Global Warming:
The Science and the Evidence

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Preface

John Kolena passed away on November 25th, 2020. He shared versions of this manuscript with several of us over the period from his retirement until just before his death. After his death, and following a virtual memorial service on January 23rd, 2021, where we solicited additional volunteers, the eight of us began meeting regularly. We wanted to honor John, and his legacy, and discussed how we might make the manuscript available. We discussed everything from releasing it as it was to “finishing” it as a readable book. We also discussed who it might serve, from alumni and friends who knew John and wanted to know more about this part of his life, to people (perhaps the same people) who might want to use this work, to the much broader public.

Ultimately, we decided it would be too much to try and produce a “book” for popular consumption. But we worried that the original version, with a lot of notes to himself, incomplete sections, and—in particular—images with unclear copyright, would be awkward to release online even if oriented to alumni and friends. People would not know if they could re-use it themselves, and might have trouble following where pieces were missing.

So we worked to clean up the copyright issues. A number of us then took specific chapters (Christian Johnson, Chapter 2; Eric Sharpe, Chapter 3; Colin Law and Billy Pizer, Chapter 4; and Dot Doyle and David Hunkins, Chapter 5). We basically edited for grammar and clarity, removed John’s notes to himself, and, where necessary, added endnotes to inform the reader of any place where we made substantial changes or otherwise wanted to provide some guidance or information.

We sincerely hope that at least some of the many hundreds (thousands?) of John’s students might find this manuscript both interesting as another side of John Kolena, but also useful in their own attempt to understand one (the?) key challenge of our time.

Dot Doyle, Adam Falk, David Hunkins, Christian Johnson, Colin Law, Billy Pizer, Jay Runge, Eric Sharpe
September 20, 2021
Chapter 1
Introduction

1.1 Audience and Goals

This book’s origins lay in the many gaps, some shallow and some deep, in my own understanding of global warming and climate change in 2013 after my retirement. I knew of the greenhouse effect largely due to being an astrophysics teacher who used it in classes to explain the measured temperatures of the solar system’s inner planets. I knew that carbon dioxide (CO\(_2\)) was the most prominent greenhouse gas in Earth’s atmosphere, and that it was mainly responsible for Earth’s livable surface temperature; without it, that temperature would be an unbearable \(-18^\circ\text{C} \ (\approx -6^\circ\text{F})\).

Unimpeachable evidence exists for the rising atmospheric concentration of CO\(_2\) since the Industrial Revolution began in the mid-1800s. I was vaguely aware that other greenhouse gases existed, although I probably couldn’t have identified either the gases or their relative greenhouse contribution with great confidence.

I did know that climate scientists (were they meteorologists? ecologists? biologists? geologists? chemists? all of the above?) claimed to have evidence of both human-caused global warming and its collateral effects such as sea-level rise, ocean acidification, changing precipitation patterns and increased storm severity, but I was pretty fuzzy on some of the connections. Was the evidence substantive or middling or something else?

It certainly made sense that humans could be responsible for increased carbon emissions as the world added more automobiles and airplanes and as less-developed nations (particularly China and India) began industrial production and satisfied their consumers’ demands. But is it possible to prove or disprove that both rising CO\(_2\) atmospheric levels and the associated global warming was due to human activities or to one or more other causes?

I often read dueling articles on the subject of climate change that appeared with
increasing frequency in newspapers and periodicals, in print and online. Anec-
dotes were provided, claims were made, and cheerleading for (or disparagement
against) one side or another in the debate were the rule, not the exception. When
phenomena (for example, rising or falling temperatures, advancing or retreating
ice, rising or falling sea levels) were presented as evidence, it was not easy for
me to tell whether these were truly evidence-based worldwide phenomena or
location-specific items cherry-picked to buttress the author’s bias.

So this book began as an exercise in education: my education. Although it began
as a selfish endeavor, I hope that it will help others who, as I did, want to learn
about (1) the science behind greenhouse-gas warming, (2) the evidence for global
warming and climate change,(3) the likely agent(s) of evidence-based warming
(humans? the sun? some natural cycle in the terrestrial geology, atmosphere,
and/or ocean?), (4) scientific, model-based short- and long-term consequences of
climate change, and (5) what practical steps we can take to remedy a problem
that is likely of our own making.

I had several other goals for the book at the start: I wanted it to be complete, yet
not lengthy. ‘Complete’ in the sense that it would cover each of the five topics
in the previous paragraph in a convincing manner, but yet not complete in the
sense of exhaustive. I would follow the evidence wherever it leads – which is not
equivalent to being even-handed to the two “sides” in the debate over whether
the planet is warming or not. I also wanted it to be sequential, to begin at the
beginning, with the present state of greenhouse-gas science and end with the best
modeled predictions for the future global temperatures and climate along with
how we might avoid permanently damaging Earth.

There were also a number of things I would not be shy about. I would be unafraid
of addressing the science (and accompanying math) involved. And even though
I would be dispassionate about presenting evidence, I would not refrain making
claims about the conclusiveness of evidence in situations where that evidence ap-
pears overwhelming. Similarly, if the evidence was unconvincing or contradictory
or if the climate models were ambiguous, I would not be reticent about saying so.

I did not intend this work to be a textbook. As a teacher/friend of mine said
to me recently: “No one actually reads textbooks anymore.” I would provide
no problems to solve and no review questions to answer. A number of excellent
textbooks have recently appeared on the scene. They provide background or
details on many of the subjects discussed here. Useful works in print and on the
web are listed at the end of this work. And also unlike a textbook, this work is
intended to be freely available.

As this work has evolved, I must admit that it has become more and more like
a textbook, in its sequentialness. However, I believe that it can perhaps best
be used either as a reference work or to answer one of the specific questions addressed in a chapter. For example, a reader might just want to know why we need a greenhouse effect to explain Earth’s present surface temperature (in which case, they want chapters 2 and 3) or one might want to know just the evidence that the planet has warmed in the past century (in which case, they would consult chapter 4).

During the writing of this work, I considered whether to include references to interactive spreadsheet models or on-line simulations. However, I also had some concern that any such references might indicate that I approved of either the viability of such models or their conclusions. Having not had the time to spend investigating such models, I have decided not to include references to such in this version of the book. Future versions of this work may, however, include such models and simulations.

In sum, I hope that this work will allow the reader to make rational and confident judgments about claims (from the obvious to the outlandish) that one hears in conversations or in print or electronic media.

### 1.2 Outline of the work

Each of the main chapters attempts to address a specific question.

Chapters 2 and 3 explain what factors determine the surface temperatures of Earth and the other planets with atmospheres in the inner solar system and whether or not these temperatures can be explained by direct solar heating alone and without resorting to additional greenhouse heating. Chapter 3 examines the evidence for an atmospheric greenhouse effect that presently operates on Earth and the science of how it works.

Chapter 4 collects the evidence for recent (since the start of the Industrial Age) global temperature changes on Earth. Evidence for temperature change can be direct (in the form of measured temperatures of the atmosphere, land, and oceans) or indirect (for example, in the form of the advance or retreat of glacier and polar ice or changes in sea level). Spoiler alert: overwhelming evidence exists for a temperature rise of 1.0°C over the past 100 - 150 years.

Chapter 5 investigates two crucial questions: (1) Is the rising concentration of greenhouse gases (particularly CO₂) responsible for the warming climate? and (2) Are human activities responsible for the rising greenhouse gas concentrations?
1.3 Terminology

Even the words used to describe the subject of climate change can often be contentious. Words such as ‘climate’ and ‘weather’ are sometimes used interchangeably. As are the phrases ‘global warming’ and ‘climate change.’ What are we to call those who, without data, adamantly reject any notion of a warming planet? Skeptics? Deniers? What about those on the other side? Warmists? Alarmists? So, to begin with, some words about words.

1.3.1 ‘Climate’ vs. ‘Weather’

The term *weather* refers to the daily, weekly, and monthly variations in temperature, precipitation, cloud cover, wind speed and such. It is affected primarily by local geographical features (such as the number of daylight hours, cloud cover, the maximum altitude that the sun reaches during the day, the location’s proximity to large bodies of water and/or temporary phenomena (regional low- or high-pressure systems, or larger-scale disturbances such as the polar vortex, El Niño, and La Niña). The term *climate* refers to weather patterns that persist over decades, centuries, millenia or even longer.

1.3.2 Why ‘Global Warming’ and not ‘Climate Change’?

The idea that increasing carbon concentrations in Earth atmosphere’s have a warming effect on the planet was originally termed ‘global warming’. Near the end of the last century, that term morphed into ‘climate change’ in order to broadly cover other effects accompanying rising global temperatures, such as the retreat of glaciers and polar ice, rising sea levels, local increases or decreases in precipitation or storm activity, and acidification of the oceans.

In short, global warming is a measurable physical effect produced by increasing carbon presence in land, sea, and/or air. Climate change is a catch-all title for climatic effects that arise from global warming.

1.3.3 ‘Skeptics’ or ‘Deniers’?

‘Skeptics’, in my view, are those who understand and accept that the planet is warming, but are troubled by the amount of uncertainty present in the temperature data (due to different measurement methods over time) and/or are concerned by the still poorly-understood and non-linear connections between small changes in terrestrial conditions and climate effects. They are also aware that our best climate models differ minimally in input parameters but can vary greatly in output predictions. They would especially emphasize the difficulty in predicting
the future given the present instability in the oil market, the rise of natural gas production and fracking, the falling prices of solar and other ‘green’ energy production, and the varying commitments of nations to stabilize or reduce carbon emissions.

There is no getting away from the fact that a significant group of global-warming ‘Deniers’ exist in the non-scientific community, particularly in the United States. The consistent rise in global mean temperatures over the past 130 years (see Chapter 4) makes it difficult to argue that the planet is not warming. Global warming deniers have since shifted their objections to other fronts. First, they argue that there has been a distinct pause in the rise of global mean temperatures during the first fifteen years of this century. Second, they claim that what global-mean-temperature rise does exist falls far short of what climate scientists’ models have been predicting. Third, that any global warming that does exist is not caused by humans but by other external factors (for example, by variations in the sun’s energy output). We’ll discuss these claims in detail.

1.4 The 2013 - 2014 IPCC Reports

The Intergovernmental Panel on Climate Change (IPCC) is a scientific body, established in 1988 by the United Nations. The IPCC itself neither carries out scientific research (i.e., as a body, it neither collects data or makes measurements), but instead relies on published peer-reviewed and non-peer-reviewed literature on climate. Although the IPCC reports are written by only a few dozen people, the reports are based on the work of several thousand scientists. Its reports are reviewed by individual governments (up to 120 participated in the last report) and the report summaries have been subject to line-by-line approval by the delegates from participating countries. The IPCC was awarded a portion of the Nobel Peace Prize in 2007.

The Intergovernmental Panel on Climate Change (IPCC) issued its Fifth Assessment Report (AR5) in 2013 - 2014. The IPCC reports contain the largest and most complete summary of climate data and of the results of climate modeling. The reports are divided into three parts: (1) The Physical Science Basis (produced by Working Group I in 2013; it contains approximately 1500 pages), (2) Impacts, Adaptation and Vulnerability (produced by Working Group II in 2014; approximately 1800 pages), and (3) Mitigation of Climate Change (produced by Working Group III in 2014; approximately 1400 pages). Each of the three reports contains a Summary for Policy Makers (typically 30 pages) and a
Technical Summary, which summarizes the most important data (Usually in the form of graphs and tables) and conclusions.

This work relies heavily on the data presented in IPCC AR5 (particularly in Summary for Policy Makers) and to a lesser extent on the conclusions presented therein.

1.5 To the reader

1.5.1 Physics and math

I started this work partly because of a perceived lack of authoritative science in many of the popular works on the subject of climate change in early 2012. Many claims are made with little serious data presented or with serious explanations of the data. I have not been afraid to use high-school math (nothing beyond precalculus) and physics. Some sections may stretch the reader (for example, sections 2.3-2.4), but they can be skimmed. Each important section will end with a final paragraph that summarizes the important science, data, or conclusions.

1.5.2 Charts and graphs

Even more important for the reader than facility with physics and math is an ability to understand charts and graphs and to make appropriate conclusions from them. I have purposefully refrained from stringing together statements of superlatives (the hottest year on record, the most dangerous greenhouse gas, the worst carbon emitters). Rather I have tried to put the data in appropriate context so that the reader can make his or her own conclusion without much prompting from me.

1.5.3 Citations and references

Much effort has been expended to find and present data that reflects the current state of climate science. That means using published, peer-reviewed data wherever possible. Fortunately, much of the relevant data has made it into the public domain.

