, was so different from today that the difference would be obvious even from space, in the massive ice sheets and altered coastlines, and yet the average temperature difference between then and today was only about 5-6°C (Chapter 8). Another implication of these natural climate shifts is that it makes it more difficult to figure out whether the present-day warming is natural or caused by rising greenhouse gas concentrations and other human impacts on climate.

Forecasting Climate Change

The fundamental process that determines the temperature of the Earth is the balance between energy flowing to the Earth from the sun, versus energy flowing away from the Earth into space. Heat loss from Earth to space depends on Earth's temperature (Chapter 2). A hotter Earth loses heat faster than a cooler one, everything else being equal. The Earth balances its energy budget by warming up or cooling down, finding the temperature at which the energy fluxes balance, with outflow equaling inflow.

It is possible to change the average temperature of the Earth by altering the energy flow either coming in or going out, for example by changing the brightness of the sun. It is known that there is a small variation in the brightness of the sun correlated with the number of sunspots. Sometimes sunspots disappear altogether, presumably indicating a particularly cool sun. The Maunder minimum was such a period, lasting from 1645-1750, coincident with the Little Ice Age.

Some of the incoming sunlight is reflected back to space without ever being absorbed (Chapter 7). When sunlight is reflected rather than absorbed, it makes the Earth cooler. Clouds reflect light, and so does snow. Bare soil in the desert reflects more light than vegetation does. Smoke emitted from coal-burning power plants produces a haze of sulfuric acid droplets that can reflect light.

The Earth is kept significantly warmer than it would be by the greenhouse effect in the atmosphere. Most of the gases in the air are completely transparent to infrared light, meaning that they are not greenhouse gases. The greenhouse effect is entirely driven by trace gases in the atmosphere, first among them carbon dioxide or CO_2. Water vapor and methane are also greenhouse gases. The impact that a particular greenhouse gas has on climate depends on its concentration (Chapter 4). The strength of the greenhouse effect also depends on the temperature structure of the atmosphere (Chapter 5).

Water vapor is a tricky greenhouse gas, because the amount of water vapor in the atmosphere is determined by the current climate. Water tends to evaporate when the air is warm, and condense as rain or snow in cool air. Water vapor, it turns out, amplifies the warming effects from changes in other greenhouse gases. This water-vapor feedback more-or-less doubles the temperature change we would expect from rising atmospheric CO_2 concentration without the feedback, in a dry world for example.

Clouds are very effective at absorbing and emitting infrared light, acting like a completely IR-opaque greenhouse gas. A change in cloudiness also affects the visible-light incoming energy flux, by reflecting it (Chapter 7). Clouds are double-edged climate forcing agents, cooling the Earth by reflecting sunlight while warming it by acting like a greenhouse gas in the atmosphere, trapping infrared light escaping to space.

Human activity has the potential to alter climate in several ways. Rising CO_2 concentration from combustion of fossil fuel is the largest and longest-lasting human-caused climate forcing agent, but we also release or produce other greenhouse gases, such as methane and other carbon molecules, nitrous oxide, and ozone. Particles from smoke stacks and internal combustion engines reflect incoming visible light, altering the heat balance. Particles in otherwise remote clean air may also change the average size of cloud droplets, which has a huge but very uncertain impact on sunlight reflection (Chapter 10).

Many of these climate drivers themselves respond to climate, leading to stabilizing or destabilizing feedbacks. Reconstructions of prehistoric climate changes often show more variability than models tend to predict, presumably because there were positive feedbacks in the real world that are missing in the models. For example, the climate cools, so forest changes to tundra, allowing more of the incoming sunlight to be reflected to space, cooling the climate even more. A climate model in which the forests do not respond to climate would underestimate the total amount of cooling. In the global warming forecast, the feedbacks are everything (Chapter 7).

The forecast for the coming century is also tricky because some parts of the climate system take a long time to change, such as melting an ice sheet or warming the deep ocean. It is hard enough to predict the equilibrium climate response to some change in forcing, but even harder to predict how quickly it will change (Chapter 12).

Carbon, Energy, and Climate

Climate change from fossil fuel combustion is arguably the most challenging environmental issue human kind has ever faced, because CO_2 emission is at the heart of how we produce energy, which is pretty much at the heart of our modern standard of living. The agricultural revolution, which supports a human population of 6 billion people and hopefully more, has at its heart the industrial production of fertilizers, a very energy intensive process. It's not so easy to stop emitting CO_2, and countries and companies that emit lots of CO_2 have strong interest in continuing to do so (Chapter 9).

The energy we extract from fossil fuels originated in the nuclear fires of the sun. Visible light carried the energy to Earth, where it powered photosynthesis in plants, storing energy in chemical bonds between atoms of carbon, hydrogen, oxygen and other elements. Plants have two motives for doing this, one to store energy and the other to build the biochemical machinery of life (Chapter 8).

Most of the biological carbon we use for fossil fuels was photosynthesized millions of years ago. Over geologic time, some of the biological carbon has been converted into the familiar fossil fuel types: oil, natural gas, and coal. Coal is the most abundant of these, while the types of oil and gas that are currently being extracted will be depleted in a few decades (Chapter 9). Stored carbon energy is used to do work, in plants, animals, and now in automobiles etc., by reacting the carbon with oxygen to produce CO_2. An automobile needs gas and air to run the engine, liberating the chemical energy by combustion. In living things the energy extracting process is called respiration, and it explains why we need to breathe (to obtain oxygen and get rid of CO_2) and eat (to get biological carbon compounds) (Chapter 8).

CO_2 is released into the atmosphere to join the beautiful cacophony that is the carbon cycle of the biosphere. Trees and soils take up and release carbon, as does the ocean. Carbon is released when tropical forests are cut, while forests in the high latitudes appear to be taking up atmospheric CO_2. Most of the CO_2 we release to the atmosphere will eventually dissolve in the oceans, but this process takes several centuries. A small fraction, about 10%, of the CO_2 released will continue to alter climate for hundreds of thousands of years into the future (Chapter 10).

Assessing the Risk

Is mankind creating a global warming trend? Climate scientists have tried to answer this question by comparing the history of Earth's temperature with the history of the different reasons why temperature might have changed, what are called climate forcings. The sun is more intense at some times than others. Volcanoes occasionally blow dust or haze into the stratosphere where it reflects sunlight back to space. Greenhouse gases and smokestack aerosols are two anthropogenic climate forcings.

Climate scientists have arrived at the conclusion that it is easy to explain the warming as caused by increased greenhouse gas concentrations, but impossible to explain it as a natural occurrence, unforced by human activity (Chapter 11). Greenhouse theory is over one hundred years old, and is required to explain why the natural Earth is as warm as it is (as well as other planets such as Venus and Mars). For the threat of human-induced climate change to go away, we'd have to toss out greenhouse theory, and come up with some other explanation for why the Earth has been warming over the past decades. But there is no existing model or theory of climate that can reproduce the present-day natural climate, but which would not warm significantly if there were more CO_2 in the atmosphere.

The forecast for the climate of the coming century is for a temperature increase of 2-5°C by the year 2100. It doesn't sound like much, until it is compared with the impacts of natural climate changes in the past such as the Little Ice Age (-1 °C) and the Medieval Climate Anomaly (+0.5 °C). These climate shifts were noticeable pretty much everywhere, and game-changing in some places.

The largest unknown in the climate forecast is the amount of CO_2 that will ultimately be released. Some amount of global warming is inevitable, but most of the carbon that could be released by 2100 is still in the ground. The decision is being made now, and in the next few decades.

The economic projections are that reducing CO_2 emissions substantially might cost a few percent of global net economic production (GNP). That certainly would be a lot of money if you were looking at it piled in a heap, but in an economy that is growing by a few percent per year, a cost of a few percent per year would only set the trajectory of economic production back by a year or two (Chapter 13).

Sometimes climate issues are framed as a balance between the costs of avoiding CO_2 emission versus the costs of living with climate change. That way of thinking seems flawed to me because it ignores the unfairness that the people who benefit from CO_2 emission, those in the developed world, are not the same as the people who pay the bill, in the developing world and in the distant future. Ultimately, the question of climate change may be a matter of ethics and fairness, as much as one of profit and loss.

Greenhouse gas emission to the atmosphere is an example of a situation called the tragedy of the commons. The benefits of fossil fuel combustion go to the individual, while the costs of climate change are paid by everyone. In this situation there is a natural tendency for everyone to over-exploit the common resource. The solution to this is to change the incentive system, so that the common costs of the decision end up being paid by the person making the decision. Carbon taxes and cap-and-trade schemes are two proposed ways to do this.

International negotiations are ongoing, within a framework called the Framework Convention on Climate Change (FCCC) under the United Nations. The first major milestone was the Kyoto Protocol, initially adopted in 1995. It succeeded in entering into force on 2005, but it has pretty much failed to decrease the rate of CO_2 emission.

The ongoing negotiations may be having an impact on energy investment, however, stimulating the growth of alternative energy technology for example. In the next few decades, the biggest changes in carbon emissions could come from conservation and efficiency. The technology exists to begin to cut CO_2 emissions. Looking farther ahead, one hundred years from now, new, larger scale energy sources will have to be found. Neither windmills nor nuclear power plants such as we have them today could scale up to the amount of carbon-free energy that humankind will need a century from now.

With our growing technological and intellectual prowess, as well as our exploding population, we are slowly taking over the job of managing the biosphere. May we do it wisely!

Part I. The Greenhouse Effect

Chapter 2. Blackbody Radiation

How light can carry heat energy through empty space.

Heat

Heat is simply the bouncing-around energy of atoms. Atoms in gases and liquids fly around, faster if it is hot and slower if it is cold. Atoms with chemical bonds between them stretch, compress, and bend those bonds, again more energetically at high temperature.

Perhaps you knew this already, but have you ever wondered how you can feel such a thing? Atoms are tiny things. We can't really feel individual atoms. But it doesn't take any state-of-the-art laboratory technology to tell how fast the iron atoms in your stove burner are bouncing around. All you have to do is touch it. Actually, another method may be occurring to you, that you could look at it; if it's hot, it will glow. It glows with blackbody radiation, which we'll get back to later.

A thermometer is like an atomic speedometer.

You can feel the hot stove because the energetic bounciness of the stove atoms gets transferred to the atoms in your nerves in your fingers. The fast-moving atoms of the burner bounce off the atoms in your finger, and the fast ones slow down a bit and the slower ones bounce back with a little more energy than they started with. Biological systems have evolved to pay attention to this, which is why you can feel it, because too much energy in our atoms is a dangerous thing. Chemical bonds break when they are heated too much; that's what cooking is. Burning your finger by touching a hot electric stove burner is an example of heat **conduction**, the easiest form of heat flux to envision.

Light

A thermos bottle is designed to slow the flow of heat through its walls. You can put warm stuff in there to keep it warm, or cool stuff to stay cool. Thermos bottles have two walls, an inside and an outside. In between the two walls is an insulator. **Vacuum**, a space with no air in it, is a really good insulator, because it has no molecules or atoms of gas in it to carry heat energy between the inner and outer walls of the thermos. Of course there will still be heat conduction along the walls. But think about a planet. There are no walls, however thin, connecting a planet with anything. The space between the Earth and the sun is a pretty good vacuum. We know how warm it is in the sunshine, so we know that heat flows from the sun to the Earth. And yet separating the sun from the Earth is 150 million kilometers of vacuum. How can heat travel through this?

Electro-Magnetic Waves Carry Energy Through a Vacuum

The energy travels by means of **light**. Electrons and protons have a property called **electric charge**. What an electric charge is, fundamentally, no one can tell you, but it interacts through space via a property of the vacuum called the **electric field**. A positive electric field attracts a negatively charged electron. This is how a TV tube hurls electrons toward the screen in a picture-tube television, in the old days, before electronic flatscreens, by releasing an electron and then pushing it around with the electric field.

The electric field interacts with another property of the vacuum called the **magnetic field**. If the strength of the electric field at some location, measured in volts, changes with time, if the voltage is oscillating up and down for example, that will cause a change in the magnetic field, such as a compass would point to. This is how an electro-magnet works, converting electrical field energy into magnetic field energy. Going the other direction, if the magnetic field changes, it can produce an electrical field. This is how an electrical generator works.

It turns out that the electric and magnetic fields in the vacuum fit together to form a closed, self-replicating cycle like the ringing of a bell or the propagation of a non-breaking wave in water. An up-and-down oscillation in the electric field will cause a complementary oscillation in the magnetic field, which reinforce the electric field in turn. The disturbances created by the electric and magnetic fields propagates the pattern in the fields, the same wave but moving through space at a particular velocity, the **speed of light**, written as the letter **c**. The bundle of electric and magnetic waves can in principal hurl through the vacuum forever, carrying energy with it.

A light wave rings like a bell

The ringing of the electromagnetic field in light can come in a range of different frequencies. **Frequencies**, of oscillators or of light waves, have units of cycles/second and are denoted by the Greek letter ν, pronounced "nu". It turns out that all different frequencies of light travel at the same speed in a vacuum. Within some non-vacuum medium such as air, water, or glass, different frequencies of light might vary in their speeds a little bit, which is how a prism separates white light into its component colors. But in a vacuum, all light travels at the same speed. The speed of light in a vacuum is a fundamental constant of nature.

The constancy of the speed of light in a vacuum makes it easy to relate the frequency of the light to its **wavelength**, the distance between the crests of a wave. You can figure out what the relationship is between frequency and wavelength by thinking geometrically, imagining the wavy line in Figure 2-1 to be moving past us at some speed c. If the crests are 1 cm apart and they were moving at 10 cm/second, then 10 crests would move past us every second. Alternatively, you can make use of units. Pay attention to units, and they will lead you to virtue, or at least to the right answer. Problem: assemble the two things we know, ν and c, such that the units combine to be the same as the units of λ. Solution:

$$\lambda\left[\frac{cm}{cycle}\right]=\frac{c\left[\frac{cm}{\sec}\right]}{\nu\left[\frac{cycle}{\sec}\right]}$$

Don't take my word for it, check and make sure the units are the same on both sides of the equation.

Scientists who discuss infrared light often use a third way of describing different colors, called the **wave number**, defined as the number of cycles per centimeter of length. It's simply a matter of convenience; when infrared light is described by its wave number, it will have a nice, easy-to-remember number; for example the CO_2 absorption of infrared light that is responsible for most of its greenhouse effect comes at a wavenumber value of about 700 cycles / cm. We will use the letter **n** to designate the wave number. How can we construct the units of n from the building blocks of λ, ν, and c? By looking at the units, it looks like all we need is λ,

$$n\left[\frac{cycles}{cm}\right]=\frac{1}{\lambda\left[\frac{cm}{cycle}\right]}$$

Different frequencies of light all have the same fundamental nature; they are all waves of the same essential physics. Figure 2-2 shows the names assigned to different types of light, based on their frequencies. Of course, if you know the frequency of light, you know its wavelength and wavenumbers also, so the figure has "mile markers" in these units too.

Our eyes are sensitive to light in what we pragmatically call the visible range. Light of higher frequencies than this carry enough energy to break chemical bonds, so they can be dangerous to us as chemical creatures. **Ultraviolet light**, or **UV**, causes sunburn, and **x-rays** and **gamma radiation** can do deeper and more extensive chemical damage. At longer wavelengths than visible we find the **infrared** range, or **IR.** Objects at about room temperature glow with IR light. Heat lamps at the skating rink warm people up by shining invisible IR light on them.

All that energy whizzing around space in the form of coupled electric and magnetic field waves would be of little interest to the energy balance of a planet, if they did not give up or carry off energy. There are a number of different mechanisms by which light may interact with matter, but infrared light interacts mostly with vibrations of the chemical bonds of a molecule. Light interacts with matter by means of the electric field that they share (Figure 2-3).

Imagine matter as constructed with charged oscillators all over its surface; little charged weights sticking out from the surface of the matter on little springs that stretch and contract. This little oscillator will have a frequency with which it will "ring". Incoming energy in the form of light brings with it an electric field oscillating up and down: voltage goes plus, minus, plus, minus. If the frequency of the cycles of voltage in the light is about the same as the frequency of the oscillations of the chemical bonds, the light can be absorbed. Its energy is transferred into **vibrational energy** of the matter.

If an object can absorb light it can emit it

This mechanism of energy transfer is a two-way street. If energy can flow from the light to the oscillator, it will also be able to go the other way, from the oscillator to light. The vibrational energy of the oscillator is what we have been calling its temperature. Any matter that has a temperature above absolute zero (zero degrees on the Kelvin scale) will have energy in its oscillators that it may be able to use to create light. The two-way street character of this process is important enough that it is given the name **Kirchoff's law.** Try an experiment of singing a single note into a piano with dampers off. When you stop, you will hear the strings echo back the note you sang into it. This sound wave to string vibration energy transfer is a two-way street, as well.

Blackbody Radiation

Where can one see electrical energy traveling the other way, from matter into light? One example is a red-hot electric burner, which shines light you can see. The light derives its energy from the vibrations or thermal energy of the matter. We normally don't think of it, but it turns out that your electric burner continues to shine even when the stove is at room temperature. The difference is that the room temperature stove emits light in frequencies that our eyes can't see, down in the infrared.

If a chunk of matter has oscillators that vibrate and can interact with light at all possible frequencies, it is called a **blackbody.** The light that is emitted by a blackbody is called **blackbody radiation.** Most solids and liquids at the surface of the Earth are pretty good blackbodies, but gases in the atmosphere are not blackbodies; they only interact with specific frequencies of light. The are like pianos with most of the strings missing.

A blackbody is like a musical instrument with all the notes.

Blackbody radiation is made up of a characteristic distribution of frequencies (colors) of infrared light. Figure 2-4 shows a plot with axes of the intensity of light in the y-direction and frequency in the x-direction. The units of intensity look a bit complicated; they are $\frac{\text{Watts}}{\text{m}^2 \text{ wavenumber}}$. The unit on the top of the fraction is **Watts**, the same kind of Watts that describe your hairdryers and audio amplifiers. A Watt is a rate of energy flow, defined as Joules per second, where energy is counted in **Joules.** The meters squared on the bottom of the fraction is the surface area of the object. The unit of wavenumbers on the bottom of the fraction allows us to divide the energy up according to the different wavenumber bands of light, for instance all of the light between 100 and 101 cm^{-1} carries this many W/m^2 of energy flux, between 101 and 102 cm^{-1} carries that many W/m^2, and so on. The total flux of energy can be calculated by adding up the bits from all the different slices of the light spectrum. The plot is set up so that you can add up the area under the curve to obtain the total energy intensity in W/m^2. You could cut the plot out with a pair of scissors and weigh the inside piece to determine its area, which would then be proportional to the total energy emitted in all frequencies of light.

This type of plot is called a spectrum. The infrared light emission spectrum of a blackbody depends only on the temperature of the object. There are two things you should notice about the shapes of the curves in Figure 2-4. First, as the temperature goes up, the curves are getting higher, meaning that light of each frequency is getting more intense (brighter). As the temperature of the object goes up, the total energy emitted by the object goes up, which you can see by the fact that the curve in Figure 2-4 is bigger. There is an equation that tells how quickly energy is radiated from an object. It is called the **Stefan-Boltzmann equation**, and we are going to make extensive use of it. Get to know it now! The equation is

$$I = \varepsilon \, \sigma \, T^4 \qquad (2\text{-}1)$$

The **intensity** of the light is denoted by **I**, and represents the rate of energy emission from the object. The Greek letter epsilon (ε) is the **emissivity**, a number between zero and one describing how good a blackbody the object is. For a perfect blackbody, $\varepsilon = 1$. Sigma (σ) is a fundamental constant of physics that never changes, a number you can look up in reference books, called the **Stefan-Boltzmann constant**. T is the temperature in **Kelvins**, and the superscript 4 is an exponent, indicating that we have to raise the temperature to the fourth power. The Kelvin temperature scale begins with 0 K when the atoms are vibrating as little as possible, a temperature called **absolute zero**. There are no negative temperatures on the Kelvin scale.

A hot object emits much more light than a cold object

One of the many tricks of thinking scientifically is to pay attention to units. Here is equation 1 again, with units of the various terms specified in the square brackets.

$$I\left[\frac{W}{m^2}\right] = \varepsilon\left[unitless\right]\ \sigma\left[\frac{W}{m^2\ \ K^4}\right]\ T[K]^4$$

The unit of the intensity I is Watts of energy flow per square meter. The meters squared on the bottom of that fraction is the surface area of the object that is radiating. The area of the Earth, for example, is $5.14 \cdot 10^{14}$ m^2. Temperature is in Kelvins, and ε has no units; it is just a number between 0 and 1 for a perfect blackbody.

Here's the important point: The units on each side of this equation must be the same. On the right-hand side, K^4 cancels leaving only W/m^2 to balance the left-hand side. In general, if you are unsure how to relate one number to another, the first thing to do is to listen to the units. They will guide you to the right answer. We will see many more examples of units in our discussion, and you may rest assured I will not miss an opportunity to point them out.

Infrared sensitive cameras allow us to see what the world looks like in infrared light. The glasses of the guys in Figure 2-5 are cooler than their skins, and therefore darker in the infrared. How much darker they will be can be estimated from equation 1 to be

$$\frac{I_{cheek}}{I_{glasses}} = \frac{\varepsilon_{cheek}\ \ \sigma\ \ T_{cheek}^4}{\varepsilon_{glasses}\ \ \sigma\ \ T_{glasses}^4}$$

The Stefan-Boltzmann constant σ is the same on both top and bottom; σ never changes. The emissivity ε might be different between the cheek and the glasses, but let's assume they are the same. This leaves us with the ratio of the brightnesses of the skin and glasses equal to the ratio of temperatures to the fourth power, maybe $(285\ K / 278\ K)^4$, which is about 1.1. The cheeks shine 10% more brightly than the surface of the coat, and that is what the IR camera sees.

The second thing to notice about the effect of temperature on the blackbody spectra in Figure 2-4 is that the peaks shift to the right as the temperature increases. This is the direction of higher frequency light. You already knew that a hotter object generates shorter wavelength light, because you know about red hot, white hot. Which is hotter? White hot, of course; any kid on the playground knows that. A room temperature object (say 273 K) glows in the infrared, where we can't see it. A stove at stovetop temperatures (400-500 K) glows in shorter wavelength light, which begins to creep up into the visible part of the spectrum. The lowest energy part of the visible spectrum is red light. Get the object hotter, say the temperature of the surface of the sun (5000 K), and it will fill all wavelengths of the visible part of the spectrum with light. Figure 2-6 compares the spectra of the Earth and the sun. You can see that sunlight is visible while "Earth light" (more usually referred to as **terrestrial radiation**) is infrared. Of course, the total energy flux from the sun is much higher than it is from Earth. Repeating the calculation we used for the infrared photo, we can calculate that the ratio of the fluxes is $(5000\ \mathrm{K} / 273\ \mathrm{K})^4$, or about 10^5. The two spectra in Figure 2-6 have been scaled by dividing each curve by the maximum value that the curve reaches, so that the top of each peak is at a value of one. If we hadn't done that, the area under the Earth spectrum would be 100,000 times smaller than the area under the sun spectrum, and you would need a microscope to see the Earth spectrum on the figure.

Red hot, white hot

It is not a coincidence that the sun shines in what we refer to as visible light. Our eyes evolved to be sensitive to visible light. The infrared light field would be a much more complicated thing for an organism to measure and understand. For one thing, the eyeball, or whatever light sensor the organism has, will be shining IR light of its own. The organism measures light intensity by measuring how intensely the incoming light deposits energy into oscillators coupled to its nervous system. It must complicate matters if the oscillators are losing energy by radiating light of their own. Infrared telescopes must be cooled in order to make accurate IR intensity measurements. Snakes are able to sense IR light. Perhaps this is useful because their body temperatures are colder than those of their intended prey.

Take-Home Points

Light carries energy through the vacuum of space.

If an object can absorb light, it can also emit light.

An object that can emit all frequencies of light is called a blackbody, and it emits light energy at a rate equal to $\varepsilon \sigma T^4$.

Study Questions

Following the units, find the formula to compute the frequency of light given its wavelength, or its wavenumber from its frequency.

Draw a blackbody radiation spectrum for a hot object and a cold object. What two things differ between the two spectra?

Use the Stefan-Boltzmann equation to compare the energy fluxes of the hot object and the cold object as a function of their temperatures.

What would an emission spectrum look like for an object that is not a blackbody?

How does the Stefan-Boltzmann equation deal with an object that is not a blackbody?

Further Reading

Blackbody radiation was a clue that something was wrong with classical physics, leading to the development of quantum mechanics. Classical mechanics predicted that an object would radiate an infinite amount of energy, instead of the $\varepsilon \sigma T^4$, as we observe it to be. The failure of classical mechanics is called the ultraviolet catastrophe, and you can read about it, lucidly presented but at a rather high mathematical level, in the **Feynman Lectures on Physics**, Volume 1, Chapter 41. My favorite book about quantum weirdness, the philosophical implications of quantum mechanics, is **In Search of Schrodinger's Cat**, by John Gribbon, but there are many others.

Figure Captions

1. The frequency and wavelength of light are related to each other by the speed of light, which in a vacuum is the same for all different types of light, $3.0 \cdot 10^{10}$ cm / second.

2. The electromagnetic spectrum.

3. A charged oscillator interacting with light.

4. The intensity of light emitted from a blackbody as a function of the wavenumber (cycles per centimeter) of the light. There are several spectra shown, for different blackbody objects at different temperatures. A warmer object emits more radiation than a cooler one.

5. A photograph taken in infrared light.

6. The shapes of the blackbody spectra of Earth and the sun. The Earth spectrum has been expanded to reach the same peak intensity as the solar spectrum, so the two can be compared on the same plot. The point is that the sun shines in visible light, while the Earth shines in infrared light.

Exercises

1. A joule is an amount of energy, and a watt is a rate of using energy, defined as
$1 \text{ W} = 1 \text{ J} / \text{s}$. 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?

2. A gallon of gasoline carries with it about $1.3 \cdot 10^8$ Joules of energy. Given a price of $3 per gallon, how many Joules can you get for a dollar?

Electricity goes for about $0.05 per kilowatt hour. A kilowatt hour is just a weird way to write Joules, since a Watt is a Joule per second, and a kilowatt hour is the number of Joules one would get from running 1000 Watts times one hour (3600 seconds). In the form of electricity, how many Joules can you get for a dollar?

A standard cubic foot of natural gas carries with it about $1.1 \cdot 10^6$ Joules of energy. You can get about $5 \cdot 10^5$ BTU's of gas for a dollar, and there are about 1030 BTU's in a standard cubic foot. How many Joules of energy in the form of natural gas can you get for a dollar?

A ton of coal holds about $3.2 \cdot 10^{10}$ Joules of energy, and costs about $40. How many Joules of energy in the form of coal can you get for a dollar?

Corn oil costs about $0.10 per fluid ounce wholesale. A fluid ounce carries about 240 dietary calories (which a scientist would call kilocalories). A calorie is about 4.2 Joules. How many Joules of energy in the form of corn oil can you get for a dollar?

Rank these as energy sources, cheap to expensive. What is the range in prices?

3. 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.

4. 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?

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?

5. 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.

6. We are supposed to eat about 2000 dietary calories per day. How many Watts is this?

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

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

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

Chapter 3. The Layer Model

Our first climate model.

The Bare-Rock Model

We are going to construct a simple model of the temperature of the Earth. The word **model** is used quite a bit in scientific discussion, to mean a fairly wide variety of things. Sometimes the word is synonymous with "theory" or "idea", such as the Standard Model of Particle Physics. For doctors, a "model system" might be a mouse that has some disease that resembles a disease that human patients get. They experiment on the mouse rather than experimenting on people.

In climate science, models are used in two different ways. One way is to make **forecasts.** For this purpose, a model should be as realistic as possible, and should capture or include all of the processes that might be relevant in nature. This is typically a mathematical model implemented on a computer, although there's a nifty physical model of San Francisco Bay you should check out if you're ever in Sausalito. Once such a model has been constructed, a climate scientist can perform what-if experiments on it that could never be done to the real world, to determine how sensitive the climate would be to changes in the brightness of the sun or properties of the atmosphere, for example.

The simple model that we are going to construct here is not intended for making predictions, but it's more like a toy, to play with and understand and learn from. The model will demonstrate how the greenhouse effect works by stripping away lots of other aspects of the real world, things that would certainly be important for predicting climate change in the next century or the weather next week, but makes the climate system more complicated and therefore more difficult to understand.

The layer model is a toy, demonstrating an idea

The model is called the **Layer Model.** Understanding the Layer Model will not equip us to make detailed forecasts of future climate, but one cannot understand the workings of the real climate system without first understanding the Layer Model. The first step is to construct the model with no atmosphere, so that the only layer is the ground, a **Bare Rock**

Model. The next step is to demonstrate the greenhouse effect by adding an atmospheric layer.

The temperature of the surface of the Earth is controlled by the energy flows, in from the sun and back out to space as infrared light. Both types of light are primarily from blackbody radiation as discussed in the last chapter. The sun is very bright because its surface temperature is high and therefore the energy flux $I = \varepsilon \sigma T^4$ is a large number. Sunlight strikes the Earth and deposits some of its energy into heat at the Earth's surface. The Earth sheds heat by blackbody radiating in the infrared, at much lower intensity and longer wavelength because the Earth is cooler than the Sun.

The Layer Model assumes that the amount of energy leaving the Earth as infrared is exactly equal to the amount of energy coming into the planet from sunlight. The real world may be out of energy balance for a little while or in some region or season, but the Layer Model is always exactly in balance. The Layer Model is essentially an algebraic story problem, and it can built up from the algebraic statement that

$$F_{out} = F_{in} \qquad \text{(eqn. 3-1)}$$

where F_{out} is the outgoing energy flux, and F_{in} is the flux of energy in.

Let's begin with incoming sunlight. The **intensity** of sunlight, I_{in}, at the top of the atmosphere, is about 1350 Watts / m^2. But not all of this energy gets converted to planetary heat. A significant fraction of it is **reflected**, rather than absorbed. If you've ever seen Venus shining brightly in the twilight sky you will have seen a planet reflecting visible light. Venus' brightness is not blackbody radiation; it is hot on Venus but not hot enough to shine white-hot. When light is reflected, for the purposes of the energy budget in the Layer Model, it is as if the energy had never arrived on Earth at all.

Reflected sunlight does not add to a planet's heat energy budget

The fraction of a planet's incoming visible light that is reflected back to space is called the planet's **albedo** and is given the symbol α (greek letter alpha). Snow, ice, and clouds are very reflective, and tend to increase a planet's albedo. The albedo of Venus is high, 70%, because of a thick layer of sulfuric-acid clouds in the Venusian atmosphere. Mars' albedo is low, about 15%, because of a lack of clouds on that planet. Earth's albedo is about 30% or 0.3, and it depends on things that might change with changing climate, like clouds and ice.

Incoming solar energy that is not reflected is assumed to be absorbed into vibrational energy of molecules of the Earth. The Earthly albedo, α, of 0.3 means that the intensity of sunlight actually absorbed by the Earth is

$$I_{absorbed} = 1350\ W / m^2 \cdot (1 - \alpha) \approx 1000\ W / m^2.$$

To get the total incoming flux for the whole planet, in units of Watts instead of Watts/m^2, we need to multiply the intensity by a factor of area,

$$F_{in}\left[\mathrm{Watts}\right] = I_{sunlight}\left[\frac{\mathrm{Watts}}{\mathrm{m}^2}\right] \cdot (1 - \alpha) \cdot A\left[\mathrm{m}^2\right]$$

but what area would it be? Sun shines on half of the surface of the Earth at any one time, but the light is weak on some parts of the Earth, near dawn or dusk or in high latitudes, and much more intense directly head-on to the sun, near the equator at noon. The difference in intensity is caused by the angle of the incoming sunlight, not because the sunlight, measured head-on at the top of the atmosphere, is much different between low and high latitudes (Figure 3-1). The sunlit side of the Earth is half of its surface area, but using the area of a hemisphere to multiply by would require taking into account all the solar zenith angles from all the parts of the hemisphere.

The shadow knows

But there is trick that makes the calculation much simpler. The amount of head-on sunlight captured by the Earth can be easily calculated from the size of Earth's shadow. Use the formula for the area of a circle, not the surface area of a hemisphere. The area of a circle is

$$A\left[m^2\right] = \pi\ r_{earth}^2$$

Putting these together, the total incoming flux of energy to a planet by solar radiation is

$$F_{in} = \pi \ r_{earth}^2 \ (1-\alpha) \ I_{sunlight} \qquad \text{(eqn. 3-2)}$$

The rate at which the Earth loses energy by radiation to space is given by the Stefan-Boltzmann equation,

$$F_{out} = A \ \varepsilon \ \sigma \ T_{earth}^4$$

As for solar energy, to convert intensity I, in Watts / m^2, to the total energy flux in Watts, we need to multiply by an area A. What area is appropriate this time? Earthlight is is different from sunlight in that sunlight is all traveling in one direction, whereas Earthlight leaves Earth in all directions (Figure 3-2). Therefore the area over which the Earth radiates energy to space is simply the area of the sphere, both sides, day and night.

The surface of the Earth is exactly four times bigger than the size of its shadow!

In the real world, the daytime side of the Earth is warmer than the nighttime side, and it's warmer near the equator than near the poles. The temperature differences from place to place would be even more dramatic on an airless planet like the first Layer Model. But the Layer Model is going to ignore that for now, and will find a single value for the temperature of the Earth, to go along with a single value for each of the heat fluxes F_{in} and F_{out}. The effects of all the heterogeneity of the Earth's surface are explored in Chapter 6.

The surface area of a sphere is given by

$$A_{sphere} = 4 \ \pi \ r^2$$

and so the total outgoing energy flux from a planet by blackbody radiation is

$$F_{out}\left[\text{Watts}\right] = 4 \ \pi \ r_{earth}^2 \ \varepsilon \ \sigma \ T_{earth}^4 \qquad \text{(eqn. 3-3)}$$

Setting the energy fluxes F_{in} and F_{out} equal to each other, from equations 3-2 and 3-3 we get

$$4 \ \pi \ r_{earth}^2 \ \varepsilon \ \sigma \ T_{earth}^4 = \pi \ r_{earth}^2 \ (1-\alpha) \ I_{in}$$

which is essentially an expanded version of equation 3-1. There are a lot of terms in this equation, but it can be simplified. There are factors of π and r_{earth}^2 on both sides, which can be cancelled. Dividing also by 4 on both sides puts the equation into units of Watts/m^2 of the Earth's surface,

$$\varepsilon \ \sigma \ T_{ground}^4 = \frac{(1-\alpha) \ I_{in}}{4} \qquad \text{(eqn. 3-4)}$$

It is as though full-strength sunlight only shines on 1/4 of the Earth

We know everything in this equation except T_{Earth}. Rearranging the equation to put what we know on the right hand side, what we don't on the left, we get

$$T_{ground} = \sqrt[4]{\frac{(1-\alpha) \ I_{in}}{4 \ \varepsilon \ \sigma}} \qquad \text{(eqn. 3-5)}$$

where the number 4 by the root sign indicates a fourth-root, instead of the usual square root.

This equation ties together several climate-sensitive quantities. Changes in solar intensity such as the sunspot cycle or the Maunder Minimum (Chapter 10) may affect I_{in}. The albedo of the planet is very sensitive to ice and cloud cover, both of which might change with changing climate. And the next chapter will show that greenhouse gases are extremely selective about the wavelengths of light that they absorb and emit; in other words they have complexities relating to their emissivity ε values.

Solving equation 3-5 for the temperature of the Earth gives a value of 255 K or about –15°C. This is too cold. The average temperature of the Earth is closer to +15°C than –15°C. Table 3-1 gives the values needed to do the same calculation for Venus and Mars, along with the results of the calculation and the observed average temperatures. In all three cases, the Bare Rock Layer Model has gotten it too cold.

The Layer Model With Greenhouse Effect

The Bare Rock Model is too cold because it lacks the **greenhouse effect.** Like the rest of the Layer Model, the atmosphere that we are going to add is absurdly simple. It is essentially a pane of glass suspended by magic above the ground Figure 3-4. Like glass, our atmosphere is transparent to visible light, so the incoming energy from the sun passes right through the atmosphere and is deposited on the planet surface, as before. The planet radiates energy as IR light according to $\varepsilon\ \sigma\ T^4_{ground}$, as before.

In the IR range of light, the pane of glass acts as a blackbody, absorbing and emitting all frequencies of IR light. Therefore the energy flowing upward from the ground, which we will call $I_{up,\ ground}$, is entirely absorbed by the glass. The glass in turn radiates energy according to $\varepsilon\ \sigma\ T^4_{glass}$. Because the pane of glass has two sides, a top side and a bottom side, it radiates energy both upward and downward, $I_{up,\ glass}$ and $I_{down,\ glass}$.

The glass is transparent to visible light but "black" in the infrared

It is more complicated to solve the Layer Model when the page of glass is included, because there are two unknowns to solve for, the temperatures of the ground and of the glass. Both of these layers are assumed to be in an energy balance, where the rate of energy coming into the layer equals the rate of energy leaving.

$$I_{out} = I_{in} \qquad \text{(eqn. 3-6)}$$

There is only one temperature for each of the layers at which both energy budgets will be in balance. The temperatures can be found with just a bit of algebra.

The energy fluxes are depicted as arrows in Figure 3-4. The **energy budget for the pane of glass** can be written as

$$I_{up,\ glass} + I_{down,\ glass} = I_{up,\ ground}$$

Since these are both infrared light energy, the intensities can be written as

$$2\ \varepsilon\ \sigma\ T^4_{glass} = \varepsilon\ \sigma\ T^4_{ground} \qquad \text{(eqn. 3-7)}$$

Both the ground and the glass have to be in a state of energy balance

The **budget for the ground** is different from in the Bare Rock Model, because now there is heat flowing down from the pane of glass. The basic balance is

$$I_{\text{up, ground}} = I_{\text{in, solar}} + I_{\text{down, glass}}$$

from expansion of equation 3-6. These intensities can be expanded into

$$\varepsilon\ \sigma\ T_{\text{ground}}^4 = \frac{(1-\alpha)}{4} I_{\text{solar}} + \varepsilon\ \sigma\ T_{\text{glass}}^4 \qquad \text{(eqn. 3-8)}$$

Algebraically, it is possible to combine equations 3-7 and 3-8 in such a way as to eliminate one of the two temperatures, solving for the other, and then plugging back in to solve for the first. But there is a nifty trick which makes it algebraically much easier to solve, and is conceptually useful to boot.

The trick is to construct an **energy budget for the Earth overall** by drawing a boundary above the atmosphere and figuring that if energy gets across this line coming in, it must also be flowing across the line out at the same rate. The budget can be written as

$$I_{\text{up, glass}} = I_{\text{in, solar}}$$

The intensities are comprised of individual fluxes from the sun and from the atmosphere

$$\varepsilon\ \sigma\ T_{\text{glass}}^4 = \frac{(1-\alpha)}{4} I_{\text{solar}}$$

This equation contains only one unknown, T_{glass}. Notice also that this equation looks a lot like equation 3-4, describing the surface temperature of the Bare Rock model. Solving for T_{glass} here gives the same answer as solving for T_{ground} in the Bare Rock model.

The skin temperature of the model is always the same.

This is actually more than just a curiosity or an algebraic convenience. What it means is that the place in the Earth system where the temperature is the most directly controlled by incoming sunlight is at the top layer, where infrared radiates to space. We will call this temperature the **skin temperature** of the Earth, and it will come up again in the next chapter.

What about temperatures below the skin, in this case T_{ground}? Now that we know that the outermost temperature, T_{glass}, is equal to the skin temperature, we can plug that into the budget equation for the atmosphere to see that

$$2\ \varepsilon\ \sigma\ T^4_{glass} = \varepsilon\ \sigma\ T^4_{ground}$$

or

$$T_{ground} = \sqrt[4]{2}\ T_{glass}$$

The temperature of the ground must be warmer than the skin temperature, by a factor of the fourth root of two, an irrational number that equals about 1.189. The ground is warmer than the atmosphere by about 19%. The One-layer Model calculation is also repeated for Venus and Mars in Table 3-1. It gets the temperature of Earth about right, while Mars is too warm and Venus is not yet warm enough.

The glass layer warms the ground by trapping outgoing heat, like a winter coat traps outgoing body heat

The Layer Model was never intended to be all that realistic. It was intended to illustrate the mechanism of the greenhouse effect, making it easier to think about and understand. So let's think about how it works. The ground gets warmer with the pane of glass installed, but the pane of glass doesn't bring any new energy to the Earth. It's not like some humungous heat lamp in the sky. How then does it change the temperature of the ground?

The situation can be understood by analogy to water flowing through a kitchen sink. Water flows in from a faucet at some rate, and it flows down the drain faster as the water level in the sink rises. This analogy will come up multiple times in this book, applied to multiple situations. For now the water is analogous to energy flowing into and out of the Earth system.

Water drains faster as the water level in the sink rises, because there is higher pressure under deeper water to push the water down the drain faster. This is just like the outgoing infrared light energy flux, which flows faster as the temperature of the Earth increases, according to $\varepsilon\ \sigma\ T^4$. The water flowing into the sink represents sunlight, corrected for reflection (albedo), which we could imagine as some fraction of the incoming water splashing out of the sink, not going down the drain. Like sunlight in Earth's energy balance, the water from the faucet is like a driver to the kitchen sink water cycle, coming in from outside at a rate which is set externally, rather than responding to the sink in some way like the water down the drain does.

Eventually the water in the sink reaches a level where the outflow of water balances the inflow. That's the equilibrium value, and is analogous to the equilibrium temperature calculated by the Layer Model. For the sink, we could ask what the water level should be where the flow down the drain balances the inflow from the faucet.

