Global Warming
Understanding the Forecast

Second Edition

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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 a hundred years, if the climate of the Earth gets 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. Skippers 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 has variable weather all by itself, naturally. Is it likely that some of our recent weather has been impacted by human-induced climate changes, or how much of this would have happened anyway? If humans are changing the climate, do we know that this is a bad thing? How does the future evolution of climate compare with the climate changes we may be seeing today, and natural climate changes in the prehistoric past?

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 rainfall 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-induced climate changes are expected to be small compared with the variability of the weather. Temperature in the coming century is projected to rise by a few degrees centigrade (Chapter 12). This change is small compared with the temperature differences between the equator and the pole, between winter and summer, or even between daytime and nighttime. 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 comparing the global average temperature trends from the 100-year thermomter record (Chapter 14). Another issue is that it makes it more difficult to know whether temperature trends are natural or human-induced.

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 the average weather is
important is in precipitation. Groundwater tends to accumulate, reflecting rainfall over the past weeks and months. It might be months since a farmer whether it rains on one day versus another, 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 integrity of soils.

In addition to day-to-day weather, there are longer-lasting variations in climate. One past climate regime was the Little Ice Age, around 1600-1800, 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 periods of prolonged drought in the American Southwest. The causes of those climate changes are 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 conditions, and yet the average temperature difference between then and today was only about 5°C (Chapter 8).

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 lost 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 equalling inflow.

It is possible to change the average temperature of the Earth by altering the energy budget, for example, by changing the brightness of the sun. The sun’s intensity correlates 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). Reflected sunlight leaves no heat energy behind, allowing the Earth to cool. 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 sulfate acid droplets that can reflect light.

Earth’s temperature is also sensitive to the outgoing energy flowing to space as infrared radiation. The greenhouse effect keeps the Earth a lot warmer than it would be without it. Most of the gases in the air are completely transparent to infrared light, meaning that they are not greenhouse gases. The greenhouse effect is driven entirely by trace gases in the atmosphere, primarily carbon dioxide (CO2), water vapor, and methane (CH4). 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).

The greenhouse effect is a tricky greenhouse gas because the amount of water vapor in the atmosphere is determined by the 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 CO2 concentration without the feedback, in a dry world, for example.

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

Human activity has the potential to alter climate in several ways. Rising CO2 concentration allows more of the incoming sunlight to be reflected to space, thereby cooling the climate even more. Climate models 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 system are nonlinear, taking a long time to change, such as melting an ice sheet or warming the deep ocean. It is hard 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 we face because CO2 emission has increased so rapidly that we are at risk of exceeding atmospheric CO2 levels that are considered to be safe. This is because CO2 is a potent greenhouse gas, and increasing levels of CO2 in the atmosphere are leading to significant changes in the Earth's climate. The impacts of these changes are far-reaching, affecting everything from weather patterns to ocean acidity to sea-level rise.

We are currently facing a critical juncture in the history of the planet, as the concentration of CO2 in the atmosphere continues to rise. This rise in CO2 is mainly due to the burning of fossil fuels, which releases large amounts of CO2 into the atmosphere. The increase in CO2 levels has been accompanied by significant changes in the Earth's climate, including warming temperatures, rising sea levels, and more frequent extreme weather events. These changes are having a profound impact on ecosystems, agriculture, and human societies.

To mitigate the effects of climate change, it is essential to reduce CO2 emissions and transition to a low-carbon economy. This will require a coordinated global effort, including the development of renewable energy sources, the promotion of energy efficiency, and the implementation of policies and technologies that reduce emissions.

Despite the challenges we face, there is reason for hope. Innovations in technology and changes in public attitudes and behaviors are providing new opportunities for addressing climate change. By working together, we can build a sustainable future for ourselves and future generations.
Part I

The Greenhouse Effect
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, vibrating more energetically at high temperatures.

Perhaps you knew this already, but have you ever wondered how you can feel such a thing? Atoms are tiny things. We cannot 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 is hot, it will glow. It glows with blackbody radiation, which we shall return to later.

A thermometer is like an atomic speedometer.

You can feel the hot stove because the energetic “bounciness” of the move 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; 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 earliest form of heat flux to civilization.

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 in it to stay cool. Thermos bottles have two walls, one inside and one outside. Between the two walls is an insulator. A 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 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?
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 Kirchhoff'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 do not 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 cannot see, down in the IR.