Given the media climate today, it should not be a surprise that a significant number of references are web hyperlinks. Unfortunately, unlike books and other printed materials, hyperlinks can be altered at whim or even vanish. Although I have made a conscious effort to refer to data in print rather than data on the web, sometimes the most current data is available only on the web. All hyperlinks were active as of August 2021.
Obviously there are competing data to be found. But more important are the competing interpretations and explanations for existing data. Examples abound of writers cherry-picking data, taking data out of context, or invoking ad hominem arguments to ridicule data that does not fit their preconceptions. I began this work because I felt relatively uninformed about the issue of global warming and climate change. I wanted to know what the best science said, and I have chosen the data that seems to have the most evidence behind it.

I invite readers who find better data or better scientific interpretations of the data to let me know.

1.5.4 Common abbreviations
A (non-exhaustive) list of the most common abbreviations used in this work.

<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>AR5</td>
<td>5th Assessment Report (published by the IPCC, 2013 - 2014)</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas(es)</td>
</tr>
<tr>
<td>GISS</td>
<td>Goddard Institute for Space Science (used in conjunction with NASA)</td>
</tr>
<tr>
<td>GMST</td>
<td>Global mean surface temperature</td>
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<tr>
<td>GWA</td>
<td>Global warming activist</td>
</tr>
<tr>
<td>GWD</td>
<td>Global warming denier</td>
</tr>
<tr>
<td>GWDL</td>
<td>Global warming denier lobby</td>
</tr>
<tr>
<td>GWS</td>
<td>Global warming skeptic</td>
</tr>
<tr>
<td>HadCRUT4</td>
<td>Climatic Research Unity at the University of East Anglia (UK) in conjunction with the Hadley Centre</td>
</tr>
<tr>
<td>IPCC</td>
<td>International Panel on Climate Change</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Agency</td>
</tr>
<tr>
<td>NCDC</td>
<td>National Climate Data Center (used in conjunction with NOAA)</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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Chemical Symbols

<table>
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<tr>
<td>Ar</td>
<td>argon</td>
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<tr>
<td>C</td>
<td>carbon</td>
</tr>
<tr>
<td>CFCs</td>
<td>chlorofluorocarbons</td>
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</tbody>
</table>
CH₄  methane
CO₂  carbon dioxide
H₂O  water
N or N₂  nitrogen
N₂O  nitrous oxide
O or O₂  oxygen
O₃  ozone

Symbols In Physics Equations

A  albedo = fraction of light reflected
AU  1 AU = Earth-Sun distance = 149,500,000 km
°C  degrees Centigrade
d  distance
F  flux = power (or luminosity) per area (generally in units of watts per square meter)
°F  degrees Fahrenheit
IR or ir  infrared (part of the spectrum)
m  methane
NH  methane
P  power (or luminosity) generally in units of watts
R  radius
SA  surface area
SH  Southern Hemisphere
T  temperature
UV or uv  ultraviolet (part of the spectrum)
λ  wavelength
λ_{max}  wavelength of maximum flux (or power)
μ  micron: 1 micron = 0.000001 meter
1.5.5 Perspectives and biases and surprises

Although it is probably not possible to write an unbiased work on this subject, I hope that this presentation is as scientifically accurate and objective as possible. However, as for all writings on contentious subjects, the writer brings with him (in this case) the baggage of educational training (in my case, as an astrophysicist) and work experience (as a teacher/research at both a big-name university and at a science- and math-oriented high school). That I have no particular expertise in climate science (except for the astronomical aspects) may be advantageous. If I am to present data or scientific interpretations in this writing, I must first judge that data believable or those interpretations convincing.
Chapter 2

What Determines the Temperature of Earth (without greenhouse gases)?

2.1 An Earth without greenhouse gases?

It wasn’t immediately clear to me how this book should begin and which question should be addressed first. An experimentalist would perhaps begin by looking for evidence for recent temperature changes on Earth. Once the temperature record had been established, then it might make sense to go looking for mechanisms that caused the temperature changes observed.

On the other hand, astronomy-oriented scientists have known for more than a century that Earth’s surface has been warmed by a substantial greenhouse effect for the past few thousands of years. As we shall soon see, humans would find life quite uncomfortable without this greenhouse effect. It is only recently that greenhouse warming may have changed measurably and in a way that may not bode well for the future. Theorists (and astronomers) might therefore begin with an explanation of the already-existing greenhouse effect. Once the greenhouse heating mechanism is understood, then it might make sense to go looking for recent changes in that mechanism.

Having the bias of an astronomer, I have taken the latter path. In order to understand (and predict) planetary temperatures in the absence of a greenhouse-gas atmosphere, we will need to understand the properties of the radiation (or light) emitted by both the Sun and Earth. If these calculations reproduce the actual temperature of Earth, there will be no need for any additional atmospheric (or greenhouse gas) correction. But, as we will see, this straightforward model will not predict the correct temperature for Earth. Nor will it work for Venus or Mars.

This work will generally assume that the reader has a passing familiarity with
basic physics concepts (for example, that light carries energy and can be characterized by a wavelength and frequency, or that the visible light we see occupies only a narrow part among the entire spectrum of light that exists). However, even those who had the experience of an introductory high-school or college course in physics are probably not familiar with the so-called ‘blackbody laws’ that describe the properties of light emitted by objects such as the Sun and Earth. We begin by discussing these laws.

Our first goal is to be able to calculate the surface temperature of a planet whose atmosphere contains no greenhouse gases. [The most common greenhouse gases are carbon dioxide (CO\(_2\)), methane (CH\(_4\)), nitrous oxide (N\(_2\)O), and ozone (O\(_3\)). Non-greenhouse gases include nitrogen (N\(_2\)), oxygen (O\(_2\)), and argon (Ar), the three primary constituents of Earth’s atmosphere. What qualifies a gas as a ‘greenhouse’ gas? The short answer is that a greenhouse gas absorbs substantial infrared light. A full discussion will follow in Chapter 3.] This will be accomplished by using the blackbody laws, some geometry, and the idea of equilibrium. Because the ideal blackbody laws that we will apply to both Sun and Earth depend only on the temperature of the light emitter, we begin with a discussion of the Kelvin temperature scale.

### 2.2 The Kelvin temperature scale

Although temperatures are most commonly expressed in Fahrenheit in this country, it is likely that most readers will have some familiarity with temperatures expressed in Celsius. For example room temperature is 20°C ( = 68°F). Water freezes at 0°C ( = 32°F) and boils at 100°C ( = 212°F).

However, the Kelvin temperature scale might be far less familiar unless the reader has had some experience with an advanced science class. The conversion between a Kelvin temperature \( T_K \) and its equivalent Celsius/Centigrade temperature \( T_C \) is straightforward:

\[
T_K = T_C + 273 \quad (2.3)
\]

\(^1\) A reminder that a Fahrenheit temperature \( T_F \) and a Celsius/Centigrade temperature \( T_C \) are related by

\[
T_F = 1.8 \ T_C + 32 \quad (2.1)
\]

and

\[
T_C = \frac{5}{9}(T_F - 32) \quad (2.2)
\]
Temperatures expressed in Kelvin have much more physical meaning to a scientist because the Kelvin temperature is a direct measure of the average kinetic energy per particle present in an ideal gas.

Consequently, we can easily deduce that the kinetic energy content of gas particles at the surface of the Sun (where the Kelvin temperature is roughly 6000 K) is approximately 20x the kinetic energy of gas particles at the surface of Earth (where the Kelvin temperature is roughly 300 K). The equivalent Celsius temperatures for the Sun’s and Earth’s surfaces, respectively, are (approximately) 5800°C and 25°C. The relative kinetic energy content per gas particle of 20x (Sun surface vs. Earth surface) is not at all evident when looking at the Celsius temperature numbers.

It should also be noted that, because the Celsius temperatures and Kelvin temperatures differ by only a constant value (there is no multiplicative factor as in the Celsius-Fahrenheit conversion), a difference in temperature on the Kelvin scale is exactly the same as the temperature difference on the Celsius scale. If a gas heats up by 20 K, it also heats up by 20°C.

### 2.3 The blackbody laws

The three blackbody laws will be important in understanding how we know a greenhouse effect operates on Earth and other planets with atmospheres.

‘Blackbody’ may seem (and is!) a strange name to give to laws that describe the emission of light. We think of light-emitting objects as bright, almost the opposite of ‘black.’ An ideal emitter of light (a ‘blackbody’) is, by definition an object that absorbs all light incident upon it. It does not reflect light (perhaps now you see the origin of ‘black’) nor does it transmit light. But if the emitting object were also maintaining a constant or ‘equilibrium’ temperature, then the energy an object absorbed would be necessarily balanced by the energy that same object emitted. Consequently, an ideal blackbody is not only a perfect absorber of light, it is also an ideal emitter of light. We will use this equilibrium principle to calculate the expected temperature of a planet.

What common objects do the blackbody laws apply to? Perhaps the most obvious set of nearly ideal blackbody objects are stars. Indeed, our star, the Sun, neither reflects or transmits light, and it does absorb any light shined on it. Other light-emitting objects in our everyday experience that come close to being ideal blackbodies include incandescent light bulbs and some types of gas discharge lamps.

---

2Although an object that reflects no light would not literally appear black. Instead, it would be invisible!

3The fancy scientific term for the state of a constant-temperature object is ‘thermal equilibrium.’
excellent blackbodies are incandescent light bulbs or the coils on or the inside of an electric stove (or the filaments of toaster or a space heater or the like). A sign that these household objects are not quite so good blackbodies as stars is that they reflect light. We can still apply the blackbodies to these household light-emitting objects as long as we are careful to take into account their reflective properties.

What might be less obvious is that Earth (or any other planet) is as good a blackbody as the filament in an incandescent bulb or a toaster. So is the human body. We don’t think of Earth or our own bodies as light-emitters only because the light they emit is in a part of the light spectrum - the infrared – that we do not see. As we shall see, they emit infrared (rather than visible as do stars and toaster filaments) because their temperatures are so low. I expect that you will be reminded that humans are emitters of infrared light when you see Figure 2.1.

![Figure 2.1: An image of a human taken with infrared light](CC BY-SA 3.0, Free Art License)

Are there examples of objects that are very poor blackbodies? Of course. Objects – particularly gases – that are transparent to most light (such as the air we breathe) are objects that the blackbody laws would not apply to.

If you look up ‘blackbody law’ in a textbook or other reference work, you would will likely find three: Planck’s law, Wien’s law, and Stefan’s law. There is really only one (the Planck law); the other two laws are derivable from it. We will encounter each of these three laws in understanding the evidence for the green-
house effect.

2.3.1 The blackbody law of Planck

The Planck blackbody law is a complicated mathematical formula that predicts the light intensity emitted by an ideal blackbody at every wavelength if given its temperature. Figure 2.2 shows the blackbody emission curves for objects of four different temperatures. A few rules are apparent from comparing these four curves:

![Blackbody Curves](image.png)

Figure 2.2: Blackbody curves show the relative light intensity emitted by ideal emitters – blackbodies – with four different temperatures. (Figure contributed by C. Johnson, public domain.)

1) Each blackbody emits some light at every wavelength in the spectrum. (In other words, the intensity curve for a blackbody is continuous, with no breaks or spikes in it.)

2) A hotter blackbody emits more light intensity at each and every wavelength than a cooler blackbody does. (In other words, the curve for a hotter blackbody lies completely over and above that for a cooler blackbody.) This conclusion

---

4Intensity is power per unit area per wavelength interval
forms the basis of Stefan’s law.

3) A hotter blackbody emits its peak light intensity at a shorter wavelength than a blackbody that is cooler. (In other words, a hotter blackbody peaks in intensity at shorter wavelengths or ‘bluer colors’ than a cooler blackbody. The wavelength of each curve’s peak – or maximum – intensity is denoted by $\lambda_{\text{max}}$ in Figure 2.2.) This conclusion forms the basis of Wien’s law.

It should also be noted in passing that the features of various blackbody curves depend only on the temperature of the object and not, for example, on its shape, its composition, or its size. We now have the basis for understanding why the Sun (surface temperature 5800 °Kelvin) is a more intense emitter of light than the filament of a bright incandescent light bulb (temperature 3000°K), which in turn is a more intense emitter of light than the hottest coil on an electric stove (temperature range: 800 - 1100°K), which in turn is a more intense emitter of light than Earth (temperature 300°K).

We will see the Planck law (and its associated blackbody curve) in action in figures 3.4 and 3.7.

2.3.2 The blackbody law of Wien

It has already been mentioned that Wien’s law associates the wavelength of the peak intensity ($\lambda_{\text{max}}$) of a blackbody curve with its temperature. A hotter blackbody emits its greatest light intensity at a shorter wavelength (or a bluer color) than a cooler blackbody.