The greenhouse effect is like a constriction in the drain, like a piece of carrot that becomes lodged in the drain filter. For a few minutes the water drains out more slowly than the inflow from the faucet, so the water level in the sink rises. Eventually the water level reaches the point where water goes down the drain fast enough to balance the water budget again. A greenhouse gas, like the carrot in the drain filter, makes it more difficult for the heat to escape the Earth. The temperature of the Earth rises until the fluxes balance again.

Table 3-1

Table 3-1. The temperatures and albedos of the terrestrial planets. The intensity of sunlight differs with distance from the sun.

	I_{solar}, W/m^2	α	T_{bare} K	$T_{observed}$ K	$T_{1\ layer}$ K
Venus	2600	71%	240	700	285
Earth	1350	33%	253	295	303
Mars	600	17%	216	240	259

Take-Home Points

The outflow of IR energy from a planet must balance heating from the sun.

The planet accomplishes this act of energetic housekeeping by adjusting its temperature.

Absorption of outgoing IR light by the atmosphere warms the surface of the planet, as the planet strives to balance its energy budget.

Study Questions

A greenhouse layer increases the amount of heat energy in the ground layer. Where does this energy come from?

Relate the pieces of the kitchen sink analogy, the water level and the flows through the faucet and the drain, to different parts of of the energy cycle through the Layer Model.

What factors in the layer model could affect the skin temperature?

What factors can change the water level in the kitchen sink analogy?

Further Reading

The Earth System, Lee R. Kump, James F. Kasting, Robert G. Crane, Prentice Hall, 1999

Kasting, J.F., and D. Catling, Evolution of a habitable planet, *Annual Review of Astronomy and Astrophysics*, *41*, 429-463, 2003.

Figure Captions

1. When sunlight hits the Earth, it all comes from the same direction. The Earth makes a circular shadow. Therefore, the Earth receives an influx of energy equal to the intensity of sunlight, multiplied by the area of the circle, $\pi \cdot r_{earth}^2$.

2. When infrared light leaves the Earth, it does so in all directions. The total rate of heat loss equals the intensity of the Earth-light multiplied by the area of the surface of the sphere $4 \cdot \pi \cdot r_{earth}^2$.

3. An energy diagram for Earth with no atmosphere, just a bare rock in space.

4. An energy diagram for a planet with a single pane of glass for an atmosphere. The glass is transparent to incoming visible light, but a blackbody to infrared light.

5. An energy diagram for a planet with two panes of glass for an atmosphere.

6. An energy diagram for a planet with an opaque pane of glass for an atmosphere.

Exercises

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. Assume for comparability that the albedo of this world is 0.33, same as Earth. 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?

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?

3. Nuclear Winter. Let's go back to the One-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?

Chapter 4. Greenhouse Gases

Why some gases are greenhouse gases, but most aren't, and some are stronger than others.

About Gases

The layer model is what is called an **idealization** of the real world. It's got the essential ingredient of the greenhouse effect, but it's missing a lot of things that are important in the real atmosphere. Starting from the Layer Model, the next few chapters will add things one at a time, assembling the rest of the ingredients that control the temperature of the real Earth. The first task is to understand how real gases interact with infrared light in the real atmosphere.

Let's begin by defining different ways of describing the amounts of gases in the atmosphere. The word **concentration** means number of molecules within some volume. The difficulty this raises for gases in the atmosphere is that the concentration, defined in this way, changes as the gas expands or contracts. It is often more convenient to talk about proportions of gases; for example oxygen is about 20% of the molecules of gas in the atmosphere, and nitrogen almost 80%. The proportion of CO_2 is currently 0.039%. We can express that in a more mnemonic way by saying 390 parts per million or **ppm**. This number is called a **mixing ratio.**

A gas exerts pressure, a pushing force, on itself or on the surface of anything in contact with it. The force comes from deflected momentum of gas molecules bouncing off of the surface. The pressure of a mixture of gases can be taken apart into what are called **partial pressures**, arising from each type of molecule in the gas, which add up to the total pressure. The partial pressure of CO_2 for example is written as **pCO_2.**

One might expect heavier gases to contribute disproportionately to the pressure, since they seem like they would hit the walls harder. It works out however that heavier gas molecules are moving more slowly than the light ones are, just enough so that the pushing force, proportional to the mass times the velocity, is the same for every molecule regardless of how heavy it is. It is as if a bunch of ping-pong balls and bowling balls rolled against the wall all pushed equally on the wall. They are equal because you have to roll the bowling balls more slowly. At a given temperature, each molecule has the same amount of energy on average invested in motion, what is called **kinetic energy.** A heavy molecule will move more slowly with its allotment of kinetic energy.

A gas pressure, in units of micro-atmosphere (μatm), is numerically nearly equal to its mixing ratio in parts per million (ppm)

The bottom line is that the partial pressure from a gas is more-or-less proportional to the mixing ratio, which is just the number count proportion of the gas. If you think in pressure units of atmospheres, the actual numbers are the same for the partial pressure and the mixing ratio, because a pressure of 1 atmosphere would equal a mixing ratio of 1 (think 100%). For CO_2, for example, the mixing ratio is 390 ppm, and its partial pressure is 390 micro-atmospheres or μatm.

Gases, Vibrations, and Light

Most of the mass of an atom is in its nucleus, which resembles conceptually a massive sun at the center of a solar system. Two nuclei of two different atoms always repel each other, because of their positive charges. Electrons float in ghostly quantum mechanical probability clouds, called **orbitals**, around the nucleus. For some combinations of atoms, the electrons fall into orbitals that are shared between the two nuclei. These electrons are the glue that holds together a **chemical bond** between the atoms.

A chemical bond is like a spring in that the two nuclei on either end of the bond have some freedom to move closer or farther apart. There is an optimum, lowest energy distance for the nuclei to be from each other. Closer, and the positive nuclei will start to repel each other. Farther, and you get less energy gain from sharing the electrons. A bond vibrates when the distance between the nuclei oscillates between the nuclei being too close together, then too far apart. This is called a **stretching vibration.**

An atom may participate in more than one chemical bond. The bonds, and extra electrons that the central atom holds on to, arrange themselves around the atom to find their positions and angles of least energy. Here again there is some flexibility in the angle of the bond, which leads to a **bending vibration.**

Chemical bonds vibrate at particular frequencies

Molecular vibrations in gas molecules are like vibrations of a piano string in that they tend to be at specific frequencies. This is because, like a piano string, a gas molecule will only vibrate at its "ringing" frequency. An oscillator made of weights and springs will vibrate at a frequency that depends on two things: the mass of the weights and the springiness of the spring holding them together. Imagine the weights moving together, nearing the lowest-energy distance but with enough momentum to carry them closer than they'd like to be, continuing the oscillation. Heavier weights would have enough inertia to keep moving closer for a longer amount of time than would a lighter pair of weights, so the frequency of the vibration will be slower. If the spring is very stiff, it will reverse the velocity of a vibration more quickly, and the frequency of the oscillation will be higher. Vibrations in chemical bonds depend on the mass of the nuclei and on the energy penalty for stretching or bending the bond, which is to say, the springiness of the chemical bond.

Most forms of liquid and solid molecules are not so choosy about frequency, because the molecules interact with each other so much that more or less all frequencies of infrared light can be absorbed and emitted. Liquids and solids are pretty good blackbodies, in other words. But gases are very choosy in the frequencies of their vibration. Gases are generally not very good blackbodies.

In fact, most of the gases in the atmosphere do not absorb or emit infrared light at all, because vibrations in their bonds do not create an imbalance in the electrical field. Both O_2 and N_2, the most abundant gases in the atmosphere, are symmetric molecules, made of two identical atoms whose electric fields just cancel each other out. Neither atom can hold the electrons any more tightly than the other, so there is no difference between the electrical field on one side of the molecule versus the other. The symmetry is unbroken when you stretch or compress the bond. Symmetrical molecules with only two atoms are never greenhouse gases.

To create or absorb infrared light, the molecule must electrically lopsided.

If the symmetry is broken by having different types of atoms on each side, like carbon monoxide (CO) or nitrogen oxide (NO), the molecules begin to have some greenhouse properties. Both of these types of molecules are very reactive and not found in enough abundance in the atmosphere to lead to much greenhouse effect, but these are good stepping-stone molecules to think about before moving to more complicated atoms like CO_2. Because the atoms have different charges in their nuclei, their chemistry is different, including how hard they pull on those electrons in their shared chemical bond. One side of the molecule will probably have a slight positive charge, and the other will be slightly negative. This charge imbalance is called a **dipole moment.** When the bond vibrates it changes the steepness of the transition from positive to negative, what's called the **electric field.** Changing the electric field is how greenhouse gases interact with infrared light. One could even oscillate the electric field by simply rotating the molecule.

Molecules with three or more atoms must have more than one chemical bond, because a single bond never connects more or less than two atoms. Imagine a set of three weights connected in a line with two springs. When this contraption is jiggled, its bonds bend and stretch together, as an integrated system, rather than each bond simply vibrating according to its own springiness and weight, independent of the other. The whole thing rings like a bell, and like a complex bell with a rich tone, there are multiple oscillations with different frequencies all going on at once.

The CO_2 molecule is shaped in a straight line with carbon in the middle (Figure 4-1). Oxygen tends to pull on electrons more tightly than carbon does, but the oxygen atom on one side pulls the electrons just as tightly as the other oxygen on the other side. The molecule has no permanent electrical field asymmetry (dipole moment). If all you do to the molecule is rotate or stretch it, you have not broken the symmetry and you will have no effect on the electric field.

The CO_2 bending vibration mode is the important one for climate

However, there are two modes of vibration that do generate an asymmetry in the electric field. The most important CO_2 vibrational mode for climate is the **bending vibration.** When the CO_2 molecule is bent, the oxygens, carrying slight negative charges (marked in Figure 4-1 using the lowercase greek letter delta, as $\delta+$), swing from one side of the molecule to the other. The CO_2 bending vibration absorbs and emits infrared light; it is said to be **infrared active.** The next section will show that the bending vibration absorbs infrared light in the heart of Earth's emission spectrum, giving it strong leverage over Earth's climate.

The other vibrational mode is an **asymmetric stretch**, in which one bond is growing longer as the other gets shorter, back and forth. There is less infrared light of this frequency to absorb in the atmosphere, so this mode has less impact on the Earth's radiation budget than the bend does.

Water, H_2O, is a molecule that is bent in its lowest energy state (Figure 4-2). This is because the oxygen has two pairs of electrons hanging off of it, which squeeze the hydrogens together somewhat. Hydrogen atoms hold their electrons more loosely than oxygen atoms in chemical bonds, and so each hydrogen has a slightly positive charge. The oxygen end of the molecule has a slight negative charge. In contrast to CO_2, water has a dipole moment built into its resting structure. Just as for the NO molecule, rotating an H_2O molecule would oscillate the electric field and generate light. Because the arrangement of the nuclei in H_2O is more complex than for NO, there are many modes of vibration of the water molecule, including a symmetric stretch and a bend. These modes are also infrared active.

Water vapor is very electrically lopsided, and can absorb and emit lots of frequencies of infrared light

How a Greenhouse Gas Interacts with Earth-Light

Figure 4-3 shows blackbody spectra for temperatures ranging from 300 K, surface temperature on a hot summer day, down to 220 K, which is about the coldest it gets in the atmosphere, up near the troposphere at about 10 km altitude. There is also a jagged-looking curve moving among the smooth ones. This is the intensity of light that an infrared spectrometer would see if it were in orbit over the Earth, looking down. Figure 4-3 is not data, but rather a model simulation from one of our on-line models. The plot was generated using an on-line model that you can play with yourself, and will be used in the Exercises. The web address is http://understandingtheforecast.org/models/infrared_spectrum.html.

The spectrum of the light leaving the Earth going into space ranges between two different blackbody spectra, a warmer one of about 270 K (Kelvins), and a colder one from about 220 K. Parts of the spectrum, most notably the broad smooth part around 1000 cycles/cm, follow the warmer blackbody spectrum. There don't happen to be any gases in the atmosphere that absorb or emit at this frequency, so this IR light is coming directly from the ground. Because the greenhouse gases in the atmosphere are transparent to infrared light in this band of frequencies, it is called the **atmospheric window**.

The blackbody curves are like the temperature scale on a thermometer. You can read the temperature of the IR source as its intensity against this scale.

Other parts of the spectrum seem to follow the colder blackbody curve, like for example at around 700 cycles/cm. This infrared light is coming from greenhouse gases in the cold upper atmosphere. The big dip in the spectrum at about 700 cycles/cm is from the bending vibration of CO_2. Infrared light emission and absorption is a two-way street (Chapter 1), so CO_2 absorbs the intense, "warm" infrared from the ground at this frequency, and re-emits the same frequency but at a lower intensity, because of its colder temperature (Figure 4-4). The atmosphere is called **optically thick** in the CO_2 bend frequency range, and optically thin in the atmospheric window.

The situation is analogous to standing on a pier and looking down into a pond of water. If the water were very clear, you could see light coming from the bottom; you would see rocks or old tires in the reflected light. If the water were murky, the light you would see would be scattered light coming from perhaps just a few inches down into the water. The old tires would be invisible, alas. The muddy lake is optically thick, so the light you see comes from near the top.

The plot is constructed so that the area under a curve of a spectrum is proportional to the total energy flux. You can eyeball the energy change as the area change. The areas of the pure blackbody curves go up proportionally to the temperature raised to the fourth power, because of the Stefan-Boltzmann equation (equation 2-1 in Chapter 2). The area trick works with the jagged spectrum as well, representing the total energy loss of the planet to space. The effect of an atmospheric absorption band is to take a bite out of the blackbody spectrum from the Earth's surface, decreasing the area and therefore decreasing the outgoing energy flux.

Methane absorbs infrared light at around 1300 cycles/cm. While the CO_2 bending vibration absorbs right at the peak of the blackbody spectrum of the Earth, methane absorbs in one of the tails of the spectrum. In a competition between CO_2 and methane for which is the stronger greenhouse gas, the advantage here goes to CO_2. However, the next section will introduce another difference between the gases, which more than makes up for this, so that methane winds up as the more powerful of the two.

The Band Saturation Effect

Figure 4-5 shows the results from a series of model runs for different atmospheric CO_2 concentrations, ranging from 0 to 1000 ppm. For reference, the atmosphere in 2010 contains about 390 ppm. With no CO_2, the atmosphere would be transparent to light of around 700 cycles/cm, like it is in the atmospheric window. Adding the first 10 ppm of CO_2 has a fairly noticeable impact on the shape of the outgoing light spectrum, a sharp v-shaped slice out of the spectrum. As the CO_2 concentration is increased to 100 ppm, the center of the peak runs into the blackbody curve from just a bit colder than 220 K, and it doesn't get any deeper as the CO_2 concentration is raised to 1000 ppm. This is the **band saturation effect**; the band referring to the range of frequencies and saturation meaning "filled up", as in with CO_2.

The reason for the saturation effect can be understood by analogy to the murky pond. As the water gets murkier, it decreases the distance that a photon of light can travel before it is absorbed. It doesn't take much mud in the water to obscure the old tire on the bottom, shifting the depth to which you can see from the bottom at say 3 meters to maybe only one meter. If the pond gets a lot murkier you will only be able to see a few cm down into the water. Making it murkier still will limit the view to only one cm. The change in depth is getting less sensitive to the murkiness of the pond. In the same way, the changes in the temperature at which the atmosphere radiates to space get smaller as the CO_2 concentration of the air gets higher. You just see the coldest light that you can get.

The center of an absorption band gets saturated as the gas gets more concentrated, but the band gets fatter.

Each model run returns a value for the total IR energy flux leaving the location, called I_{out} on the page and in units of Watts/m^2. These values are plotted in Figure 4-6. There is a huge change in the outgoing energy flux between the runs with 0 ppm and 10 ppm, because you go from having no absorption to having a quite noticeable peak by adding a relatively small amount of CO_2, just 10 ppm. Then as you go up to 100 ppm, and 1000, the change in energy balance for each new molecule of CO_2, or each new ppm of CO_2, gets weaker.

The energy balance never becomes totally insensitive to further additions of CO_2, however. More CO_2 will always make it warmer, even up to the 70 atmospheres of CO_2 in the atmosphere of Venus. In part this is because as the CO_2 concentration increases, the absorption peak in Figure 4-5 gets fatter, even if it can't get much deeper. The middle of the absorption band is saturated, but the edges are unsaturated.

Even though the center of the CO_2 bend frequency is saturated, more CO_2 would still affect Earth's infrared energy output.

Given that the absorption bands are determined by vibrational frequencies of the molecule, one might have expected that the edges of the bands would be quite sharp, as if CO_2 absorbed 600 cycles/cm light completely and 599 cycles/cm light not at all. There are several reasons for the fuzziness in the peaks. One is **Doppler shifting.** Like a train whistle which sounds a higher pitch as the train approaches, then lower after it passes and is moving away, the frequency of light that the molecule "sees" depends on the speed of the molecule, toward or away from the IR light source. If the molecule is moving away from the light source, it will absorb a slightly longer wavelength of light.

The absorption bands are also smeared out when gas molecules interact with each other, a phenomenon called **pressure broadening.** Liquids and solids are often pretty good blackbodies because the molecules are so close to each other that they share energy. Even if the frequency of the light is different than the frequency of the vibration, if the molecule is bathed in other molecules, it may be possible to take up the slop and absorb the light anyway. Gas molecules are generally too far apart from each other to act in this way, but they still do it to some extent, more so if the pressure is higher. The CO_2 on Venus, for example, is at such high pressure that its absorption bands are extremely broadened.

Even if the saturation effect was complete, so that the peaks didn't get fatter with high concentration, adding more of the greenhouse gas would increase the temperature of the Earth, for the same reason that adding layers to the layer model also increases the ground temperature. The layers in the layer model are by definition completely saturated, in that they absorb all the incoming IR, re-radiating at all frequencies. Adding a second pane of glass to the layer model increases the ground temperature (this is the answer to one of the Exercises). On Venus, even though the absorption of IR by the 70 atmospheres of CO_2 is completely saturated, adding more CO_2 would still increase its temperature further.

The awesome climate-changing power of the most dilute gases

The bottom line is that the more abundant the greenhouse gas is, the less powerful each molecule is in warming the climate. The band saturation for CO_2 makes CO_2 a less potent greenhouse gas, per molecule, than it would be if we had no CO_2 in the air to start with. Revisiting the comparison between CO_2 and methane as greenhouse gases, methane had a disadvantage because its absorption band fell in the suburbs of the Earth-light spectrum whereas CO_2 fell right downtown. Now, considering the band saturation effect, the advantage shifts to methane because it has much lower concentration. You can see from the jagged edges of the methane peak in Figure 4-3 that the methane absorption band is not saturated. For this reason, in spite of the off-peak location of the methane absorbtion band, a molecule of methane added to the atmosphere is about 40 times more powerful than is a molecule of CO_2.

For CO_2, the energy intensity I_{out} in units of W/m^2 goes up proportionally to the log of the CO_2 concentration, rather than proportionally to the CO_2 concentration itself (which would be linear in CO_2 concentration). The logarithmic dependence means that you get the same I_{out} change in W/m^2 from any doubling of the CO_2 concentration. The radiative effect of going from 10 to 20 ppm pCO_2 is about the same as going from 100 to 200 ppm, or 1000 to 2000 ppm.

Earth's temperature rises in proportion to the number of CO_2 doublings

The sensitivities of climate models are often compared as the average equilibrium temperature change from doubling CO_2, a diagnostic that is called the **climate sensitivity** and abbreviated as ΔT_{2x}. It may take a few centuries for the temperature of the land surface and the ocean to respond to a change in CO_2; this is the temperature change that we're after for the climate sensitivity as the term is generally used. Most models have ΔT_{2x} between 2 and 5 °C.

If you subjected the planet to higher CO_2 concentrations for a few thousand years, there might be changes to the huge ice sheets in Greenland and Antarctica, that could lead to even higher global temperatures, so the **long-term climate sensitivity** is probably higher than the usual ΔT_{2x} values. CO_2 emission from fossil fuel combustion will elevate the CO_2 concentration of the atmosphere for hundreds of thousands of years (Chapters 7 and 12), giving plenty of time for the full climate sensitivity of the Earth to express itself.

The climate sensitivity to doubling CO_2 is the first benchmark that climate scientists compare between models.

One can use ΔT_{2x} to calculate the ultimate temperature change response to changing CO_2 using an equation

$$\Delta T = \Delta T_{2x} \times \frac{\ln\left({}^{new\ pCO_2}\!\big/_{orig.pCO_2} \right)}{\ln(2)} \qquad (4.1)$$

where "ln" is the natural logarithm function, the reverse operation of the exponential function e^x, The symbol e denotes a number which has no name other than simply e. We will meet e again in Chapter 5. The exponential function is to raise e to a power of x. If

$$e^x = y$$

then

$$x = \ln(y)$$

Equilibrium temperature changes from changes in CO_2, assuming various ΔT_{2x} values, are shown in Figure 4-7.

The Greenhouse Effect of Gases

The basic structure of the greenhouse effect still works the way it did in the Layer Model (Chapter 3). Figure 4-8 shows the outgoing infrared spectrum of an Earth with no CO_2 in the atmosphere. Let's say that this outgoing energy flux is just in balance with incoming sunlight energy.

Now add 1000 ppm CO_2 to the atmosphere (middle panel), a huge change so that the effect in the spectra will be easy to see. The energy fluxes in these plots are proportional to the area of under the curves. The CO_2 absorption band is like a bite taken out of the curve, decreasing its area, therefore also decreasing the outgoing energy flux. The model reports that I_{out} decreases from 249 Watts/m^2 without CO_2 to 223 Watts/m^2 with CO_2.

The greenhouse effect is driven by changing the surface temperature in order to balance the energy budget. The model allows you to change the surface temperature, and by trial and error you can find that warming the Earth up by 8.5 °C brings I_{out} back up to what it was before adding the CO_2. In the bottom panel in Figure 4-8, the effect of the warming can be seen as a shift upward where the arrows are pointing. Especially in the atmospheric window the intensity of the infrared energy flux increases as the Earth warms. Visually, if the spectrum were a pile of ice cream, you could scoop out some ice cream from the hole where the CO_2 absorption band is, and then spread it back in on the sides of the pile where the atmospheric window is and other parts of the spectrum, so that in the end the overall size of the ce cream curve is the same as it was initially. Adding the CO_2 caused the planet to warm.

Take-Home Points

Gases absorb / emit infrared light if they vibrate at the frequency of the light, and if its vibration has a dipole moment that affects the electric field.

O_2 and N_2 are not greenhouse gases. All molecules of three or more atoms, including CO_2, water vapor, and methane, are greenhouse gases.

A greenhouse gas has a stronger impact on the radiative balance of the Earth if it interacts with light in the middle of the Earth-light spectrum.

Band saturation: A greenhouse gas at relatively high concentration like CO_2 will be less effective, molecule per molecule, than a dilute gas like methane.

Study Questions

Why don't most of the gases in the Earth's atmosphere contribute to the greenhouse effect?

Does the band saturation effect prevent global warming from CO_2? If not, what effect does it have?

Compare and contrast CO_2 and CH_4 as greenhouse gases. Which factor tends to make CO_2 stronger, and which factor tends to make methane stronger? Which gas is stronger overall?

Further Reading

The Discovery of Global Warming (2003) by Spencer Weart. This is a historical account of the science and the scientists who discovered global warming including my favorite, Svante Arrehnius, who used the infrared spectrum of moonlight, in 1896, to predict that doubling CO_2 would raise global temperature by 3-6° C (whereas the modern prediction is 2-5°C). There is a good discussion of piecing together the band saturation effect in this book.

IPCC Scientific Assessment 2001, from Cambridge University Press or downloadable from http://www.grida.no/climate/ipcc_tar/. Chapter 6 **Radiative Forcing of Climate Change.**

Figure Captions

1. Vibrational modes of a CO_2 molecule that interact with infrared light in the atmosphere.

2. Vibrational modes of a water molecule that interact with infrared light in the atmosphere.

3. The solid line is a model-generated spectrum of the infrared light escaping to space at the top of the atmosphere. For comparison, the broken lines are blackbody spectra at different temperatures. If the Earth had no atmosphere, the outgoing spectrum would look like a blackbody

spectrum for 270 K, between the 260 K and 280 K spectra shown. The atmospheric window is between about 900 - 1000 cm^{-1}, where no gases absorb or emit infrared light. CO_2, water vapor, ozone, and methane absorb infrared light emitted from the ground, and emit lower-intensity infrared from high altitudes where the air is colder than at the surface.

4. A comparison of the fate of infrared light in the optically thick CO_2 bend frequency (left) versus the optically thin atmospheric window (right).

5. A demonstration of band saturation by CO_2. The addition of 10 ppm CO_2 (upper right) makes a huge difference to the outgoing infrared light spectrum relative to an atmosphere that has no CO_2 (upper left). Increasing CO_2 to 100 and 1000 ppm (lower panels) continues to affect the spectrum, but you get less bang for your CO_2 buck as CO_2 concentration gets higher.

6. Band saturation viewed in a different way from Figure 4-5. This is a plot of the total energy flux carried by all infrared light, which is proportional to the area under the spectrum curves in Figure 4-5. The outgoing energy flux is less sensitive to CO_2 when CO_2 concentration is high.

7. The average temperature of the Earth as a function of atmospheric CO_2 concentration and the climate sensitivity parameter, ΔT_{2x}.

8. A demonstration of the greenhouse effect of CO_2. In the top panel, begin with no CO_2. Assume that the energy budget of the Earth was in balance at a ground temperature of 270 K. In the middle panel, add 1000 ppm CO_2, decreasing the outgoing energy flux. The ground and the atmosphere above it respond by warming up 8.5 K in the bottom panel. The total outgoing energy flux is restored to its initial value. The total energy flux is proportional to the area under the curves. CO_2 takes a bite out of the top curve to generate the middle curve, but then the bottom curve bulks up everywhere to compensate.

Exercises

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.

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) Would ten additional ppm of methane in the atmosphere have a larger or smaller impact on the outgoing IR flux than ten additional ppm of CO_2 at current concentrations?

b) Where in the spectrum does methane absorb? What concentration does it take to begin to saturate the absorption in this band? Explain what you're looking at to judge when the gas is saturated.

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

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?

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?

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?

Now turn on clouds and run the model again. Explain what you see. Why, at night, is it warmer when there are clouds?

3. Water vapor. 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 5 °C? What effect does the ground temperature have on the shape of the outgoing IR spectrum and why?

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 5 °C temperature increase. Is it higher or lower? Does water vapor make the Earth more sensitive to CO_2 increases or less sensitive?

c) Now see this effect in another way. Starting from a base case, record the total outgoing IR flux. Now increase pCO_2 to 550 ppm. The temperature in the model stays the same (it's just how the model is written) so 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?

Chapter 5. What Holds the Atmosphere Up?

How the greenhouse effect works within the temperature structure of Earth's atmosphere.

The Greenhouse Effect is Powered by the Lapse Rate

For the greenhouse effect to work, it has to be colder up high in the atmosphere than it is on the ground. It's true in the Layer Model, and it's true in the real atmosphere too, so the greenhouse effect works in both settings. However, the temperature structure of the real atmosphere is controlled by processes that are not in the Layer Model, but will be described in this chapter.

In the Layer Model, the pane of glass is colder than the ground, and it absorbs the intense IR energy flow from the ground, and re-radiates weaker IR to space. This perturbation to the energy flow results in the greenhouse effect warming.

Now imagine installing a heat exchanger system running between the glass and the ground, which carries enough heat that it ties the glass and ground temperatures together completely when you dial it up all the way (Figure 5-1). Now the ground has the same temperature as the glass, which as always is at the skin temperature. The ground is no warmer than it would have been if there had been no glass; the greenhouse effect has vanished. One way to understand this is that the intensity of the infrared energy that the glass emits is the same as what it absorbs from the ground, because the temperatures of the ground and the glass are the same. The glass doesn't change the energy budget of the planet, so it doesn't make the ground warmer. The diligent student may have also discovered this phenomenon in the Exercise from Chapter 3 on nuclear winter.

No temperature contrast, no greenhouse effect

Now dial the heat exchange down a bit, allowing a temperature difference to build up between the glass and the ground. After enough time has passed for the energy flows and temperatures to reach their steady state, the temperature of the glass will be the same as it was before, because the glass is the outermost or "skin" layer (Chapter 3). The energy flux from the skin layer has to balance incoming sunlight, fixing its temperature at a “skin” temperature. If the glass temperature is the same as before, the ground temperature must be warmer than it was before. It turns out you can dial the greenhouse effect up and down by dialing up and down the temperature difference between the skin and the ground.

Atmospheric scientists call the change in temperature of the air with altitude the **lapse rate**; in the lower part of Earth’s atmosphere where the greenhouse effect operates it is about 6 °C colder for each kilometer of altitude. The lower part of the atmosphere is called the **troposphere** (Figure 5-2), and it contains 90% of the air and all of the weather. The air temperature reaches its coldest point at the **tropopause**, a boundary of air about 10 kilometers high on average, about where commercial airplanes fly. Above this, it gets warmer with altitude in the **stratosphere**, because of ozone absorbing ultraviolet radiation from the sun (Chapter 10), and higher still are the mesosphere and the exosphere, which don’t affect the climate story very much.

The lapse rate in the troposphere is determined by the interaction of several pieces, which may seem to be unrelated, until they are brought together at the end of the chapter.

The idea of a skin layer in the atmosphere is fuzzier than it is in the layer model but it is still useful.

In a column of air, instead of two layers there is air at a range of temperatures (Figure 5-3). Infrared radiation comes up from the ground, and some of it might make it all the way to space unhindered, while the rest is absorbed and re-emitted by greenhouse gases and clouds (Chapter 4). There is no single place where the IR radiation escapes to space from, like the skin layer in the Layer Model, but it is useful to define a **skin altitude** for the air column as the average altitude from which the IR escapes to space.

In solving the layer model for the temperatures of all the atmospheric layers and the ground, it was convenient to start from the outer skin layer and work down toward the ground. Let's take that approach again in thinking about the column of air. If the skin altitude were 5 kilometers high and the lapse rate were set by some physics of the atmosphere to be 6 °C per kilometer, then the temperature of the ground would be

$$T_{ground} = T_{skin} + \frac{6\ \text{°C}}{\text{km}} \cdot 5\,\text{km}$$

On the temperature profile plot (Figure 5-3), this looks like a line coming downward from the skin altitude and temperature, following the slope of the lapse rate, until it intersects the ground.

If you put more greenhouse gases in the air, more of the IR will come from colder high-altitude air, and the skin altitude, which is the average over all frequencies of IR, moves a bit higher up. Right after you add the greenhouse gas, before the planet has had time to warm up, the temperature at the new skin altitude will be colder than it was at the old skin altitude, because the new skin altitude is higher than the old one.

More CO_2 → Higher skin altitude → Warmer ground

But as in the Layer Model, eventually the temperature at the skin altitude has to be just warm enough to balance the energy influx from sunlight. The planet warms, and the entire column of air warms with it. Eventually, it warms until the temperature at the new skin altitude is the same as the temperature was at the old skin altitude.

Beginning from this new “anchor point”, the temperature of the ground can be determined by drawing a line from the skin altitude toward the ground, again following the slope of the lapse rate. The change in temperature at the ground ΔT_{ground} that you would get from raising the skin altitude, Δz_{skin}, can be calculated as

$$\Delta T_{ground} = \Delta z_{skin}\left[\text{km}\right] \cdot \frac{6\text{°C}}{\text{km}}$$

Now imagine how it would work if the lapse rate were different than 6 °C per kilometer. A change in the skin altitude would have a different effect on the temperature of the ground. For example, if the physics of the atmosphere were to decide somehow that the temperature should be uniform with altitude, like when we dialed up the heat exchanger in the layer model above, then it would make no difference how high the skin altitude was

$$\Delta T = \Delta z_{\text{skin}}\left[\text{km}\right] \cdot \frac{0\,°\text{C}}{\text{km}} = 0$$

The temperature of the ground would be the same as the skin temperature no matter what. Just like for the Layer Model, you can dial up and down the strength of the greenhouse effect by changing the lapse rate in the atmosphere.

What sets the lapse rate in the atmosphere? The skin is colder in both the Layer Model and the real atmosphere, but the layer model is missing a crucial process that happens in the real atmosphere called **convection**, which supercedes the radiation energy fluxes in the Layer Model, just like the heat exchanger did.

Pressure as a Function of Altitude

The pressure in the atmosphere depends primarily on the weight of the air over your head. As you climb a mountain, the pressure decreases because you are leaving atmosphere behind; the air beneath you doesn't contribute to the pressure you feel.

In the ocean, every 10 meters deeper you go increases the pressure by about 1 atmosphere (atm). Each 10 m depth interval increases the pressure by about the same 1 atm: descending from 30 to 40 m would increase the pressure by the same 1 atm as going from 0 to 10 m. The pressure can be calculated as

$$P = 1\,atm + \frac{-1\,atm}{10\,m} \cdot z\left[m\right]$$

where the variable z is the vertical position, with positive numbers upward, as before, so a negative height is a depth.

The density of water doesn't change much with pressure, so the weight of the water overhead (the pressure) depends linearly on the water depth.

Because pressure is just a constant number multiplied by the depth, a graph of pressure versus depth would be a straight line (Figure 5-4), and the pressure is said to be **linear** with depth.

The pressure in the atmosphere is **nonlinear** with altitude, in that a climb of one meter at sea level changes the pressure much more than one meter of climb up at the tropopause. The equation to describe pressure as a function of height in the atmosphere is based on the **exponential function**, which is a number called **e** raised to a power. The value of e is approximately 2.71828....

The density of a gas increases with pressure, so the weight of air overhead (the pressure) follows an exponential function

The exponential function comes up time and time again in the natural sciences. Population growth and radioactive decay are two examples (Figure 5-5). In each case, the rate of change of the variable depends linearly on the value of the variable itself. Population growth is driven by the number of babies born, which depends on the number of potential parents to beget them.

$$\text{Population}(t) = \text{Population}(0) \cdot e^{k\,t}$$

In this expression the exponent is a population growth rate in units of fraction per time, like 3% per year might be a typical population growth rate. This is an example of a positive exponential function; it is essentially an explosion, either a slow one or a fast one.

The rate of radioactive decay that you would measure with a Geiger counter depends on the number of radioactive atoms present. Here the exponential function is negative, decaying rather than growing,

$$\text{Counts}(t) = \text{Counts}(0) \cdot e^{-k\,t}$$

The exponential function comes up when a quantity grows or shrinks in proportion to its current value.

A decaying exponential approaches zero **asymptotically**, meaning that it gets closer and closer but never actually gets there. In the radioactive decay equation, the scaling factor in the exponential could be converted into an **e-folding time scale**, as

$$\text{e-folding time scale} = 1 \;/\; k$$

This quantity is similar to a half-life but rather than the amount of time to decay to half the initial quantity, the e-folding time scale tells how long until 37%, 1/e, of the original is left. It takes 44% longer to decay to a fraction of 1/e than it does to 1/2 of the original number of atoms.

The atmospheric pressure decreases as a function of altitude according to an exponential decay type of equation,

$$P(z) = 1\,atm \cdot e^{\frac{-z[km]}{8\,km}}$$

shown in Figure 5-1. The height z is zero at sea level, leaving us with e^0 which equals 1, so the pressure at sea level is 1 atm. At an altitude of 8 km, pressure is lower than at sea level by a factor of e^{-1} or 1/e, about 37%. We call that altitude the **e-folding height**.

Most of the mass of the atmosphere is contained in the e-folding height. In fact, if the entire atmosphere were at 1 atm pressure, instead of smeared out in a decaying exponential function, it would fit into one e-folding height exactly. So in one sense you could say that the atmosphere is 8 kilometers thick, even though, mathematically, according to the exponential function, the pressure in the atmosphere never really gets to zero, no matter how far away you get.

From the appearance of the exponential function in the equation for pressure, you might guess that the rate of change of pressure with altitude must depend on the pressure itself in some way. This would be astute. The rate of change of pressure depends on pressure because at high pressure, gas is compressed, and so a climb of one meter through gas at high pressure would rise above more molecules of gas than would a climb through a meter of gas at low pressure.

Imagine a wall made of compressible bricks (Figure 5-6). A row of bricks is thinner at the bottom of the wall, because they are compressed. Batman climbing up the wall would pass more bricks per step at the bottom than at the top. For incompressible bricks (the normal kind), the rows are all the same height and the mass of wall above you is a linear function of height.

The bottom line is that gas expands when depressurized, and because of this, atmospheric pressure decreases non-linearly with altitude, following a exponential decay function.

Expansion, Compression, and Heat

Here begins the second apparently unrelated thread of the story. If we compress a gas its temperature goes up. This occurs even if we don't allow any heat to enter the gas or leave it, say if we had gas inside an insulated piston that we compress or expand. The condition that we are describing, a closed system with no heat coming in or out, is called **adiabatic.** If gas is compressed adiabatically, it warms up. If you ever let the air out of a bicycle tire by holding the little valve open with your thumb, you may have noticed a chill on your thumbnail. The gas expands as it flows from the high-pressure tire into the lower-pressure atmosphere, and because it expands, it cools.

If you squeeze air, does it not heat up?

When you compress a gas, its temperature rises. It takes work to compress a gas. You have to squeeze the piston in order to compress it. Your muscles push against molecules bouncing against the head of the piston. That work energy transforms into heat, the bouncing-around energy of the molecules of gas. The reverse situation, cooling while expanding is a little less intuitive to envision, but when the piston moves to expand the gas, it is taking work energy from the gas. You could use the power of the piston to do some, like turn a driveshaft. The energy to do that work comes from the thermal energy of the molecules of the gas, so the gas cools as it expands.

Figure 5-7 shows the temperature change that a parcel of dry surface air would experience if it were carried aloft. We'll worry about water vapor in a moment, but for now we are looking at the line labeled **Dry Adiabat.**

Water Vapor and Latent Heat

Here comes seemingly unrelated thread number three. Water molecules can exist together in any of three **phases**: gas, liquid, or solid. A transformation from liquid or solid to gas requires an input of a considerable amount of energy. One could write a chemical reaction for water as

$$\text{vapor} \Leftrightarrow \text{liquid} + \text{heat}$$

If you have ever burned your skin with steam from a teapot, this reaction will have meaning for you. Steam from a teapot is probably at the boiling temperature of water, 373 K. This is a temperature you might set for your oven to warm bread; you can easily blow the air from the oven on your hand when you reach in for the bread without burning yourself. Steam burns, not because its temperature is so high (what is called its **sensible heat**, because a thermometer can sense it), but because the vapor deposits its heat when it condenses on your skin. The heat that the steam is carrying is called **latent heat**. You charge up an air parcel with latent heat when you evaporate water into it, and you get the heat back again when the water condenses. A thermometer doesn't measure the latent heat content of an air parcel unless it the heat is released by condensation.

If you set a tray of water or ice in a closed box full of dry air, some of the water molecules are going to evaporate, becoming a gas. Actually, the air in the box is almost irrelevant to the water. Almost the same number of water molecules would evaporate into a box full of vacuum (no air). A chemical way to say that is that the partial pressure of water vapor doesn't care how much oxygen or nitrogen is there, it only cares about the temperature inside the box.

When water is in equilibrium between liquid and vapor, it’s called saturated, and also called 100% relative humidity.

When the temperature is high, more molecules will have the energy required to jump into the vapor phase, and the **equilibrium vapor pressure** of water will be high. In cold conditions, the equilibrium vapor pressure will be lower (Figure 5-8). If the amount of water vapor actually present is lower than the equilibrium value, it is what is called **undersaturated**, and liquid water if available will tend to evaporate. If water vapor is **supersaturated**, meaning the vapor pressure is higher than equilibrium, then water will tend to condense, perhaps into raindrops or snowflakes or it could wet the walls of the box. For water vapor the air the equilibrium pressure is also referred to as 100% **relative humidity**. More on water vapor to come in Chapter 7.

Convection

Now we are equipped to think about convection in the atmosphere. **Convection** occurs when you heat a fluid or gas from below or cool it from above. If you heat it from below, the fluid at the bottom gets warmer than the fluid overlying it. Warmer molecules bounce around more energetically, pushing outward more strongly; as a result the fluid **expands** somewhat as its temperature increases. As it expands its density (mass per volume) decreases. The result of heating from below is warm buoyant fluid underneath colder denser fluid, an unstable situation that causes the fluid column to turn over, the warm fluid rising to the top.

Consider a pan of water on a stove. Figure 5-9 shows the temperature of the water as a function of the height in the pan, a temperature **profile.** First mix the water in the pan. When the water is well mixed, it will all have the same temperature. That sounds obvious but we'll find in a moment that a well-mixed column of air does not all have the same temperature. A well mixed, uniform-temperature water column is called **statically stable**; it is not stratified but it is not unstable either.

Next turn on the burner, warming and expanding the water at the bottom of the pan. Buoyant water at the bottom tends to rise; this situation is called **convectively unstable.** The buoyant water from the bottom could potentially rise to the top like the lava in a lava lamp, in which case the water column would be **stratified.**

The temperature profile in a convecting pan of water evolves through a series of well-mixed (statically stable) states.

Alternatively the rising warm water could mix with the rest of the water, as generally occurs to a large extent in the atmosphere and ocean. In this case we end up after the convection with a second statically stable profile, at a higher temperature than the initial one.