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. They 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 Watts per square meter. The unit on the top of the fraction is Watts, the same kind of Watts that describe hairdryers and radio amplifiers. A Watt is a rate of energy flow, defined as Joules per second, where a Joule is an amount of energy, such as might be carried in a battery or a candy bar. The meter squared ($m^2$) on the bottom of the fraction is the surface area of the object. The unit of wave numbers on the bottom of the fraction allows us to divide the energy up according to the different wave-number bands of light; for instance, all the light between 100 and 102 cm$^{-1}$ carries this many W/m$^2$ of energy flux, between 101 and 102 cm$^{-1}$ carries this 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 total energy of the wave number slice is the width of the slice in wave numbers, resulting in an energy flux in units of 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.

A plot of intensity versus wavelength of light is called a spectrum. The IR 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 peaks of the curves move to the right, toward visible light. Second, 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 area under the curves in Figure 2-4 get larger as the temperature rises. 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:

$$I = \sigma T^4$$  
(2.1)
The intensity of the light is denoted by I and represents the total rate of energy emission from the object at all frequencies, in units of Watts/m². 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, ε = 1, and the lower bound is ε = 0. 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 Kelvin, 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 techniques of thinking scientifically is to pay attention to units. Here is Equation 2-1 again, with units of the various terms specified in the square brackets:

\[
I = \varepsilon \sigma T^4
\]

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 \(5.14 \times 10^8\) m². Temperature is in Kelvin, and ε has no units; it is just a number ranging from 0 to 1; 0 for an object that emits nothing and 1 for a perfect blackbody.

The Stefan-Boltzmann constant σ is the same on both top and bottom; ε never changes. The emissivity ε might be different between the skin and the glasses, but let us 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 \((285\,\text{K}/278\,\text{K})^4\), which is about 1.1. The skin shines 10% more brightly than the surface of the coat, and that is what the IR camera sees.

The other 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 knew 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 IR, where we cannot see it. An electric stove set on High (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 (5,000 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 IR. Of course, the total energy flux from the sun is much higher than it is from Earth. Repeating the calculation we used for the IR photo, we can calculate that the ratio of the fluxes is \((5,000\,\text{K}/273\,\text{K})^4\), or about 10^19. 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 had not done
Figure 2-5 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, whereas the Earth shines in infrared light.

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 IR light field would be much more complicated 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 strongly the incoming light deploys energy into oscillators coupled to its nervous system. It must complicate matters if the oscillators are energy radiating light of their own. IR telescopes must be cooled to make accurate IR intensity measurements. Snakes are able to sense IR light. Perhaps this is possible because their body temperatures are colder than those of their intended prey.

### Take-home points

- Light carries energy through the vacuum of space.
- An object that can emit all frequencies of light is called a blackbody, and it emits light energy at a rate equal to $e \sigma T^4$.
- If an object can absorb light, it can also emit light.

### Study questions

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

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

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

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

5. 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 indeterminate amount of energy, instead of the $e \sigma T^4$, 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 mechanics, the philosophical implications of quantum mechanics, is *In Search of Schrödinger's Cat* by John Gribbin, but there are many others.

### Exercises

1. A joule (J) is an amount of energy, and a watt (W) is a rate of using energy, defined as $1\text{W} = 1\text{J/s}$. How many joules of energy are required to run a 100-W light bulb for one day? Burning coal yields about $3 \cdot 10^9$ J of energy per kilogram 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 $1.3 \cdot 10^8$ J 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 because a watt is a joule per second, and a kilowatt hour is the number of joules one would get from running 1000 W times one hour (3,600 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 $1.1 \cdot 10^9$ J of energy. You can get about 5 - 10 BTUs (British thermal units) of gas for a dollar, and there are about 1,030 BTUs 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 $3.2 \cdot 10^{12}$ J 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 $40$ calories (which a scientist would call kilocalories). A calorie is about 4.2 J. 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 and demonstrate your management potential. The question is: What is the efficiency of energy production from growing corn?
Assume that sunlight deposits 250 W/m² of energy on a corn field, averaging over the day-night cycle. There are 4.186 J 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 the number of calories is that 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. The Hoover Dam produces $2 \cdot 10^9$ W of electricity. It is composed of $7 \cdot 10^9$ kg of concrete. Concrete requires 1 MJ of energy to produce per kilogram. 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 m². Assuming 250 W/m² 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 $2 \cdot 10^3$ J of energy to manufacture 1 m² of crystalline-silicon photovoltaic cell. (Actually, the number quoted was 900 kWhr. Can you figure out how to convert kilowatt hours into Joules?) Assume that the solar cell is 12% efficient, and calculate how long it would take, given 250 W/m² of sunlight, for the solar cell to repay the energy it cost for its manufacture.

6. We are supposed to eat about 2,000 dietary calories per day. How many watts is this?

7. Infrared light has a wavelength of about 10 μm. What is its wave number in cm⁻¹?

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

FM radio operates at a frequency of about 40 kHz. What is its wavelength?