More precisely, Wien’s law states that

$$\lambda_{\text{max}} = \frac{2900 \text{ } \mu m \cdot ^\circ K}{T} \quad (2.4)$$

$$\lambda_{\text{max}} = \left( \frac{2900^\circ K}{T} \right) \mu m \quad (2.5)$$

where $T$ is the surface temperature (in °K) of the emitter ($\mu m \cdot ^\circ K$ are the units of the number in the numerator, so that if a temperature in °K is substituted in for the denominator, the units of wavelength will be returned in $\mu m$, or micrometers.)

---

5 A section on the units of temperature follows
Wien’s law and the sun

If we now apply this law to the surface of the sun \((T = 5800 \degree K)\), the result is \(\lambda_{\text{max}} = 0.50 \, \mu m\), which is the blue-green portion of the visible part of the radiation spectrum \((0.39 \, \mu m \leq \lambda_{\text{visible}} \leq 0.72 \, \mu m)\). In other words, Wien’s law correctly predicts that the Sun emits a great portion of its radiation at visible wavelengths.

Wien’s law and the coils on an electric stove

The temperature of a typical (hot) coil temperature on/in an electric stove/oven is 1000\degree K. According to Wien’s law, the most intense wavelength will be 2.9 \(\mu\)m, which is far into the infrared spectrum. Although its curve is too small to be shown to scale in Figure 2.2, two conclusions can be drawn for such a coil: (1) virtually all of the light emitted will be in the infrared, and (2) of the emitted light that we can see, more of the light is red than any other visible color.

We will apply Wien’s law to the even-cooler Earth in section 3.4 below.

2.3.3 The blackbody law of Stefan

Stefan’s law predicts the total power (over all wavelengths collectively) that an ideal blackbody emits:

\[
P_{\text{em}} = \sigma T^4 \cdot SA
\]

where \(T\) is again the surface temperature of the emitter and \(SA\) is the surface area of the emitter. The constant \(\sigma\) has the value of \(5.67 \cdot 10^{-8} \, \text{W/m}^2/\text{K}^4\).

Stefan’s law predicts that an ideal blackbody of surface temperature 6000\degree K should emit \(2^4 = 16\) times more light power than an ideal blackbody of surface temperature 3000\degree K. This is equivalent to saying that the area under the 6000\degree K blackbody curve in Figure 2.2 should be 16x the area under the 3000\degree K blackbody curve.

*The reader may wonder why the sun does not therefore look blue-green. There are two reasons: (1) much of the short-wavelength, or bluer, light is scattered out by the earth’s atmosphere to make the blue sky and (2) humans’ eyes are much more sensitive to yellow light than to blue light.

The blackbody curve for the 6000\degree K blackbody in Figure 2.2 peaks – incorrectly, unfortunately – at 0.53 \(\mu\)m.

*The hottest coils on an electric oven might light orange or orange-yellow. Once again the reason is that, even though the predominant light emitted might be red, our eyes are much more sensitive to yellow light than they are to red.
We now understand why a hotter blackbody will be brighter than a cooler blackbody of the same surface area. Of course, an object such as the Sun also has a much greater surface area than an oven coil. Perhaps you own a lamp in your home that has a variable light output. Stefan’s law explains why, as you dial up the temperature with the control knob, the power or light intensity of the lamp increases.

We will use Stefan’s law in section 2.4 to calculate the temperature expected for Earth based on direct solar heating.

2.3.4 The blackbody laws: the take-away

The blackbody laws describe the emission of light from an ideal blackbody emitter. The properties of the emitted light – such as total light power or the part of the spectrum where the emitted power peaks – depend only on the temperature of the emitting object. Hotter objects emit more power per unit area than cooler objects. Hotter objects emit a greater percentage of their light at shorter wavelengths (or bluer colors) than cooler objects. The blackbody laws apply quite well to stars such as our Sun. The laws can be applied to objects such as the filaments of incandescent light bulbs or toasters and even to objects such as cats, humans, and Earth.

2.4 Calculating the temperature of a planet

The equilibrium temperature of a no-atmosphere planet is calculated under the assumption that sunlight is the sole source of energy heating the planet’s surface. The amount of power (energy/time, commonly in watts) incident on the planet’s surface is determined from straightforward geometry:

\[ P_{\text{inc}} = \left( \frac{\pi R_p^2}{4 \pi d_p^2} \right) P_* \]  

(2.7)

where \( P_* \) is the Sun’s power\(^8\) and \( R_p \) and \( d_p \) are the planet’s radius and its distance from the Sun, respectively. The quantity in parentheses is just the intercepting target area of the planet (\( \pi R_p^2 \), because a planet presents a circular target area to incoming radiation) relative to the spherical surface area (\( 4 \pi d_p^2 \)) that the Sun’s light covers when it has reached that planet’s distance from the sun\(^9\).

---

\(^8\)The astronomers’ term for power is luminosity, a term which might be encountered in other works.

\(^9\)It has been assumed that the planet’s orbit around the Sun is circular, for which the planet-Sun distance remains constant. In reality, of course, planetary orbits are elliptical, which means that the planet-Sun distance varies over the orbital period. For the case of the planets we will consider (Venus, Earth, and Mars), these variations are small. For both Venus and Earth, the variation in planet-Sun distance is less than 2% relative to the mean. The Mars-Sun distance...
By definition, the power absorbed by the planet is

\[ P_{\text{abs}} = (1 - A_p) P_{\text{inc}} \]  

(2.8)

where \( A_p \) is the planet’s albedo. Albedo is the scientific term for the fraction of light reflected by an object. Therefore, \( (1 - A) \) is the fraction of light absorbed by that object.

Stefan’s blackbody law (equation 2.5) is used to determine the power emitted by the planet:

\[ P_{\text{em}} = 4\pi R_p^2 \sigma T_p^4 \]  

(2.9)

where \( T_p \) is the planet’s equilibrium temperature.

If the temperature of the planet is to remain constant over the long term (remember the ‘equilibrium’ idea), the power absorbed by the planet and the power emitted by the planet must be the same. Combining the previous three equations yields

\[ T_p = \left( \frac{(1 - A_p) P_*}{16\pi\sigma d_p^2} \right)^{\frac{1}{4}} \]  

(2.10)

As has been previously stated, this equilibrium temperature calculation assumes that the planet has no atmosphere and that the only source of planetary heating is direct sunlight.

**Calculating planetary temperatures, without the greenhouse effect: the take-away**

To a first approximation, the equilibrium temperature of a starlight-heated planet can be calculated or predicted by balancing the power it absorbs from the star (and taking into account the planet’s surface reflectivity) and the power it radiates as a warm object. If a planet absorbs more power than it radiates, the planet will gradually warm and, in turn, radiate power at a greater rate until equilibrium is established. If a planet absorbs less power than it radiates, the planet gradually cools, and will decrease its radiative rate until equilibrium is established. In a sense, a planet acts as quite a good thermostat. It controls its temperature by balancing the energy it absorbs and the (temperature-dependent) energy it emits according to well-established laws of thermal physics.

can vary from the mean by nearly 10%.
2.5 How do the predicted planetary temperatures compare to actual temperatures?

So, how well does theory presented in sections 2.3-2.4 predict the actual temperatures of the planets? The data used and the calculations are presented in Table 2.1.

<table>
<thead>
<tr>
<th>planet</th>
<th>distance from Sun (d, AU)</th>
<th>albedo (A&lt;sub&gt;11&lt;/sub&gt;)</th>
<th>calculated equil. temperature (T&lt;sub&gt;calc&lt;/sub&gt;, °K)</th>
<th>measured temperature (T&lt;sub&gt;meas&lt;/sub&gt;, °K)</th>
<th>excess of measured over calculated temp (T&lt;sub&gt;meas&lt;/sub&gt; - T&lt;sub&gt;calc&lt;/sub&gt;, °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>0.59</td>
<td>263</td>
<td>733</td>
<td>470</td>
</tr>
<tr>
<td>Earth</td>
<td>1.000</td>
<td>0.30</td>
<td>256</td>
<td>287</td>
<td>31</td>
</tr>
<tr>
<td>Mars</td>
<td>1.524</td>
<td>0.25</td>
<td>211</td>
<td>220</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 2.1: Calculated & measured temperatures of Venus, Earth, Mars

Clearly, the physics used to determine the surface temperature of a no-atmosphere planet underestimates the temperature for each of the inner solar-system planets with atmospheres. In order to explain these discrepancies, astronomers long ago invoked the greenhouse effect as the most likely explanation. Why? One pointer was that the discrepancy between calculated temperatures for a no-atmosphere planet and observed temperatures is related to the relative abundance of the infrared-light-absorbing gases (water, carbon dioxide, and methane). The atmospheric pressures and gas compositions of the three inner planets can be found in table 2.2.

---

<sup>10</sup>1 AU is defined as the mean Earth-Sun distance; it is equivalent to 1.495 x 10<sup>11</sup> meters
<sup>11</sup>Given is the geometric albedo
The last column (column 7) of Table 2.2 has been added by the author. The entry in the last column is the product of the atmospheric pressure (relative to Earth) in column 2 and the atmospheric fraction (percentage divided by 100) of the total greenhouse gas composition in column 6. Because of the variable presence of water vapor in Earth’s atmosphere, it is not patently obvious how to perform the calculation of column 7 for Earth. Although somewhat arbitrary, the author has used a 2% atmospheric composition for H$_2$O. This average is likely higher than the average water-vapor content of Earth’s atmosphere but also includes some contribution for terrestrial cloud cover (which are composed of water in liquid and solid form).

As we shall see, different greenhouse gases contribute different greenhouse heating. Column 7 on Table 2.2 represents some estimate of the relative greenhouse warming on each inner planet. It should be no surprise, therefore, that this number bears some relation to the respective temperature discrepancy (the last column of Table 2.1) between the temperature calculation for a no-atmosphere situation and the observed temperature.

* Earth’s dry-atmosphere composition
** using an averaged 2% H$_2$O composition

2.5.1 The importance of greenhouse heating to life on Earth

It is important to recognize an important message of Table 2.1: that life on Earth would be quite uncomfortable without the greenhouse heating that presently operates here. Without the presence of greenhouse gases, Earth’s mean surface temperature would be a very uncomfortable -17°C ( = 1°F).

The takeaway

For each of the three inner-solar system planets with an atmosphere, the actual/measured planetary temperature is higher than the predicted equilibrium temperature, calculated by balancing the direct solar heating rate with the planet’s temperature-based radiative rate. For Earth and Mars, the actual temperatures are roughly 15% higher than the predicted temperatures, whereas Venus’s temperature is much, much higher than predicted. Some other mechanism – beyond that of direct sunlight – must be responsible for heating these planetary surfaces beyond their equilibrium temperatures. That mechanism is thought to be the greenhouse-gas effect.
<table>
<thead>
<tr>
<th>Planet</th>
<th>Atmospheric pressure (bar)</th>
<th>non-IR absorbing gases</th>
<th>% compos.</th>
<th>IR absorbing gases</th>
<th>% compos.</th>
<th>Product of col. 2 &amp; col. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>92</td>
<td>N₂</td>
<td>3.5</td>
<td>CO₂</td>
<td>96.5</td>
<td>89</td>
</tr>
<tr>
<td>Earth</td>
<td>1.0</td>
<td>N₂</td>
<td>78.1*</td>
<td>H₂O</td>
<td>≤ 4, var.</td>
<td>0.02**</td>
</tr>
<tr>
<td></td>
<td>O₂</td>
<td>20.9*</td>
<td></td>
<td>CO₂</td>
<td>0.040*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ar</td>
<td>0.93*</td>
<td></td>
<td>CH₄</td>
<td>0.00018*</td>
<td></td>
</tr>
<tr>
<td>Mars</td>
<td>0.006</td>
<td>N₂</td>
<td>2.7</td>
<td>CO₂</td>
<td>95.3</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Ar</td>
<td>1.6</td>
<td></td>
<td>H₂O</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2: Atmospheric properties of Venus, Earth, Mars

2.6 Is Earth’s Temperature Subject to Variability?

There are only three independent variables in the simple no-greenhouse-gas model developed in equation 2.9: the solar power \( P_\ast \), Earth’s distance from the sun \( d_p \), and Earth’s albedo \( A_\ast \). Should any of these variables change with time (either long-term or seasonally), Earth’s temperature would also change with time. In particular, any long-term global warming must have, as its root cause, a long-term cause. We examine this possibility in the no-greenhouse-gas model developed so far.
2.6.1 Orbit variability

Because Earth’s orbit around the Sun is elliptical, the Earth-Sun distance is not constant over Earth’s yearly revolution. Due to the current non-circular orbit shape\textsuperscript{12}, the Earth-Sun distance is at times 1.7% larger than average, and sometimes 1.7% smaller. It may be a surprise to learn that Earth is closest to the Sun on or about January 3 (when the majority of Earthlings, those that live in the Northern hemisphere (NH), are experiencing winter, and it is farthest on or about July 4 (when NH-ers are experiencing summer and SH-ers are experiencing winter.