Convection in a column of air is like that in a column of water, but with a few new twists added. As with the water, start by mixing everything together (Figure 5-10). After mixing, no air parcel will be more or less dense than the rest because it is all the same air. The column of air will be statically stable, because that is what mixing does.

Unlike the incompressible water, however, the air is not all the same temperature. The pressure is higher at the bottom of the column, because of the weight of the air, so the air at the bottom has been compressed and it has heated up. If a warm air parcel from the bottom were raised up to the top it would expand and cool, but because the air is well-mixed, the moving air will always find itself at the same temperature as the rest of the air in the column. The parcel was neutrally buoyant near the bottom of the column, and it is neutrally buoyant all the way up. This is what static stability looks like in a column of compressible air.

A well-mixed (statically stable) column of gas (a compressible fluid) will not all have the same temperature. It will be warmer on the bottom.

Ocean water is slightly compressible, so its temperature changes somewhat with depth in a well-mixed column, just like air does, but the effect is much smaller for water, just a few °C change between the surface and the bottom of the ocean.

Convection in the atmosphere is driven by sunlight hitting the ground, warming the air at the bottom of the column. The warmed air parcel from the ground finds itself warmer than the air around it, and so it begins to rise. As it does, it expands and cools, but throughout the ascent the air parcel remains warmer and lighter than the air surrounding it. If it doesn't mix with surrounding air on the way up, it can rise all the way to the top of the column.

If the rising plume of air mixes with the surrounding air as it goes, as it usually does in the atmosphere, the whole air column would warm up uniformly, just as it did in the column of water. And, just like the water, the temperature profile in the column would always be statically stable as it rose. For the atmosphere, the temperature profile follows a the curve labeled Dry Adiabat in Figure 5-7.

Moist Convection

Convection in the real atmosphere has one more ingredient, and that is latent heat from water vapor. Imagine a source of water vapor at the Earth's surface, so that the air above the ground has a relative humidity of 100%. If this parcel rises up in the column due to convection, it will decompress and cool.

As the temperature drops, less water would choose to be evaporated (Figure 5-8). The excess vapor is reflected in the relative humidity value, which exceeds 100% as the air cools. The supersaturation drives water to condense into droplets or ice. The story of cloud formation in climate is not a simple one and it does not end here, but will continue in Chapter 7.

As the water condenses, it releases its latent heat, just like the steam from the teapot burning your skin. It takes heat to make vapor from liquid or gas, and when you re-form the liquid or gas, you get the heat back. The latent heat warms the air parcel up a bit, counteracting some of its decompression cooling (Figure 5-11). The water vapor changes the temperature of the air; in fact it systematically changes the lapse rate (temperature decrease with altitude). To distinguish the two, atmospheric scientists talk about **dry convection** and **moist convection**, and **Dry** and **Moist Adiabatic lapse rates.**

The latent heat in water vapor drives most of the drama in our weather.

If there were no convection, only radiation like in the Layer Model, the lapse rate of the atmosphere would be about 16 °C per kilometer of altitude. The atmosphere doesn't get there because that state would be unstable to convection, like a pan of water with warmer water underneath cooler water. There are some stars that have radiation energy fluxes like in the Layer Model but have no convection. They are said to be in a state of **radiative equilibrium.** But the atmosphere of the Earth convects, finding a state called **radiative convective equilibrium.**

An atmosphere undergoing dry convection has a lapse rate of about 10 °C cooler per kilometer altitude. When you add the latent heat in moist convection, the lapse rate decreases to about 6 °C per kilometer. This is very close to the lapse rate of the real atmosphere. As the next chapter will continue to show, the circulation of the atmosphere is pretty complicated, but the process of moist convection is a good first-order description of why the temperatures in the atmosphere are stacked the way they are.

The question is important because it's possible that the lapse rate of the atmosphere could be different in a changing climate. This would be one of many **feedbacks** in the climate system (Chapter 7).

Take-Home Points

Air in the upper troposphere is colder than air at the ground, because of the process of moist convection. The process is

a) Convection is driven by sunlight heating the air near the ground.

b) The air rises and cools.

c) Water vapor condenses, releasing heat as the air rises.

If the air did not get colder with altitude, there would be no greenhouse effect.

Study Questions

Explain why a well-mixed column of gas is warmer on the bottom.

If the atmosphere got warmer with altitude, instead of cooler as it does in Earth's troposphere, what would be the climate impact of greenhouse gases?

How can the skin altitude of the atmosphere be defined?

Why does the profile of atmospheric pressure with altitude in the atmosphere follow an exponential function?

A parcel of air rises convectively in the atmosphere, losing its water as rain and getting cooler following the moist lapse rate. It gets sucked into an airplane where it is re-compressed to the pressure at the ground without replacing the water. Is this air warmer or colder than air at the ground? What is its relative humidity like?

Further Reading

Frederick, John E., 2007, Principles of Atmospheric Science, Jones and Bartlett Publishing, Inc, Sudbury, MA.

Figure Captions

1. The Layer Model from Chapter 3 with an added heat exchanger, capable of partially or completely equalizing the temperatures of the two layers.

2. Typical temperatures and pressures of the atmosphere as a function of altitude in the tropics.

3. A demonstration of the effect of the lapse rate on the strength of the greenhouse effect. If we increase the greenhouse gas concentration of the atmosphere, the infrared radiation to space will originate from a higher altitude (labeled Skin Altitude), but the Skin Temperature at the Skin Altitude will eventually be the same as the temperature at the old Skin Altitude. The increase in Skin Altitude increases the Ground Temperature. If the temperature of the atmosphere were the same at all altitudes, then raising the Skin Altitude would have no impact on Ground Temperature.

4. Pressure increases linearly with depth in water, because water is incompressible.

5. The exponential functions e^x and e^{-x}. For e^x, the growth rate of the function is proportional to its value. Examples of this type of behavior include interest on a bank account, and population growth. For e^{-x}, the value of the function decays proportionally to its value. Radioactive decay does this, as does pressure as a function of altitude in the atmosphere.

6. A wall made of compressible bricks, to demonstrate why pressure changes rapidly at the bottom of the atmosphere and slowly at the top, because air in the atmosphere is compressible (left). For water, which is incompressible, pressure increases linearly with depth.

7. The temperature decrease with altitude in the atmosphere is called the lapse rate. If the atmosphere contained no water vapor, the lapse rate would follow the Dry Adiabat. As is, most of the atmosphere is closer to the Moist Adiabat, especially in the tropics where convection is most important.

8. Water has a greater tendency to evaporate at higher temperature than at cooler. The graph shows what a chemist would call the equilibrium vapor pressure of water, and a meteorologist would call 100% relative humidity. Air in the real can have less or sometimes slightly more water vapor than this, but if the water vapor concentration gets too much higher than this curve, the water will condense into water droplets or snow.

9. The effect of convection on the temperature in a pan of water on a stove. In the top left, the water in the pan is well mixed, the same temperature throughout. After the burner is turned on, the water at the bottom of the pan warms, which makes it less dense than the water above it (convectively unstable). Either this water can rise to the top without mixing (bottom left) or it can mix with the water above it, raising the temperature of the entire pan of water (bottom right). The atmosphere tends to mix when it convects, as in the lower right example.

10. Convection in a compressible fluid like air. On the left is the statically stable configuration, analogous to the upper left panel in Figure 5-9. The temperature decreases with altitude because the gas expands, and therefore cools. This temperature profile is what you would see in a well-mixed column of air. On the right is the effect of heating from below, analogous to the top right panel in Figure 5-9.

11. The effect of water on the temperature profile in the atmosphere. Air cools as it rises, as in Figure 5-10. The cooling drives water vapor to condense into droplets, releasing its latent heat to the air. The Moist Adiabat therefore cools less with altitude than does the Dry Adiabat.

Exercises

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.

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?

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?

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

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"?

Chapter 6. Weather and Climate

How the weather affects the climate.

Chaos

Weather forecasts have really improved in the last few decades, but it's still pretty dicey to say what the weather will be ten days from now. And yet climate science claims to be able to forecast the climate 100 years from now. Perhaps an explanation might be in order.

It is indeed tricky to forecast the **weather** too far in advance, because weather is **chaotic.** To a scientist, the word chaotic brings to mind an extreme sensitivity to initial conditions, so that small differences between two states tend to amplify, and the states diverge from each other. This behavior is called the **butterfly effect**, the reference being to a puff of air from a butterfly's wing eventually resulting in a giant storm somewhere that wouldn't have happened if the butterfly had never existed.

The butterfly effect was first observed in a weather simulation model. The model computer run stopped, and the researcher Edward Lorenz restarted it by typing in the values of model variables like temperatures and wind speeds, but with small seemingly insignificant changes like rounding errors. It didn't take long for the restarted simulation to diverge from the results of the initial simulation, because of the chaotic sensitivity of Lorenz's model to its exact starting point.

Weather is chaotic, but climate generally is not.

The weather forecasts rely on computer models that are very similar to climate models. The forecast model runs are started from meteorological data and past model results. Small imperfections in the initial conditions, and in the model, cause the model weather to diverge from the real weather, so that by about 10 days the model prediction becomes meaningless.

One way to cope with this situation is to run the model lots of times with tiny variations in initial conditions; an **ensemble** of model runs. Then you can see something of the range of what's possible. It doesn't fix the problem exactly but it does result in a more reliable weather forecast.

The **climate** is defined as some time-average of the weather. One could speak of a **climatological** January, which would be the average of many Januaries, let's say 10 or 20 Januaries. Forecasting climate is not as difficult as forecasting weather, because it doesn't matter if the rain you predict comes on Tuesday or Thursday. The butterfly can't foil our climate prediction with her storm, if the model gets the large-scale tendency for storminess right. If the model doesn't follow a storm trajectory this time, it will next time; the butterflies average out. The weather is chaotic but the climate is not.

The butterfly is able to change the specifics of a particular storm, but it is not able to change the general storminess of the climate. The statistics of the weather events in the climate model ought to replicate those of the real climate, even if the exact storms are not the same between the model and reality.

Averaging

The layer model represents Earth's climate on a grand average: the warm places and the cold places, and the summers and the winters, day and night. The layer model also assumes that the radiative energy budget is completely balanced. This is a reasonable assumption for the long-term global average, because there is nowhere else for the heat energy to go; what comes in must go out.

However, in the real world, some places are hotter than others. Very warm and very cold places on Earth are significantly different from average places, in terms of how their energy budgets work. Also the real radiative energy budget for some location and time is probably wildly out of balance. The sun only shines in the daytime, for one thing; energy is dumped onto the Earth in the daytime and radiates away through the night. There is also an imbalance through the seasonal cycle, because it takes heat every spring to warm things up: the air, land surface, and especially the water.

Is an eternal, unchanging, averaging model a reasonable one for a world that is usually locally out of balance? Can you construct the average of the whole system by using averages of the pieces of the system? Or will averaging change the answer?

There could be a problem with averaging IR energy fluxes, for example, because they are a **nonlinear** function of temperature, which is to say that a plot of one variable versus the other does not trace a straight line (Figure 6-1). Algebraically one can look at the equation and see that the light flux is proportional to temperature to the fourth power, and not to the first power, which would be linear.

$$I\left[\frac{W}{m^2}\right] = \varepsilon\left[unitless\right]\ \sigma\left[\frac{W}{m^2\ \ K^4}\right]\ T[K]^4$$

Let's estimate the average energy flux of a planet that had two sides, one at 300 K (rather like Earth) and the other at 100 K (much colder than anywhere on Earth). The outgoing energy flux from the cold side would be about 6 W/m^2, and from the warm side 459 W/m^2. The average energy flux would be 232 W/m^2.

It may be OK to take the average of a linear system, but averaging a non-linear system may introduce a bias.

Now average the temperatures, run the average T through $\varepsilon\ \sigma\ T^4$. The average temperature is 200 K, and the calculated energy flux is 91 W/m^2. The averaged answer is off by more than a factor of two. You can see the effect graphically as the difference between the straight line and the curve in Figure 6-1.

The terrestrially normal range of temperatures spans a narrow enough range that it looks much straighter than in Figure 6-1, which spans an absurdly wide temperature range. An averaging model would work better for realistic temperature extremes. Still, the variations in temperature could have an important impact on the behavior of the system, and we certainly wouldn't want to neglect it in the global warming forecast.

There are many other nonlinearities in the climate system, pairs of variables that are related to each other in nonlinear ways. For example, many effects of the wind, such as exchanging heat with the ocean, depend nonlinearly on wind speed.

The Fluctuating Heat Budget

The heat input to the real Earth is not stable and unchanging like the Layer Model; instead it fluctuates rather widely. Solar energy only comes in during the day, for example, while infrared energy loss to space continues around the clock (Figure 6-2). The heat input also varies over the seasonal cycle, and from place to place on the Earth's surface.

Earth's heat budget is only in balance on average, but is usually out of balance at some particular place or time. The This shows that the

The seasons are caused by the tilt of the Earth relative to its orbit around the sun (Figure 6-3). In the winter hemisphere, the days are shorter and the sun is at a lower, more oblique angle in the sky. Added up over a day, the winter hemisphere less sunlight energy. The seasons are opposite each other in the two hemispheres because if one hemisphere is tilted toward the sun, and the other will be tilted away.

Note that the **seasons** are not caused by the relative distances of anyplace on Earth from the sun, because the size of the Earth is much smaller than the distance of the Earth from the sun. The North Pole is not really that much farther from the sun than the equator is.

Also, the seasons are not caused by changes in the distance of the whole Earth to the sun. It's true that Earth's orbit is elliptical, rather than circular, so the distance to the sun does vary throughout the year. In its current orbital configuration the Earth is closer to the sun in January than in July, the wrong way to explain winters in the northern hemisphere. If the distance from the sun caused the seasons, the whole world would get cold and warm at the same time.

The effect of the tilt and eccentricity of the Earth's orbit on sunlight intensity is shown in Figure 6-4. The axes in this figure are day of the year in the x-direction and latitude in the y-direction. The contours show the intensity of sunlight at the top of the atmosphere, averaged over 24 hours. Any location at some latitude, say 42°N which goes through Chicago, Barcelona, and Vladivostok, will get the same solar influx at the top of the atmosphere. A map of the solar intensity would look like a bunch of horizontal stripes. Figure 6-4 shows the two dimensions over which the solar influx does vary: latitude and day of the year.

Earth's seasons are caused by tilt of the poles relative to the orbit, not by its distance from the sun.

The beginning of the year is Southern hemisphere summer, and there are red colors, representing high energy flux, in the South, and blues in the North. Northern hemisphere summer is the middle of the year, centered on about day 180. Now there is red in the north and blue in the south. The color pattern arises by two mechanisms. First, the intensity of sunlight per m^2 of ground area is greater at noon in the summer than in the winter, because the ground is at less of an angle to the sun in the summer (Figure 6-3). Secondly, days are longer in summer, and this increases the 24-hour average energy influx.

It is interesting to note that the highest daily-average energy fluxes on Earth are at the North or South pole during northern or southern summer. The sun never sets in midsummer at the pole; it just whirls around in a circle over the horizon. In winter the pole gets no sunlight for months on end. The poles do not turn into tropical garden spots in summer because to some extent the temperatures average out the seasonal changes in heat forcing.

Thermal inertia tends to damp out the temperature swings of the day/night cycle, the seasonal cycle, and any global warming temperature trends as well. The liquid ocean in particular has a tremendous capacity to absorb and release heat to the atmosphere. In soils and on the land surface, the seasonal cycle of temperature only reaches a meter or two down, because diffusion of heat through solids is relatively slow. When you cool the water surface, turbulent mixing and convection quickly spread that cooler water throughout a much deeper range, typically 100 meters or more. For this reason, the seasonal cycle is much more intense in the middle of large continents than it is in "maritime" areas impacted by the temperature stabilizing effects of liquid water.

Even averaging out the seasonal cycle, the radiative energy budget of a single spot on the surface of the Earth is probably way out of balance, because heat energy is redistributed around the Earth's surface by wind and water currents (Figure 6-5). There is a net influx of heat in the tropics, as sunlight brings in energy faster than the outgoing infrared. It doesn't get hot enough in the tropics for outgoing infrared to balance the incoming sunlight locally. Heat is carried into the cooler high latitudes by warm winds and ocean currents. In high latitudes, the Earth vents the excess tropical heat, as excess radiative heat loss to space over direct solar heating.

The upshot of this chapter is that a climate model to forecast global warming will have to simulate the weather: all of the fluctuations and imbalances in the energy budget, and the way that the Earth's climate responds, by storing heat or moving it around. The layer model will not do.

The Coriolis Acceleration

Flows in the atmosphere or ocean differ from those in a sink or bathtub because they persist for long enough that they are steered by the rotation of the Earth. When water runs down the drain of a bathtub or sink, it only takes a few seconds for the swirling pattern at the drain to establish itself, and the Earth has only rotated a negligible amount in that time. So it's **not true** that water has much tendency to spiral down the drain in opposite directions in the two hemispheres! We can't feel the Earth's rotation in our everyday motions either. But if the flow down the drain persisted for several days, the rotation of the Earth would start to become significant to steering the flow.

Imagine two kids sitting opposite each other on a merry-go-round at a playground (Figure 6-6), tossing a ball back and forth while spinning. The actual rotation of the Earth is negligible here because the ball takes less than a few days to get where it's going, but the merry-go-round itself is rotating quickly enough to move as the ball flies from one side to another. The thrower (T) tosses the ball toward the catcher (C), but before it gets there, the merry-go-round has rotated, and the catcher misses the ball. Viewing the action from the ground (the non-spinning frame of reference), the ball flies straight, following Newton's laws of motion. The rotation of the merry-go-round underneath the ball doesn't actually affect the trajectory of the ball.

But a person on Earth looking at a map of the weather or the Gulf Stream is like the kids on the merry-go-round trying to make sense of the apparent trajectory of the ball. It's inconvenient to try to visualize things from the non-rotating frame. What they see is that, on the merry-go-round, the ball curved to the right.

Newton's laws of motion can be "hacked" to get them to work in the rotating frame by adding a fake force called the **Coriolis acceleration.** This fudge factor has the same effect as the rotation of the Earth that is being ignored. On the merry-go-round, the fake force should change the direction of the ball without changing its speed. To do this, the fake force must be at exactly 90° perpendicular to the direction that the object is moving. It also turns out that the force must be stronger the faster the object is moving, because it would take a stronger force to change the trajectory of a faster object. In Figure 6-6, the Coriolis fake force would have to be directed to the right of the direction of motion, so that it would turn the trajectory of the ball to the right. On Earth, the Coriolis force goes to the right of the direction of motion in the Northern hemisphere, and to the left in the Southern hemisphere.

The Coriolis force is a fudge factor, allowing us to ignore, in the equations of motion, the fact that the Earth is rotating.

Now leap from a flat merry-go-round to a rotating gravitational sphere. When we rotate the sphere, what does that do to the people trying to read their weather maps? How much rotation do they feel? The best way to envision the Earth's rotation is to see or imagine a **Foucault's pendulum.** The pendulum has to be very long so it can keep swinging all day on a single push, so they are usually set up in an atrium 10 or 20 meters high. The pendulum swings with an enchantingly long, slow period of maybe 10 or 30 seconds. The weight at the end of the wire is a rather heavy 100 kg or thereabouts. The wire is suspended from a swivel to allow the mass on the end of the wire to rotate freely. At the base of the pendulum, a museum employee sets up a circle of little dominos, which the pendulum knocks over as it swings. Over the course of the day, the swing direction of the pendulum changes, knocking over a new little block every ten minutes, or some other crowd-pleasing rhythm. Leon Foucault installed the first of these into the Pantheon in Paris for the 1850 Paris Exposition.

The pendulum is like a rotation meter, measuring the rate of rotation that drives the Coriolis effect. Start with a Foucault pendulum on the North Pole (Figure 6-7). The Earth is spinning relative to the fixed stars, but the swing axis of the pendulum stays stationary relative to the fixed stars. As the Earth turns under the pendulum, it knocks over the dominos. They will all be knocked over after the planet has rotated 180°, which takes 12 hours.

Now move the pendulum to the equator, and start it swinging in a North-South direction. The swing axis of the pendulum cannot remain completely motionless with respect to the fixed stars, because the direction "down" keeps changing as the planet rotates. But the pendulum will keep its alignment with the stars by continuing to swing in a North-South direction. The swing of the pendulum does not appear to rotate to an observer on Earth. The dominos are safe.

The pendulum rotates at the poles, but not at the equator.

In the middle latitudes, the rate of rotation is in between these extremes of the pole and the equator. The dominoes are completely knocked over in 12 hours at the pole, but they are never knocked down at the equator. In middle latitudes the knock-down time is longer than 12 hours and shorter than forever. To be technical about it, the rotation rate scales as the trigonometric function sine of the latitude.

Rotations are represented in physics as arrows called **vectors**, and the rotation of the Earth would be like a flagpole, pointing not necessarily straight upward, but pointed toward the North Star from anyplace in the Northern hemisphere. The rotation that the fluids feel in the atmosphere and ocean would be represented as the height of the tip of the flagpole above the ground. On the equator, the North Star is at the horizon, and the flagpole would be lying on the ground, so its tip would have zero altitude, meaning no rotation. At the North Pole, the flagpole points straight up, achieving its full height, and the flows feel the full rotation rate of the Earth. In between, the rotation goes as the height of the tip of the pole.

Modeling the Weather

At the heart of it, fluid flow is governed by Newton's laws of motion. Because fluid has mass it has **inertia**, which tends to keep it moving if it's moving, or keep it stationary if it is already stationary. To change the speed or direction of the flow motion requires a force, such as gravity or pressure.

One example of driving a flow by differences in pressure would be to fill up a bathtub with water and then somehow pull up on the water surface on one side, making a slope (Figure 6-8). The water will want to flow in a direction to flatten out the surface. Let's assume that the bottom of the tub is flat relative to the gravity field like the surface of a pool table, what is called a **geopotential surface.** The pressure at the bottom of the bathtub would be higher on the deep end, because there is more water overhead.

The flow is driven by the **pressure gradient,** which could be calculated as

$$\text{Pressure Gradient} = \frac{\Delta P}{\Delta x} = \frac{P_{\text{shallow}} - P_{\text{deep}}}{\text{bathtub length}}$$

Our intuition is that the fluid will not stay tilted like that and will eventually flatten out. When that happens, the pressure gradient goes to zero. Because the bathtub flows more quickly than the Earth rotates, it doesn't feel the Earth's rotation, so the Coriolis acceleration is much smaller than the real acceleration, and the water just flows downhill.

Flows in the atmosphere and ocean persist long enough for the rotation to play a role (Figure 6-9). Flows are pushed by driving forces, such as the pressure gradient in the bathtub, or ocean flows can be driven by friction with the wind. Imagine a sudden wind driving a current in the surface ocean. The water initially flows downwind, and as the fluid begins to flow, the Coriolis acceleration begins to try to deflect the flow (to the right in the Northern hemisphere).

Eventually, after a few rotations of the Earth, the current will reach a condition called a steady state, in which the forces acting on the water come into balance with each other. In the steady state, the current is sideways to the wind. The Coriolis force on the current is sideways to the current, pointing back upwind, balancing the wind.

A geostrophic flow balances the forces on it against each other.

The astonishing implication is that in a rotating world the fluid will eventually end up flowing completely cross-ways to the direction of the forcing. This condition is called **geostrophic flow.** It is as if a marble, instead of rolling down a hill, would roll around and around the hill. It is as if the sloping surface in the bathtub would drive a flow across the bathtub. The water in the bathtub does no such thing, of course, because the flow in the tub doesn't have time to find the geostrophic equilibrium shown in Figure 6-9, and also because the bathtub is not infinitely wide, and water cannot flow through the walls.

Great ocean currents that persist for longer than a few days, though, do flow sideways to their driving forces. Sea level on the east side of the Gulf Stream in the North Atlantic is about one meter higher than it is on the west side. Did I get that right? Figure out the direction that the pressure would be pushing the water, and verify that the flow is 90° to the right.

Did you ever wonder why winds blow around a low pressure cell on a weather map, instead of directly from high pressure to low?

You can see geostrophic flow on a weather map as cells of high and low pressure with flow going around them (Figure 6-10). A low pressure cell in the northern hemisphere has a pressure force pointing inward all around its circumference. 90° to the right of that, the winds flow counter-clockwise (in the northern hemisphere). Meteorologists call this direction of flow **cyclonic.** Flow around a high pressure cell would be **anticyclonic.** The fluid flows in circles around the cells, rather than into or out of the cells, preserving rather than wiping out the hole in the pressure of the atmosphere. This is why hurricanes can last for many days, and a huge geostrophic circulation system on Jupiter, the Great Red Spot, has probably been going for centuries.

The equations that govern turbulent fluid flow cannot be solved algebraically, the way the layer model can for example, but can be solved approximately using **computer models.** The domain of the model, the Earth's atmosphere or ocean, is divided up into a three-dimensional grid (Figure 6-11). At each grid point the computer keeps track of the things that drive the flow and the weather: the temperature, pressure, flow velocity, and other variables such as water vapor concentration for the air or salinity for the ocean. At each **time step**, the computer keeps track of how the flow would change the temperatures and pressures, and how the flow itself will change in the next time step. A typical time step for a climate model may be a few minutes.

Even before computers, researchers like Lewis Richardson dreamed of using human "computers" to perform the immense calculations that would be required to forecast the weather. Doing the math by hand is so slow, however, that it would never be possible to even keep up with the real weather, let alone make a forecast of the future. ENIAC, one of the first electronic computers constructed in 1945, was used for a range of scientific computation projects including weather forecasting.

If you would like to play with a climate computer model, you can download one called EdGCM (see Further Reading). The model runs on a desktop computer, and can simulate a few years of simulated time in 24 hours of computer time. It has a very nice point-and-click interface to plot maps and time-series of model variables.

The physics of air and water flow are challenging to simulate by their very nature. This is because there are patterns in the flow that are as large as the planet, and as small as a few millimeters. All of the different size scales of flow are important to the overall properties of the flow, and how it carries things around like heat and water vapor. Fluid turbulence is characterized by a phenomenon called a **turbulent cascade**, in which larger-scale flows break up into smaller flows. The energy in the flow passes from large scales to small, ultimately dissipating in fluid friction due to the **viscosity** or goopiness of the fluid.

Big whorls have little whorls,
Which feed on their velocity,
And little whorls have lesser whorls,
And so on to viscosity.
– Lewis Richardson

The flows in the atmosphere and ocean are ultimately forced by differences in temperature and heat flow, factors that arise on a global spatial scale. The global circulation patterns then tend to break up into smaller features as the energy trickles down the turbulent cascade. In the atmosphere the flows break up into storms and fronts, what's called the weather. In the ocean, large features like the Gulf Stream spawn rings and eddies a few hundred kilometers across. In atmospheric and oceanic fluid flows, there are features spanning a huge range of sizes.

Simulation of weather and climate remains one of the grand challenges in the computational sciences. This is because the mechanisms that govern fluid flow often operate at fairly small spatial scales. If we wanted a model to include everything that governs how cloud drops form and grow, for example, we would have to have grid points every few meters in the clouds. Fronts in the ocean allow fossil fuel CO_2 to mix into the ocean interior, but these can be only a few meters wide. To really resolve the mechanisms that control the climate would require an immense number of grid points in the model.

The trouble is that if we increase the number of grid points, say by a factor of 10 in each dimension, the total number of grid points goes up by a factor of $10 \cdot 10 \cdot 10$ or 1000. That's 1000 times more math the computer has to do per time step. To make matters worse, as the grid gets more closely spaced, the time step has to get shorter. A grid 10 times finer would require a time step about 10 times shorter. So it would take 10,000 times longer to do a model year of time. State-of-the-art computer models of climate are run at higher resolution all the time, and in general they look more realistic as resolution increases. But they are still far from the resolution they would like, and will be so for the conceivable future.

Climate modelers always leave the computer room hungry for more.

Some of the physics of the real atmosphere cannot be explicitly resolved, so they must be accounted for by some clever shortcut. The real formation of cloud droplets depends on small-scale turbulent velocities, particle size spectra, and other information which the model is unable to simulate. So the model is programmed to use what information the model does have, ideally in some intelligent way that might be able to capture some of the behavior and responses of the real clouds. Cloud formation may be assumed to be some simple function of the humidity of the air, for example, even though we know reality is not so simple. The code word for this approach is **parameterization**. The humidity of the air is treated as a parameter that controls cloudiness. Other important parameterizations include the effects of turbulent mixing, air / sea processes such as heat transfer, and biology modeling is full of parameterizations; the list goes on. Some of these topics will come up again in Chapter 11.

Take-Home Points

The energy budget to space of a particular location on Earth is probably out of balance, fluctuating through the daily and seasonal cycles, and with the weather. This is in contrast to the Layer Model.

The annual average energy budget for some location on Earth may not balance, either, because excess heat from the tropics is carried to high latitudes by winds and ocean currents.

The global warming forecast requires simulating the weather, which is a really hard computational challenge.

Study Questions

How can we predict a change in climate 100 years from now if we can't forecast a rainstorm more than 10 days out?

Q: Is the Earth's energy budget to space in balance? A: Yes and no. Your task: explain the answer.

Draw a diagram describing why geostrophic flow goes 90° to the direction of the forcing.

Draw a diagram of a hurricane, showing the pressure gradient, the wind direction, and the Coriolis acceleration of the wind.

Why does the turbulent cascade make Earth's climate a difficult computational challenge?

Further Reading

Chaos: The Making of a New Science (1988) James Glieck

EdGCM, http:// edgcm.columbia.edu/ NASA scientists have created a climate GCM model that you can run easily on Windows or on the Macintosh. There are graphical menus for setting up the model run: greenhouse gas concentrations, solar intensity, and so on. There are also graphical tools to make maps and time series of the model output. I can run a few decades of model time overnight on my relatively old laptop.

Figure Captions

1. An example of how averaging can bias the results of a non-linear system such as blackbody radiation energy flux σT^4. In the top panel, we average across a huge temperature range, and the flux we get from combining areas of 100 K and 300 K are very different from what we would expect if we averaged the temperature first to 200 K and then computed the answer. In the bottom panel, we see that over the temperature range of normal Earth conditions, the blackbody radiation energy flux is closer to linear, so averaging would be less of a problem, than in the top panel.

2. The surface of the Earth only receives incoming solar radiation during the daytime (heavy solid line), but it radiates infrared light all the time (thin solid line). The energy budget for this location (dashed line) is only in balance when it is averaged over 24 hours.

3. The Earth's tilt is responsible for the seasons. This is Southern Hemisphere summer, Northern Hemisphere winter.

4. The Earth's tilt determines how much heat the surface receives from the sun each day, as a function of latitude (vertical axis) and time of year (horizontal axis).

5. The energy budget between incoming solar and outgoing infrared radiation does not balance locally, because heat is transported on Earth by winds and currents. The equator receives more solar energy than it radiates as infrared, while high latitudes lose more infrared than they receive from sunlight.

6. An illustration of the Coriolis acceleration on a playground merry-go-round. The thrower (T) tosses the ball toward the catcher (C). Before the ball gets to the catcher, the merry-go-round rotates. If we observe this from the point of view of the children on the merry-go-round, it appears as if the ball veers to the right as it moves. The Coriolis acceleration is the kids' attempt to explain the motion of the ball, as if the merry-go-round were not spinning.

7. The Coriolis acceleration that we feel on Earth depends on latitude. A Foucault's Pendulum is a rotation detector. A pendulum set in motion at the pole would swing through 180° in 12 hours, knocking down all of a

circle of dominos places around the pendulum. On the equator, the pendulum is started in a north-south direction, and maintains that direction of swing as the Earth rotates. The rate of rotation, and therefore the Coriolis acceleration, is strongest at the poles. At the equator there is no apparent rotation.

8. A thought experiment in which the bottom of a bathtub is a level geopotential surface, but the water level at the surface is sloped. In this situation there would be higher pressure at the bottom of the bathtub on the deeper side than on the shallower side. This results in a pressure force that tends to push water from deeper to shallower.

9. The Coriolis acceleration affects the way that winds and currents respond to pressure forcing on a rotating planet. In the top panel, the fluid initially flows in the direction that the wind or pressure force is pushing it. As it starts flowing, it generates a Coriolis force directed 90° to the direction of its motion. In the middle panel, after a while, the Coriolis force swings the fluid flow toward the right. Eventually, the fluid itself flows 90° to the wind or pressure force, and the Coriolis force just balances the wind or pressure force, in the bottom panel. This is the steady state, where the flow stops changing and remains steady. In the Southern Hemisphere, the direction of the Coriolis acceleration and the steady-state flow would be reversed that shown here.

10. How pressure variations and the Coriolis acceleration affect weather in the atmosphere. A region of low atmospheric pressure (left panel) is surrounded by pressure gradients pointing inward, as air tries to flow from high to low pressure (see Figure 10-6). The steady-state response to that pressure forcing is flow in a direction at 90° to the right of the pressure (see Figure 9), resulting in counter-clockwise flow around the pressure hole. The direction of flow would be the opposite around a high-pressure region (right panel), and both would be reversed in the Southern Hemisphere.

11. Surface wind field from a state-of-the-art climate model (a model called FOAM, courtesy of Rob Jacob). This is a snapshot of the winds averaged over one day in the middle of January. The figure is lightly shaded to show sea level pressure, with darker shading indicating lower pressure. One can see the wind blowing counter-clockwise around low pressure areas in the Northern hemisphere, for example just to the South

of Greenland. In the Southern hemisphere, winds blow clockwise around low pressure areas, for example in the Southern Ocean south of Australia.

Exercises

1. **Earth's 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 (Orbit / Snapshot on the Forecast/Projects web page). 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. Which of the three orbital parameters is responsible for the seasons? Find an orbital configuration that has no seasons, or much reduced seasons, and explain why your scheme works.

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. The default albedo is set to be 30% in the model; change this to a more realistic value for the tropics of 10%. What would the temperature be at the equator if there were no heat transport on Earth? The temperature in the tropics of the real world is about 30 °C, a lower answer than you probably got because of heat transport from the tropics to the pole, represented in the field labeled "TOA radiative imbalance", where a negative number indicates heat export. How much heat export is required to get a reasonable temperature for the equator? What fraction of the solar influx is this?

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 Project 1. 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?

Chapter 7. Feedbacks

Complexity in the Earth system arises from the way pieces of it interact with each other.

Positive and Negative Feedbacks

A **feedback** is a loop of cause-and-effect (Figure 7-1). At the center of a feedback is a **state variable.** The state variable in many of the climate feedback loops in this book is the average temperature of the Earth. To see a feedback in action, drive the temperature a bit by changing some external factor, like the intensity of the sun. A **positive feedback** makes the temperature change larger than it would have been without the feedback, amplifying the temperature change. A **negative feedback** counteracts some of the external forcing, tending to stabilize the state variable.

Stefan-Boltzmann Feedback

The energy budget of the Earth, balancing infrared against sunlight energy fluxes, is controlled by a negative feedback mechanism (Figure 7-1a). The outgoing energy flux depends on temperature according to the Stefan-Boltzmann rule, $\varepsilon \sigma T^4$. If you were to suddenly deposit a whole lot of extra energy on the planet, say if there were a giant asteroid impact that raised the temperature of the surface, the feedback would pull the temperature back down. This is a negative feedback because the feedback pulls in the opposite sense from the perturbation.

A negative feedback is a stabilizer. The drain in the kitchen sink analogy has a negative feedback to the water level.

Ice Albedo Feedback

There is a positive feedback in the climate system known as the **ice albedo feedback**, which operates on the state variable of temperature (Figure 7-1b). An input perturbation, such as a rise in greenhouse gases, drives temperature up a bit. Ice melts, reducing the albedo (the reflectivity of the Earth: Chapter 3), allowing the dark ground to absorb more sunlight than the ice would have, warming things up a bit more. This is called a positive feedback because the directions of the input perturbation and the feedback loop agree with each other. A positive feedback can work in the opposite direction as well, taking a cold time and make it even colder. A positive feedback loop amplifies an excursion in either direction.

A positive feedback is an amplifier.

The ice albedo feedback is most important in the high latitudes, because that is where the ice is. The warming response of climate models to extra CO_2 is 2 to 4 times stronger in the high latitudes than on the global average. This is also observed in the warming pattern of the last few decades, with a caveat. Warming is stronger in the Arctic than the global average, driven in part because the sea ice in the Arctic is melting rapidly. At the other pole, the interior of Antarctica is actually cooling, which may be a special case, the result of the Antarctic ozone hole (see Chapter 9) and its impact on a spinning column of air called the polar vortex.   Sea ice around Antarctica is also holding relatively steady, not melting like in the Arctic. But the Antarctic Peninsula, a little farther north, has warmed more than any place else on Earth, and this is where most of the exploding ice shelves are from, like the Larsen B pictured in Chapter 12.

The presence or absence of sea ice can also have a huge impact on local temperatures, because air temperatures over open water are moderated by the heat sink of the water column. As the air draws heat from the water, turbulent mixing and convection in the water will quickly refresh the surface water from below. As a result, air over water doesn't get much colder than freezing, 0°C, but air over ice or land can be much colder. If a landmass is frozen into a vast expanse of sea ice, it will have a climate more typical of the interior of a continent. This sea ice temperature feedback helps explain the abrupt climates recorded in the Greenland ice cores (Chapter 12).

Water Vapor Feedbacks

Water vapor is responsible for more greenhouse heat trapping on Earth than CO_2 is, and yet global warming seems to be about CO_2, not water vapor. No one seems concerned about global warming from running a lawn sprinkler. Why not? The answer is that there is a negative feedback loop that controls the amount of water vapor in the atmosphere at any given temperature, having to do with rainfall and evaporation (Figure 7-

1c). If there is too much water vapor in the air, it will condense out as rain. In the other direction if the air is extremely dry, any available liquid water will tend to evaporate into it. The lawn sprinkler is not going to lead to global warming, because any water forced to evaporate into the atmosphere today will just rain out next week.

But water vapor is also involved in a positive feedback loop acting on global temperature (Figure 7-1d). Because warmer air holds more water vapor than cooler air, warming allows more water to evaporate before it rains (Figure 5-8). Water vapor is a greenhouse gas, so its increase tends to warm the planet still further. The water vapor feedback is a positive feedback, powerful enough to more-or-less double the climate impact of rising CO_2 concentration, according to climate models. If it weren't for the water vapor feedback, Earth's climate would be much less sensitive to CO_2, and maybe we wouldn't be worrying so much about global warming.

Water vapor traps more infrared than CO_2 does, but it uses its power to amplify climate changes driven by CO_2.

It is possible for the water vapor feedback to feed into itself, running around the loop of cause and effect in what is known as a **runaway greenhouse effect.** It happened on Venus, but we are in no immediate danger of it happening on Earth. A runaway greenhouse effect stops if the vapor concentration in the air reaches saturation with liquid water or ice, so that any further evaporation would just lead to rainfall or snow.

Figure 7-2 is called a **phase diagram**, and it shows what phases of water you will find as a function of temperature and pressure. The **phases** of water are solid, liquid, and vapor. At high temperature and low pressure, you expect to find only vapor. Vapor likes it hot. Cool it down and increase the pressure and you get liquid coexisting with the vapor, and when it gets colder there will be ice and vapor. At the triple point, a specific pressure and temperature combination, you get all three phases coexisting together, a glass of boiling ice water. Of course, you can throw ice cubes in a pot of boiling water on your stove any time you like, but the ice will quickly melt, because it is not at equilibrium. The phase diagram in Figure 7-2 shows only equilibrium states.

To understand the water vapor feedback, imagine what happens if you suddenly introduce water to a planet that initially had none. This starting position on Figure 7-2 is all the way at the bottom of the figure, where the pressure of water vapor in the air is low. From here, what will happen is that water will evaporate, and the vapor pressure in the atmosphere will rise. Water vapor is a greenhouse gas, so as the water vapor content of the atmosphere increases, the temperature warms. Therefore as the condition of the planet moves upward on the figure, to higher water vapor pressure, it veers to the right, which is higher temperature.

The amplifying loop of cause and effect stops if the vapor pressure and temperature hit the liquid or ice stability fields.

The middle of the three curves on Figure 7-2, labeled Earth, moves up and to the right until it intersects the stability field of water. At this point, the atmosphere is holding as much water vapor as it can carry. Any further evaporation just makes it rain. The water vapor feedback has increased the temperature of the planet above what it would have been if it were dry. But the runaway greenhouse effect was called on account of rain. The curve on the left on Figure 7-2 represents something like the situation on Mars. Here the water vapor feedback path intersects the stability field of ice.

The only planet on this diagram with a runaway greenhouse effect is Venus, the curve on the right. Water on Venus would evaporate, increasing the temperature, as before. The difference is that the path that Venus follows never intersects the stability fields of either liquid or solid water. Planetary scientists presume that Venus originally had about as much water as Earth, but that the high solar heat flux associated with orbiting so close to the sun drove that water to evaporate into the atmosphere, rather than condense into oceans as it has on Earth.

Evaporation of a planet's water is a one-way street, because if water vapor reaches the upper atmosphere, its chemical bonds will get blown apart by the intense ultraviolet light. The hydrogen atoms, once they are disconnected from oxygen, are small enough and light enough that are able to escape to space. The water is lost for good. This is the presumed fate of Venus' water.

A runaway greenhouse effect means the end of a planet’s water.

Earth has retained its water due to the temperature structure of the atmosphere. It gets colder aloft until you reach the tropospause, the boundary between the troposphere and stratosphere (Figure 5-2). The tropopause acts as a cold trap for water vapor, making sure that most of it rains or snows out before the air rises too close to space. The oceans, viewed from space, look heartbreakingly vulnerable, but they are protected, and apparently have been for billions of years, by a thin layer of cold air. Marvelous!