\textsuperscript{12}Earth’s orbital eccentricity varies with time; see Section 5.3.1
Figure 2.3: Earth has seasons because Earth’s rotation axis maintains the same direction in space as Earth revolves around the sun. Consequently, the Southern hemisphere has summer in December when the sun’s rays shine most directly on it (topmost of the 4 diagrams). Six months later, in June, sunlight shines most directly on the Northern hemisphere (third from the top) accounting for its summer. (NOAA/JPL-Caltech, public domain)
Hopefully you’ve remembered your grade-school geography: the cause of the seasonal temperature variation (on Earth, at least) is not the variation in Earth-Sun distance. Instead, seasonal changes are due to the variation in the directness of sunlight, due to the 23.5° tilt of the Earth’s equatorial plane and its orbit plane, as shown in Figure 2.3. Around the time of the summer solstice, the sun’s rays shine more directly on the Northern Hemisphere and less directly on the Southern Hemisphere. (Clearly it was an NH-er who named this solstice the ‘summer’ one.) Another way to think about this is that the Sun is closer to overhead at mid-day for NH-ers (and therefore a given amount of sunlight is concentrated on a smaller terrestrial area) at the time of the summer solstice.

For the SH-ers, summer solstice is a time when the Sun is low in the sky at mid-day, and therefore its rays are more slantily-directed and consequently spread out over a larger terrestrial area. Consequently, the sunlight-heating power per area is significantly less. The situations are reversed, of course, at the winter solstice.

One might surmise (based on the fact that Earth is closer to the Sun during the SH-summer than during the NH-summer) that SH summers are warmer than NH summers. Not so. The reason often given is that the SH is dominated by oceans and not land. Given that water has a significantly higher specific heat than land (in other words, it takes more energy to raise the temperature of water by a given number of degrees than it does to do the same for land), the extra solar heating of the SH during its summer is balanced by the extra energy needed to warm up the oceans.

Has there been any long-term change in the mean Earth-Sun distance? There is no evidence for Earth’s secular migration either inward or outward from the Sun over its history. However, Earth’s orbital eccentricity does vary with time. This periodic variation along with the periodic variation in the magnitude and direction of Earth’s rotation-axis tilt are believed to be responsible for large long-term terrestrial temperature changes and the explanation for ice ages (see section 5.2).

However, because the period of these orbit/axis variations is so long (tens of thousands of years), these variations cannot be the explanation of significant temperature changes over the past century (which, as we will see, has happened on Earth).

2.6.2 Solar variability

Although astronomers had known of several classes of time-variable stars (variable not only in luminosity, but in temperature and radius as well) since the early 20th century, they had generally assumed for most of the 20th century that the

13 Why does Earth have seasons?: http://scijinks.jpl.nasa.gov/earths-seasons/
Sun was constant, at least in terms of light output. This assumption was not rigorously based on actual data, as there was no way to measure the significant amount of the sun’s luminosity in the wavelength bands (e.g., infrared, ultraviolet) that do not penetrate the atmosphere. Those measurements would have to wait until the satellite observations in the late 1970s.

On the other hand, it had been discovered in the 1843 that the number of dark spots appearing on the solar surface varied with an 11-year cycle. It would not have taken a great leap in imagination to suspect that as portions of the solar surface became dark, the solar light output might also drop in light output. (However, since the late 1970s, it has become clear that the opposite is actually true. Peak sunspot activity corresponds to peak solar luminosity.) In the 20th century astronomers realized that sunspots were magnetic phenomena, and that the 11-year cycle applied to other solar magnetic phenomena (such as the extent of the sun’s corona and the output of solar wind) as well.

In 1976, John Eddy established\textsuperscript{14} the significance of the Maunder solar minimum – a time period from 1645 to 1715 during which solar magnetic activity effectively ceased. Eddy further reminded the scientific community that this time period coincided roughly with that of the Little Ice Age – notorious for its cool summers and snowy winters. This reminder resulted in renewed interest in measuring the total solar irradiance incident on Earth’s atmosphere by satellites in the late 1970s.

Despite this forewarning, astronomers were nonetheless somewhat surprised when satellite radiometer measurements showed that solar irradiance (or energy flux) at Earth (and, by extension, the solar luminosity) varies in step with the solar magnetic cycle (which includes sunspot numbers), as shown in Figure 2.\textsuperscript{15}

Note, however, that the amplitude of the luminosity variation is only 0.5 W/m\textsuperscript{2} (equivalent to a variation of 0.04%), which translates a temperature variation on Earth of only 0.03 °C (equivalent to a variation of 0.01%).


\textsuperscript{15} Solar Irradiance Changes and the Sunspot Cycle: https://spacemath.gsfc.nasa.gov/weekly/Earth8.pdf
Figure 2.4: Solar irradiance and sunspot number since January 1979 according to NOAA’s National Geophysical Data Center, NGDC. The thin lines indicate the daily irradiance (red) and sunspot number (blue), while the thick lines indicate the running annual average for these two parameters. The amplitude of the variation in solar irradiance is approximately 0.6 W/m$^2$ during one sunspot cycle. (NASA, public domain)

### 2.6.3 Albedo Variability

The overall albedo of Earth ($\approx 0.30$; see Table 2.1) is dependent on many different material components with quite different albedo values. The mix of these components varies with time, both seasonally and long-term. We consider only the long-term effects here. Table 2.3 gives the albedos of a number of terrestrial components. Remember that (according to equation 2.10) increasing the albedo lowers the planetary temperature; decreasing it raises the temperature.

---

<table>
<thead>
<tr>
<th>Material</th>
<th>Percent Reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Snow</td>
<td>80-95</td>
</tr>
<tr>
<td>Thick Cloud</td>
<td>70-80</td>
</tr>
<tr>
<td>Water (sun near horizon)</td>
<td>50-80</td>
</tr>
<tr>
<td>Old Snow</td>
<td>50-60</td>
</tr>
<tr>
<td>Light soil</td>
<td>25-45</td>
</tr>
<tr>
<td>Thin Cloud</td>
<td>20-30</td>
</tr>
<tr>
<td>Dry soil</td>
<td>20-25</td>
</tr>
<tr>
<td>Wet soil</td>
<td>15-25</td>
</tr>
<tr>
<td>Deciduous forest</td>
<td>15-20</td>
</tr>
<tr>
<td>Dark soil</td>
<td>5-15</td>
</tr>
<tr>
<td>Asphalt</td>
<td>5-10</td>
</tr>
<tr>
<td>Crops</td>
<td>10-25</td>
</tr>
<tr>
<td>Coniferous forest</td>
<td>10-15</td>
</tr>
<tr>
<td>Water (sun near zenith)</td>
<td>3-5</td>
</tr>
</tbody>
</table>

Table 2.3: Albedos of different terrestrial materials.
Dust and Aerosols

Albedo changes following volcanic eruptions

The drop in average global temperatures after significant volcanic eruptions is well documented. For example, the 1991 explosion of Mt. Pinatubo, the largest eruption of the twentieth century, was responsible for a drop of 0.3 - 0.6 °C (0.5 - 1.0 °F) in global temperatures in the subsequent two or three years. The two most notable volcanic explosions in the previous century (Krakatoa in 1887 and Lim in 1815), along with others in the past two millennia, have been linked to unusual snowfalls in the years following the eruptions. But volcanic eruptions have not only reduced global temperatures. The Pinatubo eruption also modified global rainfall patterns and was responsible for the flooding of the Mississippi River and the drought in the African Sahel 1993, two years after the main eruption.

The effects of volcanic emissions depend strongly on the size and physical state of particles introduced into the atmosphere. Large grains (sand-grain size and larger) fall out of the atmosphere (due to gravity) almost immediately. Volcanic ash (particles smaller in size than 2 millimeters), which can remain in the lower atmosphere for up to a week, are capable of cooling and darkening the surface below due to their absorption of solar radiation. However, these lower-atmospheric particles are washed to the ground by rain, and therefore have little long-term cooling effects. Some volcanic ash, however, reaches the upper stratosphere, where the particles can spread over large geographic areas and remain for months before drifting back to ground. They also block sunlight and contribute to some global cooling while in the stratosphere.

The main long-term volcanic cooling effects, however, arise not from dust but from the various gaseous sulfur oxides that are emitted by volcanoes. These sulfur compounds combine with atmospheric water vapor to form a haze of sulfuric acid droplets that can remain in the upper stratosphere (where removal by rain is much less likely) for as long as two or three years in the case of a major eruption. The sulfuric acid droplets are light in color and therefore reflect significant solar radiation back into space, thereby causing a measurable drop in global temperatures. Eventually, the droplets grow large enough for gravity to bring them down to ground.

The one exception to the general rule that dust/aerosols increase Earth’s overall albedo is that of black carbon (or soot). In general, the effects of black carbon are very small compared to those of volcano-generated aerosols. See the radiative-
forcing effects in Figure 3.12.

**Land use**

The main land-use change contributing to global warming/cooling is deforestation. Because trees (and other plants) take up CO\textsubscript{2} during photosynthesis, deforestation contributes to global warming. Its contribution is second in importance to that of greenhouse gases. Again, see the discussion of radiative-forcing effects in Figure 3.12.

**Clouds**

Cloud prediction in a changing climate is apparently a dicey subject. The IPCC-AR5-WG1 consensus is that the interaction of aerosols with the atmosphere-ocean system results in a net global cooling. However, the level of confidence in this result is low. See the radiative-forcing effects in Figure 3.12.

2.7 **The Take-away: An Earth without the Greenhouse Effect**

Astronomers and planetary scientists have long known that Earth would be largely uninhabitable without our greenhouse-gas atmosphere. As Table 2.1 shows, the mean global temperature is presently a comfortable 11°C, rather an ice-world temperature of -17°C.

We have also seen that all three of the independent variables that determine Earth’s surface temperature in equation 2.9 do vary with time. Earth’s orbital changes happen over time scales of thousands of years, not over times as short as decades or even a century, so it is difficult to see how these orbital effects could be responsible for secular terrestrial temperature changes over these smaller time periods.

On the other hand, changes in the sun’s power and in Earth’s albedo have occurred in measurable amounts over time periods as short as months or years. However, changes in solar power (or its irradiance/flux at Earth) have shown (see Figure 2.4) no long-term trend over the past 35 years, over which time (as we will see in chapter 4) the Earth’s temperatures have increased.

Changes in Earth’s albedo do happen on both short-term (e.g., due to volcanic dust emission) and long-term time scales (e.g., due to deforestation). The question for further investigation is whether any long-term albedo changes are of sufficient magnitude to explain the long-term warming that Earth has experienced.
Chapter 3

What Determines the Temperature of Earth (when greenhouse gases are present)?

3.1 How does the greenhouse effect raise the temperature of a planet?

3.1.1 A short description of Earth’s greenhouse effect

A bare-bones description of the greenhouse effect (using Earth as an example) follows. A descriptive schematic of the process is shown in Figure 3.1.
(1) The sun emits a large portion of its radiation in the visible spectrum.

(2) Earth’s atmosphere is relatively transparent to that visible light, so that it absorbs relatively little of the incoming sunlight.

(3) Significant sunlight therefore reaches Earth’s surface, where it is absorbed. The surface rises in temperature until an equilibrium is established between the rate at which Earth absorbs energy and the rate at which it emits energy. Due to its much lower (than the sun) temperature, Earth emits all of its energy in the infrared part of the spectrum.

(4) Greenhouse gases in Earth’s atmosphere are relatively opaque to Earth’s infrared radiation. These gases absorb significant portions of the infrared spectrum, and thereby keep a significant amount of this energy trapped at the surface and in the lower atmosphere. This trapped infrared energy warms Earth to a higher temperature than it would otherwise reach from direct solar heating alone.

\[\text{http://people.uvawise.edu/pww8y/Reviews/ES/ESRevs/GrnHsEff4.jpg}\]
3.2 Earth’s energy budget

Before we examine each of these steps in more detail, we examine Earth’s energy budget (Figure 3.2). Such diagrams are common in the popular climate-change literature. We shall refer to some of the numbers in the detailed sections that follow.

Figure 3.2: The energy budget of Earth tracks in detail what happens to the incident solar flux of 340.4 W/m². (NASA, public domain)

Because we are in a situation where the Earth’s temperature is roughly constant over the long term (in scientific speak, ‘thermal equilibrium’), the amount of ‘incoming’ power must match the total ‘outgoing’ power (examples of outgoing


[2]It should be understood that there is an uncertainty of a few percent in each of these numbers. Consequently one will find diagrams with slightly different numbers in the literature.

[3]Power is defined as the change in energy divided by the change in time, with units of Watts (or joule/sec) (example of incoming power include incident light and absorption of light) and with symbol W)
power include reflection of light, emission of light, and evaporation) from Earth. (The numbers in Figure 3.2 are actually for power per unit area (units of $W/m^2$ rather than power. The incoming power per area and outgoing power emitted per area must also match, of course.)

### 3.2.1 Energy budget for Earth overall

**Incoming**

- incident solar radiation 340.4

  *total incoming* 340.4

**Outgoing**

- reflection of incident light by Earth’s atmosphere/clouds 77.0
- reflection of incident light by Earth’s surface 22.9
- emission of IR radiation by Earth’s atmosphere 169.9
- emission of IR radiation by Earth’s surface 40.1
- emission of IR radiation by Earth’s clouds 29.9

  *total outgoing* 339.8

Some important conclusions from the data:
1) Notice that – for the case of Earth overall – the incoming power per unit area (340.4 W/m$^2$) exceeds the outgoing power per area (339.8 W/m$^2$) by a relatively small amount. This is the basis of the global-warming greenhouse effect which, if unchecked, will result in a continued (and perhaps runaway) increase in Earth’s temperature.

2) Roughly 30% of the incident sunlight is reflected by Earth as a whole. This number matches Earth’s bond albedo found in many reference works (see also Table 3.1).

### 3.2.2 Energy budget of Earth’s Surface

Energy balance must also occur individually for both the surface and from the atmosphere/clouds (the atmosphere and clouds are combined for simplicity).
Incoming

absorption of IR radiation emitted by greenhouse gases 340.3
absorption of incident solar energy 163.3

\textit{total incoming} 503.6

Outgoing

emission of IR radiation by Earth’s surface 398.2
evaporation of liquid water into atmospheric vapor 86.4
rising convective thermals 18.4

\textit{total outgoing} 503.0

Not surprisingly, there is an excess of the incoming energy over the outgoing which matches the same excess for Earth overall (see above).

3.2.3 Energy budget of Earth’s Atmosphere/Clouds

It is left to the reader to show that there is an exact balance (using the same numbers from Figure 3.2) of the incoming and outgoing powers per unit area. Answers and method are in Appendix B.

It should be noted that there is some controversy about the use of such ‘energy budget’ diagrams. Global-warming supporters point to the observations by several satellites\textsuperscript{6} that back up the claim that the planet is a net energy absorber. Global-warming deniers claim that the numbers are meaningless, partly because they are a two-dimensional projection of a three-dimensional system and partly because such portrayals are not based on a molecular level of energy exchange.

The take-away

The claim that Earth presently absorbs slightly more power (from the combined effects of direct solar radiation and greenhouse-gas trapping of energy) than it emits is supported by observational satellite data. The blanketing effect of

\textsuperscript{6}Satellites that have directly measured the imbalance include: Earth Radiation Budget Experiment; Earth’s Radiant Energy System (CERES); NASA’s Terra and Aqua satellites. The excess energy absorbed by Earth range falls in the range 0.6 - 2.4 Watts per square meter as opposed to the value of 0.6 Watts per square meter used in Figure 3.2.
Earth’s atmosphere works by allowing visible sunlight through but preventing infrared Earth radiation from completely escaping.

### 3.3 The greenhouse effect in detail: solar radiation

We now revisit each of the steps of the planetary greenhouse effect (section 3.1) in detail. We again use Earth as an example.

---

**Figure 3.3: The energy emitted (per time per unit area) is graphed vs. wavelength of light.**

[gray curve] The ideal emission spectrum from a 5800 K black-body. [yellow] The actual solar emission incident at the top of Earth’s atmosphere. [red] The solar spectrum that makes it through the atmosphere and reaches the surface. Absorption bands due to various atmospheric constituents are identified; the transparency/opacity of the terrestrial atmosphere will be discussed in detail in the next section. (Image created by Robert A. Rohde / Global Warming Art; licensed for non-commercial use.)

We have already talked about the sun behaving as a very good blackbody (section 2.3). An ideal blackbody spectrum for the Sun’s temperature is the gray curve in Figure 3.3. However, the Sun is not quite an ideal thermal emitter (or blackbody) due to various effects present in the solar atmosphere (sunspots, flares, coronal emission), and therefore the actual energy spectrum that reaches the top
of Earth’s atmosphere (yellow-shaded in Figure 3.3) is slightly different. We also determined the wavelength at which the most energy is radiated (\( \lambda = 0.05\mu m = 500 \text{ nm} \)) in section 2.3.2.

As can be seen from Figure 3.3, the most significant amounts of sunlight are radiated in the visible and in the infrared (720 nm \( \leq \lambda_{ir} \leq 0.01 \text{ m} \)) portion of the spectrum along with a small portion radiated in the ultraviolet (\( \lambda_{uv} \leq 390 \text{ nm} \)).

The solar spectrum that reaches the top of Earth’s atmosphere is then modified by molecular scattering and absorption in the Earth’s atmosphere; the energy distribution that actually reaches Earth’s surface is shown in Figure 3.3 as the red-shaded curve.

### 3.4 The greenhouse effect in detail: Earth radiation

Earth is also a blackbody, although not quite as ideal as the Sun. (For example, Earth reflects light, whereas an ideal blackbody absorbs all light incident on it. The Sun does not reflect any incident light.) Therefore, Earth also obeys the blackbody laws, with some corrections.

If we now apply Wien’s law (equation (2.4)) to Earth which has a mean surface of 287\(^\circ\)K, the result is that \( \lambda_{max} \) (Earth) = 10 \( \mu \text{m} \), which lies in the infrared portion of the spectrum. Note that this matches the smooth blue Planck blackbody curve (the intermediate of the 3 curves peaking near 10 micrometers) in Figure 3.5. The shaded irregular blue region in the same figure is the portion of the infrared emission that escapes Earth’s atmosphere. As can be seen from a comparison of the ideal blackbody emission curve and the emission that actually makes it through the atmosphere, the majority of Earth’s thermal radiation (Figure 3.5 says 70-85%) does not penetrate the atmosphere and, instead, is absorbed by various greenhouse gases.

We now have a deeper understanding of the origin of the greenhouse effect: The Sun’s peak thermal energy emission is in the middle of the visible part of the spectrum, and it happens that Earth’s atmosphere is transparent to much of this visible-light radiation. The radiation that does reach the surface of Earth and is absorbed heats Earth until there is a balance between the rate of energy absorbed and the rate of energy emitted. Earth’s surface temperature is lower than the Sun’s surface temperature by a factor of approximately 20, and consequently Earth’s peak energy emission is at a wavelength that is 20x longer than the Sun’s. The wavelength of the peak terrestrial emission happens to be in the infrared part of the spectrum. Unlike its transparency to much of the Sun’s
visible spectrum, Earth’s atmosphere is opaque to much of Earth’s own infrared radiation.

The details of why Earth’s atmosphere is transparent to visible radiation but opaque to infrared radiation is the subject of the next section.

### 3.5 The greenhouse effect in detail: Earth’s atmosphere: transparency and opacity

**Composition of Earth’s atmosphere**

<table>
<thead>
<tr>
<th>Component</th>
<th>Concentration in</th>
<th>Concentration in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Percent</td>
<td>Parts Per Million</td>
</tr>
<tr>
<td>by Volume</td>
<td>(PPM)</td>
<td>(PPM)</td>
</tr>
<tr>
<td>Nitrogen (N(_2))</td>
<td>78.084</td>
<td>780,840.0</td>
</tr>
<tr>
<td>Oxygen (O(_2))</td>
<td>20.946</td>
<td>209,460.0</td>
</tr>
<tr>
<td>Argon (Ar)</td>
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</tr>
<tr>
<td>Carbon dioxide (CO(_2))</td>
<td>0.0315</td>
<td>315.0</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>0.00182</td>
<td>18.2</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>0.000524</td>
<td>5.24</td>
</tr>
<tr>
<td>Methane (CH(_4))</td>
<td>0.00015</td>
<td>1.5</td>
</tr>
<tr>
<td>Krypton (Kr)</td>
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<td>1.14</td>
</tr>
<tr>
<td>Hydrogen (H(_2))</td>
<td>0.00005</td>
<td>0.5</td>
</tr>
<tr>
<td>Nitrous oxide (N(_2)O)</td>
<td>0.00003</td>
<td>0.3</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>0.000012</td>
<td>0.12</td>
</tr>
<tr>
<td>Ammonia (NH(_3))</td>
<td>0.000001</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 3.1: The composition of the dry terrestrial atmosphere (1977). Water vapor is an additional component, but is highly dependent on location. CO\(_2\) levels exceed 400 PPM as of this writing.

---

The composition of the dry Earth’s atmosphere is shown in Table 3.1. Water vapor is present in an amount that varies significantly (0 to 4%) by location and is therefore not included in the table.

Although the main components of Earth’s atmosphere (that is, nitrogen, oxygen, argon, and water\(^9\)) have remained relatively constant in abundance over the past several hundred years, the abundance of trace gases has not.

**Transparency of Earth’s atmosphere to visible light**

By and large, Earth’s atmosphere is transparent to only two significant parts of the electromagnetic spectrum: (1) visible light (0.39 \(\mu m\) \(\leq\) wavelength \(\leq\) 0.72 \(\mu m\)) and (2) radio waves (wavelength \(\geq\) 0.01 m). The atmospheric transmittance (or transparency) as a function of wavelength is shown in Figure 3.4.

![Figure 3.4: The transmittance of Earth’s atmosphere as a function of wavelength. The 4 significant causes of absorption/scattering are 3 molecules (H\(_2\)O, CO\(_2\), and O\(_3\), whose peaks are marked), and the Rayleigh scattering phenomenon. Note for example the existence of a window in which visible light is transmitted.](http://astro.wsu.edu/worthey/astro/html/lec-climate.html and the Modtran interface at http://climatemodels.uchicago.edu/modtran/ to see how transmittance varies as input parameters are varied.)

\(^{h}\) An alternative view of atmospheric transparency as a function of wavelength is shown in Figure 3.5.

\(^{9}\)water vapor abundance averaged annually
Figure 3.5: The top panel shows the light emitted by Sun (red) and Earth (blue) as a function of wavelength. The curves have been normalized to fit on the same axes; the Sun emits far more light (approximately $1.6 \cdot 10^5$ time more light overall. The smooth curves represent the emission by ideal blackbodies for the temperatures shown. The curves shaded underneath show the light that actually passes through Earth’s atmosphere. The very bottom panel shows (in 6 parts) the relative absorption/scattering potential of various gases. The middle panel shows the cumulative absorption/scattering of all the gases. (Robert A. Rohde, Global Warming Art, CC BY-SA 3.0)

Three features of Figures 3.4 and 3.5 are worthy of note:

(1) In the visible portion of the spectrum, there is relatively little absorption of light.

(2) The primary reason that visible solar radiation does not reach Earth’s surface (in the absence of obstructions such as clouds or particulate matter, e.g.,
that ejected by volcanoes) is Rayleigh scattering. The two main components of Earth’s atmosphere (oxygen and nitrogen) scatter (or absorb and then re-emit in a different direction) solar radiation with a probability that is proportional to \((\text{wavelength})^{-4}\). The effect of this scattering is shown by the shaded gray curve in Figure 3.4 and in the very bottom panel in Figure 3.5. Note that Figures 3.4 and 3.5 plot complementary parameters: fractional transmittance (graphed in Figure 3.4 and the top panel of Figure 3.5) = 1 - fractional absorption (graphed in the middle and bottom panels of Figure 3.5).

3) Whereas Earth’s atmosphere is largely transparent to visible light, it is largely opaque to infrared light. The most significant absorber of light is water vapor, followed by carbon dioxide, and then by ozone, methane, and nitrous oxide. The gases that absorb significantly in the infrared are called greenhouse gases.

### 3.6 The greenhouse effect in detail: greenhouse gases

#### 3.6.1 What is a ‘greenhouse gas’?

As we have just seen, a gas is considered to be a greenhouse gas if it is a significant absorber of infrared radiation. Such trapped infrared energy raises the temperature of the planet beyond that from direct sunlight alone. Figures 3.4-3.5 show the absorption bands of various gases in the infrared that are believed responsible for greenhouse warming.

Molecules have excited vibrational and rotational energy levels similar to the excited energy levels that electrons have within atoms. In general, vibrational excitation is effected by infrared radiation and rotational excitation, by radio radiation. (Remember that electron excitation is generally effected by visible radiation.)

As for the case of electron excitation, a non-zero electric dipole moment must be present in order for vibrational or rotational motions to absorb electromagnetic energy (aka light). The most common molecules in Earth’s atmosphere, molecular oxygen and molecular nitrogen are symmetric. The only vibration mode available for these diatomic molecules is a stretch, which has no associated dipole moment. Consequently, these molecules do not absorb radiation.