Theoretically, if the sun were to get hotter, or if CO_2 concentrations were high enough, the Earth could move to the right on Figure 7-2, sufficiently far that it could escape the liquid water stability field and hence run away. But don't worry; there is not enough fossil fuel carbon on Earth to do this. The sun is heating up over geologic time, but only very gradually, and the runaway greenhouse effect from this is nothing to worry about for billions of years.

Interestingly, if the equator were isolated from the poles, blocked from any heat transport and forced to balance its energy fluxes using outgoing IR only, the tropics would be a runaway greenhouse. It is a lucky thing that the Earth has the high latitudes to act as cooling fins!

Earth's climate won't run away, but the tropical Earth would if it didn't have the high latitudes as cooling fins.

The role that the water vapor feedback plays in the global warming forecast can be drawn on this same diagram, although global warming climate change is tiny compared with Venus' climate, so I've drawn it horribly exaggerated so it can be seen. An initial temperature perturbation, say from rising CO_2, moves the water-vapor feedback path a bit toward the right, toward Venus. The path ends as it hits the liquid saturation line, as for the unperturbed Earth but at a higher temperature. The temperature difference between the two raining, moist Earths (where they intersect liquid water) is greater than the temperature difference between the two dry Earths (at the bottom of the plot). The water vapor feedback amplifies the temperature change that you would get from increasing CO_2 on a dry planet.

On the real Earth, mercifully, the relative humidity is not everywhere 100%. One mechanism controlling the distribution of atmospheric water vapor is the **Hadley circulation** (Figure 7-3). Warm air at the equator rises convectively. Water condenses as the air rises and cools. This column of air generally has a lot of water vapor in it. The air spreads out at high altitude, then begins to **subside** in the subtropics, about 30° latitude North and South. That air has been through the wringer, the cold tropopause, and there is not much water vapor left in it. The great deserts of the world are located under these dry air subsidence regions. The air flows back equatorward along the surface, picking up water vapor as it goes. In general the humidity of the atmosphere depends on the patterns of circulation and access to evaporating water.

Globally, the average humidity of surface air is about 80%. The real Earth on Figure 7-2 might allow the humidity to rise to 80% of the way to the liquid phase boundary, rather than making it all the way to 100%. But even this is too simple, because water vapor is most important as a greenhouse gas at high altitude, where the air is cold. Relative humidity in the coldest air can be lower than at the surface, like 10% relative humidity in the subsiding areas.

The strength of the water vapor feedback depends on whether the relative humidity changes in the upper atmosphere, where water vapor is most important as a greenhouse gas.

Climate models tend to predict that the relative humidity of the atmosphere should stay about the same as the temperature rises. Since the saturation vapor pressure increases with temperature, the absolute humidity (number of molecules of H_2O per molecules of air) rises with temperature. So the water vapor feedback still works even though the air is not everywhere 100% saturated.

It is possible that the models are wrong, and the absolute humidity could change more or less than this. One could imagine changing the relative humidity by changing the strength of the Hadley circulation, or the rate of turbulent mixing of air by storms. Is it possible that the water vapor feedback in the real world could be weaker than in the models? If so, it would make a huge difference in the amount of climate change to expect. An ultimate answer to that question comes from paleoclimate and CO_2 reconstructions, discussed in Chapter 12.

Clouds

There are three main types of clouds (Figure 7-4). High altitude clouds are called **cirrus.** These are thin and wispy, often barely noticeable in the sky, made of ice crystals. There are also two major types of low-altitude clouds. **Cumulus clouds** are towers, the result of a focused upward blast of convection. Thunderstorms come from cumulus clouds. **Stratus clouds** are layered, formed by broad diffuse upward motion spread out over a large geographical area.

Clouds interfere with both the visible light and the infrared energy fluxes in the Earth's radiation balance. In the infrared, clouds act as blackbodies (Chapter 3), warming the climate. The effect on the visible light energy budget is to reflect light to space, cooling the planet. The overall impact of a cloud depends on which of these two effects is stronger, which depends on what type of cloud it is.

Clouds are pretty good blackbodies, absorbing and potentially emitting pretty much any frequency of infrared. This makes them different than greenhouse gases, which are choosey about what frequencies of infrared radiation they interact with. Clouds are blackbodies because they are made of liquid droplets or ice crystal solids. In general, liquids and solids at the Earth's surface tend to be black in the infrared.

The effect of a cloud on the infrared energy budget depends on the temperature at the top of the cloud, where infrared radiation heading upward escapes the cloud and heads to space. High clouds emit infrared radiation at cold temperatures, blocking the bright infrared from the warm ground. Clouds with low tops have a smaller effect on the outgoing IR light. Table 7-1 records the conclusions that the effect of clouds on infrared light is to warm the planet, and that high clouds warm the Earth more than low clouds do.

The infrared effect of clouds (1) warms the Earth (2) depending on the altitude (temperature) of the cloud tops.

The effect of clouds in the visible light energy budget is to send solar energy back to space, increasing Earth's albedo and cooling the planet. Cloud particles (droplets and ice crystals) can simply **absorb** the sunlight, transforming its energy into heat in the particle. Absorbing the heat in the atmosphere instead of absorbing it at the ground has only a small impact on Earth's climate.

The more powerful option is called **light scattering**. The electric field of the incoming visible light causes the electric field in the particle to oscillate. The oscillating electric field in the particle then emits visible light, the same frequency as the light that came in. The energetic difference between absorbed and scattered sunlight is that when light is scattered, its energy is never converted to heat. It can be lost to space as part of the planet's albedo.

The fraction of incoming sunlight that is scattered versus absorbed by a cloud varies a lot between different types of clouds. You can't see through low clouds, meaning that they are optically thick, capturing or scattering most of the light that tries to get through. Cirrus clouds contain 10 or 100 times less water per volume than lower altitude clouds typically hold. They are so thin you can often see blue sky right through them. Cirrus clouds therefore have a weaker cooling impact on the visible light budget than high clouds do (Table 7-1).

Putting together the infrared and visible parts of the energy budget, high clouds warm the Earth and low clouds cool. The greenhouse effect wins for high clouds, and the albedo effect wins for low clouds.

High clouds warm, low clouds cool.

The scattering efficiency of clouds varies a lot with meteorological conditions, and it is also affected by human pollution. The important factor is the **cloud droplet size**. Scattering would be most efficient if the droplets were about the same size as the wavelength of the light. But cloud drops are almost all much larger than the wavelength of visible light, so the smaller the drop, the better for scattering. Rain clouds look dark because their large droplets don't scatter light very well. Changing the cloud droplet size from 8 to 10 microns in the on-line NCAR full-spectrum radiation code (Exercise 7-3) changes the energy budget by several Watts / m^2, a radiative forcing comparable to that of doubling CO_2.

Different types of cloud droplets scatter light in different directions. Most of the light scattered by spherical liquid drops continues in a more-or-less forward direction, which, if the incoming direction is downward, would mean to continue downward toward the Earth. Ice crystals are better at actually reversing the direction of light, sending it back up into space.

The size of cloud droplets can be affected by **cloud condensation nuclei**, "seeds" that help droplets form. There are natural cloud condensation nuclei from sea salt, dust, pollen, smoke, and sulfur compounds emitted by phytoplankton. The strongest human footprint in the clouds comes from coal-fired power plants releasing sulfur. Sulfur is emitted in flue gas as SO_2, and it oxidizes in a week or so to sulfuric acid, H_2SO_4. The sulfuric acid condenses into small droplets less than 1 micron in size called **sulfate aerosols.** These are so small that they scatter a lot of the light that encounters them. The aerosols act as cloud condensation nuclei, because the strong acid tends to pull water out of the air like those silica gel packets that ship with electronics equipment. Humans also produce cloud condensation nuclei with internal combustion engines, especially on ships, burning forests, cooking fires, and other combustion products.

Most of the near-surface atmosphere has enough natural condensation nuclei that the issue is not whether to form a droplet or not. But adding more condensation nuclei will encourage the water to form a greater number of smaller-sized droplets. The climate impact of changing the cloud droplet size is potentially huge because smaller droplets scatter light more efficiently than larger droplets. This is called the **sulfate aerosol indirect effect.** The indirect effect, by changing cloud drop size, is very uncertain but is probably even larger than the direct effect of scattering light by the aerosols themselves (Figure 10-2 in Chapter 10).

Clouds that form in dirty air tend to be better scatterers with a higher albedo, cooling the planet.

Contrails are another example of cloud seeding by humans. Contrails form when a jet airplane passes through clean air that is somewhat supersaturated with water vapor. The exhaust contains cloud condensation nuclei that quickly absorb water from the air to form droplets. The contrail particles spread out and eventually become indistinguishable from natural cirrus particles. For this reason it is difficult to know how much impact aircraft have on the cloudiness of the upper atmosphere. Contrails tend to warm the planet, just like natural high clouds. The overall effect of clouds induced by airplanes is pretty small, about 1% of the climate forcing from greenhouse gases. Contrails and sulfate aerosols both differ from greenhouse gases in that they would go away very quickly if producion stopped, while the greenhouse gases, especially CO_2, persist.

Clouds are the largest source of uncertainty in climate models. Most of the differences in climate sensitivities between different models are due to the different ways they deal with clouds. The processes of cloud droplet formation and growth are controlled by details of the windy turbulence in the cloud which cannot be explicitly modeled in a global model, because the computational grid of the model is much larger than the gusts of wind (see Chapter 6).

So even with the astonishing explosion of computer power available, modeling clouds globally from first principles is pretty much out of the question. Instead, clouds must be parameterized, meaning approximated, at a higher level, as functions of humidity, temperature, or whatever other variables seem to be important. Cloud models are tested by comparing the distributions of clouds today with weather data. There is a huge range of atmospheric conditions around the globe, so this is a strenuous test, but it could be that things could change in a changing climate in ways that aren't anticipated. For reasons such as this, it is important to compare the results of climate models to historical changes in Earth's temperature, over the past few decades or through reconstructed climate changes of the prehistoric past (Chapter 11).

Clouds are loose cannons in climate models.

Ocean Currents

The oceans interact with climate, in many ways. One example is the periodic flip-flop between two self-reinforcing states of the ocean, called **el Niño** and **la Niña** (Figure 7-5). On the atmospheric side there is a cycle in the atmospheric pressure difference on opposite sides of the Pacific, called the **Southern Oscillation.** Emphasizing that this is a coupled atmosphere / ocean phenomenon, the el Niño cycle has been abbreviated **ENSO,** which stands for el Niño / Southern Oscillation. The state of the ENSO cycle affects the climate all around the world. In general the land surface is drier during el Niño.

The world dries out during El Niño.

In the la Niña state, there is cold water at the sea surface in the eastern part of the Pacific Ocean near Peru. The cold water contains nutrients that allow phytoplankton to grow, feeding the very productive Peruvian anchovy fishery. The contrast in sea surface temperatures between the Eastern and Western equatorial Pacific drives a wind along the equator that blows from East to West. The warm water, floating on the colder water with a boundary call the **thermocline**, piles up in the West. The tilted thermocline keeps the surface waters cold near Peru, which drives winds, which keep the thermocline tilted and keeps the cold water at the surface.

The cold water near Peru gets covered with warm water during el Niño. Fishermen were the first to notice the el Niño cycle, because the warm waters were less fertile and the fisheries would collapse that year. The winds along the equator falter because the sea surface temperature difference that drove them has disappeared.

Although both of these states seem to be self-stabilizing (the winds and thermocline tilt arrayed in a positive feedback system), the system flips back and forth between the two climate states, about one cycle every 4-7 years.

There is a possibility that with global warming, the Pacific may tend to favor the el Niño state, the climate impacts of which could be considered a feedback. However, the extent and strength of this potential feedback are impossible to forecast reliably.

A warmer world might have a permanent el Niño.

Another potential feedback from the ocean to climate is called the **meridional overturning circulation** in the **North Atlantic Ocean.** Warm water is carried to the North Atlantic in the Gulf Stream. As the water cools, its density increases and it sinks into the abyss, making room at the surface for more warm water to carry more heat from the tropics. The Pacific Ocean has a surface current analogous to the Gulf Stream, called the Kuroshio current, but surface waters in the Pacific are not salty enough to get dense enough to sink, so there is no meridional overturning circulation in the Pacific.

Reconstructions of the climate and oceanography of North Atlantic region from the last ice age point to an instability in the meridional overturning system. The climate records from ice cores in Greenland show huge temperature swings called **Dansgaard-Oeschger** events, changes of 10°C within just a few years. Oceanographic reconstructions from sediment cores show that the meridional overturning circulation in the North Atlantic starts and stops in synchrony with these temperature swings. One large climate shift called the **8.2k event**, 8,200 years ago, has been correlated with the catastrophic release of a Great Lake's worth of fresh water into the North Atlantic, as an ice dam holding the lake finally let water past.

Sudden changes in the overturning circulation in the North Atlantic have driven abrupt global climate changes in the past. In the future this circulation might be impacted by warming or by melting Greenland ice.

The meridional overturning circulation in the North Atlantic may be sensitive to future changes in climate and fresh water discharge. If the Greenland ice sheet were to melt within a century (faster than expected), it would release enough fresh water to slow the overturning circulation. Climate models also predict a slowdown in the circulation with very high CO_2 levels, say 4 times higher than today. If the overturning circulation slows, it could lead to cooling in the high Northern latitudes, driven by the loss of heat coming up from the tropics in the poleward surface current.

The climate models generally predict that the warming from the CO_2 would probably exceed the local cooling from the collapse of the circulation. This makes the "Day After Tomorrow" scenario, of a sudden collapse into a new ice age, seem unlikely. However, climate models also tend to under predict the severity and spatial footprint of past abrupt climate changes driven by instability of the meriodional overturning circulation. So the future could also be more variable than the models predict.

Terrestrial Biosphere Feedbacks

The terrestrial biosphere has the potential to feed back to climate, if changes in vegetation alter the albedo of the land surface. Expansion of the Northern forests into areas previously covered by tundra, for example, could make the land surface darker, tending to warm things up.

The land surface affects the albedo, and it stores carbon.

Trees also impact the hydrological cycle by extracting ground water and evaporating it from their leaves, a process called **transpiration.** Rain forests in particular are thought to perpetuate their own existence, by extracting ground water and evaporating it to the air, recycling it to rain again, rather than allowing it to escape in river flow to the ocean. In a drought, vegetation dies and soils dry out, losing the ability to retain water, thereby perpetuating the water shortage in a positive feedback. It takes an extra boost of water supply to get out of a drought, overcoming this vegetation feedback.

Carbon Cycle Feedbacks

There are many potential feedbacks between climate and the carbon cycle, the subject of the next three chapters. Warming the atmosphere increases the temperature of the surface ocean, which tends to drive CO_2 to degas from the ocean to the atmosphere. The ultimate trigger of the glacial / interglacial cycles is thought to be variations in the Earth's orbit, but the climate swings would have been much smaller if the carbon cycle had not somehow shifted, pulling CO_2 out of the atmosphere as the ice sheets started to grow in a positive feedback.

The land surface stores a lot of carbon. If the Amazon or Indonesian rain forests were to burn, for example, they could release a significant amount of carbon as CO_2 to the atmosphere. Other sources of carbon that might feed back to climate change include peats, organic carbon in permafrost soils, and methane hydrates in the ocean. The methane cycle could also feed back to climate, if there are climate-driven changes in wetlands for example or changes in the radical oxidation chemistry of the atmosphere (Chapter 10).

Feedbacks in the Paleoclimate Record

In general, first-attempt climate models seem to have an inherent tendency to underpredict the extremes of climate variation in the real climate, as inferred from climate records such as ice cores. I believe this is due to the difficulty of capturing feedbacks in climate models. Feedbacks often couple together very different parts of the climate system, requiring cloud physicists to work together with an oceanographers, for example. It takes creativity to think of some of these relationships! The message is that the future may surprise us, and test our creativity in thinking of couplings, interactions, and feedbacks, that may not be obvious at first glance.

Take-Home Points

Positive feedbacks act as amplifiers of variability, while negative feedbacks act as stabilizers.

The water vapor feedback doubles or triples the expected warming due to rising CO_2 concentrations.

The ice albedo feedback amplifies the warming in high latitudes by a factor of three or four.

Clouds have a huge impact on climate. Human activity is already changing the nature of clouds on Earth. Future changes are difficult to predict.

Study Questions

Explain why a stabilizing feedback is called “negative”.

Describe and characterize as positive, negative, or unknown, feedbacks associated with ice, water vapor, clouds, ocean circulation, and the carbon cycle.

Is Earth’s climate vulnerable to a runaway greenhouse effect? Why or why not?

What factors determine the climate impact of a cloud?

Further Reading

The Earth System, Lee R. Kump, James F. Kasting, Robert G. Crane, Prentice Hall, 1999.

Numerical Adventures with Geochemical Models, James C.G. Walker, Oxford Press, 1991.

Table 7-1

	High Clouds (cirrus)	Low Clouds (stratus and cumulus)
IR effect	Strong warming influence, because high altitude cloud top	Weaker warming influence, because cloud tops are lower
Visible light effect	Weak cooling influence, because they're optically thin	Stronger cooling influence, because they're optically thicker
Overall effect	Warming	Cooling

Figure Captions

1. Feedback diagrams. (a) An example of a negative feedback, resulting from the Stefan-Boltzmann infrared energy flux σT^4. (b) An example of a positive feedback. Some external perturbation increases the temperature. The increase in temperature causes ice to melt, allowing the land to absorb more of the incoming solar radiation (by decreasing the albedo). The melting ice drives temperature up further. (c) The negative feedback that controls atmospheric water vapor, given an atmospheric temperature. (d) The water vapor feedback, which amplifies the temperature effect of rising CO_2.

2. A phase diagram for water demonstrating that the water vapor feedback on Earth and Mars is limited, while Venus is free to have a runaway greenhouse effect.

3. The Hadley circulation and its effect on the humidity of the air in the troposphere.

4. Schematic of the three main types of clouds.

5. The configuration of the atmosphere and ocean along the equator in the Pacific Ocean during el Niño and la Niña phases of the el Niño climate

oscillation. Top panel: During la Niña, the boundary between warm water and cold water in the ocean slopes up from West to East, exposing cold water to the atmosphere in the East near Peru. In addition to stimulating the Peruvian fisheries, the cold water drives a strong wind from East to West that tends to sustain the slope in the ocean temperature boundary. In the el Niño phase of the oscillation, bottom panel, the slope in the ocean temperature boundary, and the winds in the atmosphere, collapse. During the climate oscillates back and forth between these two states every 4-7 years or so, affecting climate conditions around the rest of the world.

Exercises

1. Compare Two Radiation Codes. Global climate models handle energy carried by light, both visible and infrared, in a much simpler way than the line-by-line calculations that Modtran does for IR. Modtran would be too slow to run at every grid point of a global model. Find the full-spectrum radiation code at http://understandingtheforecast/Projects/full_spectrum.html. The page can run either of two radiation schemes, called CCM and Chou.

a) Run the model twice, one with default conditions and the other with doubled CO_2 concentration, to determine the climate sensitivity, ΔT_{2x}, for each of the two models.

b) Run one of the models, comparing the temperature effect of doubling CO_2 from 100 to 200 ppm. Do you get the same ΔT_{2x} as you got for 350 to 700 ppm?

c) The model includes the water vapor feedback automatically, but you can turn this off by zeroing the relative humidity. What is the ΔT_{2x} without the water vapor feedback?

2. Clouds and Infrared

Use the on-line IR radiation model http://understandingtheforecast/Projects/infrared_spectrum.html.

a) Add some altostratus clouds, then stratus clouds, using the cloud pulldown menu. Describe the effect the clouds on the outgoing IR spectra between the three cases. Draw a layer-model type cartoon showing the ground, the cloud, the CO_2, and two flavors of IR light at 700 and 900 cycles/cm (the CO_2 bend and the atmospheric window). Which type of cloud has the biggest impact on the outgoing IR flux and why?

b) Set the Sensor Altitude to 0 km, and choose the Looking Up option. Do this first with no clouds. You see infrared light coming down from the sky. Where does it come from? How can you turn it off? Now turn on some clouds and describe how it affects the IR spectrum. Why, at night, is it warmer when there are clouds?

3. Clouds and Visible Light. Use the NCAR model to calculate the radiative forcing, in W/m^2, from high and low clouds.

a) First determine the equilibrium ground temperature with no clouds. Then add 100% high cloud cover. The temperature will change severely. Change it back to the original temperature by dialing up or down the TOA (top of atmosphere) radiative imbalance. This tells you how much the clouds change the balance of energy fluxes.

b) Do the same thing for low clouds. Clouds affect both the IR and the visible light energy fluxes – which effect is strongest from each type of cloud?

c) With the low clouds still at 100% and the TOA radiation imbalance still set to keep a temperature near the default 16 °C, change the drop size from 10 to 8 microns, and find the radiative forcing again, by dialing up or down the TOA to bring the temperature back as before. Now turn clouds off, and double atmospheric CO_2, and find the radiative forcing of that. How do the radiative effects of cloud droplet size compare with the effect of doubling CO_2? You can see how important it is to get the cloud droplet size right in a climate model!

Part II. The Carbon Cycle

Chapter 8. Carbon on Earth

It's alive!

The Chemistry of Carbon

Carbon has rich, spectacular, wondrous chemistry. There are more scientists studying the chemistry of carbon than any other element, I am sure. The nearest relative of carbon is the element silicon, which is located directly underneath carbon on the periodic table. Silicon is one of the more abundant elements on Earth, and the chemistry of the rocks in the mantle is controlled to a large extent by the whims of silicon. Silicon tossed out into the environment finds its way into hundreds of different crystal forms, including the minerals in rocks and clays. However, silicon chemistry is regimented, flat -- one could almost say lifeless -- compared with the chemistry of carbon.

Carbon chemistry is kept highly organized within living things, but after life is finished with it, carbon left in soils, sediments, and rocks forms itself into a disordered, indescribable goo called **humic acids** or **kerogen.** Silicon forms hundreds of crystals, but the number of possible configurations of carbon is essentially infinite. I scoff at the cliché from Star Trek, "carbon-based life forms" spoken as though this were some sort of novel idea. Certainly I am close-minded and lack vision, but I honestly have difficulty imagining life based primarily on any element other than carbon.

Planetary scientists presume that the three terrestrial planets Venus, Earth, and Mars all received about the same amounts of carbon when they formed. The carbon on Venus is mostly found in the atmosphere, and there is so much carbon that the pressure on the surface of Venus from CO_2 is 70 times higher than the total atmospheric pressure on Earth. The carbon on Earth is mostly found in limestone sedimentary rocks, with only 0.038% of one atmosphere of pressure. The amount of CO_2 in the atmosphere of Venus is 180,000 times higher than the amount in Earth's atmosphere. Clearly a planet has a wide range of options about where to put its carbon.

Carbon on Earth is the backbone for constructing the machinery of life. In addition to serving as the framework and scaffolding for that machinery, carbon chemistry also provides the means of storing energy. Photosynthesis converts the energy of sunlight into carbon biomolecules. This energy might be used by the plant, or perhaps an animal eats the plant and uses its energy for itself. Over geologic time scales, carbon stores energy on a planetary scale, "charging up" the biosphere with a store of biomolecules and atmospheric oxygen like a gigantic battery. When we extract energy from fossil fuels, we harvest some of the ancient energy stores of the biosphere. In the process we rearrange the distribution of carbon among its various reservoirs on Earth.

To understand how all of this works, you need to know about a fundamental property of atoms in molecules, called **oxidation state.** An example of oxidation state that you are familiar with is that iron oxidizes when it rusts. Three simple carbon molecules demonstrate the spectrum of reduction / oxidiation (abbreviated **redox**) chemistry for carbon.

	Oxidized	⇔	Reduced
Simplest Example	CO_2	CH_2O	CH_4
Carbon Oxidation State	+4	0	-4
General Category	Inorganic Carbon	Carbohydrates	Hydrocarbons

The first is carbon dioxide, the greenhouse gas. The last is methane, also a greenhouse gas. CO_2 is the **oxidized** form of carbon in this spectrum, and methane is the **reduced** form. You might guess that the phrase "oxidation state" implies that we must be talking about oxygen in some way, and in fact the oxidized form of carbon has oxygens on it.

Oxidation and reduction has to do with bookkeeping of electrons.

In more general terms, however, oxidation state is a measure of the surplus of deficit of **electrons** around the carbon. Oxygen is a very greedy element for the two electrons that it requires to find its most stable electronic configuration. Usually oxygen in a molecule is credited with stealing two electrons from its bond partner (an exception is if its bond partner is another oxygen, in which case they must share equally). The carbon in CO_2 has two bonds with oxygen, so it has given up four electrons, two to each oxygen atom. Since each electron has a charge of –1, a deficit of four electrons leaves the carbon in CO_2 with an **oxidation state** of +4.

Hydrogen, in contrast, is relatively generous with its single electron. The four hydrogens in methane each donate one electron to carbon, so carbon ends up with an oxidation state of –4. The oxidation state of CH_2O, the middle compound in the spectrum, is zero, because carbon gains two electrons from the hydrogens, but donates two to the oxygen.

There are many other carbon compounds that have these oxidation states, and it makes sense to group them together into families in this way. Most of the carbon on Earth is oxidized carbon, also called **inorganic carbon**, in $CaCO_3$ (limestone) rocks or dissolved in the oceans. Inorganic carbon has a fascinating chemistry (spoken as one who has devoted his life to understanding it), but it is nowhere near complex enough to create the machinery of life.

At the reduced end of the spectrum, **hydrocarbons** include oil as well as natural gas. Some biomolecules are hydrocarbons, such as fats. Again, amazing stuff, but life could not be constructed from fats alone. Life is comprised of carbon largely in the intermediate oxidation state, called **carbohydrates.** Sugars for example have formulas that are multiples of that of humble CH_2O (a chemical called formaldehyde), like glucose for example is $(CH_2O)_6$.

Historically, "organic" carbon is reduced, because it was thought that only life could make it. Today, the common use of "organic" means "natural", as in free of industrial chemicals.

Hydrocarbons and carbohydrates are together referred to as **organic carbon.** Here is a case where scientific and common usages of a word are completely different. To a chemist, compounds made of reduced carbon, such as DDT, dioxin, and PCB's, are considered organic compounds. To the common person, "organic" produce at the grocery store is supposed to be free of toxic man-made compounds such as these.

The most stable form of carbon in the chemical environment of the Earth's surface, in the presence of oxygen, is the oxidized form. The carbon pools on Venus and Mars are also both nearly entirely oxidized. Reduced carbon at the surface of the Earth comes from photosynthesis, which harvests energy from sunlight to make organic carbon

$$CO_2 + H_2O + \text{energy} \Leftrightarrow CH_2O + O_2. \qquad (8\text{-}1)$$

The energy from light is absolutely required; photosynthesis cannot happen in the dark, say in the deep sea or buried in soils. The only forms of life on Earth who do not owe their chemical energy to sunlight are communities living near hot-water springs in the deep ocean called **deep sea vents**. These vent communities ultimately get their energy by catalyzing chemical reactions between the vent fluid and the seawater. Life may have gotten its start in this way, and it may exist in this way on other worlds, but on Earth photosynthesis is by far the dominant source of energy for life.

Carbon at the Earth's surface wants to be oxidized. It takes energy to make reduced carbon.

The backward direction of the chemical reaction is called **respiration**, the only energy source for animals and fungi, and also done by plants and bacteria. The organic carbon in this reaction is our food, and the oxygen comes from the air. The products of respiration, CO_2 and water vapor, come out when we exhale.

Photosynthesis serves two purposes in the biosphere. First, it creates carbon in the oxidation state at which its chemistry is versatile enough to build the machinery of life. Second, it stores energy from sunlight in the form of reduced carbon. Some biomolecules have a clear use in the living machine, such as **proteins**, which can be structural or can catalyze chemical reactions, in which case they are called **enzymes**. DNA stores patterns for making proteins, the genetic material, and there are **lipid** or fat molecules in cell membranes like soap bubbles, holding stuff in and keeping stuff out. Other types of biomolecules are more obviously for storage of energy, such as glucose in "blood sugar" or the fat deposits underneath our skin.

Carbon is the structural backbone of life, and the way life stores energy.

Nearly all of the organic carbon produced by photosynthesis is respired sooner or later. Peat deposits on land may hold organic carbon for thousands of years, but overall, the best chance an organic carbon molecule has of escaping degradation back to CO_2 is to hide in the sediments of the deep sea.

Life on Earth has built up a sizable pool of carbon in the reduced form in ocean sediments and **sedimentary rocks** (former ocean sediments that are currently on land). When oxygen-producing photosynthesis first began on Earth, the oxygen that was released reacted with other reduced species such as dissolved iron in seawater. Sulfur was oxidized to the chemical form of sulfate, SO_4^{2-}, a component of sea salt in today's ocean.

After the biosphere "rusted" as much as it was going to, oxygen started to build up in the atmosphere. As a result of these other chemical reactions, there is enough organic carbon buried in sediments to use up the O_2 in the atmosphere ten times. Visionary Earth scientist James Lovelock imagines the biota "charging up" the biosphere like a giant battery, by building up a surplus of reactive oxygen and reduced carbon. Fossil fuels are a way of extracting some of the energy in Lovelock's battery.

Oxygen in the air and organic carbon in the ground are the poles of the battery of the planetary biosphere.

The CO_2 in the atmosphere is only the tiniest fraction of the carbon on Earth (Figure 8-1). It contains about 700 **gigatons** of carbon. A gigaton, abbreviated Gton, is a billion (10^9) metric tons, equivalent to 10^{15} grams. The amount of CO_2, relative to the other gases, is about 380 parts per million, or 0.038%. For every CO_2 molecule in the air, there are roughly 2500 molecules of other gases, mainly nitrogen and oxygen. If we were able to gather up all of the CO_2 in the atmosphere and bring it down to the ground, to build a column of pure CO_2 gas at sea level pressure, that column would be about 3 meters high, reaching perhaps some second-story windows. If we were to precipitate the CO_2 into a snowfall of dry ice (solid CO_2), we would end up with about 7 cm of snow on the ground. The atmosphere is a very small, very thin carbon reservoir.

There is also carbon stored at the land surface, in the oceans, in sedimentary rocks, and the deep interior of the Earth. These other carbon reservoirs all "breathe" CO_2, causing atmospheric CO_2 to vary, naturally, on all sorts of time scales, from yearly cycles to changes over millions of years. The reservoirs interact with each other through the atmosphere, which is like the Grand Central Station of the carbon cycle.

The Land Breathes

There are two forms of carbon associated with the landscape that we live in. The actual living carbon, trees and camels and all the rest of it, is called the **terrestrial biosphere.** There are about 500 Gtons of C in the terrestrial biosphere, so it is comparable in size to the atmosphere.

The other land carbon reservoir is the **soil carbon pool.** You can see in Figure 8-1 that it holds about twice as much carbon as the terrestrial biosphere. The organic carbon in soils is mostly dead rather than living: decomposing leaves and other plant material. Organic carbon concentrations in soils are very patchy, depending on the climate, the forestry, and the history of the land such as fires and agriculture. Deserts do not have much carbon in their soils, while grasslands tend to have quite a bit. There is more soil carbon in colder climates than in warmer, because organic carbon decomposes more quickly when it is warm.

The land breathes on an annual cycle.

The terrestrial biosphere inhales CO_2 from the atmosphere during the growing season, and exhales during winter. You can see a seasonal cycle in atmospheric CO_2, especially in the top panel in Figure 8-2. The CO_2 annual cycle in the Southern Hemisphere is smaller than that in the North, because there is less land in the South, and is out of phase with the North because the seasons are reversed. The cycles are smaller in the Southern Hemisphere than they are in the North because there is less land in the South. One interesting observation, foreshadowing Chapter 10, is that the annual cycles in atmospheric CO_2 have been getting larger as atmospheric CO_2 has risen. It's not obvious by eyeballing Figure 8-2, but the trend emerges when the data are treated statistically. The terrestrial biosphere has been breathing more deeply, as if it's getting larger, with increasing atmospheric CO_2.

The Ocean Breathes

The **ocean carbon reservoir** is larger than either the land surface or the atmosphere. The ocean's carbon is not only dead, it is oxidized: energetically dead as well as biologically dead. The carbon is in the forms CO_2, H_2CO_3, HCO_3^-, and $CO_3^=$, all of whom we will get to know better in Chapter 10. The sum of all of them is called **dissolved inorganic carbon.** There is about 50 times as much carbon in the ocean as there is in the atmosphere.

There is also organic, reduced carbon dissolved in sea water; like the soil organic carbon it comes from photosynthesis but is no longer alive. Its molecule structure is disordered, a similar chaotic goo to organic carbon in soils. And of course there are fish and dolphins and plankton, but the total amount of living carbon in the ocean is small, only about 1 Gton C.

Carbon is released from the water to the air in some parts of the world ocean, and dissolves into the water in other places. The total rates of carbon exchange are large, comparable to the breathing rates of the terrestrial biosphere and much greater than the rate of anthropogenic carbon release (Chapter 9). The oceans would seem to have the clout to affect the CO_2 in the atmosphere as strongly as the terrestrial biosphere does, and yet the year-to-year breathing variations in the ocean are much less obvious in variations in atmospheric CO_2. The ocean breathes more steadily than the land does, with less of a seasonal cycle.

Computer models predict that it takes hundreds of years for CO_2 to reach an equilibrium between the atmosphere and the ocean. If CO_2 is released to the atmosphere it will take this long for the ocean to inhale its fill. This is about how long it takes for all the waters to come to the ocean surface somewhere to exchange carbon with the atmosphere.

The ocean affects atmospheric CO_2 on time scales of centuries. The glacial / interglacial cycles were amplified somehow by the ocean carbon cycle.

The clearest example of the power of the ocean to affect CO_2 in the atmosphere is the **glacial / interglacial cycles**, rhythmic and large fluctuations in the amount of ice on Earth, in which the climate flips back and forth between glacial states and interglacial states (Figure 8-3). The Earth is currently in an interglacial state called the **Holocene**, and has been for about the last 10,000 years. This is the stage upon which human civilization has developed, although biologically modern humans evolved considerably earlier.

Before that was a time when it was about as cold as the glacial cycles ever get, call the **Last Glacial Maximum.** The surface of the Earth was about 5-6° K colder than today, and North America and Northern Europe were covered with massive ice domes like what currently exists in Greenland. The ice sheet in American is called the **Laurentide ice sheet**, and the one in Europe is called the **Fennoscandian ice sheet.**

The beat of the ice age rhythm apparently originates from variations in the Earth's orbit around the sun. The orbit varies through three main cycles, each ringing on its own characteristic frequency (Figure 8-4). The first cycle is called the **precession** of the seasons or sometimes precession of the equinoxes (Figure 8-5). The axis of rotation of the Earth spins around like a wobbling top, completing the entire circle in 20,000 years. Most of the solar heat influx variability at high latitudes, and nearly all of the variability in the tropics, comes from precession.

Orbital variations drive climate by changing the distribution of sunlight at the Earth's surface.

Precession has an effect on climate because the orbit of the Earth is not circular but elliptical. In its present-day orbital configuration, the Earth is closest to the sun during winter in the Northern hemisphere (Figure 8-5). The seasonal cycle in the North is weakened by this orientation, because Earth is close to sun when the Northern hemisphere is tilted away from the sun. The seasonal cycle in the Southern hemisphere is stronger in this configuration, because the Earth is close to the sun and tilted toward the sun at the same time. Remember, it is the tilt of the Earth that causes the Earth's seasons (Chapter 6). The precession cycle modifies the seasons somewhat.

Another cycle involves the **obliquity** of the angle of the pole of rotation, relative to the plane of Earth's orbit (Figure 8-6). The Earth rotates, making day and night, on a rotation axis of the North and South poles. This rotational axis is not perpendicular to the plane of Earth's orbit around the sun, but is tilted somewhat. The angle of tilt is currently 23.5°, but it varies between 22° and about 25.5°, on a cycle time of about 41,000 years (Figure 8-4). The impact of obliquity on solar heating is strongest in high latitudes.

The third orbital cycle involves how elliptical the orbit of the Earth is, also called its **eccentricity**. At present, the orbit of the Earth is nearly circular. The eccentricity of the orbit has cycles of 100,000 years and 400,000 years (Figure 8-4). The strongest climate impact of eccentricity is to determine the strength of the precessional forcing. If the Earth's orbit were circular, it would make no difference where the Earth was in its precession cycle, because the Earth is equally far from the sun at all parts of the orbit. When eccentricity is low, the orbit is circular, and the 20,000-year waves in the precession cycle vanish (shaded area in Figure 8-4).

When you average over the entire surface of the Earth and over the entire year, the orbital cycles only have a tiny effect on the amount of heat the Earth gets from the sun. The orbital cycles affect climate by rearranging the intensity of sunlight from one place to another, and from one season to another.

It turns out that the climate of the Earth is especially sensitive to the solar heat flux at about 65° latitude in the Northern hemisphere summer. This is like the solar plexus of global climate, land a sucker punch there and the whole climate keels over. It makes sense that the sweet spot is in the Northern hemisphere, because this is where the ice sheets grow and melt the most through the glacial cycles. The ice sheets in Antarctica and Greenland grow and melt back somewhat through the climate cycles, but they have not been disappearing entirely during warm times the way the Laurentide and Fennoscandian ice sheets have. It is summer sunlight that matters most, rather than winter as you might have expected, because it is always cold enough to snow in winter at these latitudes, but the question is whether the summer is warm enough to melt the snow, or keep it around to add to the snow from the next winter. Variations in sunlight intensity in June, 65° North latitude, calculated from models of the Earth's orbit, correlates well with the history of the amount of ice on Earth, inferred from ice core and deep sea sediment records.

Summer solstice, 65° North latitude, is the sweet spot for sunlight intensity to drive Earth's climate through the glacial cycles.

The **glacial cycles in atmospheric CO_2** were discovered by measuring the CO_2 concentrations in from bubbles of ancient atmosphere trapped in the ice sheet of Antarctica. The trapped air bubbles from glacial times have a lower proportion of CO_2 in them relative to the other gases, about 180-200 ppm, rising to 260-280 ppm during interglacial intervals before the industrial era. The decreased CO_2 concentration during glacial time is responsible for about half of the cooling relative to the interglacial time. The increase in the albedo of the Earth, from the large ice sheets, is responsible for the other half. The climate during glacial time is an important test of the climate models used to forecast global warming (Chapter 11).

No one is sure exactly why CO_2 in the atmosphere cycles up and down along with the ice sheets, but the ocean must be a major player. The land carbon reservoirs were if anything smaller during the glacial time, which by itself would have left atmospheric CO_2 higher, not lower as the ice cores show. The carbon cycle to and from the solid Earth, discussed in the next section, is too slow to explain the CO_2 changes, some of which are as fast as 1,000 years, the time scale for CO_2 to equilibrate between the atmosphere and the ocean. The ocean is the only pool that is large enough and potentially reactive enough to explain the ice core data. This book will not answer the question of how exactly the ocean did this, but will discuss ocean carbon chemistry a bit further in Chapter 10.

The Rocks Breathe

The **sedimentary rock carbon pool** is larger still than the ocean, land, or atmospheric pools. Carbon in the solid Earth exists in the form of **limestones**, $CaCO_3$, and to a lesser extent organic carbon. These carbon reservoirs together contain about 500 times as much carbon as the atmosphere and the landscape combined.

The solid Earth is the largest but slowest-breathing of the carbon reservoirs.

Most of the organic carbon in sedimentary rocks is in a form called **kerogen.** Kerogen is useless as a fossil fuel, because it is dilute, usually less than 1% by weight of sedimentary rocks, and because it is in a solid form making it difficult to extract. Fossil fuels will be discussed in Chapter 9.

Carbon is exchanged between the atmosphere and the sedimentary $CaCO_3$ rocks by means of a chemical reaction called the **Urey reaction**, which is

$$CaSiO_3 + CO_2 \Leftrightarrow CaCO_3 + SiO_2$$

as shown in Figure 8-7.

$CaSiO_3$ on the left-hand side is a simplified chemical formula for a rock typical of the Earth's bedrock, called a **silicate rock.** These usually solidify from melted rock, which is called **lava** if it is found at Earth's surface and **magma** if it is subsurface. Real silicate rocks have other elements in them and a wide range of chemical formulas, but the simple formula $CaSiO_3$ works for conveying the essential idea. $CaCO_3$ and SiO_2, the solid phases on the right-hand side of the reaction, are typical sedimentary rocks, which form at cold temperatures from elements that were dissolved in water.

The Urey reaction running from left to right, producing sedimentary rocks from silicate rocks, is called **chemical weathering.** A silicate rock weathers by dissolving into river water, ultimately to be delivered to the ocean. Real silicate rocks often contain other elements that don't dissolve in water very well, like aluminum, so these elements form other solids called **clay minerals**, the stuff that soils are made of. After the dissolved calcium and silica reach the ocean, organisms like corals and shell-forming plankton construct solid $CaCO_3$ and SiO_2 from them.

At the cool surface of the Earth, oxidized carbon wants to be in $CaCO_3$.

Weathering is the preferred direction for this chemical reaction under the relatively cold, wet conditions of the surface of the Earth. If weathering were allowed to continue to its equilibrium, it would pull nearly all of the CO_2 out of the atmosphere.