On the other hand, molecules such as water, carbon dioxide, methane, ozone and other molecules have various asymmetries in either their bending or stretching motions. Consequently, they can absorb characteristic infrared wavelengths that...
Figure 3.6: The three vibration modes of carbon dioxide. The central carbon atom is black; the oxygen atoms are red. The symmetric stretch mode (a) does not produce a net electric dipole moment, so absorption of light at this wavelength is suppressed. The other two modes ((a) bending, (c) antisymmetric stretch) do produce dipole moments and therefore produce active absorption at the wavelengths shown. Compare to the absorption bands shown for CO$_2$ in Figure 3.4 (Figure contributed by C. Law, public domain)

excite these motions.

We now take a look at each of the important greenhouse gases in turn.

### 3.6.2 Carbon Dioxide (CO$_2$)

**Details of molecular absorption**

Carbon dioxide has three vibration modes, as shown in Figure 3.6. Although CO$_2$ is a symmetric molecule at rest, two of the three possible vibration modes (bending and the asymmetric stretching; middle and right pictures, respectively) result in a non-zero electric dipole moment and therefore can absorb characteristic wavelengths of light that excite those motions. The bending mode absorbs far more energy at wavelength $\lambda = 15$ microns (equivalent to the labeled $\lambda^{-1} = 667$ cm$^{-1}$) than the asymmetric stretching at $\lambda = 4.3$ microns (equivalent to $\lambda^{-1} = 2349$ cm$^{-1}$).

Notice that the these 2 asymmetric vibration modes show up strongly in the spectrum in Figure 3.5 at the wavelengths indicated. Note also that the symmetric vibration mode – which does not produce an electric dipole moment and therefore produces no absorption – (\(\lambda = 7.5\) microns, equivalent to $\lambda^{-1} = 1336$ cm$^{-1}$) does not appear in absorption in the Figure 3.6 spectrum.

---

The rising level of CO$_2$ in the atmosphere

Figure 3.7 shows the concentration of carbon dioxide as a function of time beginning in the year 1000. The CO$_2$ concentration as measured directly from the atmosphere (since 1958) is shown in Figure 3.8. Notice that there is an annual oscillation in the CO$_2$ concentration, in addition to the long-term increase.

![Graph showing concentration of CO$_2$ over time](image)

Figure 3.7: The variation of the atmospheric CO$_2$ concentration since 1000. Data before 1958 comes from the Law Dome DE08, DE08-2, and DSS ice cores. Data since 1958 are direct atmospheric measurements at Mauna Loa (HI) Observatory. (2 Degrees Institute [CC BY-NC 3.0](http://www.co2levels.org/))

The annual (or seasonal) variation (see inset of Figure 3.8) is caused by the uptake and release of CO$_2$ due to plant growth and decay. Because the lion’s share of Earth’s land mass is in the northern hemisphere, the CO$_2$ seasonal variation largely reflects the plant growth/decay cycle in that hemisphere. CO$_2$ levels reach a maximum in May and then decrease as new plant growth removes CO$_2$ from the atmosphere via photosynthesis. The CO$_2$ concentration reaches a minimum in October and then begins to rise again as plants die and leaves fall, thereby releasing CO$_2$ back into the atmosphere.

---

1[http://www.co2levels.org/]
2[http://scrippsc02.ucsd.edu//history_legacy/keeling_curve_lessons]
The variation of the atmospheric CO$_2$ concentration since 1958 from direct atmospheric measurements at Mauna Loa (HI) Observatory. (Image created by Robert A. Rohde / Global Warming Art, licensed for non-commercial use.) See also https://scrippsco2.ucsd.edu for more information.

The reader should not be left with the impression that the atmospheric CO$_2$ concentration has always varied so smoothly with time. The long-term variability of the CO$_2$ concentration (determined from ice core sampling) is shown in Figure 3.9. It is certainly noteworthy that the present CO$_2$ concentration is greater than at any time in the past 800,000 years, a time period during which Earth experienced a number of ice ages.

The long-term variation in CO$_2$ concentration – and its relationship to Earth’s temperature – will be revisited in section 5.1.

14https://keelingcurve.ucsd.edu https://www.ncdc.noaa.gov/paleo-search/study/6091
The rising level of \( \text{CO}_2 \) in the oceans

It should not be a surprise that the \( \text{CO}_2 \) concentration of the oceans is also increasing (Figure 3.10, top panel\(^{15} \)). As the concentration increases, the oceans become more acidic, as shown by the decrease in the pH of seawater over time (Figure 3.10, bottom panel).

\(^{15}\)Climate Change: Evidence and Causes RAS, NAS (2013). Data adapted from Dore et al. (2000) and Bates et al. (2012)
Figure 3.10: CO$_2$ concentration levels in atmosphere and ocean, and pH measures of ocean surface water. (Source: NOAA, public domain.) See also "Climate change: evidence and causes" at https://royalsociety.org/topics-policy/projects/climate-change-evidence-causes/.

The rising level of CO$_2$ in continental rocks: weathering via the carbonate-silicate cycle

But it should also not be a surprise that the CO$_2$ concentration in continental rocks will also increase, as more CO$_2$ is combined chemically with silicate rocks, in the presence of liquid water, through the carbonate-silicate (C-Si) cycle, a process often called weathering. And some of this CO$_2$-bearing continental rock may end up deposited beneath the ocean through metamorphic processes.

In some sense, this inorganic C-Si cycle is a cousin of the organic carbon cycle, in which biological processes convert CO$_2$ and H$_2$O into molecular oxygen and organic matter (aka carbohydrates) via photosynthesis.
These C-Si cycle includes the following four typical reactions; other metals may replace calcium (Ca) in these weathering processes, although Ca participation is by far the most common.

\[
CO_2 + CaCO_3 + H_2O \rightarrow Ca^{++} + 2 HCO_3^- \quad (3.1)
\]

\[
2 CO_2 + CaSiO_3 + H_2O \rightarrow Ca^{++} + 2 HCO_3^- + SiO_2 \quad (3.2)
\]

\[
Ca^{++} + 2 HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \quad (3.3)
\]

\[
CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2 \quad (3.4)
\]

Processes \((3.1)\) and \((3.2)\) can occur on land in the presence of water (generally rainfall). Rainwater washes the resulting calcium ions and the bicarbonate \((HCO_3^-)\) ions into the oceans, where they increase the overall alkalinity of the oceans, which in turn allows the ocean water to absorb additional CO\(_2\). Note that twice as much CO\(_2\) is used in the breakdown of silicate rocks versus carbonate rocks.

Process \((3.3)\) uses the calcium produced in the previous two reactions. The increase in ocean content of CO\(_2\) lags the increase in atmospheric content (see Figure \(3.9\)).

**C-Si cycle weathering as climate feedback**

The C-Si cycle is the key to regulating the abundance level of CO\(_2\) in the atmosphere. The cycle acts as critical negative feedback connecting the atmospheric CO\(_2\) levels and global warming. This cycle therefore also regulates global temperatures.

For example, if excess CO\(_2\) builds in the atmosphere, the greenhouse effect will raise Earth’s surface temperature, which in turn increases the evaporation of water, increased rainfall, and, therefore increased C-Si weathering. Note that this removes CO\(_2\) from the atmosphere, opposite (or in NEGATIVE feedback) to the original CO\(_2\) increase.

Consequently, over long times scales, the C-Si cycle has a stabilizing effect on Earth’s global temperatures. The cycle indeed acts as Earth’s thermostat.

The rate of weathering via the C-Si process is dependent on many factors, including
The variety of these effects therefore makes the understanding and predictability of the details of this climate feedback somewhat problematic.

**Historical changes in climate feedback**

There have been several large-scale feedback changes in past history. Two that involve Earth are plate tectonic changes and those due to biological evolution. Plate tectonic changes include those due to uplift of major mountain ranges. The rise of the Andes and Himalayas is likely to have initiated the Late Cenozoic Ice Age via increased C-Si weathering (on the expanded surface area) and the consequent dropoff in atmospheric CO$_2$ abundance.

Biological processes in soils can produce organic acids that increase weathering. In addition, root respiration and oxidation of organic soil also produce CO$_2$, increasing weathering.

Two other feedback changes are of great importance: (1) periodic solar irradiation changes caused by periodic variations in Earth’s orbital parameters (e.g., orbit shape, inclination of rotation axis to orbit, precession), and (2) rising CO$_2$ emissions due to changes in human behavior. This work will concentrate much more on these latter two effects (at the relative expense of the first two mentioned: tectonic and biological processes).

**The C-Si cycle on other planets**

The C-Si cycle depends on the presence of liquid water. But such water may not be present on other planets for a variety of reasons. At the inner edge of the Habitable Zone (HZ, defined as the orbital distance range around the Sun where water is liquid and the chance for life is greater), liquid water may evaporate completely via the runaway greenhouse effect. As temperatures start to increase, more water is forced into the atmosphere, along with more CO$_2$ leached out of the rocks or returned to the atmosphere by volcanism. This positive feedback raises temperatures (and water and carbon dioxide levels) even more. This gaseous water is susceptible to dissociation by solar ultraviolet, and the resulting ions escape. Venus may be such a planet.

On the other hand, near the outer edge of the HZ, the planet may become so cold that water exists as ice. Ice, unlike liquid water, cannot effect the C-Si cycle. Consequently there is no weathering. If the CO$_2$ freezes out, the greenhouse
effect is reduced further, and all of the once-volatiles will condense into polar caps.

There are water worlds (planets completely dominated by liquid) known in the solar system and also as exoplanets. In a recent paper, authors show that these water worlds, dominated by seafloor (rather than continental) weathering, are superior in global temperatures against gradual evolutionary changes in the host star’s luminosity (or power), indicating that such water worlds may be more suitable targets in the search for life.

3.6.3 Water (H₂O)

Details of molecular absorption

Water also has three vibration modes, as shown in Figure 3.11. Two of the three possible vibration modes of H₂O [bending (left, a) and the asymmetric stretching (right, c)] result in a non-zero electric dipole moment and therefore can absorb characteristic wavelengths of light that excite those motions. The bending mode absorbs far more energy at wavelength $\lambda = 5.8$ microns (equivalent to the labeled $\lambda^{-1} = 1711$ cm$^{-1}$) than the asymmetric stretching at $\lambda = 2.6$ microns (equivalent to $\lambda^{-1} = 3850$ cm$^{-1}$).

Notice that the these 2 asymmetric vibration modes show up strongly in the spectrum in Figure 3.5 at the wavelengths indicated. Note also that the symmetric vibration mode does not produce an electric dipole moment and therefore produces no absorption.

Water is the dominant contributor to the terrestrial greenhouse effect, but ....

There is common agreement among climate scientists that water is responsible for the majority of Earth’s greenhouse effect. Figures 3.3, 3.4, and 3.5 indeed show that water is the atmospheric constituent the broadest absorption bands in the infrared. Various sources estimate that water’s contribution to the terrestrial greenhouse effect is between 60% and 80% of the total (CO₂’s contribution is approximately 20%, and methane and other trace gases 5% or less.)

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Figure 3.11: The three vibration modes of water. The symmetric stretch mode (center, b) does not produce an electric dipole moment, so absorption of light at this wavelength is suppressed. The two modes on the left and right do produce dipole moments and therefore produce active absorption at the wavelengths shown. Compare to the absorption bands shown for H$_2$O in Figure 3.5 (Figure contributed by C. Law, public domain)

If water is indeed the major contributor to global warming, then one might ask why all the fuss is being made about CO$_2$.

Unlike other atmospheric constituents, the abundance of water is highly variable both in time (able to change dramatically on times scales as short as hours) and in geographical location (e.g., think the Sahara desert versus the Amazon rain forest). And indeed this temporal/geographic variation is responsible for weather events ranging from precipitation (which can change by the hour) to cyclonic storms such as tornados or hurricanes (which can last from minutes to several days) to long-term effects such as El Niño, monsoons, and the polar vortex (which can last for months). Water vapor’s contribution to the atmosphere can range from virtually zero on up through 5%.

However, when averaged over periods of years or decades, the global average of water in the atmosphere is relatively constant, and it is kept in modulated equilibrium by the hydrologic cycle (the interaction of atmospheric water – vapor and clouds – with oceans or other ground water and with plants via such processes as rainfall, evaporation, etc.).

If the water vapor concentration becomes too high, the rate of precipitation and condensation in the form of rain, snow, frost, etc. exceeds the evaporation rate from plants or ground water, thereby lowering the amount of water in the atmosphere. If the water vapor concentration becomes too low, evaporative processes that return water to the atmosphere exceed such processes as precipitation and condensation, thereby raising the amount of water in the atmosphere.