At high temperatures in the Earth's interior the Urey reaction can run in the other direction, making silicate rocks from sedimentary rocks. This chemical reaction is called **metamorphic decarbonation.** This direction is generally favored at high temperature, mainly because the CO_2 would "prefer" to be a gas molecule if you give it enough energy (heat), rather than being locked up in a crystal of $CaCO_3$. The CO_2 released by metamorphic reactions may find its way back out of the solid Earth by what is called **degassing**, in volcanic gases or in hot water springs (deep sea vents) at the bottom of the ocean. Some of the carbon degassing from the Earth may be **juvenile** carbon, which has spent the last 4.5 billion years of Earth history bound up in the deep Earth, only to emerge now, but most of it is recycled carbon from subducted $CaCO_3$.

In the hot interior of the Earth, oxidized carbon wants to be free, as a gas.

The fluxes of CO_2 by weathering and degassing are small compared to the other fluxes in Figure 8-2, but if they were out of balance, if you were stop all degassing for example, you could use up all the CO_2 in the atmosphere in a few hundred thousand years. The Earth is much older than this, so if you wait long enough the weathering and degassing fluxes of CO_2 have to balance. Eventually what goes up must come down.

The way the Earth manages to balance the degassing and weathering fluxes is by finding the right CO_2 concentration, a climate-stabilizing mechanism called the **silicate weathering CO_2 thermostat.** The rate of weathering depends on the availability of fresh water rainfall and runoff that rocks can dissolve into. The rate of fresh water runoff depends, in turn, upon the climate of the Earth. In a cold climate there is less overall rainfall, and therefore a slower rate of CO_2 uptake by weathering reactions. The imbalance in the fluxes would allow CO_2 to accumulate in the atmosphere, increasing the weathering rate and pushing the carbon cycle back toward balance. If the climate is too warm, CO_2 is consumed by weathering faster than it is degassed from the Earth. The CO_2 thermostat stabilizes the CO_2 concentration of the atmosphere and the climate of the Earth through geologic time.

The CO_2 thermostat regulates atmospheric CO_2 and climate on time scales of hundreds of thousands of years.

This is another opportunity to apply the **kitchen sink analogy** first used in Chapter 3. Water inflow through the faucet represents CO_2 degassing from the Earth, and flow down the drain, representing weathering, depends on the amount of water in the sink, the stand-in for atmospheric CO_2. The CO_2 in the air drifts toward the value at which the budget balances, just like the water level in the sink does.

The existence of a natural thermostat mechanism that controls the CO_2 concentration of the atmosphere sounds like good news for humanity with our tendency to add CO_2 to the air, but the catch is that it takes hundreds of thousands of years for the thermostat to stabilize CO_2 and climate. On time scales shorter than that, it is perfectly possible for things to be out of whack, such as through the glacial cycles or as a result of fossil fuel CO_2 release. These would be like dumping buckets of water into the sink, or removing water, perturbing the water level for a while until it recovers.

Just like the kitchen sink, the equilibrium of the CO_2 thermostat can be tweaked by messing with the faucet or the drain. The faucet represents CO_2 degassing from the solid Earth, which could be stronger or weaker depending on the geometry of the continents and the volcanoes. Today a large fraction of the global rate of CO_2 degassing is coming from a particular volcano called Mt. Etna in Sicily, an accident of lava and $CaCO_3$ coming together.

Today there is more $CaCO_3$ accumulating on the sea floor than is subducting into the Earth, because more of the $CaCO_3$ accumulates in the Atlantic but more sediment subducts in the Pacific and Indian ocean. This probably means that at some time in the past, the $CaCO_3$ subduction rate was probably higher than it is today, releasing more CO_2 into the atmosphere, maybe making the Earth warmer.

It is possible to change the set-point of the thermostat, creating a hot-house world like that of the dinosaurs, or an icy world like today.

The drain can also drive water level changes in the kitchen sink analogy. The drain represents weathering reactions that take up CO_2. A mountainous terrain weathers more quickly than a flat plain covered in thick soil, because the soil isolates the silicate bedrock from the rainwater that weathering requires. The Himalayas are the most prominent mountainous feature on Earth, uplifted by the collision of India and Asia a few tens of millions of years ago. Paleoclimatologists have suggested that the uplift of the Himalayas might be responsible for our current era of relatively cool climate, as opposed to the hothouse conditions before then, such as the **Cretaceous period** when dinosaurs ruled the Earth, and **Early Eocene optimum** which followed (Figure 8-8), when there may have been 10 times more CO_2 in the air than there is today.

Plants affect of the rate of silicate rock weathering by pumping CO_2 into the gas spaces in the soil. Soil gas CO_2 concentrations might be 10 times higher than in the atmosphere. Extra CO_2 tends to supercharge the rate of chemical weathering, because CO_2 is an ingredient in the weathering reaction, and because CO_2 is an acid (see Chapter 10), which drives rocks to dissolve. Plants invaded the land surface in the Silurian, about 400 million years ago. Carbon cycle models suggest that this change in land surface geochemistry might have had an impact on the long-term climate of the Earth.

The terrestrial planets **Venus, Earth,** and **Mars** provide a perfect Goldilocks parable to end this Chapter. The sin of Venus (the planet) was to be too close to the sun. The water that must have originally been packaged with Venus evaporated in a runaway greenhouse effect and its hydrogen lost to space forever. With no water, silicate weathering reactions come to a halt, allowing Venus' allotment of carbon to build up in the atmosphere. The thermostat is broken. As a result, the pressure of CO_2 on the surface of Venus is about 70 atmospheres. CO_2 is strictly speaking no longer a gas at those pressures but is instead what is known as a supercritical fluid. In this respect the atmosphere of Venus is more akin to our ocean than our atmosphere.

The thermostats of Venus and Mars are broken.

Mars blew it by being small, about half the diameter of the Earth, so that its interior cooled faster than Earth's. Mars boasts the largest volcano in the solar system, Olympus Mons, but today Mars is geologically dead. The partial pressure of CO_2 on the surface of Mars is actually higher than it is on Earth, but there is not enough CO_2 in the air to bring the planet to the melting point of ice, which would allow chemical weathering reactions to occur. If there were ongoing CO_2 degassing from the planet, and if there were water, presumably eventually the CO_2 concentration would build up to that level. The CO_2 thermostat on Mars is broken but in a different way than it is broken on Venus.

Take Home Points

The most stable form on carbon on Earth is oxidized, as CO_2 or $CaCO_3$. Photosynthesis stores energy from the sun by producing organic carbon, which also serves as scaffolding for the machinery of life.

There is less carbon in the atmosphere than there is in other carbon reservoirs on Earth, such as the terrestrial biosphere and the oceans. These other reservoirs tug on atmospheric CO_2, seasonally for the land, and on glacial interglacial 100,000-year time scales from the ocean.

The weathering of igneous rocks on land controls the pCO_2 of the atmosphere on million-year time scales. This "silicate thermostat" stabilizes climate. The thermostat is broken on Venus, because there is no water left, and on Mars, because there is no active volcanism left.

Study Questions

Describe the special role of the atmosphere in the global carbon cycle.

Describe the multiple roles of the element carbon at or near the surface of the Earth.

Write examples of organic and inorganic carbon molecules, and figure out their oxidation states.

Is the CO_2 thermostat a positive or a negative feedback? Relate the components of the thermostat to the different parts of the kitchen sink analogy.

Does the carbon cycle provide a positive or a negative feedback through the glacial / interglacial cycles?

Describe how the CO_2 thermostat mechanism broke on our sibling planets, Venus and Mars.

Further Reading

The Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future (2002) Richard B. Alley. Princeton.

Figure Captions

1. Carbon reservoirs on Earth, and carbon fluxes between them.

2. CO_2 concentrations in the atmosphere over the past decade.

3. CO_2 and methane concentrations in the atmosphere over the past 400,000 years, along with temperature in Antarctica.

4. History of orbital forcing of Earth's climate, since 400,000 years ago.

5. The precession orbital cycle.

6. The obliquity of Earth's orbit.

7. Components of the silicate weathering thermostat.

8. History of the temperature of the deep ocean, which tells us about the temperature of the high latitude surface, since 65 million years ago.

Exercises

Answer these questions using an on-line geologic carbon cycle model located at http://understandingtheforecast.org/Projects/geocarb.html. The model predicts the influence of geologic processes on the CO_2 concentration of the atmosphere.

The model does an initial spinup phase, to make sure that the initial condition is an equilibrim where all the various budgets balance. You will only see that last few years of this phase in the model output. Then there is a transition to a new set of conditions, say an increase in CO_2 degassing flux from volcanoes. We can watch the transition from one equilibrium state to another.

At the moment of the transition from spinup phase to transient phase, you can inject a slug of new CO_2 into the system, say by fossil carbon combustion and release to the atmosphere. For the problems below, we'll set the fossil fuel carbon spike to 0.

1. **Weathering as a Function of CO_2.** In steady state, the rate of weathering must balance the rate of CO_2 degassing from the Earth, from volcanoes and deep sea vents. Run a simulation with a higher CO_2 degassing rate at the transition time.

a) Does an increase in CO_2 degassing drive atmospheric CO_2 up or down? How long does this take?

b) How can you see that the model balances weathering against CO_2 degassing?

c) Repeat this run with a range of degassing rates, and make a table of the equilibrium 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.

d) Make a plot of weathering as a function of atmospheric pCO_2 using your model runs.

2. **Effect of solar intensity on steady state CO_2 concentration.** 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 500 million years to when the sun was cooler than today. What do you get for the steady-state CO_2, and how does this compare with what you get for today's solar intensity? Explain why.

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, to see which way the CO_2 effect of plants will go.

a) What happens to the rate of chemical weathering immediately after the plants are introduced, does it go up down? What does it do after some time has passed?

b) What happens to atmospheric CO_2 and why?

c) When the CO_2 concentration changes, where does the carbon go?

Chapter 9. Fossil Fuels and Energy

Where fossil fuels come from and how they're used.

Energy Sources

The flow of energy drives the biosphere of the Earth and it drives human civilization. Energy flows can be described in units of **Watts**, equal to Joules per second, where Joules is a unit of energy like calories. A hairdryer might use 1000 W of power, or 1 kiloWatt, kW. For global energy fluxes, it is convenient to speak in terms of **terawatts**, equal to 10^{12} Watts, abbreviated as TWatts.

The sun bathes the Earth in energy at a rate of about 173,000 TWatts. Photosynthesis captures about 100 TWatts. Mankind is consuming about 13 TWatts of energy per year. Some of our energy use comes from the sun; wind, hydroelectric, solar, and biomass energy are all driven ultimately by sunlight. Of these, the largest source of energy is hydroelectric power, which makes up about 2% of the global energy supply (Figure 9-1). Renewable energy, defined as geothermal, solar, wind, and wood and waste electric power, supplies about 0.3% of our power.

All of our energy ultimately comes from stars, mostly our sun.

Humans are also mining one-use-only energy sources from the Earth, in fossil fuels and radioactive elements. Nuclear energy is mostly driven by decay of uranium, which was produced in its unstable high-energy nuclear state in supernova explosions of stars. I guess you could say that nuclear energy is fossil starlight. It accounts for another 2% of global energy production.

Fossil fuels derive their energy from ancient sunlight, photosynthesis that took place millions of years ago. Over Earth's history, photosynthesis has preserved a sizable amount of reduced carbon, the energy in which can be harvested by reacting it back with O_2 to regenerate CO_2 and H_2O. The carbon can be burned, releasing its energy as heat, or it can be respired, as when you digest your lunch, capturing the energy to drive biological processes.

Most of the reduced carbon on Earth is so diluted in rocks and sediments that for practical purposes it is useless as a fuel. It takes very special circumstances to preserve the carbon in a pure enough form to be a convenient energy source. Fossil fuel carbon comes in all three phases: solids, liquids, and gases.

Only a small fraction of the buried organic carbon is in a convenient form for fuel.

The largest traditional fossil fuel reservoir is **Coal.** The carbon in coal comes from land plants, mosses particularly, that were deposited in swamps. The organic carbon is preserved in swamps because the standing water protects them from degradation by oxygen in the atmosphere.

Coal from fresh-water swamps contains less sulfur than coal from salt-water swamps, because of the sulfate, SO_4^{2-}, dissolved in seawater. Upon combustion, the sulfur forms droplets in the air called aerosols that scatter sunlight, then it deposits as acid rain. High sulfur coal also has more mercury in it, making coal power a leading source of mercury to the environment.

Coal is the most abundant fossil fuel, and the future of Earth's climate depends mostly on what happens to that coal.

Over time, the carbon accumulates in thick layers of what is called **peat.** If the peat is buried and cooked for millions of years, it turns into coal. There are different grades of coal depending on how well-cooked it is. The highest grade coal has been cooked the longest, and it is composed almost entirely of carbon, the original hydrogen and oxygen driven off as water.

The British Petroleum Company, in their annual report on global energy (see Further Reading) estimates that there are 1000 Gtons of carbon in coal reserves. Another source, an academic paper by Rogner (also listed in Further Reading), estimates that the total amount of coal ultimately available might be 10 times that. There appears to be enough coal to supply our needs for several centuries, if we choose to use it.

In the United States, coal is mostly used for generating electricity (Figure 9-2). Coal itself is cheap and abundant in many parts of the world, and if a coal-fired power plant is already built it can produce electricity more cheaply than pretty much any other source.

Oil and **natural gas** mostly come from ancient photosynthesis that took place in the ocean. Plants in water are generically called **algae.** Microscopic algae suspended in the ocean are called **phytoplankton.** Phytoplankton in the ocean produce about as much organic carbon by photosynthesis every year as the terrestrial biosphere on land does. A tiny fraction of the dead phytoplankton ends up in sediments, while the rest gets eaten by somebody, animal or bacteria, in the water column or in the top layer of sediments.

The sediments covering most of the sea floor do not contain enough organic carbon to ever make oil. Typical deep-ocean sediments have less than 1% organic carbon by weight, but typical **oil source rocks** contain something like 3-10% organic carbon. Most oil comes from very specific oil source rock layers just a few feet thick. These source rocks formed near continents and under water that has no oxygen dissolved in it, which is called **anaerobic** conditions.

If organic-rich sediments are buried to a depth in the Earth between 2 and 5 kilometers, they will be heated to temperatures of 50-150 °C. This has the effect of converting some of the dead plankton into oil, consisting of chains of carbons with hydrogens attached (Figure 9-3). If the temperature goes higher, the carbon winds up as methane in natural gas.

Oil is probably the most convenient but the least abundant of the fossil fuels, so it is the most expensive.

If the mud is too impermeable, any oil or gas produced could just sit there in small droplets or bubbles, out of drilling reach. Alternatively it could flow through the pores of a sandstone or through faults and cracks in the sediment column, perhaps to collect in some upside-down pool in an upside-down bowl of impermeable rocks. Probably only a tiny fraction of the oil and gas ever produced is in a harvestable form today, that is to say mobile enough to have collected together but not mobile enough to get squeezed all the way out of the Earth.

Oil is the most expensive of the fossil fuels, because it is uniquely suited to supplying energy for transportation (Figure 9-2). As a combustable liquid it easily carries more energy per weight than any batteries that have been developed so far. Coal hasn't been used for transportation since the days of the steam locomotive, and gas must be carried in a pressurized container, as opposed to petroleum, which sits happily in an unpressurized fuel tank.

Perhaps because such special conditions are required to produce harvestable oil, the distribution of oil deposits on Earth is very spotty (Figure 9-4). Most of the oil is in the Middle East, although there is a smattering scattered throughout the rest of the world. We don't know precisely how much oil there is available to harvest. The British Petroleum report tallies the proven reserves of oil, stuff that has been discovered and documented already. They say 1150 thousand million barrels of oil, which we can translate into 135 Gton C. The amount of oil that is likely to be ultimately extractable is almost certainly higher than this. Technological advances in oil extraction can double the amount of oil you can get from an oil field. More oil fields will certainly be discovered, although there are limits to how much more oil we can expect to discover. Half of the world's oil reserves today are in the 100 biggest oil fields, and most of the largest ones were discovered decades ago.

There is a class of carbon deposits for which the geological conditions were never quite right to produce oil, but from which oil can be extracted if the rocks are mined and cooked. These nontraditional oil sources are called **oil shales** and **tar sands**. The Canadians are mining and processing tar sands now. If future discoveries, technological progress, and non-traditional sources are counted together, the estimates are all over the map, but some of them begin to reach 500 Gton C or so.

How long will the oil last? One way to calculate a number with units of time would be

$$Lifetime\left[yr\right] = reserves\,size\left[kg\right] \cdot \frac{1}{production\,rate}\left[\frac{yr}{kg}\right]$$

British Petroleum calls this the **Reserves to Production** or **R/P** ratio. The R/P ratio tells us how long it would take to use up a resource if we continued using it at the rate we're using it now. Notice that the units on both sides of the equation balance. The funny thing about this ratio is that its value hasn't changed in 15 years (Figure 9-5). According to BP figures, we have 40 years of oil left, and it looks like we always had 40 years left, and we could have 40 years left forever. The clock seems to be ticking very slowly. Actually, what is happening is that oil is being discovered, and extraction efficiency is increasing, about as quickly as oil is being used. Also, the amount of oil that is classified as reserves depends on the price of oil, because it only counts if it's currently profitable. The rate of consumption is growing with time, but we have been discovering new oil quickly enough to more or less keep pace with that growing demand.

There is enough oil to keep pumping for decades, but the peak rate of oil extraction could be happening right now.

Another way to estimate the lifetime of the age of oil was developed by geologist M. King Hubbert (see the Deffeyes books listed in Further Reading). Hubbert pointed out that the rate of extraction of a limited natural resource such as oil tends to follow a bell-shaped curve (Figure 9-6). The rate of extraction has a spin-up time at the beginning, gets going faster and faster, then slows down as the resource starts becoming depleted. The crucial point is that the maximum rate of extraction comes when the resource is about half used up.

This is an example of an **empirical** observation; there is no theoretical underpinning to the curve, although it sure does fit nice. But one could imagine an extract-the-juice-from-a-popsicle-on-a-hot-day curve. The popsicle consumption rate starts off slowly at the beginning because the popsicle is too cold to eat, then at the very end you have to swallow the last half of the popsicle in one gulp to keep it from hitting the sidewalk (Figure 9-7). Oil analysts like Daniel Yergin (see supplemental reading section) argue that political and economic factors could modify the oil extraction trajectory to look more like my popsicle curve, or some other.

This could be, but a bell curve seems to have worked in the past, for individual oil fields. Hubbert used his idea, in 1956, to forecast the peak extraction of oil in the United States. He predicted the peak to be sometime between 1965 and 1972, and in fact it came in 1970. The solid line in Figure 9-6 shows the time up to Hubbert's forecast, and the dashed line a prediction like his for the future (benefiting a bit from hindsight, I confess). Hubbert's prediction came at a time when oil production in the United States seemed endless. Figure 9-8 shows a Hubbert's peak for sperm oil harvesting back in the whaling days.

The forecast for when the peak in world petroleum will come depends a lot on what you call oil and how much is ultimately out there. Figure 9-9 shows world oil production in the past, fit to two **Gaussian** (bell) curves, one for 200 Gton C in oil that will ultimately be extractable, and one for 500 Gton C. Humans have already extracted 117 Gton C. If 500 Gton C is ultimately right, then the peak comes in the 2030's sometime. If 200 Gton C is right, consistent with BP, the peak should be happening now. And in fact most oil producers are pumping oil as fast as they can now, although oil analysts argue that logistics and infrastructure are slowing things down, in Iraq for example or in the number of refineries that are operating.

The crucial feature of the bell curve is that the maximum rate of extraction, the peak, occurs when half of the resource is still in the ground, as opposed to the peak of the popsicle-eating curve, which comes at the very end. During the first part of the extraction, the growth in supply rate follows along with an exponential growth in demand, driven by increasing population and GDP. If the production rate stops growing at the peak but demand continues to grow, it will appear to us as a shortage. In that sense, the reserves to production ratio from British Petroleum gives the wrong impression, because the shortage would begin long before the oil is down to the last drop.

As a fossil fuel, **methane** carries more energy per carbon than the others because methane is the most chemically reduced form of carbon. You get energy from making CO_2 from the carbon from all fossil fuels, but you also get energy from converting hydrogen to H_2O. Methane, being more reduced, has more hydrogen than coal or oil.

Turning it around in Figure 9-10, a Watt of energy from methane releases less carbon than a Watt from coal or wood. Methane also burns more cleanly than either, producing neither the acid rain, mercury, and aerosols from coal or the smog from petroleum combustion. Methane is more difficult to transport than liquid petroleum, because it is a gas and must be held under pressure. For this reason, methane associated with oil in remote locations is sometimes just burned, dramatic flares into the sky, rather than collected. Natural gas prices vary widely around the world, and they tend to fluctuate in time more than, say, coal prices do.

Methane is the cleanest fossil fuel, and it carries the most energy per CO_2 produced.

The amount of extractable natural gas on Earth is not known as well as it is for petroleum, because gas hasn't been explored for as intensively. Industry estimates of gas available are similar to the amount of oil, about 100 Gton C as proven reserves. Just like for oil, the ultimately available natural gas reservoir will certainly be higher than that.

Under the right conditions methane can freeze with water into a **methane hydrate** or **clathrate** structure, soccer-ball cages of water ice, each surrounding a single molecule of methane. Most of the methane hydrate is in mid-depth sediments of the ocean, but some can be found on land in permafrost soils. The deep sediment column is sort of a backwater in the carbon cycle, where life and chemical reactions move very slowly. But over millions of years, thousands of Gton C of methane has built up, swamping by a factor of ten the other reservoirs of swamp gas on Earth. There is enough methane down there to totally clobber the climate of the Earth if it were to be released all at once, since methane is such a powerful greenhouse gas.

The methane in the hydrates seems intrinsically precarious in the carbon cycle. A model of hydrates predicts that there wouldn't be much frozen hydrate if the ocean was about 3 °C warmer, as warm it could eventually get if the climate of the surface warmed from fossil fuel CO_2. Fortunately it takes thousands of years for the heat from the surface to reach the hydrates.

Methane hydrates could be a slow positive feedback in the global carbon cycle, but they will probably not burp all at once.

Melting hydrate could destabilize the sediment column by producing bubbles that lift the mud grains off of each other. Hydrate ice is like regular water ice in that it would float in water if it were not buried in mud. So it is possible that submarine landslides could release methane, some of which might reach the atmosphere. Fortunately again for us the amount of methane that could be released in a single landslide is not enough to really change the climate.

Methane hydrates are not traditionally thought of as a fossil fuel because they are difficult to extract, since they are frozen and don't flow unless you melt them, and since they are dangerous, leading potentially to submarine landslides. But fuel companies are exploring ways of extracting methane from hydrates on land, which may end up supplying some modest fraction of our natural gas consumption.

The bottom line is that coal is the most abundant available fossil fuel, ten to fifty times as abundant as either traditional oil or natural gas. The climate impacts of releasing various amounts of carbon will be discussed in Chapter 13, but the conclusion there will be that coal is the form of fossil fuel with the capacity to take the climate of the Earth well beyond a sort of turning-point temperature change of 2 °C. The future of Earth's climate will depend most on what happens to that coal.

Energy Consumption

Different parts of the world get their energy from very different portfolios of sources (Figure 9-1). India and China, the largest of the developing world, use a lot of coal, while Brazil uses mostly petroleum and hydroelectric power. Denmark is remarkable for windmills, which fall into the category "renewable" on this plot. France has invested heavily in nuclear energy (not renewable). The United States energy sources are similar to the global average. In part this is because the United States is a big consumer of energy, accounting for about a quarter of energy use globally (Figure 9-11).

Dividing the energy use of a country by the number of people in it gives the energy use per person or **per capita.** China has recently overtaken the United States as the country emitting the most CO_2, but there are many more Chinese people than there are Americans, so that the average Chinese person only emits one tenth of the amount of carbon as the average American. The Europeans and Japanese only use half the energy per capita as the U.S. Energy use in the U.S. is five times higher than the global average, so that if everyone adopted the American lifestyle it would increase the global rate of carbon emissions by about a factor of five.

Energy use is closely related to economic productivity, which is measured by the total value of everything produced for sale in a country in a year, the gross domestic productivity or **GDP**, units of dollars / year. Dividing energy use by GDP gives the **energy intensity**, a measure of the energy efficiency of an economy, reflecting waste but also the difference between heavy industry such as steel production versus high-tech industry. Figure 9-11 shows that the Europeans and the Japanese can make money using less energy than we can, while the Chinese and Indians are more energy intensive (less efficient). The patterns of carbon emissions from these countries are similar to energy use (Figure 9-11). The United States is responsible for an about a quarter of global CO_2 emissions.

Energy use and carbon emissions are related to population, economic activity, efficiency, and energy sources.

The factors that control CO_2 emission can be combined together to predict carbon emissions in the future if there were no effort to stop: a scenario known as **business as usual**. The equation is called the **Kaya Identity**, and it is the basis for one of the on-line models used in the Projects section. There are results from the model shown in Figure 9-12. The Kaya Identity is

$$\begin{aligned} \mathrm{CO_2\ emission}\left[\frac{\mathrm{kg\ C}}{\mathrm{year}}\right] &= \mathrm{Population}[\mathrm{persons}] \\ &\times \mathrm{GDP\ per\ capita}\left[\frac{\$}{\mathrm{person}}\right] \\ &\times \mathrm{energy\ intensity}\left[\frac{\mathrm{Watts}}{\$}\right] \\ &\times \mathrm{carbon\ efficiency}\left[\frac{\mathrm{kg\ C/year}}{\mathrm{Watt}}\right] \end{aligned}$$

Check it out for yourself that the units cancel correctly.

Population has been rising at a rate of about 1.3% per year, but this rate of growth is not expected to continue forever. Rates of population growth tend to decrease with affluence of societies. Population is forecast to level off at some value, but that value could be 9 billion people or it could be 15 billion people. A typical “business-as-usual” forecast puts the leveling-off point at about 11 billion people.

The second factor, $GDP / person, has been rising throughout the last century at a rate of about 1.6% per year, rising from $930 in 1990 U.S. dollars in 1900, to $4800 per person in 2000.

The third factor is the energy intensity, how many watts of energy it takes to make a dollar GDP. The energy intensity reflects efficiency but also the difference between heavy and light industry (Figure 9-12, bottom). Energy intensity has been dropping by a rate of about 0.55%/year over the past century, but the last few decades have seen a drop by about 1%/yr. According to the model on the web site, the slower rate of decrease results in 825 ppm pCO_2 in 2100, while 1%/yr results in about 700 ppm (Figure 9-13).

The final factor, the carbon released per energy yield, is the result of efficiency of the power plants but also on the characteristics of the feedstock energy source. Coal contains intrinsically less energy per carbon than does oil or gas, while nuclear and hydroelectric energy do not result in much carbon release, if any. CO_2 emission scenarios from the **Intergovernmental Panel on Climate Change**, or **IPCC**, ranged from 6 to 26 Gton C emission per year in 2100. Chapter 10 describes what happens to that CO_2 after it is released, and Chapter 13 will discuss what it means, in terms of energy, to avoid as much as possible the climate impacts of fossil energy.

Take-Home Points

Ultimately, the energy available to mankind includes instantaneous solar energy, which is abundant but spread out; stored solar energy in the form of fossil fuels; and stored energy from stellar explosions in the form of radioactive uranium deposits.

Of the fossil fuels, coal is the most abundant. Oil may run out in the coming decades, and the peak rate of oil extraction may be upon us even now.

We can project energy demand in the future as the product of population, economic growth, and energy efficiency.

Study Questions

Contrast the three forms of fossil fuel carbon, in terms of their origins, inventories, and uses.

Which are the least and most reduced forms of carbon fuel? Which form carries the most energy per carbon?

Compare peak oil theory to last-drop R/P calculations. What are the strengths and weaknesses of each? How does each relate to economic shortage of oil?

Further Reading

Hubbert's Peak: The Impending World Oil Shortage (2003) Kenneth S. Deffeyes. Princeton

Rogner, H.-H., An assessment of world hydrocarbon resources, *Annu. Rev. Energy Environ.*, *22*, 217-262, 1997.

BritishPetroleum, Energy in Focus, in *BP Statistical Review of World Energy*, 2009.

International Energy Outlook 2003. Energy Information Administration, U.S. Department of Energy. www.eia.doe.gov

Figure Captions

1. The sources of energy used globally and in various countries. From U.S. Energy Information Administration, data from 2006 and 2007

2. How different forms of fossil energy are used in the United States. From U.S. E.I.A.

3. The structure of normal octane, a hydrocarbon chain such as found in petroleum.

4. The amount of proven petroleum reserves, by region, from British Petroleum.

5. The value of the Production / Reserves ratio over the last 25 years, from British Petroleum.

6. Oil production in the United States follows a bell curve. M. King Hubbert predicted in 1956 that the peak would come at around 1970, and he turned out to be right.

7. A bell curve and an eating-a-popsicle-on-a-hot-day curve.

8. A Hubbert curve for the rate of sperm oil production.

9. Global oil production, history so far plus two Hubbert's peak projections.

10. Natural gas emits less CO_2 per Watt of energy than oil or coal.

11. Energy consumption (top panel), energy consumption per person (middle), and energy consumption per dollar gross domestic product, GDP (bottom), globally and from various countries.

12. Carbon release in CO_2 per year (top panel), carbon release per person (middle panel), and carbon release per dollar gross domestic product, GDP (bottom), globally and from various countries.

13. Results from the Kaya Identity model (http://understandingtheforecast.org/Projects/kaya.html.

14. More results from the Kaya Identity model.

Exercises

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 as well, but with different values. How much wiggle room is there for U.S. oil production?

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?

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? Make a table showing the high and low values that you find plausible for each parameter. 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. Remember that these assume business-as-usual, with no decrease in carbon emissions to avoid climate change.

b. How much carbon is mankind predicted to emit by the end of the century? For each of the input parameters that you estimated the uncertainty of in part a, which end of the uncertainty range gives the highest and lowest carbon emissions? Add columns to your table showing the CO_2 emission rates for the high and low parameter estimates. Combining the uncertainties in all of the parameters, run the model with all the high-CO_2 emission values of the parameters, and then the low-emission values, to find what is the highest and lowest plausible carbon emission for 2100? The emissions are used to drive a carbon cycle model, called ISAM, the results of which are shows in in the second output plot. According to the ISAM model, what could the range in atmospheric pCO_2 be like then?

c. What rate of improvement in carbon efficiency would be required to limit atmospheric CO_2 to at most 450 ppm?

d. Politicians often talk about CO_2 cuts as a fraction cut by the year 2050. The rate of carbon emission as a function of time would decrease with time following an exponential function according to

$$\text{fraction cuts} = \text{emission rate(time)}/\text{emission rate(0)} = e^{k\,t}$$

where

$$k = x\%/\text{yr} \;/\; 100\%$$

if x is the rate of change of carbon efficiency, like the –0.3%/yr that comes up in the model interface by default. Using the carbon efficiency improvement rate from part c, calculate the fraction cut from 2000 to 2050 required to stabilize CO_2 at 450.

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?

Chapter 10. The Perturbed Carbon Cycle

Where the fossil carbon goes.

Ozone

Let’s get one issue out in the open and out of the way before thinking about global warming. The ozone hole is not the same as global warming. **Ozone** is a reactive oxygen molecule comprised of three oxygen atoms. Ozone in the stratosphere is produced as O_2 molecules are zapped by energetic UV-C ultraviolet light, breaking apart into two very reactive oxygen atoms. Each of these may find another O_2 molecule and join it, to form O_3, ozone. Ozone itself absorbs UV light called UV-B that is less energetic but more abundant than the UV-C required to break up an O_2 molecule. Stratospheric ozone filters UV-B radiation that might otherwise reach the surface, causing skin cancers and sunburn.

The ozone hole is a separate issue from global warming.

Atmospheric chemists predicted that ozone concentrations in the stratosphere might be depleted by chemical reactions accompanying the breakdown of chemicals called chlorofluorocarbons or Freons, inert chlorine-bearing compounds that are used in refrigerators and air conditioners. The prediction was that stratospheric ozone concentrations would gradually decrease over decades. This has been observed, but what scientists did not anticipate was a surprise called the **ozone hole**. The ozone hole is located in the Southern hemisphere over Antarctica. In wintertime in this region, it gets cold enough that an unusual form of cloud forms in the stratosphere, comprised of frozen particles of nitric acid, HNO_3. It turns out that the frozen nitric acid clouds convert the chlorine from breakdown of Freons into a very reactive form that doesn't just deplete ozone by a small amount, but consumes it entirely within that air mass as soon as the sun rises in the Antarctic spring. The ozone hole was first observed in measurements of ozone concentration made by hand, on the ground. After these measurements, old satellite ozone records were examined, and it turned out that the satellite had been seeing the ozone hole for several years, but a data quality algorithm had been programmed to throw out any data which violated common sense, and out with the bad data went the ozone hole. This is an indication of how much of a surprise it was.

The ozone hole is a terrific example of a **smoking gun**, clear-cut proof of the detrimental effects of chlorofluorocarbons on stratospheric ozone. Before the ozone hole was detected, the models predicted a gradual decrease in stratospheric ozone globally, superimposed on natural variability: a difficult prediction to decisively test. As a result of the ozone hole, and the availability of economically and technologically viable alternatives, many countries of the world ratified the Montreal Protocol in 1987, phasing out further production and release of chlorofluorocarbons to the environment.

A "smoking gun" makes it easier for a society to decide to act.

Ozone is also produced by reaction of gases from industrial activity, mostly automobile exhaust, in surface urban smog. The ingredients for ozone production in urban air are evaporated organic carbon compounds, like evaporated gasoline or molecules that are emitted naturally from trees and plants, nitrogen oxide compounds that are emitted from automobiles, and sunlight. When ozone concentrations exceed a toxic limit, asthma sufferers begin to feel discomfort, and plant leaves get "burned" and scarred.

Ozone in the stratosphere interacts with climate change caused by greenhouse gases such as CO_2. The main role that ozone plays in the energy budget of stratospheric air is it absorbs ultraviolet light from the sun, heating up the air. Ozone is the reason why there is a stratosphere. If ozone did not heat up the stratosphere, the atmosphere would continue to get colder with altitude, and the atmosphere would be one big troposphere. The effect of decreasing ozone concentration is less heating, and therefore cooler air in the stratosphere.

Rising CO_2 concentrations also cool the stratosphere. The role that CO_2 plays in the heat balance of stratospheric air is that it acts like a radiator fin, shedding heat energy as infrared radiation. For this reason, an increase in CO_2 concentration in stratospheric air causes the temperature there to go down. Ozone is also a greenhouse gas, but ozone has a stronger influence on the heat balance of the stratosphere by absorbing

UV. So the stratospheric is cooling for two reasons: falling ozone concentration and rising CO_2.

Ozone is confusing to the student of the environment because ozone in the stratosphere is a good thing but industrial activity is acting to deplete it, while ozone in the troposphere is a bad thing and industrial activity tends to produce it.

Methane

Methane is a greenhouse gas, about 40 times more powerful per molecule than CO_2 at current concentrations (see Chapter 4). Methane is released to the atmosphere from natural sources and anthropogenic sources (Table 10-1). Once released to the atmosphere, the methane reacts, in about a decade, turning into CO_2 and H_2O.

Methane is a short-lived gas in the atmosphere. This means that the methane concentration would respond quickly to decreasing the human methane sources.

The chemical reaction that spells the end for methane involves a very reactive molecule called OH radical. OH is like a water molecule missing a hydrogen, and in fact it would much prefer to be a water molecule, which is to say, water is a more stable, lower-energy molecule than OH is. So the OH radical steals one hydrogen from methane, CH_4, leaving CH_3, another very reactive and unstable molecule that quickly reacts further.

The OH radical is like the flame at the wick of a lit candle. In the absence of sunlight, there is no OH, and the flame is out. Methane and O_2 gas can coexist together for hundreds of thousands of years, for example in bubbles of ancient air trapped in ice sheets, like a candle can sit in oxygen forever and not decompose, if there is no flame. But in sunlight, methane and oxygen slowly burn up.

The methane cycle in the atmosphere is another use of the kitchen sink analogy, already used to describe the energy budget of the surface of the Earth in Chapter 3 and the weathering CO_2 thermostat in Chapter 8. The water level in the sink represents the methane concentration in the air. Inflow from the faucet stands for the production of methane from natural or human sources, which will be described below. Flow down the drain is the chemical breakdown of methane in the atmosphere, and as in the other examples, the rate of flow down the drain depends on the water level in the sink.

The kitchen sink analogy – yet again!

The kitchen sink analogy has an equilibrium where the water flow out balances the input, as does the methane concentration in the air. The budget that has to be balanced for methane is

emission [Gton C / year] = decomposition [Gton C / year]

Assuming that the decomposition rate is proportional to the concentration gives

decomposition [Gton C / year] = inventory [Gton C] / lifetime [years]

Substituting emission for decomposition,

emission [Gton C / year] = inventory [Gton C] / lifetime [years]

which can be rearranged to calculate the amount of methane in the air at equilibrium to be

inventory [Gton C] = CH_4 emission [Gton C / year] × lifetime [years]

The inventory is in units of Gton C, which can be converted to the more usual methane units of concentration (mixing ratio, see Chapter 4) in our atmosphere as

1 Gton C in our atmosphere ≈ 2 ppm = 2000 ppb

The methane cycle in the atmosphere has an equilibrium state like the sink does, but like the sink, it doesn't always have to be in that equilibrium state. The water level in the sink could be rising or falling, although it can't do this forever because it should be rising for falling toward the equilibrium state, and when it gets there the water level stops changing.

If you start with the sink at equilibrium and dump a bucket full of water into the sink, the water level will spike upward and then relax back toward the equilibrium level, and the amount of time it takes to do that depends on the lifetime of the water in the sink. The same is true for methane; if there were a sudden release of a slug of methane, the concentration would spike upwards and relax back on a time scale of the methane lifetime, which is about a decade.

The other way to change the water level in the sink is to alter the equilibrium by changing the flow in through the faucet or by changing the drain in some way, say by partially obstructing it. The water level in the sink will drift toward the new equilibrium and then remain there.

For methane, changes in methane sources are thought to be driving most of the rise in atmospheric methane due to human activity. There were natural sources of methane to the air before humans arrived, but if humans doubled the rate of emission, after a few decades, the steady-state concentration would about double. The real world may be a bit more complicated, because the lifetime may also change somewhat as the methane concentration goes up.

The rise in atmospheric methane is thought to be due to our sources, rather than a change in the reactions that consume methane.

One of the natural sources of methane to the atmosphere is the degradation of organic carbon in freshwater swamps. Organic carbon degrades first by reaction with O_2, as we have discussed in Chapter 8. In seawater, after the O_2 is gone, organic carbon reacts with sulfate ion, SO_4^{2-}, to produce hydrogen sulfide, H_2S. After oxygen and sulfate are depleted, methane is produced from organic carbon by fermentation. This is how the methane is produced that freezes into clathrate deposits below the sea floor.

In fresh water, there is not much SO_4^{2-}, so as soon as oxygen is gone, methane production begins. Methane is found much shallower in fresh water mud than in saltwater mud. If you step in mucky swampy freshwater mud you may see bubbles of methane rising up around your legs. Methane is sometimes referred to as swamp gas for this reason.

Bubbles of ancient atmosphere preserved in ice cores tell us that the methane concentration has fluctuated with climate state over the past 650,000 years (the longest ice core yet available), with lower methane concentrations during colder, drier climate stages (Figure 8-3). This is interpreted to be the result of the changing abundance of swamps.

Rice is grown in artificial swamps called rice paddies. The rice plant doesn't strictly speaking require the swampy conditions, but the water chokes off some of the competition from other plants. Other human-caused sources of methane include production in the guts of ruminant animals, and release as leakage by the fossil fuel industry.

The lifetime of methane in the atmosphere seems to have been about constant through the past decades. This is in spite of the fact that there have been significant increases in the abundance of some chemicals in the atmosphere that produce OH radical, like ozone and some nitrogen radical compounds in urban smog. The concentrations of molecules that OH radical reacts with, methane and carbon monoxide, CO, have also increased, which change by itself ought to have decreased the amount of OH in the air. It seems as though these two types of chemical changes in the air have just about balanced out, so that the methane lifetime has been holding steady.

Overall, as a result of the human impact on the atmosphere, the methane concentration has doubled over its pre-anthropogenic concentration (Figure 10-1), and is responsible for a quarter of anthropogenic greenhouse heat trapping (Figure 10-2).

CO_2

The CO_2 rise in the atmosphere differs from methane in that the sinks for CO_2 are much more complicated. CO_2 dissolves in the oceans, and ultimately goes back to the solid Earth by means of the weathering CO_2 thermostat discussed in Chapter 8. Methane is an unstable, transient gas in the atmosphere, whereas CO_2 essentially accumulates in the atmosphere / ocean / land surface carbon cycle, because the weathering reactions that provide the ultimate sink are so slow that on human time scales we might as well forget about them.

Methane is transient, but CO_2 accumulates.

There are two main anthropogenic sources of CO_2 to the atmosphere. One is deforestation. A dense forest holds more carbon per area than does a plowed agricultural field. The world's forests started to feel the ax thousands of years ago with the development of agriculture and the growing of the human population. Most of the temperature latitudes have been cut long since, but deforestation in the tropics is still going on today, accounting for about 2 Gton C / year release of CO_2 to the atmosphere.

Atmospheric CO_2 started to rise, according to measurements of the chemistry of bubbles in ice cores, about the year 1750, after millennia of holding steady at a natural value of about 280 ppm (Figure 10-1). For the first century or so after that, most of the concentration increase was probably caused by deforestation, perhaps in the New World (the “pioneer effect”). Today, visible deforestation is mostly to be found in the tropics, and accounts for about 1.5 Gton C per year release of CO_2 to the atmosphere.

Cut down trees and their carbon eventually goes to the atmosphere.

The other main anthropogenic CO_2 source is of course the combustion of fossil fuels discussed in the last chapter. Fossil fuel combustion today releases about 8.5 Gton C per year, and it is rising exponentially, driven by population growth and economic growth, rising in spite of increases in energy and carbon fuel efficiency.

Combining the ocean and tropical deforestation, mankind is releasing carbon to the atmosphere at a rate of about 10 Gton C per year. The atmospheric CO_2 inventory is rising at a rate of about 4 Gton C per year. Where is the other 6 Gton C per year? There are two main natural sinks for CO_2 that are operating today; one is the oceans, and the other is the terrestrial biosphere.

In addition to the deforestation source for carbon, there appears to be a significant amount of carbon being taken up by the land surface, the **terrestrial carbon sink**, probably in places that are not being deforested. The deforestation source can be seen and quantified in satellite images, but the land sink for carbon is pretty hard to see or measure.

The land surface is taking up a lot of carbon today, but we can’t find it.

In comparison with the ocean, the distribution of carbon on land is very spotty. Recall from Chapter 7 that most of the carbon on land is in the soil, rather than in the trees where we could see it. In soils, the amount of carbon depends on recent land-use history, things like fires, agriculture, or forest re-growth. It is difficult to know precisely how much carbon there is on land because the measurements are so variable; you would have to make a lot of measurements in order to average out all the noise of natural variations. As a result of this, it would be possible to increase the amount of carbon on land, a little bit here or there, in a way that would be entirely invisible to direct measurements, and so this carbon uptake is called the **missing sink**.

The best way to estimate the magnitude of the missing sink, in Gton C per year globally, is to put together the rest of the carbon budget, and assign the terrestrial biosphere whatever is left over. Figuring out where it's going, and why, is trickier. The best approach to actually tracking the CO_2 uptake is to measure CO_2 concentrations as the winds blow across the land surface. If the CO_2 concentration goes down as the air blows over a land area, there must be uptake in that area. There is a network of "CO_2 observatories" around the globe, where precise CO_2 concentration measurements are made daily, for uses such as this, and the measurements are analyzed together, for the whole globe and over long periods of time, within atmospheric circulation models that predict wind directions, to try to come up the regional distribution of the land sink. Most of these studies conclude that the missing sink is located in the high latitude northern hemisphere.

There are several reasons why the land may be willing to take up CO_2 as the atmospheric CO_2 concentration rises. One is that with warming, there will be a longer growing season. This has been observed in many climate and botanical records. Also with warming, some tundra areas become amenable to conquest by forests.

Rising CO_2 in the atmosphere may directly encourage plants to grow faster, by a process known as **CO_2 fertilization.** Plants run their photosynthetic machinery inside waxy walls on the surfaces of leaves. Gases are exchanged with the outside atmosphere through adjustable vents called **stomata.** When the leaf needs CO_2 for photosynthesis, the stomata open. The cost of opening stomata, though, is loss of water. So if CO_2 concentrations were higher in the outside atmosphere, plants could get the CO_2 they need without opening their stomata as much or as often.

There is no doubt that CO_2 fertilization is a real effect. CO_2 concentrations in greenhouses are typically higher than in the outside atmosphere, one of the ways that greenhouses are good for plants. However, in the real world, plant growth is very often limited by something else other than water stress or CO_2 limitation, such as fertilizers like nitrogen of phosphorus. Scientists do CO_2 fertilization experiments in natural settings by pumping CO_2 continuously into the air upwind of a grove of trees. When the wind changes, they adjust the location of the CO_2 vent, so that the target grove is always downwind from a CO_2 source. These experiments go on for years! What they tend to find is an initial growth spurt from CO_2 fertilization, followed by a leveling off at something like the initial rates. The bottom line is that there is still considerable uncertainty in the strength and importance of the CO_2 fertilization effect.

Another process that may affect CO_2 storage on land is the temperature sensitivity of respiration in soils, the process that converts organic carbon back into CO_2. Soil respiration really gets going as it gets warmer. Think of a ham sandwich, half of which is safely stowed in the refrigerator while the other half sits at room temperature. After a few days, which half will be tastier?

Because of faster decomposition rates, there is very little organic matter in tropical soils, while prodigious amounts of carbon have accumulated in high latitude soils, especially frozen permafrost soils. Warming, melting, and decomposition of high-latitude permafrost may ultimately release CO_2 to the atmosphere.

The land carbon uptake could saturate, or reverse itself in a warming world.

Uptake of fossil fuel CO_2 by the oceans is called the **ocean carbon sink.** At first glance one would think that the ocean should dominate the CO_2 concentration of the atmosphere, because there is much more carbon dissolved in the water than there is in the air. The ocean covers 70% of the Earth's surface, and the length and width of the ocean are huge compared with its depth, which averages about 4 kilometers. One could imagine that the ocean would be pretty quick about taking up any extra CO_2 we put in the air.

But the circulation of the deep ocean is governed by differences in the densities of the waters in the ocean. The deep ocean fills up with the densest water, which in our ocean means the coldest waters. Once a water parcel sinks its temperature doesn't change much. The deep ocean fills up with water that last saw the atmosphere in very cold places, such as the Antarctic and the North Atlantic, in their local winters. The surface of the ocean is huge, but the deep ocean, which is the largest water type in the ocean, only sees the atmosphere through a very small window in the ocean surface. The deep ocean is so close to the surface, and yet it is very far away.

Ocean uptake of fossil fuel carbon depends on the circulation...

The cold deep ocean fills up until cold polar waters underlie the warm surface waters in lower latitudes. The warmer waters mix with the cooler, eroding the cold water and making room for more of the coldest water to continue filling the deep sea. As new cold water flows from the high-latitude surface ocean into the abyss, it carries with it atmospheric gases like anthropogenic CO_2, a process known as **ocean ventilation.** It takes many centuries for the waters of the deep ocean to travel through this loop. For this reason, it will take centuries for anthropogenic CO_2 to invade the deep ocean.

Other water masses of the ocean take up fossil fuel CO_2 more quickly but ultimately in smaller amounts. A water mass separating the warm waters near the surface from the cold water below is called the **thermocline.** The thermocline traces through the water column, a few hundred meters deep, outcropping in the high latitudes where surface waters are colder. Thermocline waters ventilate to the atmosphere on a time scale of decades. The **surface ocean mixed layer** is formed by turbulence generated by the wind, and is typically about a hundred meters deep. This is not as large as the deep sea or the thermocline, but it is a respectable carbon reservoir of its own.

... and on the buffer chemistry of inorganic carbon in seawater.

When CO_2 dissolves in seawater it interacts with a small but elegant cascade of chemical reactions called **pH reactions.** First CO_2 reacts with water to form **carbonic acid,** H_2CO_3.

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \qquad (10\text{-}1)$$

Carbonic acid loses a hydrogen ion (that's what acids do, in general, is release hydrogen ions) to form **bicarbonate ion**, HCO_3^-

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \qquad (10\text{-}2)$$

A second hydrogen ion can be released to form **carbonate ion**, $CO_3^=$

$$HCO_3^- \Leftrightarrow H^+ + CO_3^= \qquad (10\text{-}3)$$

The concentrations of carbonic acid, bicarbonate, and carbonate ions control the acidity of the ocean, just as they control the acidity of our blood and cell plasma. **Acidity** is a measure of the concentration of hydrogen ions, H^+, in a water-based solution. Hydrogen ions are very reactive, which is why a strong acid such as the sulfuric acid in a car battery can burn your skin or clothes.

The standard way to describe acidity is using a number called the **pH** of the solution, which can be calculated as

$$pH = -\log_{10} [H^+]$$

The $\log_{10}$ is the base-10 logarithm, meaning that if $x = 10^y$, then $\log_{10} y = x$. The hydrogen ion concentration is denoted by the square brackets, and is expressed in units of moles of H^+ per liter of solution. A **mole** is simply a specific number of atoms or molecules, called Avagadro's number, equal to $6.023 \cdot 10^{23}$. The hydrogen ion concentration in seawater usually ranges from 10^{-7} to $10^{-8.3}$ moles of H^+ per liter. The pH of seawater therefore ranges from 7 to 8.3.

The pH of a solution describes the balance of H^+ in it. Lots of H^+ is acidic, which is a pH value less than 7. Not much H^+ means lots of OH^-, which is basic, and a pH value greater than 7.

These particular chemical reactions are fast enough that the distribution of chemical species will always be in their lowest-energy distribution, what is called **chemical equilibrium.** Not all chemical reactions reach equilibrium quickly or even reach it at all, like for example the CH_4 and O_2 in the dark bubbles of an ice sheet, which resist the transition the lower-energy equilibrium state (converting to CO_2 and H_2O). But these pH reactions in seawater reach equilibrium for practical purposes instantaneously.

The response of an equilibrium chemical system, such as the seawater carbon buffer, to a perturbation, such as the addition of new CO_2, can be described using a simple idea known as **le Chatelier's principle.** The addition of one of the chemicals on say the left-hand side of the chemical equilibrium reaction will cause the reaction to shift to the right, the direction that tends to compensate for the perturbation. The principle works in either direction; take some of something out, the equilibrium will put some of the something back. Add more something, the equilibrium will remove some of the something.

Le Chatelier's principal is treacherous for students of the carbon system in seawater, though, because we have an innate human tendency, I have found, to ignore the hydrogen ions. They are such tiny things, after all. There are far fewer hydrogen ions in seawater than there are of the dissolved carbon species. What this means, however, is that a small change in the concentrations of the various types of carbon molecules might make a huge change in the hydrogen ion concentration, relative to how much was already there.

The safest assumption to make is that the carbon species have to get along together without counting on sloughing off too many hydrogen ions at all. Hydrogen ion is such a tiny slush fund, it might as well not exist. Reactions 10-1, 10-2, and 10-3 can be combined into a single reaction that doesn't allow any production or consumption of hydrogen ions, just interconversion of the carbon-containing molecules

$$CO_2 + CO_3^{=} + H_2O \Leftrightarrow 2\ HCO_3^{-} \qquad (10\text{-}4)$$

To this reaction we can apply le Chatelier's principle with impunity. If we were to add CO_2 to this system, the equilibrium would compensate somewhat by shifting to the right, consuming some of the CO_2 by reacting it with $CO_3^{=}$.

CO_2 dissolves in seawater by reacting with $CO_3^{=}$, an "antacid", in the carbonate buffer system.

Seawater has the capacity to absorb or release more CO_2 than it would if CO_2 had no pH chemistry, because of the other carbon reservoirs, HCO_3^{-} and $CO_3^{=}$. The chemical system is called a **buffer**, because changes in CO_2 concentration are buffered by the shifting equilibrium reaction. Most other gases, like O_2 and N_2, don't have anything like this buffer chemistry.

If you double the CO_2 concentration of air, a bucket of water in equilibrium with the air will want to roughly double the dissolved concentration of CO_2 in the water. But because of the buffer system, it takes a lot more CO_2 added to the water to double the CO_2 concentration. Most of the CO_2 added reacts with $CO_3^=$ to make HCO_3^-.

It is like sitting at a poker game, with a rich partner sitting behind you covering about 90% of your losses and taking about 90% of your winnings. You could endure a losing streak ten times longer, losing 10 times as much money, because your partner is buffering your bank. Similarly, a bucket of seawater can absorb about ten times more CO_2 than it would if this pH chemistry did not exist.

The amount of CO_2 that the buffer can absorb depends on the concentration of carbonate ion, $CO_3^=$. Carbonate ion is like anti-CO_2. In natural surface seawater, there is about ten times more $CO_3^=$ than dissolved CO_2, so that the buffer strength is about a factor of ten, the same as in the poker game. But as more CO_2 is added to the water, the proportions of CO_2 and $CO_3^=$ change, CO_2 going up and $CO_3^=$ going down, and the buffer gets weaker. This will result in a slowing of ocean uptake of human-released CO_2 in the future.

The relative concentrations of CO_2 and $CO_3^=$ in seawater determine its acidity or pH. In an acidic solution like a fizzy cola, the carbon is pretty much all in the form of dissolved CO_2, which is for this reason called the acidic form of carbon. The opposite of acidic is called **basic**. Make the solution more basic, and more of the carbon will be in the basic form of carbon, which is $CO_3^=$.

Fossil fuel CO_2 makes seawater more acidic, which may affect life forms that make shells of $CaCO_3$.

When CO_2 is added to seawater, the pH of the water becomes more acidic. This phenomenon is called **ocean acidification.** The surface ocean is already about 0.1 pH units more acidic than it was naturally. Because the equilibrium pH chemistry of the carbon buffer is well understood and simple, the pH change due to changing atmospheric CO_2 can be predicted very confidently.

Organisms that make shells out of $CaCO_3$ will feel the changing pH most strongly. Corals are the poster child (see Chapter 12), but other organisms that make $CaCO_3$ include coccolithophorids, which are **phytoplankton** (free-floating microscopic plants) at the base of the ocean food chain, and pteropods, swimming animals with shells like snails that are a primary food source for some salmon, mackerel, herring, and cod.

The pH chemistry of seawater is counter-intuitive in that when you put CO_2 in, it causes $CaCO_3$ to dissolve. One might have thought that adding CO_2 to the oceans would lead to an increase in the amount of carbon that winds up in $CaCO_3$, the rising tide floating all boats. It goes the other way because of the change in acidity. $CaCO_3$ is chemically a base, and if you put it in acid it dissolves.

The future of ocean uptake of fossil fuel CO_2 may also be affected by changes in the circulation of the ocean. Surface warming is expected to be most intense in high latitudes because of the ice-albedo feedback (Chapter 7). If the high latitudes warm, the overall circulation of the subsurface ocean may decrease. The circulation of the ocean may stagnate, slowing uptake of CO_2.

Biology in the ocean acts to decrease the CO_2 concentration of surface waters, by converting CO_2 into organic carbon via photosynthesis (Chapter 8). Dead phytoplankton sink out of the surface waters, carrying their carbon to the deep sea. This processes is called the **biological pump**. If all the life in the ocean were killed, that is if the biological pump were stopped, then the CO_2 concentration of the atmosphere would rise. On the other hand, stimulating the biological pump to work harder could eventually decrease the CO_2 concentration of the atmosphere (see the discussion of ocean fertilization in Chapter 13).

In contrast to the missing sink on land, there are many fairly reliable ways to measure the uptake of CO_2 into the oceans. One way is to measure the CO_2 concentration in surface ocean water, from which you can calculate how quickly CO_2 is dissolving or evaporating across the sea surface. To get a global CO_2 flux takes lots of measurements (about three million have been made and compiled so far), because the temperature and chemistry of the surface ocean varies a lot from place to place and through the seasons. The net CO_2 invasion into the ocean is calculated to be about 2 Gton C per year. This is a small imbalance between the much larger CO_2 exchange fluxes between the atmosphere and oceans, about 100 Gton C per year. CO_2 goes out of the ocean in some places and into the ocean in others, driven by the huge variability in the temperature and chemistry of the surface ocean.

It is easier to measure carbon uptake into the ocean than into the land surface.

There are computer models of the circulation, biology, and chemistry of the ocean that can be used to estimate human-released CO_2 uptake. The models can be tested and calibrated using chemical **tracers** in the ocean like carbon-14 and industrial chemicals like Freons, which show the pathways by which atmospheric gases flow into the deep ocean. The models agree with the surface CO_2 data, that the oceans are taking up about 2 Gton C per year.

Another way to measure the balance between carbon uptake into the land versus the ocean is to measure the change in atmospheric oxygen along with the rising CO_2. Land uptake uses photosynthesis to create organic carbon in trees or soils, and it releases oxygen to the atmosphere to do so. Ocean uptake does not involve photosynthesis; the CO_2 just dissolves in the water and doesn't affect oxygen at all. There's a lot more O_2 than CO_2 in the atmosphere, so the changes in O_2 are tiny and have to be measured very precisely. The story they tell is consistent with the other methods, about 2 Gton C per year into the oceans.

So, by difference, it works out that carbon uptake by the missing sink on land is taking up quite a bit of carbon, about 4 Gton C per year. This is more than the deforestation CO_2 release rate of about 1.5 Gton C per year, so the land surface overall is taking up about 2.5 Gton C per year, about a quarter of our emissions.

A reconstructed history of the carbon fluxes is shown in Figure 10-3. The land surface was a net source originally, deforestation outpacing any natural uptake. Then the missing sink started kicking in just in the last few decades. What the future will bring is difficult to tell. Ultimately there is enough fossil fuel carbon available (5000 Gton C) to overwhelm any uptake by the land surface (1500 Gton C including soil carbon). The fact that tropical soils have so little carbon compared to cold soils, especially frozen soils, suggests to me that eventually the land surface may dump carbon as the climate warms. The land surface is important in the carbon budget today and for the next few decades, but ultimately the fossil fuel CO_2 will be cleaned up by the oceans.

Eventually, after a few centuries or millennia, the human-released CO_2 will spread out among the carbon reservoirs of the atmosphere, ocean, and land surface. Computer models of the ocean carbon chemistry, physics, and biology predict that in this new equilibrium state, the atmospheric CO_2 concentration will be higher than it was before the CO_2 was released. The extra CO_2 molecules in the air won't be the exact same molecules that came from fossil fuels, because carbon is always passing back and forth among the different reservoirs. But the amount of extra carbon in the air represents a significant fraction of the human-released carbon slug, around 25% of it, more or less (Figure 10-4).

After fossil fuel CO_2 equilibrates with the ocean, there will still be some left in the air, a "long tail" to the atmospheric lifetime, awaiting slow weathering reactions to carry it back to the solid Earth.

Some of that extra CO_2 in the air will go away when the pH of the ocean recovers, driven by an ongoing $CaCO_3$ cycle in the ocean called the **$CaCO_3$ pH stat**. Dissolved $CaCO_3$ flows into the ocean in river water, the product of weathering (dissolving) rocks on land. Solid $CaCO_3$ is re-formed from the dissolved ingredients in the ocean to make shells and coral structures. Most of the shells and corals eventually redissolve, but some fraction of the $CaCO_3$ that forms every year is buried in ocean sediments. This is the mechanism for $CaCO_3$ removal from the ocean.

Eventually, the budget for dissolved $CaCO_3$ into and out of the ocean has to balance, just like the water fluxes eventually balance in the kitchen sink analogy. The way the ocean balances the $CaCO_3$ budget is by changing its pH. $CaCO_3$ is a base, and it dissolves in acid. The burial rate of $CaCO_3$ depends in part on the pH of the ocean; less would be buried in an acidic ocean. As the pH of the ocean gets more basic, $CaCO_3$ tends to form, like lime crusting out on a real faucet.

Applying the sink analogy to the $CaCO_3$ pH stat, the water level would be the ocean pH, which depends on the amount of dissolved $CaCO_3$ in the ocean. The burial rate of $CaCO_3$ depends on ocean pH the way flow down the drain depends on the water level. A deeper water level in the sink corresponds to a basic ocean, increasing $CaCO_3$ burial, and a shallower water level would be a more acidic ocean.

The pH of the ocean however can also be affected by invasion of CO_2 acidifying the ocean, which would be analogous to scooping some water out of the kitchen sink. As part of the oceans' recovery, some $CaCO_3$ would dissolve on the ocean floor, which in the sink analogy could be mimicked by allowing water to flow back up the drain pipe if the water level in the sink got too low. Also, the warmer climate will probably increase the rate of weathering on land, which would be like a burst of extra flow from the faucet when the water level went down. Both of these effects would tend to push the pH of the ocean back toward its natural balance.

As the buffer chemistry recovers, the airborne fraction of the extra CO_2 drops, until after a few thousand years, when the $CaCO_3$ budget is back in balance, the airborne fraction of the extra CO_2 in carbon cycle models drops to about 10%. What would happen in the real world could be different if there are feedbacks in the carbon cycle, such as the positive feedbacks that appeared to operate through the glacial / interglacial cycles (Chapter 8).

The climate cycle will ultimately recover from the fossil fuel era when the carbon returns to the solid Earth due to the **silicate weathering CO_2 thermostat** from Chapter 8. This mechanism is thought to control the CO_2 concentration of the air on time scales of hundreds of thousands of years. The longevity of the global warming climate event stretches out into time scales of glacial / interglacial cycles, time scales that are longer than the age of human civilization by far. The climate impacts of the long tail are most pronounced in slowly-changing components of Earth's climate, such as the ice sheets in Greenland and Antarctica (Chapter 12) that would ultimately drive the largest changes in sea level.

Take-homes

The ozone hole is not global warming. They are different issues.

Methane has about a 10-year lifetime in the atmosphere, so its concentration reaches an equilibrium after about this long.

The land surface and the ocean are absorbing some of our fossil fuel CO_2, but this could slow or reverse in a changing climate.

Releasing fossil CO_2 to the atmosphere will affect climate for hundreds of thousands of years -- as far as we are concerned, forever.

Study Questions

What are the links between the ozone hole and climate change? In what ways are they different from each other?

What are the processes that remove anthropogenic methane and CO_2 from the atmosphere? Are those processes reliable, or could they change in the future?

Describe the change in the carbonate buffer chemistry in seawater in response to addition of CO_2. Why does adding CO_2 make seawater more acidic?

Further Reading

Online Trends, a Compendium of Data of Global Change, from the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. http://cdiac.esd.ornl.gov/trends/trends.htm

The Discovery of Global Warming (2003) by Spencer Weart. The history book again. Read about early measurements of atmospheric CO_2.

IPCC Scientific Assessment 2001, from Cambridge University Press or downloadable from http://www.grida.no/climate/ipcc_tar/. Chapter 3 **The Carbon Cycle and Atmospheric Carbon Dioxide.**

Archer, D., Fate of fossil-fuel CO_2 in geologic time, *J. Geophysical Res. Oceans*, doi:10.1029/2004JC002625, 2005.

Tans, P. An accounting of the observed increase in oceanic and atmospheric CO2 and an outlook for the future. Oceanography 22 (4): 26-35, 2009.

Tables

1. Natural and anthropogenic sources of methane, Gton C per year.

Natural Sources	
Wetlands	0.075 – 0.15
Termites	0.015
Human Sources	
Energy	0.075
Landfills	0.03
Ruminant Animals	0.075
Rice Agriculture	0.05
Biomass Burning	0.03

Figure Captions

1. History of CO_2 and CH_4 concentrations in the atmosphere, from ice cores (symbols) and atmospheric measurements (solid lines). Replotted from IPCC (2001).

2. The impact of various human-related climate drivers on the energy budget of the Earth, in Watts per square meter, relative to the year 1750. Replotted from IPCC (2001).

3. Reconstructions of past CO_2 fluxes due to human activity, from Tans (2009)

4. Long-term fate of fossil fuel CO_2 , reprinted from Archer (2005).

Exercises

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?

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.

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?

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?

Part III. The Forecast

Chapter 11. The Smoking Gun

The human impact on climate can be seen in temperature trends since the 1970's.

Is the Globe Warming?

Greenhouse theory is all well and good, but people understandably want to see it in action in the real world. They want to see a "smoking gun", some proof of climate changing as a result of human activity. Greenhouse theory, codified in the numerical climate models, can be tested by comparing the model results against climate changes in the past. Even better is to look for predictions that can be made in advance, so that they can afterward be put to the test of whether they came true or not.

The search for a smoking gun.

The first question is how much warming has actually occurred. Answering this question is trickier than one might have thought, because temperatures vary from place to place and through time, and measurement techniques have changed. One measure of success is to find global temperature reconstructions from independent methods that agree with each other.

The next task is to come up with the histories of natural and anthropogenic **climate forcings.** A climate forcing is a change in some factor that affects the temperature of the Earth. The big ones are changes in the intensity of the sun, scattering of visible light by human-released and volcanic aerosols in the atmosphere, and changes in greenhouse gas concentrations. Humans affect climate most strongly through greenhouse gas concentrations and aerosols, plus there are a few other, smaller, so-called **anthropogenic climate forcings.**

Thermometer Records

To see a trend in the global average temperature of the Earth, all the variations, between day and night, through the seasons, and through the weather, have to be averaged out. The temperatures have to be weighted, so that parts of the world that have lots of historical weather observations don't dominate the global average over places with sparse data. To get a temperature trend across decades of time, we also need to know if there were changes in the methodology of making the measurements through time. It would be treacherously easy for some bias in the raw data to be undetected or otherwise not corrected for.

On land there is a potential source of bias known as the **urban heat island effect.** Sunlight hitting pavement warms it up, the light energy converted to what climatologists call **sensible heat**, "sensible" because you can measure it with a thermometer or feel it with your hand. When sunlight hits land with plants on it, it drives water to evaporate, carrying away **latent heat** (Chapter 5), which you can't feel or measure with a thermometer until the water condenses. A vegetated landscape doesn't warm up as much as a paved landscape, because some of the heat is escaping invisibly, or insensibly I suppose one would say, as water vapor. The urban heat island is an observed phenomenon; cities can be 5° C warmer than their surrounding countryside. Nighttimes in particular are warmer in cities.

What if a weather station was established a century ago in some idyllic rural area, only to have the landscape urbanize since then? The temperature record would show a warming, which would be real for that location, but it would not be due to chemical changes in the atmosphere. Also, if cities were over-represented in the temperature data, the computed average temperature could be higher than the real average temperature of the Earth.

Independent competing studies find about the same amount of global warming, so their answer seems to me pretty reliable, even though I didn't do the analysis personally.

Three independent studies of the land temperature data made an attempt to throw out data from locations that might have seen urbanization (Figure 11-1). The studies all agree that removing urban locations has only a small impact on the global average temperature trend that you calculate from the data. They find that it doesn't matter how they deal with the urban data, they get pretty much the same answer regardless.

The sea surface temperature, known as **SST**, used to be routinely measured by heaving a bucket on a rope into the ocean to collect surface water, and sticking a thermometer into the bucket on deck. Evaporation carries away heat, cooling the water in the bucket somewhat. Some of the buckets were made of wood, others of canvas. Canvas buckets cooled more than wooden ones, because wet canvas is a poor insulator. After 1942, mariners began measuring the temperature of surface water as it was pumped into the ship for engine cooling water. This is a more accurate measurement, but there is still the possibility of bias. The waters in the surface ocean sometimes get cooler with depth. A large ship might sample waters from a few meters below the waterline, which might be systematically a bit cooler than the real SST. These effects must be corrected for, if we are to calculate a global average value of SST through time. Looking at the corrected and uncorrected sea surface temperatures, the largest correction that had to be applied to the temperature records was the bucket correction for the sea surface temperatures. The abrupt change in SST in 1942 resulted from a switch between bucket and engine-room temperature measurement.

The land and sea records cannot be directly compared because the land tends to warm up more than the ocean. The ocean has an infinite supply of water to evaporate and carry away latent heat, and heat can be mixed down from the ocean surface more quickly than heat can penetrate the soils and rocks on land. These temperature records are compared (Figure 11-2) within a climate model in which the ocean temperatures are driven by measurements, and the model land temperatures are then compared with the measurements from land areas. The two independent data sets, each with their own potential biases hopefully corrected for, appear to be consistent with each other.

Sea surface temperatures agree that the Earth surface on average is warming.

Michael Crichton in his fiction book “State of Fear” shows temperature records from selected locations around the world, where temperatures have cooled over the decades. These do not disprove the warming trend for the global average temperature, because these cooling areas are more than counterbalanced by places that Crichton does not show that are warming, such as the Arctic for example. The global average temperature record is based on thousands of individual locations around the world.

The existence of a few where climate is cooling does not disprove the warming trend in the global average.

Temperatures Measured from Satellites

Satellites provide another source of global temperature trend information, by measuring microwave light emission from oxygen gas, O_2, in the atmosphere. Because of the way that electrons are distributed around the nuclei of oxygen molecules, when oxygen molecules rotate they emit electromagnetic radiation in the microwave part of the spectrum. This is longer wavelength, lower energy radiation than the infrared that greenhouse gases absorb and emit. It is far from the main IR wavelengths of the blackbody spectrum of the Earth (Chapter 4), which is why O_2 is not considered a greenhouse gas like CO_2. The intensity of microwave radiation emitted from O_2 increases with increasing temperature, just as the intensity of IR goes up with temperature.

Temperature estimates from satellites used to disagree with the thermometers on the ground, but this was caused by errors in data processing that have been fixed now.

These satellite temperature estimates have been the subject of considerable scientific and political discussion because for many years the satellite estimates of warming disagreed with the reconstructions from thermometers. This has now changed, as scientists learn how to calculate near-surface temperatures from the raw satellite sensor data (solid black line in Figure 11-3). The satellites measure microwave emission at several wavelengths, and use them to calculate atmospheric temperatures in different altitude ranges. The lowermost altitude range they can resolve spans from the surface to about 8 km altitude, with an exponential decay kind of a shape, like the curve describing pressure with altitude (Figure 5-2). Even though the weighted average is affected most strongly by temperatures near the ground, there is still some influence from temperatures higher up, including in the stratosphere where it has been getting colder, masking some of the warming below in the satellite signal until it was corrected for.

The satellite temperature record comes from a series of satellites, which must be well-calibrated against each other as they are pieced together into a longer composite record. The raw data must be corrected for things like changes in the orbit of the satellite. The current calibration of the satellite data shows good agreement with the land and sea instrumental records.

Glaciers

The most visual indication of climate change is the melting of mountain glaciers. The vast majority of the mountain glaciers, all around the world, are melting (Figure 11-4). Figure 11-5 shows records of the lengths of 20 glaciers. Many have been melting back since the 1700's, as a result of natural warming since the Little Ice Age. However, the rate of melting has accelerated in the past decades. Mountain glaciers tend to disappear at the altitude where the temperature is somewhat above freezing, so it is not too difficult to relate glacier lengths to temperature changes. The glaciers are in general telling of the same warming as the thermometers, a third independent confirmation.

Changes in Climate Forcings

Different climate forcings can be compared in terms of their effect on the energy budget of the Earth, in units of W/m^2, which is called their global average **radiative forcing** values. One W/m^2 in solar output, for example, doesn't have exactly the same climate impact as one W/m^2 of infrared light trapped by CO_2, but they are not too far off, so the radiative forcing makes a convenient starting point for comparing different drivers of climate. The radiative forcing is calculated immediately after the change has been enacted in the climate system, but before the climate has had a chance to respond to the change, because when the climate responds, it eventually drives the energy inbalance back to zero.

The radiative forcing in Watts per squared meter allows us to compare the causes of climate change on a roughly equal footing.

Some factors that affect climate are considered internal to the climate system, like the water vapor feedback, clouds, and changes in the albedo of the land surface and from melting ice. These are not considered forcings, which should be externally driven; because they are internal to the climate system, they are considered feedbacks.

Radiative forcings are related to Earth's temperature by means of a new version of a **climate sensitivity parameter.** The usual way to describe the sensitivity of climate is the equilibrium warming you get from doubling the CO_2 concentration of the air, a parameter written as ΔT_{2x}, described in Chapter 4. The new climate sensitivity relates the equilibrium warming to the radiative forcing; it could be called ΔT_R. A middle-of-the-road estimate for ΔT_{2x} is 3° C, which corresponds to ΔT_R of about 0.75° / (W/m^2). The current anthropogenic climate forcing today is about 1.5 W/m^2 (Figure 10-2). Multiplying by the climate sensitivity gives us a temperature change estimate of about 1.1 K. This is larger than the Earth has warmed, because it takes time for the climate of the Earth to reach equilibrium (Chapter 12).

The next step is to reconstruct past changes in the climate forcings. **Solar intensity** varies over the 11-year sunspot cycle by about 0.2-0.5 W/m^2 (Figure 11-6). Direct measurements of the intensity of the sun are best made from satellite, avoiding interference from the atmosphere. These measurements go back to about 1975. Earlier than that, the solar intensity can be reconstructed from the number of sunspots that were observed through time, using records that go back to Galileo's invention of the telescope about 400 years ago.

The sun varies in its intensity, through the 11-year sunspot cycle and through the centuries, but it hasn't been getting hotter the last fifty years, so it can't explain the recent warming.

Even earlier still, the solar intensity has been estimated by the accumulation rate in ice cores of particular radioactive atoms that were produced by cosmic rays hitting the atmosphere, such as ^{10}Be and ^{14}C. These are called **cosmogenic isotopes.** The idea is that a brighter sun has a stronger magnetic field that serves as a better shield to cosmic rays. So a high deposition rate of ^{10}Be at some depth in an ice core is interpreted to mean that the sun was weaker, unable to deflect cosmic rays, and was therefore not very bright at that time. It sounds a bit convoluted, but we do in fact observe a correlation between cosmic rays, ^{10}Be production, and solar intensity over the 11-year sunspot cycle in recent times (Figure 11-7).

There are times in the past such as the Maunder Minimum, from about 1650 to 1700, when there were no sunspots. This was the coldest period in Europe in the last 1000 years, and glaciers advanced all over the world, including in the Southern hemisphere, so it's pretty clear that the solar luminosity was less then than it is now. However, we have no direct solar measurements from a time when the sun acts like this, so we don't have a very solid constraint on how much lower the solar output was. You can see that there is a factor-of-two uncertainty in the solar forcing in the past, as the thickness of the grey region in Figure 11-6. The time-history of solar forcing variability is to drift up and down on timescales of about 100 years.

Volcanic eruptions inject particles into the atmosphere, sulfate aerosols and dust. Particles injected into the troposphere only last a few weeks before they are rained out, but if the eruption is large enough to get particles into the stratosphere they can spend several years floating around before they eventually sink out. The Mt. Pinatubo eruption in 1991 cooled the planet by 0.5° for several years, for example. **Volcanic climate forcings** look like randomly spaced spikes of random but high intensity in Figure 11-7.

To the two natural climate forcings we add the two main anthropogenic ones, **greenhouse gases** and anthropogenic **aerosols.** Neither was important before about the year 1750. Greenhouse gases warm, and sulfate aerosols cool. The greenhouse gas radiative impact is fairly uniform globally, while the climate forcing from sulfate aerosols is concentrated in the Northern hemisphere, downwind from industrialized and heavily populated areas.

The Smoking Gun

A comparison of the historic temperature record with model results is shown in Figure 11-8. The observed temperatures in the heavy black lines rose in the period from 1900 to 1950, declined from 1950 to 1970, and then started rising again from 1970 to today.

The temperatures are compared with results from climate models that participated in an exercise coordinated by the IPCC for its 2007 Fourth Assessment Report. There were 19 models participating, from around the world, and they are all driven by the same time series of climate forcings. These are divided in natural climate forcings, changes in solar intensity and volcanic eruptions, and then natural plus human climate forcings by adding the effect of greenhouse gases and sulfate aerosols.

The trajectories of many model runs are plotted on top of each other, looking like tangled clouds of lines, and also averaged in the heavy tan lines.

Only the models that were told about human climate forcings were able to simulate the warming since the 1970s – the smoking gun.

The model simulations do a pretty good job of capturing the temperature rise in the early part of the 20th century, but only the runs that include the human impact on climate are able to reproduce and explain the warming in the last few decades. This plot is considered to be the "smoking gun", proof that humans have already affected the climate of the Earth.

Climate scientists have used measured warming and the rise in greenhouse gases to infer what the climate sensitivity of the real world is. The climate sensitivity, ΔT_{2x}, is the amount of warming that you would get after a few centuries if you doubled atmospheric CO_2 and held it there (Chapter 4). A half-dozen studies in Figure 11-9 were based on temperature changes in the last few decades, and three others were based on reconstructed climate changes from pre-historic times, like the warming at the end of the last glacial period. The studies come up with a most-likely range between about 1.5 and 4.5 °C. This is a confirmation of the climate models, which predict climate sensitivity values in that same range.

So this is the smoking gun for global warming, the temperature rise since the 1970's. Climate models reproduce the warming when you tell them about rising CO_2 concentrations (and aerosols), and can't reproduce the warming when you don't tell the models about the gases. The strength of the argument can be seen by turning things around, asking the question, What would it take for the global warming forecast to be substantially wrong? Is it possible, or does it seem likely, that humans could put as much CO_2 in the air as we like without changing the Earth's climate, and the whole global warming issue could just go away?

What would it take for the fear of global warming to be wrong?

There are two obstacles to this possibility. First, there would have to be some other mechanism to explain the recent warming since the 1970's:

some large perturbation to the energy budget of the Earth that no one has measured or conceived of yet. It takes a lot of energy to warm up the whole surface of the Earth including the ocean, it can't happen just by random chaos. Certainly there will always be things about the natural world that are not perfectly understood, maybe even things about which we have no clue yet. But so far, in spite of intensive and highly motivated searching, no one has come up with an idea that works. This can be seen in the failure of the climate models without the human climate forcings to warm up enough.

Second, there would have to be a reason to throw out the greenhouse effect theory, some explanation of why increasing CO_2 would not block outgoing IR energy by absorbing in its bending vibrational mode, perhaps, or how some negative, compensating feedback might neutralize the warming tendency from the CO_2, somehow allowing the Earth to shed the excess energy without warming up.

Overcoming either one of these obstacles seems like a long shot, given how much intense, motivated searching has been done. Overcoming both obstacles together seems extremely unlikely to me. No one would be happier than I would about a reprieve from global warming, but honestly I just can't see it.

The smoking gun warming was forecast in advance.

It's one thing to hindcast the past, where you already know the answer, but much better to predict the future and then see how it came out afterward. But can climate models and theory also predict the future? Figure 11-10 shows a global temperature made in the First Assessment Report in 1990, a similar forecast made in 1996 in the Second report, and again in 2001 in the Third Assessment Report. The actual measured temperatures, and a smoothed trend derived from there, are also plotted for comparison. The first forecast was a bit higher than it turned out to be, the second forecast a bit lower, but in general the agreement is quite good. The Mt. Pinatubo volcanic eruption was also a good test of climate models, which were used to predict the amount of cooling as soon as the eruption was done and they has some idea of how much sulfur went into the stratosphere. Climate models and the real world both cooled by about 0.5 °C.

The Climate of the Last Millennium

The thermometer and satellite temperature records indicate a warming trend since about 1970, but this begs the question: is this warming unusual, or do excursions like this happen all the time? To try to answer this question, paleoclimatologists have extended the temperature record further back in time, before the era of technological measurements. Temperatures from before the days of thermometers can be estimated by a variety of techniques, measurements of something we can measure, interpreted as indicators of things we would like to know. These alternative measurements are known as **proxy** measurements.

Proxy temperature measurements will have to do for times before the thermometer was invented.

One source of proxy temperature measurements is the thickness of annual **tree ring** layers in wood (Figure 11-11). In places where winter is much colder than summer, there is a seasonal cycle in the density and color of the wood that grows, leading to the formation of annual rings. Trees grow more quickly during warmer years than colder years, so it makes sense that tree ring thickness might carry information about temperature. Long records of tree ring thickness can be assembled from collections of many individual trees that lived long ago, by matching the patterns of widths to fit the different trees together in time.

The widths of the rings must be **calibrated** against temperature changes from part of the record where the temperature is known independently. This is tricky, because lots of factors can affect how well trees grow besides the annual average temperature, like the availability of water, nutrients, and even atmospheric CO_2. Young trees grow more vigorously than old ones. The types of trees, and their locations, have to be carefully selected to reduce the impacts of growth factors other than temperature.

Then proxy temperature records from around the world are put together into a global average. When this is done, the “noise” (non-temperature signals) can be reduced still further by training statistical methods to look for spatial patterns in the tree ring temperatures that match patterns in the climate today, like el Nino for example. These spatial patterns are used as a kind of filter to extract the temperature signal from the noise in the tree ring data.

Other proxy measurements for temperature include the temperature as a function of depth in the Earth and in ice cores, called **borehole temperatures.** The temperature goes up with depth in the Earth or in the ice, because heat is flowing from the interior of the Earth to the surface. The more heat there is flowing out of the Earth, the steeper the temperature change with depth will be. If the temperature at the Earth's surface were held constant for a long time, then the temperature profile with depth in the Earth or the ice would be a straight, linear increase with depth (Figure 11-12).

Now imagine warming the surface of the Earth. The warmth will propagate down into the Earth or the ice, and eventually, the whole temperature profile would move to warmer values, with about the same slope as before (assuming the heat flow from the Earth is about the same). At some instant in time, take a snapshot of the evolving temperature profile. Mathematical methods called inverse methods can be used to figure out how the temperature at the surface must have changed in the past to generate a given temperature profile snapshot. These borehole temperature records lose the little wiggles in the real temperature record, acting as a low-pass filter on the real temperature changes. Also the uncertainty gets greater as you try to infer surface temperatures too far back in time. Borehole temperatures show warming throughout the past 500 years, more or less consistent with the tree-ring record (Figure 11-11).

Other sources of information about past climates come from ice sheets and mountain glaciers. Glacier lengths have been used to construct a third independent pre-historic temperature reconstruction in Figure 11-11, in substantial agreement with the results from tree rings, boreholes, and where it exists, the instrumental temperature record.

The proxy records reveal that Earth's climate does vary naturally, driven by fluctuations in the intensity of the sun ....

Temperature reconstructions of the last millennium sometimes show a period of warmth from 800-1200, called the **Medieval Climate Anomaly**, and cooler temperatures from 1350-1800, called the **Little**

Ice Age. The Little Ice Age was clearly a global event, as indicated by longer mountain glaciers around the world. The Little Ice Age coincided with a time of low solar flux inferred from cosmogenic isotope production, and the Maunder Minimum dEarth of sunspots (Figure 11-7).

Glaciers don't leave a record from the warmest times, however, and the tree ring records come mostly from the Northern hemisphere, so the intensity and footprint of the Medieval Climate Anomaly period is a little harder to pin down. Unlike today when the Earth is warming up pretty much everywhere, during Medieval time there were regional warmings and coolings but no "global" warming. Medieval time does not look anything like the globally synchronous warming of our climate since the 1970's.