If the atmospheric concentration of water vapor in the atmosphere remains constant over the long-term, then it cannot be responsible for any long-term global
temperature changes.

Figure 3.12: The variation in the abundance of various greenhouse gases in Earth’s atmosphere since 1975 from direct atmospheric measurements at Mauna Loa (HI) Observatory. (NOAA, public domain)

3.6.4 Methane (CH$_4$)

Figure 3.12 shows the abundance of methane in the terrestrial atmosphere as a function of time. The methane concentration has increase by 12% since the early 1980s and by a factor of 2.6 since the pre-Industrial Age. Human activities which have led to a significant rise in the atmospheric methane concentration include livestock raising; cultivated rice paddies; landfills; and rising use of natural gas as an energy source (some methane escapes into the atmosphere during its extraction, transportation, and land use).

3.6.5 Nitrous Oxide (N$_2$O)

Figure 3.12 also shows the atmospheric abundance of nitrous oxide as a function of time. Nitrous oxide was not included in the abundance table (Table 3.1) because its abundance was below the 0.00004% limit of the table. The nitrous oxide concentration has increase by 8% since the early 1980s (Figure 3.12) and by about 25% since the pre-Industrial Age. The rise is primarily due to the use of nitrogen-based fertilizers in agriculture.
3.6.6 Halocarbons (CFC/HCFC/HFC)

Figure 3.12 also shows the atmospheric halocarbon abundance as a function of time. Halocarbons were not included in the abundance table (Table 3.1) because their abundances were below the 0.00004% limit of the table. Halocarbons (particularly the chlorofluorocarbons) were commonly used as refrigerator coolants and fire retardants in the last century. It was realized in the 1950s that CFCs were particularly damaging to the ozone later in the upper atmosphere (the protects us from harmful ultraviolet radiation). CFC production is now largely banned, and consequently CFC levels in the atmosphere have decreased.

3.6.7 The relative importance of various greenhouse gases

<table>
<thead>
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<th>time-averaged</th>
<th>clear sky scenario</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O (vapor)</td>
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<td>60</td>
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</tr>
<tr>
<td>H₂O (clouds)</td>
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<td></td>
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</tr>
<tr>
<td>CO₂</td>
<td>20</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>CH₄, N₂O, O₃</td>
<td>10</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Estimated % contributions to greenhouse warming by various absorbers

3.7 Quantifying the relative importance of climate-influencing factors

An increase in atmospheric CO₂ abundance over the past 100 years is certainly a necessary condition for CO₂ to be the responsible culprit for global warming over that same period. But it is not a sufficient condition. Remember that correlation is not necessarily causation. After all, the atmospheric abundances of two other greenhouse gases, methane (CH₄) abundance and nitrous oxide (N₂O), have also increased (see Figure 3.12 for recent data.) How do we know that one of these gases isn’t the primary cause of recent global warming?

The relative contribution of various greenhouse gases toward global warming is dependent on the concentration of the gas in the atmosphere, the degree to which the gas absorbs infrared radiation, and the lifespan of the gas in the atmosphere. It would be nice if there were a unique simple-to-understand and simple-to-calculate measure that combines all these factors and comes up with a here’s-how-much-the-temperature-will-rise-if-we-put-this-much-greenhouse-gas-into-the-atmosphere...


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number. Alas, not. Three of the more common attempts to do something like this are ‘radiative forcing’, ‘climate sensitivity’, and ‘global warming potential.’ We discuss each in turn.

### 3.7.1 Radiative forcing

The IPCC and others have latched on to something called ‘radiative forcing’ which the IPCC defines as “change in net irradiance at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.” That needs translation into English.

Agents that drive climate change can be divided into two categories: **climate forcings** and **climate feedbacks**. A **climate forcing** is an energy imbalance imposed on the climate system either externally (e.g., by volcanic emissions or changes in the sun’s power output) or by human activities (e.g., by anthropogenic greenhouse-gas emissions or by changes in land-use management). A **climate feedback**, on the other hand, is an internal climate process that amplifies or reduces the climate’s response to a specific forcing. For example, an increase in the atmospheric concentration of water vapor (H$_2$O) [due to warming caused by increased atmospheric CO$_2$ concentrations] serves to amplify the initial warming because H$_2$O is itself a greenhouse gas.

Because forcing is defined as an ‘irradiance’ or ‘insolation’ (a quantity that is normally termed ‘flux’ in most of the physics and astronomy community), that means that it has units of W/m$^2$. Values for radiative forcing (RF) can be calculated not only for greenhouse gases, but also for changes in other quantities that determine global temperatures, such as Earth’s albedo or the amount of solar flux incident at Earth. A positive value of radiative forcing (RF) indicates that the global mean temperature will rise; a negative value indicates a temperature drop. Furthermore, RF is calculated relative to a baseline year, a year in which global temperatures were neither rising or falling. A baseline year of 1750 is often chosen because it precedes the Industrial Age.

Climate forcings can be further divided into radiative forcings and non-radiative forcings. **Radiative forcings** affect the radiative energy budget. An example of a radiative forcing is a change in the sun’s power output (or, more appropriately, the flux of solar radiation that hits Earth’s surface) relative to that of the chosen baseline year. **Non-radiative forcings** affect the climate in a manner that doesn’t directly involve radiation budget. An example of a non-radiative forcing is a change in the atmospheric H$_2$O concentration due to changes in agricultural crop or soil conditions. The change in the water vapor concentration ultimately affects the radiative energy flux absorbed by the atmosphere.
Supposedly RF values are straightforward to calculate (even if RF is not easy to define in simple language) although easy to calculate seems to mean in this case ‘simple if you have a big computer that can do modeling.’ A supposed advantage of the radiative forcing number is that there is a linear relationship between it and the change in mean global temperature caused by the RF agent.

Figure 3.13: Radiative forcing (RF) estimates from the IPCC AR5-WG1 report (page 14, figure SPM-5). A positive RF value indicates that the factor will cause an increase in the global mean surface temperature. A negative RF, a temperature decrease. (IPCC licensed for non-commercial use)

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21IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Sci...
3.7.2 Climate sensitivity

*Climate sensitivity* is defined by the equation

\[
\Delta T_S = \lambda \Delta F
\]

where \( \Delta F \) is a change in the radiative forcing at the top of the atmosphere; and \( \Delta T_S \) is the resulting change in average global surface temperature as a result of that radiative forcing.

The classic equilibrium climate sensitivity: The consequences of a doubling of the carbon dioxide concentration

Of course there are multiple sources of the climate’s radiative forcing: the individual abundances of multiple greenhouse gases and the individual albedos of clouds, ice, vegetation, among others. The classical way of quantifying this is the Earth’s equilibrium climate sensitivity which describes what happens to Earth’s equilibrium temperature if the atmospheric concentration of carbon dioxide doubles.

A recent study\(^{22}\) narrowed the range of the CO\(_2\) climate sensitivity to 2.6°C - 3.9°C (for 66% probability) from its long-standing previous value of 1.5°C - 4.5°C\(^{23}\). The narrowing of likely possibilities was made possible by new measurements from ice cores, more sophisticated computer modeling of climate variability and feedback mechanisms (including albedo, water vapor, atmospheric composition changes, and those from various cloud types), and the inclusion of paleoclimatic data from historical warming episodes and interglacial transition periods.

The results of this study must be viewed in context of the goals of the 2016 Paris Agreement on climate and the following 2018 report which quantified the actions necessary to limit warming to 1.5°C or 2.0°C (above pre-industrial levels). The greatest uncertainty in the future CO\(_2\) increase and consequent warming is human behavior in the coming decades. Human sources of greenhouse gases


\(^{23}\)Carbon Dioxide and Climate: A Scientific Assessment, National Academies of Sciences, Engineering, and Medicine, 1979, 34 pages: https://www.nap.edu/catalog/12181/carbon-dioxide-and-climate-a-scientific-assessment. This assessment was also verified by the IPCC 2013 report.
(particularly from fossil-fuel plants, transportation, buildings, agriculture, and deforestation) are not only the dominant cause of the planet’s warming, but their production is accelerating. More than half of human greenhouse gas emission has taken place since 1990.\footnote{Institute for European Environmental Policy, April 29, 2020: https://ieep.eu/news/more-than-half-of-all-co2-emissions-since-1751-emitted-in-the-last-30-years}

The real question is when (or if) the current accelerating trend will bend the opposite way. The dirtiest source of energy (coal) is presently declining. Some nations have managed to cut emissions substantially, while others have set aggressive targets for the future. But it still appears that the Paris climate goals may already out of reach.

### 3.7.3 Global warming potential

The **global warming potential** (GWP) of a greenhouse gas measures the relative (to CO\textsubscript{2}) amount of energy that a gas can add to the atmosphere in a given duration of time. GWP depends on 3 factors:

- the wavelengths that the gas absorbs. The gas must absorb in the IR part of the spectrum where Earth emits. The absorption will be more effective at wavelengths at which CO\textsubscript{2} and H\textsubscript{2}O are not absorbing.
- the strength of absorption. The greater the absorption, the greater the GWP.
- the lifetime of the molecule in the atmosphere. The longer the lifetime, the greater the GWP.

More specifically, GWP values reflect the warming effect if 1 kilogram of the gas is added to the atmosphere (relative to the effect of adding 1 kilogram of CO\textsubscript{2} to the atmosphere).

Table\,\ref{tab:global-warming-potential} compares concentrations and GWPs of terrestrial greenhouse gases.

Referring to the GWP values listed in Table\,\ref{tab:global-warming-potential} the GWP of 72 for CH\textsubscript{4} during a 20-year span means that the addition of 1 kg of CH\textsubscript{4} to the atmosphere will have 72 times the warming effect over the next 20 years relative to the warming from the addition of 1 kg of CO\textsubscript{2}. Note that methane has a much greater effect on GHG warming than carbon dioxide in the short term (due to a methane molecule’s significantly smaller lifetime in Earth’s atmosphere).

No lifetime is listed for CO\textsubscript{2} in Table\,\ref{tab:global-warming-potential} because its atmospheric residence time is quite complicated. The sources and sinks of carbon dioxide involve the hydrosphere (primarily oceans), the lithosphere (rocks and soil), and the biosphere.
(living systems). The hydrosphere interaction with CO$_2$ depends critically on the ocean temperatures. The lithosphere interaction depends on rock weathering and soil deposition. The biosphere interaction depends primarily on photosynthesis and respiration rates.

Approximately half of the CO$_2$ emitted today will be gone in a century, but some portion will remain for thousands of years.

GWP values for water and ozone are not calculated because their atmospheric lifetimes are on the order of days and their concentrations vary from day to day. Water vapor’s atmospheric abundance is controlled almost entirely by temperature conditions of the atmosphere and hydrosphere and the ice sheets and glaciers – and not by human activity. Rising global temperatures increase atmospheric water vapor concentration and, therefore, global warming. This positive feedback mechanism has the potential to be dangerous.

### 3.8 The take-away: Earth’s global greenhouse effect allows the presence of liquid water and life

The blanketing effect of a planet’s atmosphere – the so-called greenhouse effect – heats planetary surfaces beyond the temperatures predicted by direct solar heating of a no-atmosphere planet. Greenhouse heating occurs because a planet’s atmosphere is transparent to much (visible light) of the Sun’s radiation, whereas it is opaque to much (infrared light) of Earth’s radiation.
<table>
<thead>
<tr>
<th>GHG</th>
<th>current atmospheric conc. (ppm)</th>
<th>pre-industrial atmospheric conc. (ppm)</th>
<th>atmospheric lifespan (yrs)</th>
<th>GWP t = 20 yr</th>
<th>GWP t = 100 yr</th>
<th>GWP t = 500 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>412</td>
<td>280</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td>1.87</td>
<td>0.700</td>
<td>12</td>
<td>72</td>
<td>25</td>
<td>7.6</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.327</td>
<td>0.270</td>
<td>114</td>
<td>289</td>
<td>298</td>
<td>153</td>
</tr>
<tr>
<td>CFCs</td>
<td>0</td>
<td>10⁻⁴</td>
<td>100</td>
<td>11,000</td>
<td>10,900</td>
<td>5200</td>
</tr>
<tr>
<td>O₃</td>
<td>237</td>
<td>337</td>
<td>hours, days</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3: Concentrations and GWPs of various greenhouse gases. Quantities which are highly variable are not listed. For example, H₂O is an important greenhouse gas, but its contribution is variable, as the text indicates.
Chapter 4

Is the Planet Warming?

Evidence for a warming planet should show up in three distinct ways: (1) a rise in the mean global temperature, (2) melting of ice (both glacier and polar), and (3) sea-level rise (the necessary consequence of both melting ice and the thermal expansion of water). It would be difficult to construct a scenario in which all three of these global-warming signs would not happen simultaneously. Furthermore, physics constrains the relationship between any temperature rise and the amount of ice melted and sea-level rise, although admittedly this is an extraordinarily complex system.