Models are broadly able to simulate the Medieval Climate Anomaly and Little Ice Age, largely driven by long-term changes in solar forcing. But the climate record of the past millennium is a less stringent test of the climate models than the record from the last century, because there is more uncertainty in both the radiative forcing and in the temperature record the models should try to match.

Much has been made of the question of whether the Earth is warmer now than it was naturally during the medieval time. In the end this question is a red herring; the smoking gun for global warming is still the thermometer records since the 1970's, not the Medieval Climate Anomaly. Imagine sitting on an electric stove burner in your kitchen. You think the burner is off, but you might have turned the knob when you jumped up there to sit. Should you get off? You feel the current temperature of the burner, and let's say it is 105 °F, a bit warmer than it ought to be. But you remember that last summer, during the heat wave, that burner was at 105 °F, for natural reasons. Does this mean it's safe now? Not really; a better test would be to track the temperature of the burner over the next few minutes, and see if you can figure out why it's getting warmer this time.

Climate Variations on Orbital Timescales

Looking farther back in time, the uncertainties in climate reconstructions get larger, but on the other hand, the climate changes get more dramatic, too. The **Last Glacial Maximum**, about 18,000 years ago, was a wildly different climate than today, everywhere in the world but especially in the

Northern hemisphere, which hosted massive ice sheets which have since disappeared.

... and, on longer time scales, by variations in Earth's orbit around the sun.

Tree ring and borehole temperatures, used to reconstruct the climate of the last 1,000 years, generally don't work as far back as the Last Glacial Maximum, but constraints on temperatures during the ice age come from sediments in the ocean and lakes, and ice cores. In general, it cooled down more in high latitudes than in the tropics, the "polar amplification" caused largely by the ice albedo feedback described in Chapter 7. Overall, the surface of the Earth was perhaps 5 to 6°C cooler than our natural interglacial climate.

The atmosphere contained less CO_2 and methane at this time (Figure 8-3), resulting in a radiative forcing of about 2 - 3 W/m^2. All of the ice, in ice sheets, sea ice, and snow, changed the albedo of the Earth, by about another 3 – 3.5 W/m^2. Three studies have used the climate of the ice age to diagnose the climate sensitivity, ΔT_{2x}, of the Earth. These are plotted alongside the results from the instrumental record on Figure 11-9, and they get pretty much the same answer: something like 3 °C for doubling atmospheric CO_2. If the climate models were somehow too sensitive to greenhouse gases, then we would expect the climate models to predict a colder Last Glacial Maximum than we piece together from the proxy records.

Past climate changes are consistent with the temperature sensitivity of climate models to changing CO_2.

CO_2 is only part of the reason for the colder glacial climate, but it is striking to look at how similar the CO_2 and temperature records are. Every little wiggle lines up between the two records. It is difficult to argue that CO_2 is somehow unimportant to climate, after looking at this record.

The Paleocene Eocene Thermal Maximum

A final test of the global warming forecast comes from an interval of time 55 million years ago called the **Paleocene Eocene Thermal Maximum** event. This is much further in the past than any time we have considered yet, and the data are much scantier.

A deep-past analog for global warming, but so long ago that it is not very useful for testing our understanding.

Measurements of the isotopes of carbon in $CaCO_3$ shells in ocean sediments tell of a sizable release of carbon to the atmosphere or ocean (Figure 11-13). The carbon that was released had a different ratio of carbon-12 to carbon-13 than the CO_2 in the atmosphere and ocean, and so it changed the isotopic ratio of the ocean and in the $CaCO_3$ that formed in the ocean that we measure today.

It is impossible to know how much carbon was released in the spike, because we don't know the isotopic ratio of the carbon in the spike. If it were methane, which has an extremely low ratio of carbon-12 to carbon-13, we would need a few thousand Gton C. If it were organic carbon, which has a less extreme carbon isotopic ratio, a larger slug would be required to explain the isotopic excursion. For comparison, the entire inventory of minable coal, using present-day technology, is about 5000 Gton C (Chapter 8). The Paleocene Eocene Thermal Maximum is therefore a reasonable analog to the potential effect of fossil fuel combustion.

The isotopes of oxygen provide an indication of the warming of the deep sea that resulted from the carbon release. Temperatures were already somewhat warmer in the deep ocean than they are today, before the carbon release. After the carbon was released, temperatures warmed by about 5 °C.

It is impossible to use the extent of warming as an indication of the climate sensitivity of the Earth at that time, because it’s not known what the CO_2 concentration in the atmosphere was. However, the data serves as confirmation of the prediction, from Chapter 10 and Figure 10-4, that it will take hundreds of thousands of years for temperatures to recover to their natural baselines, after a sizable fossil fuel CO_2 release.

Take-home Points

The past few years have been warmer than the thermometer records of the past 140 years, and warmer than reconstructed records over the past 1000 years.

Climate change is driven by natural and human-induced changes in radiative forcing, including volcanic eruptions, solar variability, greenhouse gases, and human-released aerosols.

Models cannot explain the rise in global temperature since about 1970 without including anthropogenic forcing. This is the smoking gun for a human impact on climate.

Study Questions

What is a proxy measurement? Describe two types of proxy measurements.

What is a climate forcing? Which ones are human in origin, and which ones natural?

What is a radiative forcing and why was this concept developed?

Why is the warming since the 1970's the smoking gun for a human impact on climate?

Further Reading

IPCC Scientific Assessment 2001, from Cambridge University Press or downloadable from http://www.grida.no/climate/ipcc_tar/. Technical Summary.

realclimate.org is a commentary site on climate science by working climate scientists, including myself, for the interested public and journalists.

Figure Captions

1. Instrumental land temperature reconstruction, from nine independent studies published between 1881 and 2006. Replotted from IPCC [2007].

2. Land temperatures, reconstructed from land thermometers, and predicted using sea surface temperature reconstructions, corrected and uncorrected for the bucket effect. Replotted from IPCC (2001).

3. A comparison of the global average temperature reconstruction with the satellite record. Data replotted from Mears and Wentz [2005].

4. The disappearance of the Qori Kallis glacier in the Peruvian Andes.

5. Glaciers are melting all over the world. Replotted from IPCC [2001].

6. Reconstructed history of radiative climate forcings from solar variability, greenhouse gases, anthropogenic aerosols, and volcanic particle emission to the stratosphere. Replotted from Crowley [2000].

7. History of sunspot number, and cosmogenic isotope production, over the past 1000 years. Data from Beer [2000] and Lean [2000].

8. Model simulations of the climate of the last 140 years, using human plus natural natural climate forcing (top), and natural forcings only (bottom). Replotted from IPCC [2007].

9. Probability distributions of the value of the equilibrium climate sensitivity of the Earth, ΔT_{2x}, diagnosed from temperature and greenhouse gas concentration changes through the last decades and reconstructed for the prehistoric past. The studies find it most likely that ΔT_{2x} is between 1.5 and about 4.5 °C. From IPCC [2007].

10. Past predictions of future warming and how they turned out. From IPCC [2007].

11. Northern hemisphere mean temperature reconstructions. Replotted from IPCC [2007].

12. Time evolution of subsurface temperature, when the surface warms up. From a snapshot of the current temperature profile (black line), scientists can reconstruct the history of the surface warming (arrows).

13. The Paleocene Eocene Thermal Maximum event. Replotted from Zachos [2001].

Exercises

Point your web browser to http://understandingtheforecast.org/Projects/bala.html. This is a system to browse the output of a climate model run to the year 2300, from Bala et al [2005]. The browser allows us to explore the output of a coupled atmosphere, ocean, and land surface model. The atmosphere model comes from the National Center for Atmospheric Research in Boulder, Colorado, and the ocean model comes from Los Alamos National Laboratory in New Mexico.

The browser allows several options for making plots.

1. There are two model runs, one with CO_2 emissions simulating the eventual combustion of the entire coal reservoir, about 5000 Gton C. This run is labeled "**CO_2**" on the browser. The other model run is called a **control**, in which there are no CO_2 emissions. This is labeled "**Ctl**". You can view results from either of these runs, or you can select a "**Drift-corrected**" option that will subtract changes in the control, the model drift, from the rising CO_2 run.

2. Some of what you will see is simple multi-year variability. In order to remove this, perhaps for comparing one climate state with another, select the **averaging, 10-year climatology** option.

3. You can highlight the changes in a climate variable by subtracting one from another, to say things like "it is 2°C warmer than it used to be". This is called an **anomaly** plot.

4. Push the **Plot** button to generate a contour plot.

5. Click on a contour plot to display the numerical value from that location on the plot, both for the rising CO_2 run and for the control run. In principal, it should be possible to guess what the value should be using the colors and the contours, but it is often helpful to see a number expressed as a number, instead of as a color.

6. The **Time Series** option brings up another type of plot entirely, a plot of the year-to-year variations in the global average of the variable. The averaging option does not apply to this type of plot.

7. A final option is to view pre-made movies of the model results, using the **Play Movie** button.

Use these tools to compare model output with a paleo-temperature reconstruction, say from Figure 11-3.

(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.

(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.

(c) Add a pair of new columns to your table, labeled $T-T_{mean}(CO_2)$ and $T-T_{mean}$(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 $2\ \sigma$? How many do you find?

(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 $2\ \sigma$. How many of the data points actually are outside of $2\ \sigma$?

(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?

(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?

Chapter 12. Potential Climate Impacts

Drought and storms and sea level, it's not just the warming.

The warming itself

The actual global warming part of "global warming", the change in the average temperature of the Earth, is probably not going to be the most important change in Earth's climate to affect people on the ground. Most of the climate impacts will come from secondary impacts like droughts and storms, things that are regional in footprint rather than global. Not even the warming itself will be smoothly spread about the Earth's surface, but rather some places and times warm more than others. But the average temperature of the Earth is still a good metric, an indicator of the severity of climate change, even if that particular number, the average temperature of the whole planet, is not the actual number that will affect people the most.

Transient climate runs forced by various IPCC emission scenarios predict temperatures 1-6°C warmer by the year 2100 (Figure 12-1). The uncertainty in our forecast for the temperature in the year 2100 derives from two sources, which contribute about equally. One is the temperature response to a given amount of CO_2, and the other is how much CO_2 will actually be released.

A temperature change of 1-6° C may not sound like very much. The daily cycle of temperature is greater than that, to say nothing of the seasonal cycle. The main impacts of future climate change may come from changes in rainfall, rather than temperature. But the temperature change by itself is far more significant to the landscape of the world than you might think.

Natural temperature changes of a few degrees C in the past changed the landscape of the Earth.

One point of comparison is the temperature difference between now and the last ice age, which is estimated to be about 5-6° C. This was a huge climate change. If we were looking forward to a glacial maximum in the future, rather than backward into the safe past, we would be in a panic. It would be apocalyptic. Europe was an occasionally-habitable tundra.

The ice sheet in North America dwarfed what exists today in Greenland. Greenland, in spite of its name, is a pretty fierce place. Of course, Europe and North America were extreme cases, because the ice sheets were there, but the landscape elsewhere also changed significantly. Traces of changing snowlines make it clear that it was noticeably colder. Pollen data show huge changes in vegetation type. The coastlines were barely recognizable. Truly it was a different world.

Another comparison is to the Little Ice Age and Medieval Climate Anomaly periods (Chapter 11). Some reconstructions of the global mean temperature, or Northern hemisphere temperature, show temperature changes of perhaps 0.5 to 1° C. These climate intervals were not the end of the world, but they definitely sufficed to rearrange civilizations. In medieval time, European agriculture was a bounty of plenty, in a stable, benign climate. Meanwhile a 500-year drought coincided with the demise of two organized civilizations in the New World, the Classic Maya and the Anasazi.

The Little Ice Age climate was much more unstable than it was in medieval times. Temperature or rainfall would change suddenly for a year, or decades. There were periods of drought, periods of hot summers, of arctic winters, and of mild periods of moderate climate and good harvests. In the years 1690 – 1730, roughly coincident with the Maunder minimum time of no sunspots, there was sea ice around Britain and northern France, and a complete rearrangement of the fisheries in the Atlantic.

The impression I have is that a warming of 1° C would probably not be a world-shattering change, at least globally, although there is the risk of prolonged or perpetual regional droughts, such as occurred in the American southwest during the medieval warm time. By analogy to the intensity of the climate changes that came with the end of glacial time, I would guess that a global mean temperature change of 5° C would catastrophic.

The distribution of the forecast temperature change is not uniform geographically or in time. Plate 12-1 shows the mean annual temperatures from a climate model described in the Exercises section from Bala et al. [2005]. The atmosphere model was developed at the National Center for Atmospheric Research, a government agency in Boulder, Colorado. The ocean model was developed at the Los Alamos

National Lab in New Mexico. In general, this particular model has a relatively low climate sensitivity, ΔT_{2x}, of 2-3°C for doubling CO_2. The temperatures are plotted as anomalies, differences from the temperatures in year 2000 in Plate 12-2.

Global warming is not globally uniform.

The high latitudes warm more than low latitudes, by a factor of 3 or 4, mostly because of the ice-albedo feedback. Temperatures in Alaska and Western Canada have warmed by 3 – 4 °C, compared with a global average of perhaps 0.6 °C. Models predict that the tundra ecosystem could disappear almost entirely in a business-as-usual world of 2100.

Much of the high-latitude land surface is **permafrost**, defined as soil that is frozen year round. The surface of the soil may melt in the summer, in which case it is called the **active zone.** As temperatures rise, the active zone gets thicker, and the soil column can collapse, leaving houses and trees tilted at crazy angles. Most of the Trans-Alaska oil pipeline has its foundation in permafrost soil. Arctic lakes suddenly drain away, as melting ice leaves holes in the soil column. Coastlines are collapsing at rates of 40 meters per year in some parts of the Canadian Arctic and Siberia.

Greenhouse gases lead in general to more intense warming in the cold parts of the Earth's surface: in wintertime and at night rather than in the summer and in daylight. This is because greenhouse gases impede the loss of heat to space, so temperatures rise just as quickly in the sun but cool down more slowly due to infrared energy. Air over land also tends to warm more than air over water, because evaporation can always carry away heat from the water, but the land surface may dry out.

An increase in the average temperature of the Earth's surface translates into many more extreme heat events, such as European heat wave in August, 2003, for example, which killed an estimated 35,000 people. It was thought to be a once in a century event, but it was followed by a similar event in 2006. Greenhouse heat waves tend to remain hot all through the night, instead of cooling down and allowing people and foliage some cool nighttime reprieve to recover.

Emergent effects

The rise in global temperature is like a fever, in that most of its impact is not directly due to the warmth itself. Changing the average temperature of the Earth scrambles the climate, rearranging weather patterns and water supply in ways that are not easy to forecast reliably, and so not easy to prepare for.

Global weirding.

Overall, more rain is expected to fall in a warmer world. On the face of it this sounds like it might be a good thing, in a time when fresh water availability is a problem in many parts of the world. However, for the rainfall forecast the devil is in the distribution, even more than it is for temperature (Plate 12-3).

In the tropics, the weather patterns are mostly governed by an overturning pattern called the Hadley circulation (Figure 12-2). Air rises convectively at the equator, where the solar heating is most intense. The rising air cools down due to expansion under lowered pressure, and its water vapor condenses into rain. Air subsides in the subtropics, bringing bone-dry air down to the surface and creating areas of minimal rainfall at about 30° latitude North and South. Warming the climate is expected to increase the Hadley circulation pattern, intensifying rainfall at the equator and further drying out the desert regions in the subtropics.

Meanwhile, precipitation in the highest latitudes is expected to increase because of the increase in temperature (because there is more water vapor in warm air). This increase in high-latitude precipitation plays a role in the projections for the large ice sheets (next section).

Rainfall away from the equator can be divided into two types: storminess and monsoons. Storm-driven precipitation is strongest in particular “storm alleys” on Earth (Figure 12-2). Presumably the rate of storm-driven rainfall would increase in a warmer world, because the warmer air carries more water vapor, and because the atmosphere is in general stormier.

Monsoons are driven by a temperature contrast between the land surface and the ocean. The different temperatures drive the winds to blow in ways that systematically dump water as prodigious rainfall. Monsoon systems are sensitive to changes in the temperature differences that drive them, and their strength tends to vary from year to year even in a natural world. According to climate records derived from cave $CaCO_3$ deposits, monsoons are variable on longer time scales as well, switching on and off abruptly and staying switched for centuries and longer. The projection for the monsoon in Southern China and India is to become stronger and stormier. Rainfall in the American Southwest is actually monsoonal in type, in that it is driven by Pacific surface temperatures, and it seems to be collapsing.

Monsoons are particularly vulnerable to climate rearrangement.

Continental interiors are expected to dry out due to faster evaporation into warmer air. Even though rainfall globally averaged would increase in a warmer world, areas on Earth that are dry today in general are expected to become drier, increasing the likelihood of drought.

Droughts are driven by changes in the water cycle that vary from one climate model to the next, so forecasts of the impacts in specific regions are not very reliable. This is too bad, because water stress is probably more likely to interfere with agriculture than the changes in temperature would alone. When the results from the 22 different climate models that took part in the latest IPCC exercise are combined, however, there is a consistent picture of drying in particular regions, such as the American southwest, the Mediterranean, and Australia, which are already undergoing drought conditions (Plate 12-4).

Droughts are exacerbated by the response of the plants. Healthy plants act to capture groundwater, preventing it from running off in a stream but instead evaporating it into the atmosphere, a process called **transpiration.** In this way, plants, and in particular the aggressive plant life of the tropical rain forests, sustain their own existence by recycling rainfall. If the plants die back, rainwater tends to run off, ultimately flowing back into the ocean in rivers, rather than re-evaporating into recycled rainfall. The plant response acts to “lock in” the drought, making the onset of the drought more of a flip-flop than the decline of the rainfall that drove it. It tends to take more rainfall to break out of a drought when plants have to be re-established.

Dying vegetation can lock in a drought.

The carrying capacity of the land ultimately depends on water availability. During the **Dust Bowl** drought in the American Southwest in the 1930's, 85% of the residents of the state of Oklahoma picked up and left. There are proxy records in lake and ocean sediments of droughts in the prehistoric past that were much stronger and more persistent than the Dust Bowl. The Classic Mayan civilization collapsed in several stages that correlated with strong decade-long droughts as documented in lake sediments and cave deposits.

Glaciers are expected to melt with warming, and indeed have already begun doing so (Figure 11-4). This water contributes to sea level rise (next section). Perhaps the most pressing social concern about the loss of glaciers is that they supply water through the summer to a lot of people (see Human Impacts section).

A warmer world would be a stormier world, because storms are driven primarily by the heat of water vapor condensing into precipitation. Warmer air carries more water vapor, so there is more energy to be wrung out when warmer air rises and cools. Storms and weather are already observed to be getting stronger and more extreme. There have been more hard rains, longer and hotter heat waves, stronger tropical cyclones, and more droughts.

Tropical cyclones, also called typhoons or hurricanes, may get more intense or more prevalent in a warmer world, although there is considerable uncertainty in this aspect of the forecast. The number of hurricanes per year has been holding steady through the decades, but the frequency of the most powerful hurricanes, called Category 5 storms, has doubled in the past 30 years (Figure 12-3).

A warmer world would be stormier.

Every year there are about 90 tropical storms, 40 of which become cyclones. These storms grow from particular combinations of winds and pressures that serve as "seeds" for the storms. Whether the seeds grow or dissipate is determined by the structure of winds in the air, whether they blow in the same direction through the entire atmospheric column or whether they "shear" the growing storm apart by blowing in different directions at different altitudes.

The hurricane draws its power from the water vapor in the surface air over the ocean. When the air rises, the vapor condenses and releases its latent heat, warming the air and driving it to rise, strengthening the storm. A hurricane gradually dies after it makes landfall.

Hurricanes do not form if the sea surface temperature is cooler than about 26°C, so their range would expand in a warmer world. Also, everything else being equal, warmer sea surface temperatures will make them stronger. But the future of hurricanes is difficult to predict reliably, because their birth and growth are affected by subtleties in the structure of the atmosphere and ocean, which might change in a warmer world. Changes in wind shear are difficult to forecast reliably, meaning that different climate models disagree in how much wind shear in the hurricane growing region and season they predict. The strength of a cyclone also depends on the subsurface temperatures of the ocean, because the wind tends to mix cold water up from below, and on the air temperature near the top of the troposphere. The bottom line is, there are good reasons to worry that cyclones might get more intense with rising CO_2, but the connection is not as simple as, say, the link between CO_2 and global mean temperature.

Model simulated hurricanes are more intense in a doubled-CO_2 world. Ordinary climate models do not have enough resolution, meaning that their grid points are not close enough together, to simulate hurricanes very well. Hurricanes can be simulated in global models, however, by a technique called **adaptive grid refinement**, essentially inserting grid points into a model when and where they are needed. Alternatively you can think of it as running a second, high resolution model in the area where a hurricane is, coupled to and exchanging information with a low-resolution global model. In general, models predict that there will more very intense, Category 5 hurricanes in a high-CO_2 world (Figure 12-4).

The low atmospheric pressure in a hurricane cell tends to raise sea level locally, by pure suction, a phenomenon called a **storm surge**. The storm surge is the aspect of hurricane Katrina that destroyed New Orleans. If storms get stronger, their higher storm surges will add to the impact of higher sea level discussed next.

Ice and Sea Level

There are two reasons why sea level would rise in a warming world. One is the **thermal expansion** of the water. Warmer water expands, filling up the ocean basin like mercury rising in a thermometer. Depending on the amount of warming, and the circulation and mixing in the ocean, the IPCC forecast calls for about 0.1 to 0.4 meters of sea level rise due to thermal expansion alone by the year 2100. This is just the beginning, because it would take centuries to warm the ocean completely. Coupled atmosphere / ocean climate models suggest that a long-term CO_2 doubling might eventually, after a thousand years or so, raise sea level by 0.5 to 2.0 meters due to expansion.

The other component of sea level rise is from **melting ice on land.** There are several functionally different types of ice in the Earth's climate system. **Sea ice** forms from seawater freezing at the surface, and may be augmented by snow that lands on the ice. **Glaciers** are formed from compacted snow on a mountaintop, and flow down mountains like silent rivers of ice (Figure 11-4). **Ice sheets** are larger than glaciers, and are found today in Greenland and Antarctica. **Ice shelves** are pieces of ice sheets that have flowed out onto water, floating but still attached to the ice sheet.

Sea level changes slowly, and will continue to rise for centuries.

Floating ice, the sea ice and ice shelves, doesn't raise sea level when it melts, because the ice already displaces its own weight in water. When floating ice melts, its water exactly fills the hole that the ice had previously occupied. This is **Archimedes' principle.**

Ice on land does increase sea level when it melts. Of the land ice, the ice sheets in Greenland and Antarctica hold most of the water by far. Together, the two ice sheets could raise sea level by about 70 meters if they melted, about the height of, say, a mid-rise 14-story hotel on Miami Beach. The mountain glaciers hold much less ice, about 0.5 meters worth of sea level, but since they're smaller they can respond much more quickly to changes in climate. Today, mountain glaciers are contributing more to sea level rise than the major ice sheets are, and about as much as from thermal expansion.

The ice sheets in Greenland and Antarctica are the slow giants of sea level rise.

The ice in an ice sheet flows, very slowly, from the center where it accumulates as snow, to the fringes where it melts or runs into the ocean and breaks up into icebergs. The air at the base of the **Greenland ice sheet** is close to the melting temperature, and ice sheet models predict that the Greenland ice sheet would eventually melt if the world were about 2° warmer than our natural preindustrial climate (say the year 1950). Melting Greenland would raise sea level by about 7 meters, the height of a two-story building.

The **Antarctic ice sheet** is colder than the Greenland ice sheet, and most of the ice in Antarctica is thought to be relatively stable, not as sensitive to changes in temperature as in Greenland. The vulnerable part of Antarctica is the **West Antarctic Ice Sheet**, which holds enough water to raise sea level by about five meters. This ice sheet is unique in that it is sitting on rocks that are below sea level (Figure 12-5). When the ice sheet first started forming, the bedrock was above sea level, but the crust gradually sank under the weight of the accumulating ice. The crust sank most deeply in the center, so the ice sheet is sitting in a bowl below sea level.

The concern is that a warmer ocean might drive the edges of the ice sheet to melt, allowing it to float free of the bedrock. Floating ice flows much more easily than grounded ice, pulling more ice from the ice sheet. Because the water gets deeper toward the center of the ice sheet, it would get progressively easier for the ice to float free, leading to an accelerating cycle of float, flow, and melt.

There is geological evidence that the size of the West Antarctic ice sheet may have fluctuated in the past, during the warmer-then-today Pliocene time about three to five million years ago. The results suggest that the West Antarctic Ice Sheet might become unstable after 3 °C of warming, a slightly higher trigger than for Greenland.

Overall, the IPCC forecast for the rest of the century is for 0.1 to 0.5 m of sea level rise, approximately half due to expansion and half due to melting of ice, mostly from small mountain glaciers. Models of Antarctica and Greenland tend to predict that it would take thousands of years for these ice sheet to respond fully, and that not much will happen in the coming century. However, recent events, and reconstructions of prehistoric events, give reason to believe that real ice sheets might know a few things about melting that the ice sheet models can't simulate yet. For this reason, IPCC specifically didn't include the possibility of changes in the flow of ice from the sheets into the ocean, what they called "dynamical changes" in the ice, in their latest sea level rise forecast. The forecast comes with a potentially very large asterisk.

Ice on Earth knows a few things about how to melt that we haven't figured out yet.

Ice shelves have demonstrated a dramatic ability to self-destruct catastrophically. A piece of the **Larsen ice shelf** on the Antarctic peninsula, the size of Rhode Island, exploded into a vast expanse of icebergs within a few months in 2002 (Figure 12-6). Ice shelves do not themselves affect sea level when they collapse into bergs and melt, because they were already floating in the water. However, their presence seems to restrict ice flow in the ice sheet further inland.

Within the ice sheet are rivers of ice called **ice streams**, flowing at flowing at speeds of hundreds of meters per year. Upstream of the Larsen B ice shelf on the Antarctic Peninsula, and the collapsing Jakobshavn ice shelf in Greenland, the ice streams accelerated markedly after the ice shelves collapsed. Several of the ice streams draining the West Antarctic ice sheet run into the Ross ice shelf, which is itself within a few °C of exploding like the Larsen ice shelf did.

The significance of iceberg discharge is that it is an extremely efficient method of melting ice. Melting of an ice sheet in place is slow because it takes a long time for the atmosphere to carry that much heat up there. Icebergs move the ice mountain to the sun.

There is also evidence from the pre-historic past of fast ice sheet collapses. The Laurentide ice sheet, perched on North America during glacial time, purged large amounts of ice into icebergs periodically in what are called **Heinrich events**. The primary evidence is the finding of layers of rocks (**Heinrich layers** comprised of **ice-rafted debris**) in North Atlantic Ocean sediments, large enough that they could only have been carried there in floating ice. The sediments tell us that the events lasted a few centuries, and there must have been a veritable flood of icebergs, enough to change the circulation of the North Atlantic and disrupt the climate around the world. The events lasted a few centuries, and are estimated to have raised sea level by something like five meters.

Currently there are no computer models of ice sheets that can reproduce the Heinrich events. There is too much ice-rafted debris spread out over too much of the North Atlantic. Ice sheet models don't collapse that quickly or pick up that much debris. The question is whether the Greenland or West Antarctic ice sheets could similarly collapse in a similar way. Presumably if it started it would be completely unstoppable, running its course over a few centuries. Maybe sea level rise from one collapsing ice sheet could provoke the other to go.

Sea level at any given location on the Earth depends on the total volume of water in the ocean, of course, but also on local geological movement of the ground, up or down. The largest vertical motions on the surface of the Earth today are the result of melting of ice sheets from glacial time. Remove all that weight and the crust will float higher relative to the surrounding crust. There is also vertical motion in other parts of the world that is comparable to the projected rate of sea level rise. Bangladesh is a sad example; the local sinking or subsidence rate of the land there is about 0.5 cm / year, comparable to the projected rate of sea level rise, doubling the inundation that Bangladesh would experience just from the rising ocean.

It may be possible to defend the some of the land against the invasion of the ocean. Much of Holland is located below sea level, and the ocean is kept at bay with dikes and pumps. This could presumably work for Manhattan and New Orleans as well. For Bangladesh and Egypt, where the coastlines are longer, it would be less tractable. A sea level increase of 1 m would inundate about 10% of the farmland in these countries, displacing millions of subsistence farmers. Today the Pacific island of Tuvalu imports food because they can no longer grow their own, due to salt encroachment in their ground water.

The long-term geologic record tells a much more alarming story about Earth's temperature and sea level than one would infer from the IPCC forecast to the year 2100 (Figure 12-7). During glacial climate, temperature was about 6°C colder than today, and sea level 120 meters lower. The Pliocene, 3 million years ago, comes before the time of glacial

/ interglacial cycles, a warmer time with sea level 25 meters or so higher than today.

During times of hot-house climate, say 40 million years ago, the temperature of the Earth was perhaps 4-5°C warmer than today. The sea level 40 million years ago is difficult to pin down because of all the motions of the crust, continental crust bobbing up and down, moving the beaches and corals that we find today down and up in ways that have nothing much to do with global sea level. However, the hothouse world was a time when there were no ice sheets on Earth, which would raise sea level on Earth today by 70 meters if the Earth returned to that climate state.

Eventually sea level could change 100 times more than the forecast for the 2100.

Sea level in the geologic past changed by 10 or 20 meters for each 1° C of temperature change. This is about 100 times more sea level change than the IPCC forecast for the year 2100. The reason for the difference is the presumption that it will take longer than 90 years for the ice sheets to respond to the change in climate.

As explained in Chapter 10 (Figure 10-4), carbon mined from the Earth and emitted as CO_2 to the atmosphere affects climate for tens of thousands of years into the future. Global temperature could remain several °C warmer for thousands of years, plenty of time for the ice sheets to respond. So ultimately, although ice sheets may respond slowly to climate, the carbon cycle is patient and can afford to wait. The target year of 2100 for IPCC forecasting is set by our own life times and the time scale for some kind of conceivable political decision-making. But 2100 is not really the appropriate time scale to discuss the phenomenon of the ice sheets responding to CO_2. It is as if we saw someone standing at the edge of a cliff, contemplating jumping, and we advise that person that in the first 0.1 seconds after he jumped, nothing bad would happen (because the person hadn't hit bottom yet). We would be using an inappropriate time scale to evaluate the situation.

Abrupt Climate Change

An abrupt climate shift would be a surprise, like the ozone hole. Once the climate rearranged into some different mode, it could conceivably remain locked in that mode for centuries. Paleo climate records show sudden flip-flops, where the climate changed in a few years then remained in its changed state for centuries. The ice core record from Greenland shows a period of stability called the **Holocene**, the past 10,000 years when civilization and agriculture developed (Figure 12-8).

Prior to this, during the last ice age 20 to 80 kyr ago, the climate of Greenland was not so stable. Temperatures varied wildly in 1,000 year swings called **Dansgaard-Oeschger events**, sudden warmings of 10-15° C within a few years, followed in general by more gradual coolings. The D-O cycle is punctuated by the **Heinrich events**, times when the Laurentide ice sheet collapsed into bergs in the ocean. The climate impacts of these abrupt climate changes were most intense in the high Northern latitudes, but were felt as far away as New Zealand and Antarctica.

In a way, the IPCC forecasts represent best-case scenarios, because they are smooth, and there are no surprises.

Scientists are still trying to figure out the reasons for all of the variability in the glacial climate (Figure 12-9). The circulation in the North Atlantic is one player. The Atlantic carries a considerable amount of heat into the high latitude Northern hemisphere. Warm surface waters in the high latitudes cool and sink, making way for more warm surface flow, bringing in more heat. Tracers for the circulation and chemistry of the ocean, preserved in sediment cores, show that the climate changes were correlated with changes in Atlantic circulation.

Another ingredient in the climate shifts was sea ice. Cutting heat transport, perhaps capping the ocean with fresh water that would freeze before it would sink, resulted in an expansion of sea ice cover. Ice reflects sunlight, cooling the area down further. Air over sea ice can also get much colder than air over open water can. The climate of Greenland, where ice cores come from, is sensitive to massive sea ice formation because it loses its maritime influence.

The abrupt climate change scenario for the future that people have fretted about is a cousin to the cold configuration of the glacial climate, in which the overturning circulation in the Atlantic slows down, allowing the northern high latitudes to cool. This the “Day After Tomorrow” scenario already mentioned in Chapter 7. The circulation could be impeded by new fresh water input to the North Atlantic surface ocean. The largest potential source of fresh water is the Greenland ice sheet, but it would also rain and snow more in a warmer world.

Current thinking is that the Day After Tomorrow scenario, of a return to an ice age triggered, paradoxically, by global warming, is unlikely, because the warming influence of the rising CO_2 will be stronger than the local cooling influence of changing the ocean circulation. My personal intuition is that looking too slavishly at past abrupt climate changes to predict the future is like a General in an army always planning for the last war. Future abrupt climate changes are going to be surprises, would be my bet.

Biological Impacts

The character of the land surface, for example whether it is hardwood forest or grassland, is determined to a large extent by the local climate. Temperature is important of course, although it may be the coldest temperature of the year that really matters, or the warmest, rather than the annual average. Precipitation also plays a huge role in shaping the natural landscape.

The infinite complexity of the real landscape can be modeled by simplifying it into some manageable number of different biome types, such as "tropical deciduous" or "savanna" (Plate 12-5). Biome models are based on the physiologies of plants of various types, and keep track of plants metabolic energy, water stress, nutrient availability, and soil properties. Different biomes have different capabilities and tolerances, and they compete with each other for land surface area.

The equilibrium biome response to a new climate can probably be predicted fairly confidently, because the distribution of biomes on Earth today is fairly well correlated with climate. The simplest model for terrestrial biomes could simply be a look-up table of the ranges of conditions inhabited by each biome type.

It is more difficult to forecast transitions between one climate state and another. Some organisms, like insects, move easily, but forests have to move by scattering seeds, and a slow process called **ecological succession.** When a forest grows after a clear-cut, for example, the first set of plant and tree species will be different from the species that you would find in an old-growth forest under the same climatic conditions. The process of ecological succession is not trivial to understand in the natural world, which makes it even more difficult to forecast for the future.

The biotic response of a climate model is shown in Plate 12-5. The most striking change in Earth's landscape is in the Arctic. The biome response is strong there because the climate change is intense. The melting permafrost described above also changes the biotic landscape. The model in Plate 12-5 experienced a near total loss of the tundra biome by the year 2300, and the loss of most of it by 2100.

Polar bears are vulnerable to melting sea ice. Polar bears only eat in the winter, by fishing for seals through holes in the ice. In summer, when the ice near the coast melts, the polar bears have to live on their accumulated fat. The polar bear as a species may find refuge in a remnant area of sea ice north of Greenland, but where the ice is gone the polar bears will go locally extinct.

In the ocean, **coral reefs** appear to be particularly vulnerable. Reefs are built by sedentary animals called corals. The corals house symbiotic algae, plants that can perform photosynthesis to aid the nutrition of the corals. Corals almost everywhere in the world are under attack from runoff pollution clouding the water and cutting the algae off from sunlight. Overfishing threatens the coral community, as do diseases and invasive species. In addition to all of these struggles, corals are vulnerable to increases in temperature.

When corals are stressed, they respond by expelling their symbiotic algae. This is called **coral bleaching** because of their loss of color. Bleaching may be a mechanism for the coral to try to find new symbiotic algae that are more suited to the conditions they find themselves in, but it is a measure of desperation. Bleaching is often followed by the death of the coral. Figure 12-10 shows a record of temperatures in Tahiti, with arrows indicating times of coral bleaching events. The correlation between heat spikes and bleaching is very clear. Sediment cores in Caribbean reefs indicate that the degradation of reef communities is more widespread than has been seen in centuries. The projected warming in the future looks like it will have catastrophic effect on corals.

In general, the diversity of life (number of species) on Earth is already decreasing because the natural world is restricted and fragmented by human land use. Climate change can only amplify this extinction trend, by demanding that natural ecosystems get up and move, just when they are restricted by human land use and therefore least able to do so.

Human Impacts

The strongest direct effect of a warming climate on human welfare will probably be due to changes in water availability. The world is drier today than the more natural world of 1950, and would continue drying in a warmer world. A drought of a few years' duration, or a decade, can be endured, but the rearrangements of the climate system in a warmer world could persist for centuries. Adding to the problem would be melting mountain glaciers and snow pack which today serves as a source of summertime fresh water in many parts of the world such as along the Himalayas in India, Pakistan, and Uzbekistan, along the Andes in Lima, La Pas, and Quito, and in the North American Pacific Northwest.

Other aspects of climate changes may also affect crop yields. Corn yields are sensitive to heat spikes; just a few can impact the bottom line for the entire season. On the other hand, increasing CO_2 concentration in the air is expected to boost agricultural production by the CO_2 fertilization effect (Chapter 10). Higher CO_2 levels help plants deal with water stress by allowing them to get the CO_2 they need for photosynthesis without opening their stomata as much. Another factor that is important in the forecast is adaptation. Perhaps if corn no longer grows in a region because of frequent heat waves, the farmer will plant some other crop that is more heat tolerant.

The story of agriculture in the past century has been explosive, with production growing even faster than population, at ever diminishing costs. The agricultural revolution is in large part due to industrial production of fertilizers like nitrate and ammonia from atmospheric nitrogen, an energy intensive process. The great success of the agricultural revolution seems to argue against worrying about a collapse in global food production.

On the other hand, agricultural yields and the number of people that the Earth can support are products of the infrastructure of our civilization: fertilizers, transportation, and processing of the food. If that infrastructure broke down, it could lead to a collapse of the human population. It has happened before, to the Classic Mayans for example. Sustained regional drought or coastal flooding from a storm surge with rising sea level could lead to distressed migration of millions of people, which would stress the ability of civilized governance to cope. How many of us would survive if there were no food delivered to the grocery stores?

There is a concern that rising temperatures will widen the area where tropical diseases such as **malaria** and **dengue fever** will spread. Both have a significant impact on public health, and both appear to be spreading with an increase in the tropical zone of the Earth. It must be said here that malaria could be fought much more effectively than is currently being done everywhere, with mosquito nets and health care. I guess my personal feeling is that the spread of tropical diseases is a serious threat, but it is not the first and most important reason to combat global warming.

In general, the impacts of a changing climate are expected to become stronger as climate warms more intensely, and become more clearly negative at higher temperatures. The impacts would be stronger in the tropics and in the developing world, where there is less wealth to buffer setbacks from the weather, and less infrastructure to deal with the aftermath.

Take-home points

Climate models that simulate the past predict huge climate changes in the future, relative to what civilized humanity has ever seen before.

Drought is one of the most dangerous aspects of climate change, as continental interiors warm and dry out, in spite of a global increase in the amount of rainfall overall.

The intensity of extreme weather events is already getting stronger, and is expected to continue.

Sea level will continue to rise for centuries, from thermal expansion and melting land ice.

Study Questions

How can the forecast talk about increased rainfall globally and also increased drought?

What is the role of vegetation in a drought?

Why would storminess increase in a warming world? What kinds of storms are they talking about?

What are the factors that would increase the risk of storm-surge flooding associated with tropical storms?

Why do some kinds of ice on Earth change the sea level when they melt, and other kinds not?

Why does sea level take so long to respond to climate?

How do reconstructions of sea level changes in the geologic past compare with the forecast for the year 2100? Why?

Further Reading

For a street-level description of what climate change might be like, see **Six Degrees, Our Future on a Hotter Planet** (2008) by Mark Lynas.

Kolbert, E. **Field Notes from a Catastrophe** (2006).

Emanuel, K. **Divine Wind** (2005) about hurricanes. This is an elegant treatment of the history and physics of hurricanes written by the guy who, well, wrote the book on hurricanes. The book is replete with color photos, plots, and paintings, with a few equations and many quotes from antiquity.

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Figure Captions

1. Model global temperature predictions for the coming century for several different CO_2 emission scenarios labeled B1, A1T, and so on. These are all business-as-usual scenarios with no effort assumed to slow CO_2 emissions for the climate’s sake, but they make different assumptions about future trends, along the lines of the Kaya Identity equation in Chapter 9. They grey shaded areas show the likely ranges of the responses, based on model results (the bars on the right) plus observational estimates of the climate sensitivity.

2. The atmospheric circulation and the rainfall forecast.

3. The frequency of different intensities of hurricanes through the last decades, from Webster [2005].

4. The distribution of wind speeds in model hurricanes, for a control world (natural climate) and doubled CO_2. From Knudson and Tuleya [2004].

5. A cross-section through the West Antarctic Ice Sheet, redrawn from Oppenheimer [1998].

6. Satellite images of the Larsen ice shelf on the Antarctic Peninsula. A huge area of ice shelf exploded in to ice bergs in just a few weeks.

7. The relationship between sea level and temperature on geologic time scales. The IPCC forecast for the year 2100 is for less than one meter of sea level rise, whereas the geological reconstructions suggest that if the Earth stayed 3 °C warmer for long enough, sea level could rise by something like 50 meters.

8. Temperature reconstruction from Greenland, from the GISP II ice core.

9. How the overturning circulation in the North Atlantic might affect the climate.

10. Coral bleaching events in Tahiti. Bleaching events occur whenever temperature exceeds a threshold value. A future warming of 2.5°C would be very large compared to the coral stress level. From Hoegh-Guldberg [2005].

Plate Captions

1. Maps of climate model annual mean temperature, from the CCM3 Browser at the book web site. Data from Bala et al [2005].

2. Maps of climate model temperature changes from the year 2000, from the CCM3 Browser at the book web site. Data from Bala et al [2005].

3. Maps of climate model precipitation in the year 2000, and precipitation changes from the year 2000, from the CCM3 Browser at the book web site. Data from Bala et al [2005].

4. Precipitation changes predicted by the IPCC AR4 suite of 22 climate models from around the world. From Solomon et al. [2009].

5. Maps of climate model biome types, from the CCM3 Browser at the book web site. Data from Bala et al [2005].

Exercises

Point your web browser at http://understandingtheforecast.org/Projects/bala.html . The physics part of the model, temperatures and winds and currents and all that, was described in the Projects section of the last chapter. In addition to that, the run had a land biosphere model, developed at the University of Wisconsin in Madison. Plants on land are described by 16 different biome types, which compete with each other for the land surface. The biomes are listed in Figure 12-16. The run also used a simple groundwater scheme, much simpler than real soils. Instead of allowing groundwater to flow as happens in the real world, model soils collect water and allow it to evaporate, like a bucket. If too much water accumulates, it will overflow into rivers and to the oceans.

You can see annual mean surface temperatures, and mean surface temperatures for December through February, and June through August. You can also see precipitation, soil moisture content, and vegetation type.

Use the different data-processing and visualization tools described in the Chapter 11 Exercises section to investigate the following questions.

(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".

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

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

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

Chapter 13. Decisions, Decisions

It's not technically or economically too difficult, but it will be hard to make the decision.

Global Warming is a Large-Scale Problem

Global warming is a difficult problem to cope with politically because its footprint is so large. It is a global problem, subject to an effect known as the **Tragedy of the Commons.** An example of this effect is of a field for grazing sheep used in common by all residents of a village. Let's say that each new sheep added to the flock decreases the harvestable weight of each of the other cute little sheep by 10% (Figure 13-1). A farmer with one sheep can add a second, doubling his number of sheep. But the result is that all sheep, including the farmer's, lose 10% of their harvestable weight (denoted as "lamb chops" in Figure 13-1). Each will provide 0.9 times as many lamb chops as the original sheep did, so the farmer will now own the equivalent of 1.8 of the original-sized sheep. Our farmer is better off than when he only had one sheep, while all the rest of the farmers lose 10% of their prior sheep stock.

In this particular example, there is an overall optimum number of sheep to graze on the common, which will result in the greatest overall number of lamb chops. That optimum number of sheep turns out to be about six. If we compute the self-interest of our individual farmer now, let's assume he has one of the six already. The farmer's sheep is worth 0.5 lamb chops at this sheep density. Our farmer buys one more, and in the end has 2 sheep that will each produce 0.4 lamb chops, for a total of 0.8 lamb chops. It turns out to be in the farmer's self-interest to add sheep, up until there are 9 sheep on the yard.

Competing interests using a shared resource will tend to over-exploit the resource.

The point is that each farmer's personal best interest is served by grazing as many sheep as he or she can afford, without regard to the damage to the field. This results in a tendency to overgraze. From each farmer's point of view, the other villagers are all also overgrazing the common yard, so his own personal sacrifice, to preserve the common, would be in vain anyhow, and would put his family at a disadvantage. The end result is far more sheep than can be most efficiently supported on the common, decreasing the net yield of sheep in total. Everyone might be better off if they backed off a little bit and cooperated.

There are two potential approaches to preserving the common space. One is to divide it up and assign property rights to individuals. In this case, each individual would have the incentive to preserve the field by not overgrazing, because that individual would directly benefit from careful stewardship.

However, for land stewardship, private ownership is not a universal environmental panacea, because some element of commonality remains. The aquifer holding water underneath the ground may be over-tapped, or soils may be depleted throughout the lifetime of the individual (a sort of commons over time). For fisheries, the ownership society system has holes in it because fish swim around. For the case of global warming, dividing the atmosphere up into parcels is impossible by the nature of the problem. The other potential solution is for some form of collective self-regulation (see Negotiations section).

The decisions made by a single individual are often irrational, and therefore not really well described by economic theory. The collective decisions made by whole societies of individuals, in contrast, often exhibit great sagacity. Economics aficionados speak with reverence of the **market**, economist Adam Smith's "invisible hand". The market with its law of supply and demand is a negative feedback system, just like the many natural examples in Chapter 7.

However, the market has its blind spots, leading to effects like the tragedy of the commons. In economics, a cost that is not paid by the decision maker is called an **external** cost. An example of an external cost associated with driving to work is the traffic. One more car will tend to slow down all the other cars on the road, costing other drivers their time. The cost of climate change is not only paid by people who are responsible, but by everybody, soon and far into the future. Our sheep farmer made the other farmers pay part of the cost of his new sheep. If true costs are left external, then the economic balancing act of the market does not take them into account, and tragedies of commons are the result. An external cost can be **internalized** by means of taxes or regulations. The idea is to make the market aware of the true cost of a decision to take this path versus that path.

Cap-and-trade and carbon tax would both tend to bring the cost of common environmental damage into a private decision to emit CO_2.

One way to harness the balancing abilities of the market for preventing global warming is a scheme called **cap-and-trade.** A regulatory agency allocates permits for emission of climate forcing agents such as CO_2, with the total number of permits they issue totaling some lower overall rate of emission than business-as-usual. If a company or a country is able to cut its emissions to even lower than its allocation, it has the right to sell its allocation in what are called **carbon offsets.** Some companies already exist whose function is to sell carbon offsets, using the money to find ways of cutting CO_2 emissions. The price of the permits is set by supply and demand, same as any other commodity. The industry for which it is most expensive to reduce emissions would be willing to pay the most for the emission permits. It will induce other industries to reduce their emissions, because they can make money doing it, selling their permits to the highest bidder.

In this way, the market finds the most efficient, that is to say cheapest, means of limiting global CO_2 emissions to the cap value. A cap and trade scheme for sulfur emissions (generating acid rain) from power plants in the United States has worked well, cutting emissions far more cheaply than anyone had projected. The difficulty with cap and trade for a regional problem like acid rain is that it may allow all the pollution to concentrate in one region, which may be too much for that region. CO_2 is a truly global problem, in contrast, and it makes no difference where the CO_2 is released, so CO_2 emissions would be an ideal problem for limitation by cap-and-trade.

A disadvantage of cap-and-trade is that it seems inherently slippery, as if it could reassure people without actually solving the climate change problem. One can buy carbon offsets today on various private markets, and they are absurdly cheap. An American can theoretically eliminate his or her carbon footprint by buying a few hundred dollars worth of carbon offsets per year. However, if the entire country wanted to go carbon-neutral, it would cost much more than a few hundred dollars per person. The price discrepancy is because the carbon offsets available now are based on what is called low hanging fruit, the cheapest carbon emissions to eliminate. So in an overall sense, the buyer of the offsets is not really paying the true cost of their carbon emission. Cap-and-trade might also encourage richer nations to continue emissions, because they can afford to.

The alternative strategy is to **tax** carbon emission, using the tax code to internalize the costs of the environmental damage. In the end, carbon tax and cap-and-trade accomplish the same thing, but the tax specifies the price and allows the market to choose the emission, whereas cap and trade sets emissions and lets the market choose the price. A carbon tax is easier for a company to plan for financially, and may have more stability than the effects of cap-and-trade, encouraging the company to invest in reducing emissions rather than speculating on the future of the carbon market with cap-and-trade. On the other hand, it is impossible to know in advance what tax rate would be required to reach particular rate of carbon emissions. A carbon tax would have to be tuned repeatedly if it is to achieve a pre-defined cutback of carbon emissions.

The market may influence the global warming debate through the insurance industry. The last few decades have seen a huge increase in insurance payout to cover atmospheric-related natural disasters. It is not at all clear to what extent this trend is due to climate or to social factors, but the insurance industry is certainly concerned about the possibility of climate change affecting their bottom line. Insurance companies have been responsible for other preventative measures, such as requirements for hard hats on construction sites.

Pollution problems get more difficult to solve, politically, as their footprints expand from regional to global, because of the commons effect. Local issues like contaminated drinking water or urban smog are clearly in the interests of local individuals to solve. You fix it, just as you would fix the roof over your head. A clear link exists between the costs of cleaning up and the benefits. Larger-scale, regional problems tend to run into us-versus-them issues. Why should the state of Ohio sacrifice their right to burn high-sulfur coal when the costs of that consumption are paid by the folks in New York? Why should power plants in Chicago pay to clean up their mercury emissions when most of the mercury emission to the atmosphere comes from China? At the most difficult, worst end of this problem, global warming is the most global of issues, the most complicated type to solve.

Global warming is also a difficult issue to address because it is long-term. Values need to be related not only from one place to another, but across time. The way that economists deal with values across time is via a construct known as a **discount rate**. The idea is based on a question: which would an individual prefer, a cost today or a cost in the future? A cost in the future, certainly, would be the natural response. A rational reason to justify that choice is that one could invest money today and use the interest to help pay the costs in the future. If we were to assume an interest rate of say 3% per year (above the rate of inflation), we could pay a cost of $100 in 100 years by investing $5 today (Figure 13-2). It would be worth paying $4 today to avoid a $100 cost in 100 years, but it would not be worth paying $6 today. The bottom line of this idea is that costs tend to shrink as they get further off into the future.

Of course, the idea of anybody actually going out and opening a bank account with $5 in it, to save for that cost in 100 years, seems rather quaint. However, economic theory is more than just a prescription for how one could rationally make the most of one's assets; it is also a description of how money tends to flow in our society. The discount rate theory illustrates why financial decisions made by the market tend to be somewhat short-sighted. It's a description of the way money flows. Water flows downhill. Money flows short-term.

Negotiations

In 1988, agencies of the United Nations formed the Intergovernmental Panel on Climate Change. The role of IPCC is to assess "the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation".

Climate science is such a vast field that it is difficult for a single person to know it all. But it has been summarized and integrated by the IPCC.

The purpose of the IPCC is to publish reports summarizing the scientific literature. These reports are divided into three topic areas, written by different working groups. Working Group I deals with the scientific basis for the climate change forecast. WG II deals with the impacts of climate change on the natural and human world. WG III assesses options for limiting greenhouse gas emissions or otherwise avoiding climate change. The most recent reports from all three are available on line at http://www.ipcc.ch/ .

The reports consist of chapters and various levels of summaries. Much of the work of writing and reviewing the documents is done by researchers at universities, not necessarily employed by any government. The rules are that the chapters may present no previously unpublished research, but are based only on published, peer-reviewed scientific papers.

Of course, not every paper published in the scientific literature is guaranteed to be correct in every way, but the practice of sending manuscripts out to rival scientists for review makes sure that most of them are at least plausible. If a scientist disagrees with a paper that has already been published, he or she is free to write another paper attempting to disprove the first. Papers are sometimes retracted by their authors if they are proven wrong, or sometimes a disagreement just festers in the literature, requiring judgment on the part of the readership to decide which is more likely to be right or wrong.

Once an IPCC chapter is drafted, the chapter is subject to another round of reviews by scientific experts and government workers. The chapters are grouped together into books which also come with technical summaries and summaries for policymakers. These summaries are subjected to line-by-line review, voting, and approval by the entire IPCC Panel. This is a long and painful process!

The conclusion of the first, 1990, IPCC report was that it was not yet possible to detect human-induced global warming. This was largely because the climate models were driven at that time by the observed rise in CO_2 and other greenhouse gases, without regard to aerosols, the other human impact on climate, and changes in solar intensity, so the model temperatures didn't fit reality very well. By 1995 these effects had been added, and the models fit better. In addition, the spatial patterns or **fingerprinting** of the temperature changes, such as an observed cooling of the stratosphere, fit the signature expected from greenhouse gas forcing of climate. The 1995 report issued a now-famous statement that "the balance of evidence suggests a discernable human influence on global climate", thus providing the impetus for drafting the Kyoto Protocol in 1997.

Negotiations to limit CO_2 emission began with a document called the **Framework Convention on Climate Change** or **FCCC** that was drafted during the Earth Summit meeting in Rio de Janeiro in 1992. The objective of the FCCC was to achieve “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” FCCC deferred defining what the dangerous concentration would be, a discussion that continues to this day.

Countries have started talking to each other about avoiding climate change, but they haven’t done much of it yet.

FCCC established a procedure for negotiations by setting up a series of meetings between countries, called **Conference of Parties** or **COP** meetings. FCCC also established a procedure for creating amendments to itself, the most famous and significant of which was drafted during the COP-3 meeting in 1997 in Kyoto, Japan, called the **Kyoto protocol**. The Kyoto protocol attempted to limit global CO_2 emissions to about 6% below 1990 emission levels, by the year 2010.

The treaty came into force when countries accounting for 55% of CO_2 emissions globally agree to its terms. The United States withdrew from negotiations under the Bush administration in 2001, presenting a fairly sizable obstacle to achieving this target, seeing as how the United States accounts for 25% of CO_2 emissions. In spite of this setback, the agreement came into force when Russia agreed to the Kyoto protocol in 2005. Unfortunately, the agreement has to no real teeth, and the rate of CO_2 emission has grown with time, rather than declined. In fact, emissions are higher today than the most aggressive-growth business-as-usual scenario from the year 2000, called the A1F1 scenario.

The Kyoto Protocol expires in the year 2012, and there are COP meetings every half year or so with the aim of negotiating a successor agreement. So far progress has been slow. In fact, the Montreal Protocol, an agreement to limit Freon emissions to save the ozone in the stratosphere, arguably has done more to slow global warming than the Kyoto Protocol has!

One line of dispute can be drawn between the rich industrialized and developing nations. Historically most of the fossil fuel emissions have come from industrialized countries, although Brazil comes up as a large historical emitter when carbon release from land-use changes are also considered. The developing nations argue that it would be unfair to base national emissions allowances in the future on past emissions, because it would be carving into law the imbalance between industrialized and developing nations. We have seen in Chapter 10 the intimate relationship between CO_2 emission, energy, and economic activity. Within our current technological stage of development, CO_2 emission is the key to national wealth and comfort. The developing world understandably wants these benefits also, and can claim that capping their emissions according to current emissions would be unfair.

On the other hand, emissions are growing rapidly in China and India, and China has recently surpassed the United States as the largest national emitter of carbon. This is the emission of carbon for the whole country, so the emission rates per person are still ten times lower in China and India than in the U.S. Even so, stabilizing the atmospheric CO_2 concentration will require emission restrictions from the developing world too; restrictions on the rich nations alone would not be enough.

Economics

One way to approach the decision of whether to limit CO_2 emissions is based on economics. Which path costs less, to prevent climate change aggressively or instead to endure it?

A caveat: the economy is much harder to forecast than climate. Physical sciences are based on a solid foundation of natural laws such as Newton's equations of motion, conservation of energy, and so on. It is not always possible to derive the physics of climate solely from these natural laws. Higher-level processes like turbulence and clouds are called "emergent behavior", surprisingly difficult to build from the fundamental laws of physics. But at least the foundation exists.

Economics is a somewhat awkward tool for environmental decision-making.

In contrast, economics and the other social sciences are not as securely founded. Economic trends are strongly impacted by technological progress, which is impossible to forecast, and by social and political fancies. One could even argue that economics is pathologically unforecastable because it is self-aware. If I came up with a model that could successfully forecast stock prices, I could use it to make money, until everyone else discovered my methods. At that point, the stock prices would reflect everyone's knowledge of the model forecast, and the future trajectories of the stock prices would alter to evade my forecast. I wouldn't make money any more. Not even on my darkest days do I imagine that the physical world that I model for a living is going to change its behavior for the purpose of making my model wrong!

Economics is an awkward tool for the climate change decision, because many aspects of the natural world are simply not economically fungible. The economic value of coral reefs could be tabulated as the tourist dollars they generate, same as Euro-Disney, but somehow something is missing in this tabulation. If coral reefs cease to exist because it gets too hot, we cannot purchase more coral reefs for any amount of money.

The bulk economic framework also hides an issue of fairness, in that people who benefit from business-as-usual are not the same people who pay for business-as-usual, say by living in an increasingly drought-prone world far in the future. I imagine that giving up the institution of slavery in the United States entailed a cost, too, for somebody. Ultimately the abolition of slavery was not an economic decision, but an ethical one.

In general the costs of climate change are predicted to be non-linear with temperature increase. A small increase in temperature, say 1° C or less, will probably not do too much damage, and may even be beneficial on the global average. As the temperature rises to 2° or 3°C or higher, however, the economic impact starts to rise sharply. This is true for many aspects of climate change: farming, sea level rise, health impacts, and the possibility of abrupt climate change.

While economics is not really well suited to computing a cost of climate change, it can be used at least in the short term to estimate the costs of reducing carbon emission from human activity. The reports written by Working Group III of the IPCC are devoted to this question: the technology and economics of reducing, or "**mitigating**", the human impact on climate.

There are more and cheaper CO_2 emission cuts possible in the next few decades from improvements in energy efficiency than there are from new alternative energy sources.

The results of the 1300-page Working Group III report are summarized in Table 13-1, a listing of options for reducing carbon emission from different sectors of the economy. In each category there is a quantity of carbon emission cuts, or of the equivalent amount of some other greenhouse gas, usually methane, available today for a specified cost of \$366 per ton of carbon (which comes to \$100 per ton of CO_2 molecules). The time window for this table is now to the year 2030.

Most of the potential emission savings in this time frame comes from improvements in energy efficiency rather than changes in where energy comes from. There are six entries in Table 13-1, all comparable in magnitude of about 1 Gton C per year. One of these is driven by changes in **energy supply**, and the other five all have to do with **efficiency.** One of the entries, energy use in **buildings** (heating, lighting, and air conditioning), actually has negative costs for a substantial fraction of the emissions cuts, changes like improved insulation and lighting, which would save money over the long run rather than costing extra.

In aggregate, averting climate change is projected to cost a few percent of the global domestic production, **GDP**, a measure of economic activity. A few trillion dollars per year is a lot of money, but this cost would probably not be noticeable to people in their everyday lives. It would be comparable to the cost of a major war, such as the American involvement in Iraq. Perhaps the average citizen of the U.S. would be financially better off if that war had never started, but it is purely hypothetical, because that other world does not exist.

The GDP of the Earth is growing every year by an amount comparable to the projected costs of clean energy. A GDP growth rate of 3% per year sounds small, a few pennies out of a dollar, but yet somehow that economic growth has a huge impact on people's livelihood and sense of prosperity. If the economy grows by 5% each year everyone gets rich and shoe-shine boys trade stock tips. The great depression decreased global productivity by about 25%. The reunification of Germany put a drain of about 5% on the GDP of West Germany, producing noticeable malaise among West Germans.

Let's compare two hypothetical worlds, with and without cuts in CO_2 emissions, in Figure 13-3. The CO_2-abatement cost is like a tax, applied to all the money that we make, every year. When we put together the 3% cost and the 3% / year growth rate in GDP, we see that the effect of the cost would be to set everything back about a year. A person would only get $97 this year instead of $100, for example, because of that 3% cost. But by next year, the economy will have grown to $103, and she would get her $100, just one year late.

Costs of avoiding climate change would be comparable to the costs of deciding to go to war – significant but not prohibitive.

A 3% cost only slows the actual growth rate of the GDP from our baseline growth of 3% per year to an adjusted growth rate of 2.91% per year. In the long run, this does not seem like a long-term catastrophe to a naïve non-economist like your author. To an Earth scientist, any positive exponential growth like this is an explosion, whether it explodes quickly or slow, it cannot persist forever.

Although current negotiations are far from the ultimate goal of preventing climate change, a strong agreement does provide the benefit of guiding investment toward decreasing CO_2 emission. Coal power plants, for example, can be built using newer technology called "integrated gasification combined cycle", enabling future CO_2 capture for sequestration into the geological repositories. If CO_2 is released to the atmosphere, IGCC plants cost about 20% more than traditional plants. If CO_2 sequestration starts to be common practice, however, IGCC plants would be cheaper overall than traditional plants. In the regulated United States energy market, regulators often require power companies to use the cheapest technologies. In general this rule makes sense, if we want to limit the power of monopoly power companies to spend money wantonly, passing the costs on to their captive customers. But in this case, the cost of climate change is external to the accounting, and so the regulation may not be choosing the overall cheapest option. Once a power plant is built, it has a life span of fifty years or so. The ultimate costs of decreasing CO_2 emissions would be lowered by starting now, rather than continuing to invest in high-emission technology.

Dangerous Anthropogenic Interference

Our discussion so far this chapter has centered on what can be done to limit CO_2 emissions at what cost. The other end of the question is, What would it take to really avoid changing Earth's climate too much? The goal of the Framework Convention on Climate Change is to "prevent dangerous anthropogenic interference with the climate system", but the FCCC didn't specify what dangerous interference is, leaving that topic to future discussion, which is still ongoing.

The most basic metric of the changing climate is the change in the average temperature of the Earth. Negotiators have been using a temperature change of 2 °C as a benchmark target. Mostly this temperature change was set by comparison with global temperature changes in the past. It is probably as warm today or warmer than it has been throughout the history of civilized humanity and agriculture. Global mean temperature may have been 1.5°C warmer during the last interglacial period, 120,000 years ago, or the last time the Earth's orbit resembled the way it is today, a time called Stage 11, which was about 400,000 years ago. A human-induced warming of 2 °C would make the Earth warmer than it has been in millions of years. The 2 °C limit is not really a "danger limit", in that a temperature change of 1.9 °C still seems plenty dangerous. But the projected damages tend to go up pretty drastically with warming greater than 2 °C, so that amount of warming provides a benchmark to talk about what it would take to avoid going past.

Jim Hanson [2004] argues for 2 meters of sea level rise as a danger limit. The IPCC forecast for sea level rise is about half a meter in the next century, detrimental but not yet a show-stopper according to Hanson. But if the oceans were to rise by 2 meters, a serious amount of land would be lost. The longer-term trends from the past (Figure 12-8) seem to predict tens of meters of sea level change with long-term doubling of CO_2. Hansen argues that the past would suggest the possibility that 1°C temperature increase beyond today might exceed his 2 m sea level danger limit.

The other issue is how fast the temperature change occurs. The FCCC document states that warming should be slow enough for ecosystems to adapt naturally, with no threat to food production, "and to enable economic development to proceed in a sustainable manner". In other words, the transition to a new climate regime should be slow enough for natural and human systems to adapt. Here again history can be a guide. The trick is that temperature changes in the past tend to be faster for short periods of time, but when averaged over longer periods of time the rates of change tend to be slower. Comparisons must be made over similar stretches of time.

The current rate of warming globally over the past decade is 0.2°C per decade: higher than this in some locations. The rate of change averaged over multiple decades drops to 0.1°C per decade on average. Historically, warming at 0.1°C per decade is a fairly unusual warming. Based on this, a science advisory ground, the German Advisory Council (http://www.wbgu.de) concludes that 0.2°C per decade seems about the upper safe limit to the long-term temperature rise.

The next tasks are to figure out what the climate change targets mean in terms of atmospheric CO_2 concentration, and then what CO_2 emissions would stay within that atmospheric CO_2 limit, then finally to changes in energy policy to keep within those carbon emissions. As a first step, the climate sensitivity can be used to predict the eventual warming that would result from increasing atmospheric CO_2 for a long time, say a few centuries (Chapter 4). According to equation 4-1, a temperature change of 1°C is already in the works from our pCO_2 concentration of 385 ppm; 2°C would be generated by pCO_2 of about 450 ppm, and 560 ppm would generate about 3°C (Figure 4-7).

To relate atmospheric concentrations to the allowable emissions, the initial approach was to construct what are called **stabilization scenarios**, somewhat arbitrary but reasonable-looking trajectories for the CO_2 rise in the atmosphere, ending up at stable concentrations of 350, 450, 550, 650, or 750 ppm.

A few decades ago scientists seemed to treat 550 ppm as a good CO_2 target, about double the natural value of 280 ppm, but this has been ratcheting down as the climate has actually started to change. Limiting the warming to 2 °C would require a limit of roughly 450 ppm. Now many scientists are embracing 350 ppm as a real “danger limit” CO_2 concentration, as articulated again by Jim Hansen. The idea is that the Earth would continue to warm even if CO_2 remained at its current 385 ppm and didn’t rise any further, as the so-called committed warming materializes. Dangerous changes in climate are already underway, his reasoning goes, in the form of droughts and general storminess. Preventing the committed further warming would require backing the atmosphere down from 385 to 350 ppm.

We may already be past a reasonably defined “danger limit”.

Carbon cycle models can be used to predict how much carbon would be taken up into the ocean and the land surface. But it was discovered that the details of the carbon emissions you could get away with, whether cuts have to be made this year, versus in the next decade or several decades into the future, depends a lot on the details of the CO_2 rise in the stabilization scenario. It was very confusing; the scenarios didn't really answer the more pressing question of how deeply carbon emissions had to be cut, and how soon, in order to avoid exceeding the climate change benchmark.

The picture gets clearer if we frame the question in terms of the total human-released carbon slug, and just ask about the maximum warming at the peak. A lot of the complexity of the carbon cycle and climate system cancels out this way.

One piece of the story is that if CO_2 is released more quickly, the oceans and land surface would lag behind, so that the airborne fraction of the released CO_2 would be higher. A higher airborne fraction tends to increase the warming you get.

Compensating for this is the time lag between rising CO_2 and the changing climate. It takes decades, even centuries, for the climate of the Earth to respond fully to a change in atmospheric CO_2 concentration, mostly because of the thermal inertial of the oceans. A fast CO_2 release would have a somewhat lower climate impact than a slower one, because the CO_2 reaches the peak and starts back down sooner for the fast release.

When these two competing effects are put together, it turns out that they more or less compensate for each other, so that the peak temperature change that the Earth will ever see doesn't really depend on how quickly the carbon is released. Framing the question this way doesn't answer the question of how much carbon needs to be cut today versus in a decade or a few decades. But it says that if carbon is emitted now it cannot be emitted later, a zero-sum game that could be used as the basis for carbon emission regulation.

Slug theory -- the amount of warming at the peak warming is determined by the total amount of CO_2 ever emitted by humankind.

So far, humankind has combusted about 300 Gton C worth of fossil fuels, and deforested about another 200 Gton C worth of trees, for a total of about 500 Gton C. It turns out that limiting the peak warming to 2 °C requires limiting the total slug of carbon to about 1000 Gton C, more or less. So we are half-way there.

Our current rate of carbon emission is about 10 Gton C per year, so we could go for perhaps 50 years if the rate of carbon growth held steady, and then it would have to drop immediately. But the rate of CO_2 emission is growing rapidly, projected to double by mid-century under business as usual. In that case we would run into the limit sooner, say in 30 years. Both of these scenarios require the emissions stop cold turkey when we reach the limit, which is not very realistic.

If instead we imagine that at some point in the future, the rate of CO_2 emission begins to decline at some rate, the trajectories would look like Figure 13-4a. The total slug of emitted CO_2 is proportional to the area under the curve. Start now, and we could get there with cuts of 2% per year, but if growth continues for twenty years, the cuts have to be sharper (Figure 13-4b). Because cutting emissions requires changing infrastructure, faster cuts would cost more. The situation is like a term paper assignment for a class that has some flexibility in the due date, but if you hand it in late it has to be longer.

Alternatives

The on-line model for the Kaya identity in Chapter 9 (http://understandingtheforecast.org/Projects/kaya.html) can be used to estimate how much carbon-based energy would have to be replaced by carbon-free energy to achieve atmospheric stabilization.

The Kaya model makes a forecast of energy use and carbon emissions based on past trends, what is called business as usual. The resulting CO_2 rise is shown in the middle panel of Figure 9-14, along with atmospheric CO_2 trajectories of the CO_2 stabilization scenarios. The bottom panel of the figure shows how much carbon-free energy would be required to get from business-as-usual to each of the stabilization scenarios. The calculation assumes that the carbon-free energy is replacing coal. To stabilize at 450 ppm would require about 17 terawatts of carbon-free energy by the year 2100. For comparison, mankind is currently consuming about 13 TW of energy.

The biggest short-term opportunity is conservation. The United States uses twice the energy per person as is used in Europe or Japan (Figure 9-11). In part this is because the human terrain of the United States developed in a more automotive way, while public transit and trains are better developed in Europe and Japan. In addition, Americans drive larger cars and live in larger houses.

The easiest cheapest solution for now is energy efficiency, out in front of new energy sources.

On the other hand, it seems unlikely that conservation alone will solve the world's energy problems. Most of the world lives at a standard far below that of Europe or the United States. If the citizens of the developing world ultimately consume as much as the American model, the footprint of humanity on the Earth would increase by about a factor of five. Projections of energy use in the future already assume continued increases in energy and carbon efficiency, and still predict a thirst for energy that results in higher CO_2 concentrations than the stabilization scenarios.

None of our traditional sources of carbon-free energy seems capable of making up the shortfall for the coming century by itself [Hoffert et al., 2004; Pacala and Socolow, 2004]. So the strategy has been devised of dividing up the emissions cuts into manageable pieces called "wedges", each of which ramps up from nothing today to savings of something like1 Gton C per year by 2050 (Figure 13-5).

The first option that seems to come to people's minds is **nuclear energy**, because it generates no carbon, and we know it works. The French are using nuclear for more than a third of their energy needs. However if we want to generate 17 terawatts of nuclear energy, using present-day standard 1000 Mwatt reactors, it would require 17,000 new reactors within 100 years, for an average reactor construction rate of about one new reactor every second day, continuously, for 100 years. That seems like a lot of nuclear reactors, or else of reactors much larger than today's.

Wedge theory – no single change in infrastructure can accomplish the goal.

It is a close call whether or not there would be enough minable uranium to support this level of nuclear energy production. The global inventory of minable uranium today would be sufficient to generate 10 terawatts of energy at our current efficiency for a few decades before it would be exhausted. However, uranium today is rather inexpensive, and we only bother to mine the purest uranium deposits, because production of nuclear energy is limited by supply of reactors, not by supply of uranium. We could move to lower-purity uranium deposits. Ultimately it may be possible to extract uranium from seawater, where it is present in huge amounts but at very low concentrations.

In addition, it is theoretically possible to stretch the energy yield of natural uranium by converting it to plutonium in what is known as a **breeder nuclear reactor**. This increases the energy yield from the uranium by about a factor of 50, but the downside is that it is very easy to produce nuclear weapons from plutonium. For this reason, breeder nuclear reactors are not used today.

Windmills are becoming economically competitive with new traditional power plants. Windmills supply 7% of the energy needs of Denmark with no adverse impact on the beauty of the landscape of Denmark in my opinion. Wind energy currently accounts for 0.3% of energy globally and is growing at 30%/yr. At this rate wind could supply 10% of the world's energy within the next couple of decades. Scaling up current wind energy production by a factor of 50 would generate about 2 terawatts of energy.

Both surface wind and solar power share a technical difficulty that energy must be stored, because periods of maximum power demand may not coincide with times of maximum windiness or sunshine. To some extent, solar and wind technology complement each other, in that when the sun isn't shining, the wind is more likely to be blowing. Another way to deal with this problem is to improve the power grid, so that electricity could be efficiently transported farther around the world.

It may be possible to extract energy from winds at high elevations in the atmosphere. Winds get faster with altitude in the troposphere, peaking in the jet stream winds in mid-latitudes of both hemispheres. The air up there is at lower pressure than down here, and so therefore has less density to drive wind blades, but still the power density is much higher at high altitude than it is at the Earth's surface. Wind energy collectors could function like giant kites tethered to the ground by electrically conducting cable, remaining aloft passively by riding the wind. It has been proposed that high-altitude windmills could scale up to tens of terawatts of energy (http://www.skywindpower.com).

The sun bathes the Earth in energy at a rate of about 173,000 terawatts, enough to power all of our energetic ambitions 10,000 times over, but the difficulty is that the power is spread out over the entire Earth's surface. Photosynthesis manages to capture about 100 terawatts globally.

There are two technologies for extracting electricity from sunlight, solar thermal and photovoltaic. **Solar thermal** is the lower-tech of the two, concentrating the solar power with mirrors into a stream of water, which is converted to steam and used to power an electrical generator. It is similar to a traditional coal plant except that it uses the sun instead of coal to make steam. Because it relies on mostly established industrial technology, commercial-scale solar thermal plants can begin construction now. One downside of both wind and solar power is that they are intermittent, dependent on the weather. However, the heat from a solar thermal plant could be stored in a reservoir such as molten salt. Heat could be extracted from the reservoir to generate power even at night or on cloudy days.

Solar cells, or **photovoltaics**, generate electricity directly from sunlight using semiconductor technology. Photovoltaics are currently rather expensive to produce, but if solar energy generation were scaled up by a factor of 700 from present-day rates, they could generate several terawatts of energy. Similarly to surface windmills, photovoltaics seem unable to solve the entire energy problem, but they could certainly help.

In the long run, to the year 2100, large new carbon-free energy sources will be required, of a kind that doesn't exist yet.

One cool idea is to build solar cells on the moon [Hoffert et al., 2002], beaming energy back to the Earth as microwaves. The moon would be an ideal location for solar cells, in that it never rains there, there are no clouds, and no birds. The cells could be produced from lunar soil, reducing the amount of mass that would have to lifted out of Earth's gravity by rockets, a huge savings in energy and cost. The energy from the solar cells could be transmitted to Earth via microwaves; this is apparently feasible, safe, and relatively efficient. An array of solar cells in orbit around the Earth would also share the benefits of a clean environment and solar flux that is unimpeded by the atmosphere. Solar cells in orbit however have to be produced on Earth and lifted to orbit.

You have probably heard of the **hydrogen** economy. Hydrogen itself is not a primary energy source. There are no minable sources of energy as hydrogen like the energy in fossil fuel deposits. Hydrogen is produced from other sources of energy. For example, electricity can be used to break water into components hydrogen and oxygen gas, a process called **hydrolysis.** Hydrogen can also be produced chemically by **gasification** of coal.

Hydrogen could be used to store energy for use in transportation. Because hydrogen is a gas, it must be contained under pressure, as opposed to gasoline, which is liquid at room temperatures, or propane, which can be liquefied at moderate pressure. However, methane is also a gas, and it is being used to power buses and cars already. Hydrogen is more explosive than methane, but in crash tests, this added danger is offset by the tendency of hydrogen to rise up, like helium would, escaping from a crashed vehicle. Hydrogen burns with an invisible ultraviolet and infrared flame unless the flames happen to hit some other material that emits light.

Another option for carbon-free power is to use fossil fuels and then dispose of the carbon, a strategy called **CO_2 sequestration.** CO_2 can be captured from the exhaust stream of a power plant, or even captured chemically from the free atmosphere. The CO_2 can then be injected and stored in particular geological formations in the interior of the Earth. Methane gas has remained stable in deep Earth reservoirs for hundreds of millions of years, so the idea is in principal possible.

Old oil wells are the most immediate possibility, but they have limited capacity and might leak through undocumented old drill holes. The largest type of geological formation that would fit the bill is called **saline aquifers.** These deposits contain water in their pore spaces, but the water has salt dissolved in it, so the assumption is that this water is no good for anybody and we might as well inject CO_2 into it. These aquifers are thought to have the capacity to store 10,000 Gton of C as CO_2.

Scientists are also discussing the possibility of sequestering CO_2 in the deep ocean. CO_2 released into the atmosphere will ultimately mostly dissolve in the ocean anyway; about 75% of the carbon would be in the ocean after the air and water reach equilibrium after hundreds of years, leaving an airborne fraction of about 25%. One could envision direct injection into the ocean as simply by-passing the transit of CO_2 through the atmosphere. CO_2 released in the ocean will equilibrate with the atmosphere toward the same 25% airborne fraction after hundreds of years. Ocean injection would cut the head off the peak, but it would have no impact on the long tail of the extra CO_2 in the air (Chapter 10). The immediate difficulty with ocean injection is that the CO_2 is very concentrated right near the injection site, acidifying the water and killing marine life.

You may have read about an idea called **ocean fertilization**, with the goal of stimulating the plankton in the ocean to take up CO_2 as a means of carbon sequestration. The idea is superficially attractive in that plankton in may parts of the ocean, in particular in the cold surface waters around Antarctica, are starving for tiny amounts of the element iron. Iron is typically supplied to the surface ocean in dust blown through the atmosphere, but the Southern Ocean is remote enough that not much dust blows down there. When oceanographers add iron to surface water in the Southern Ocean, the plankton bloom. One atom of iron could theoretically allow plankton to take up 100,000 atoms of carbon (more or less), so iron could be a powerful lever in the carbon cycle. The idea is that the plankton would grow, die, then sink to the deep ocean, extracting CO_2 from the surface ocean, ultimately from the atmosphere, and transporting it to the deep ocean for us.

As an ocean chemist, I don’t buy this as a way to solve the climate problem. The phytoplankton do bloom in the fertilization experiments, but the extra plankton has not been observed to sink to deeper waters. And even if a large region of the ocean could be fertilized until the plankton are limited by other nutrients, like nitrogen and phosphorus, models of the carbon cycle don’t predict much drawdown in the CO_2 concentration of the atmosphere. The reason is that it takes hundreds of years for the atmosphere and ocean to reach equilibrium. Ocean fertilization could have a larger impact on atmospheric CO_2 if we were willing to wait 500 years, but the impact in a few decades is too small to be worth it. Also, it would be impossible to really say whether adding iron resulted in any uptake of CO_2 from the atmosphere, making the technique too opaque to use in the financial carbon offset market.

The last idea to mention is to deliberately cool the climate of the Earth by **geoengineering**, to counteract the warming from CO_2. One possibility is to generate a haze in the stratosphere by releasing sulfur or some other chemical. Aerosols cool the Earth by scattering sunlight, as the sulfate aerosols in the troposphere from coal combustion do today (Chapter 11). The advantage of the putting particles in the stratosphere is that no rain originates from there, so the lifetime of the injected aerosols would be several years, as opposed to several weeks in the troposphere. The volcanic eruption of Mt. Pinatubo in 1992 injected a haze into the stratosphere, and cooled the planet down by about 0.5 °C for over a year. The aerosols could be shot up to the upper atmosphere in 1-ton shells fired by large cannons, or sulfur could be added to jet fuel of commercial airliners.

Another proposal for climate engineering include the placement of a large reflective object in space, in orbit around the Earth or at the stable "Lagrange" point between the Earth and the sun where objects can sit indefinitely. The space-based option would be more costly, and would require active removal if its effects were eventually judged to be detrimental, and it would require ongoing management and maintenance in order to continue working.

My own personal objection to this idea is that the warming effects from CO_2 will last for millennia, committing mankind to taking an active role in climate maintenance essentially forever, in exchange for a few decades of careless energy production. If the climate management in the future broke down for whatever reason, the brunt of the higher CO_2 concentrations would kick in very quickly. We would be leaving the Earth on life support. I could imagine emergency geoengineering efforts to cool the climate down for a few decades, buying time for natural or human-driven CO_2 extraction from the atmosphere. But geoengineering cannot be considered a "fix" for the climate problem: it could only be a temporary band-aid.

Take-home points

Human-induced climate change is an example of the tragedy of the commons. Economists refer to climate change as an external cost, which can cause the market to make poor decisions. Economic forces also keep the market focused on short-term profit and cost, disregarding costs that come far in the future.

International negotiations under the auspices of the United Nations have not made much progress so far in actually reducing greenhouse gas emissions.

The ultimate goal of negotiations is to prevent "dangerous interference" with the climate system. Danger, in this context, might be benchmarked in terms of global temperature, rate of warming, sea level rise, peak atmospheric CO_2 concentration, or the total amount of CO_2 ever released.

The sooner we begin changing the energy infrastructure, the cheaper it will be to avoid dangerous climate change.

Study Questions

What is an external cost in economics? How does it relate to the tragedy of the commons?

Why is the discount rate an important factor in people's view of the economics of avoiding climate change?

How can danger limits for climate change be defined? What specific implications do they have for carbon emissions in the future?

Which can provide more carbon emission reduction in the next few decades, efficiency or alternative energy sources? What about to the year 2100?

Further Reading

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Tables

1. Potential cuts in CO_2–equivalent emissions between now and the year 2030, available at a cost of \$100 / ton of CO_2-equivalent. The other greenhouse gases are included in this total, converted into their equivalent CO_2 emissions based on their relative potency as greenhouse gases. The numbers are from table TS.17 in the IPCC WG III Report. Where there was a range of uncertainty in the original table, it has been averaged to the middle value.

Sector	Carbon-equivalent emissions savings, Gton CO2 per year	
Energy Supply	1.0	Shifting to carbon-free renewable energy, and capturing CO_2 from coal
Transportation	0.8	Major improvements in efficiency are possible at low cost
Buildings	1.1	Large savings possible which would pay for themselves
Industry	1.1	This slow-growing sector could be more efficient
Agriculture	0.9	No-till agriculture could capture carbon from the atmosphere
Forestry	0.7	Reforestation
Waste Treatment	0.3	Smaller emissions savings, mostly methane and N_2O

Total	5.9

Figure Captions

1. The tragedy of the commons demonstrated in a totally made-up story about sheep.

2. The discount rate and future costs. How much it would be worth, today, to avoid a cost of \$100 at some point in the future, assuming a 3% discount rate.

3. The effect of an ongoing expense equivalent to 3% of GDP every year, on an economy which is growing at a rate of 3% per year.

4. Rates of CO_2 emission cuts required to keep the total slug of CO_2 ever released (the area under the curve) under 1000 Gton C. The bottom panel shows the required rate of decrease plotted as a function of the year in which the cuts begin.

5. The difference between business-as-usual emission trajectory and one which stabilizes atmospheric CO_2 has been divided into manageable pieces called "wedges".

Exercises

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?

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

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

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?

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.

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?

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?

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.