Caveat: data and its origin

This is the first of two chapters that not only present the measurement of important climate-change indicators (e.g., temperatures, sea levels, glacier and other ice masses) today but also attempt to determine these indicators (from both direct and indirect evidence) in times past. As you read this and the subsequent chapter, keep the following questions in mind: (1) How do we know? (2) What is the source of the data? (3) Is the data (or evidence) directly measured or indirectly inferred? (4) How reliable is the data/evidence?

The GWDs (which, remember, consists almost entirely of media and political figures who not only are not scientists but also have generally little training or understanding of science) have put forth objections both to the scientific consensus and to much of the data. Skeptics/deniers will often draw attention to seemingly conflicting scientific data, cherry-pick subsets of data that point toward different conclusions than the whole data set, or ignore subtle but important differences in the kinds of data presented. They often have little appreciation or understanding of scientific uncertainty. Any of these can be used to as grounds to reject any or all scientific evidence or reasoning.

It goes without saying that scientists are not immune from the same temptations or habits. As anyone human, scientists tend to defend their own work, sometimes beyond reasonable bounds. The GWDs would claim that scientists must
buy into the global-warming ‘plot’ or otherwise lose research funding or become an outcast in the scientific community.

But my experience and bias as a trained scientist inform my attitude that scientists are far more dispassionate about scientific accuracy than the GWDs. And even if the scientific work is unbiased, anyone who summarizes the work of others (as this book attempts!) will introduce an additional bias. The best way to get closest to scientific ‘truth’ it to go back and read the original research. But, of course, few of us are equipped to do so - and that’s why you, the reader, are here. In any event, let the reader beware!

4.1 Direct temperature measurements

4.1.1 Which temperature?

Whenever one encounters the phrase ‘global average temperature’, alarm bells should go off. First, which temperature is being talked about? Is it the surface temperature of the land? the surface temperature of the ocean? the temperature of the ocean depths? the temperature of the troposphere (or lower atmosphere)? the temperature of the stratosphere (or upper atmosphere)? Second, how does one determine an average global temperature from the temperatures of the various components of Earth?

It is not an easy task to reconstruct the mean temperatures of the individual components of Earth’s various components in the past. Although we do have a fairly good record of the air temperatures from weather/climate stations in populated places (at least since thermometers became reliable in the latter half of the 19th century), the record of land temperatures and ocean temperatures is far less complete. Even today, there is a relative dearth of such stations in the Arctic and in Africa. Characterizing a mean global temperature even for the recent past is clearly problematic.

Furthermore, temperature changes do not always directly reflect the heat energy absorbed by various terrestrial components. For example, heat energy could go into volume expansion (water’s volume expansion contributes to a rise in sea level) or into phase changes (for example, it takes thermal energy to change snow or glacier ice into liquid water, even though the water’s temperature does not change in the process).

IPCC AR4 estimates that the excess thermal energy absorbed by Earth goes into the following sources (the numbers in parentheses representing the estimated % of absorbed thermal energy):

70
1) ocean (both surface and deep-ocean) temperatures (93.4%)
2) atmosphere temperatures (2.3%)
3) land (continent) temperatures (2.1%)
4) extent and thickness of Arctic and Antarctica ice (1.2%)
5) extent and thickness of glaciers (0.9%)
6) sea level height

The latest IPCC report used the three oldest (and most complete) land/ocean temperature datasets:

1) The HadCRUT4 dataset[^1] is produced by the Met Office Hadley Centre in collaboration with the Climatic Research Unit of The University of East Anglia.

The HadCRUT4 temperature survey has been criticized for biased global coverage (due to its unsampled regions not being globally distributed) by Colton and Way[^2], who have suggested some methods to relieve the bias.

2) The NOAAGlobalTemp dataset[^3] is produced by the National Oceanic and Atmospheric Administration (NOAA) and the National Climatic Data Center[^4].

3) The GISTEMP(NASA GISS) dataset[^5] is produced by the National Aeronautics and Space Administration Goddard Institute for Space Studies.

Two other temperature databases are less well known:

4) The Berkeley Earth dataset[^6]


Methods of determining global temperature averages can be found at web links provided for each data base.

In general, the temperatures in the above datasets are air temperatures above land (nominally 2 meters above), and are measured at meteorological stations around the world. The measurement of ocean temperatures will be described in a later section.

[^1]: HadCRUT4 Temperature Data: http://www.cru.uea.ac.uk/cru/data/temperature/
[^3]: NOAA NCDC: http://www.ncdc.noaa.gov/
[^6]: Berkeley Earth: http://berkeleyearth.org/data/
[^7]: Copernicus Climate Change Service: https://cds.climate.copernicus.eu/
Most of the ocean temperature change has long been thought to occur near the upper ocean surface. Oceanographers think of oceans as three-layer cakes: the surface layer (the very top 0.25 km), a middle layer (called the ‘thermocline’), and the deepest layer (depths greater than 1 km).

The ocean’s surface layer has a mean global temperature of 22°C and is relatively uniform throughout the layer. The temperature of the middle layer drops from 22°C at the top to 4°C at its bottom. The temperature of the deep ocean is thought to remain at a nearly uniform 4°C. However, even these assumptions have begun to be reconsidered in the light of better and more frequent measurements.

### 4.1.2 Measuring ocean temperatures

#### Pre-2000: random sampling by commercial ships

Measurements of ocean temperature in the 20th century relied on voluntary sampling of ocean sites by commercial ships. Ship personnel would lower a device into the ocean to measure ocean temperature and chemistry and to bring back ocean samples for later testing in the lab. However, the sampling was generally limited to depths of 500 m at most; typically it was far less.

The sampling took place primarily along the narrow range of commercial shipping lanes and, therefore, was also very limited in geographic scope.

To increase the global coverage of such measurements, satellites were used to measure ocean heights. Since water expands as it warms, scientists could use these measured heights along with modeling to infer average ocean temperatures. However, neither of these methods (ocean sampling by commercial ships and ocean-height measurements by satellites) gave information about how ocean temperatures varied with depth.

#### Post-2000: Argo floats

Beginning in 2000, a small group of ocean scientists envisioned and began to deploy a system of semi-permanent floating submersible ‘buoys’ called Argo floats. The number of Argo floats grew to nearly 3900 by mid-2019 deployed Earth-wide over the entire extent of ice-free ocean.

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9Argo: http://www.argo.ucsd.edu/
A typical Argo float resides at a resting ocean depth of 1 km. Every 10 days, the float changes its effective density (via a hydraulic bladder) and sinks to a depth of 2 km. It then rises from the 2-km depth to the surface while measuring the ocean temperature, pressure, and conductivity as a function of depth. The conductivity data collected can be converted to ocean salinity. The float also measures ocean-current velocity at its resting depth of 1 km. Once at the surface, the Argo float transmits the profile data, via satellite, to collection centers for analysis. The data is freely available to anyone within hours of collection.

The Argo system has several advantages over the previous ship-collecting system: (1) the 3900 floats are evenly deployed (approximately 300 km apart) over the entire ocean extent (rather than random sampling that took place primarily along commercial shipping lanes) (2) they collect ocean-profile data (from 2-km depths to the surface; (3) a given data profile is relatively location-specific, which thereby allows a comparison of any profile to those collected at that same site.

An Argo float is approximately 1.3 m long, has a 20-cm diameter, weighs about 25 kg, and costs approximately 15,000 US dollars. The floats are noiseless and made of materials found elsewhere in the ocean. They are believed harmless to ocean life and not a significant hazard to ships or boats. The lifetime of a float is approximately 4 years. Eventually the battery is too weak to pump the float to the surface; most disabled floats eventually sink to the ocean floor.

Accurate measurements of ocean temperature and chemistry led to determinations of ocean heat and composition chemistry (dissolved CO2 and O2 concentrations, salinity, etc.) as a function of ocean depth. See section 4.6 for results.

4.1.3 Land, ocean, and atmosphere temperature changes over the past 150 years

Figures 4.1 and 4.2 show NASA GISS data for, respectively, global mean air temperatures and global mean land-ocean temperatures for a large number of meteorological stations since 1880.

Figure 4.1: Global air temperature means since 1880, with reference period 1951-1980. The black line is the annual mean and the solid red line is the five-year mean. The green bars show uncertainty estimates. (NASA, public domain source)
Figure 4.2: Global Land–Ocean temperature means since 1880. Black, red, and green symbols have the same meaning as in the previous graph. (NASA, public domain)

In order to give the reader some sense of the consistency of (or differences in) various global-temperature data sets, Figure 4.3 shows the mean global temperatures from three different data sets (top panel) along with decadal averages (bottom panel). The use of decadal averages takes the scatter out of annual measurements (which can be affected by short term weather events such as El Niño, La Niña, polar vortices, and volcanic emissions).

Figure 4.3: (top panel) Annual global mean land-ocean surface temperatures from three different data sets. (bottom panel) Decadal global mean surface temperatures from the same three data sets. Gray shaded regions show uncertainties for one of the data sets (black). (IPCC AR5-WG1 report, figure SPM-1a[13] licensed for non-commercial use)

A number of conclusions are obvious from these three figures: (1) There is a remarkable consistency between the various data sets. (2) Global mean air temperatures show a larger increase than do global mean land-ocean temperatures. (3) Each of the figures indicate the air, land, and ocean temperatures have all risen since accurate record-keeping began in the later half of the 19th century.

The IPCC further concludes that (4) The global mean land-ocean temperature has increased by an average of 0.85 °C (± 0.20 °C) during the period 1880 - 2012. (5) Each of the last three decades has been successively warmer at the Earth’s surface than any preceding decade since 1850. In the Northern Hemisphere, 1983 - 2012 was likely the warmest 30-year period of the last 1400 years. (6) Global mean surface temperatures exhibits substantial year-to-year variations due to natural variability (due to El Niño or La Niña systems, polar vortices, and volcanic emissions, among others), and trends based on short records that are very sensitive to beginning and ending dates.

4.1.4 A case study: A global warming pause in recent years?

The consistent rise in global mean surface temperatures (GMSTs) over the past 130 years (shown in various data sets in Figures 4.1 - 4.3) makes it difficult to argue that the planet is not warming. However, the GWDL have shifted their objections to two other fronts that are actually separate but are often conflated. One, skeptics argue that there has been a distinct pause in the rise of GMSTs in the past 10 - 15 years. Second, they also claim that what global-mean-temperature rise does exist falls far short of what climate scientists’ models have been predicting. The first issue, a possible recent hiatus in global warming, will be treated, whereas the issue of whether warming patterns follow current climate models (a totally separate issue) will be left to the section 4.1.7.

Semantics: a pause or a slowdown? significant or insignificant?

Before proceeding, let’s agree on what the words mean (at least in this work). A pause or hiatus will be taken to mean that the rise in GMSTs (clearly evident during the 20th century in Figures 4.1 - 4.3) has stopped for a significant period of time. If there has been a pause in the rise of GMSTs, the slope of the graphs in Figures 4.1 - 4.3 must be, on average, zero.

A slowdown is taken to mean that the more recent the rate of rise in GMSTs is less than the rate of rise either overall during the 20th century or during the latter half of the 20th century for a significant period of time.

Perhaps the most important (and therefore controversial) word is whether any pause or slowdown is significant or not. And whether it is significant or not depends on whether the claimed pause or slowdown stands out over short-term variations in GMSTs (due to El Niño or La Niña systems, polar vortices, and volcanic emissions, among others) and the time period over which those variations last (equivalent to the difference between short-term weather and long-term
climate). Unfortunately, there is no standard definition of 'significance' on which everyone agrees.

What do the data say?

As anyone familiar with data analysis knows, there are multiple ways of analyzing any data set. The range from the unsophisticated (simply “eyeballing” graphical data), through applying least-square fits, to even more refined statistical tests such as chi-squared.

The supposed ‘hiatus’ in global warming is claimed (note, for example, the three claims quoted above, which are typical) to have begun somewhere between 1995 to 1998 and continues to the present day. This time interval contains the decade 2001 - 2010, which happens to be the hottest decade on record, as shown in Figure 4.3. That decade was warmer than the previous decade by a significant 0.2 °C that is beyond the range of the uncertainty. We are not quite to the middle of the next decade, so it is hard to know where the next data point will fall, but one of the four years (2014) in the present decade is already the hottest-ever year on record.

A visual inspection of Figures 4.1 - 4.3 might result in seeing a plateau in the GMSTs beginning in 2003/2004 and continuing to the present day. A case could be made that because so many of the documented ‘warmest years’ have occurred since 2000 (8 of the 10 hottest years occurred in the decade 2001 - 2010), it is possible to simultaneously account for the decadal temperature rise (shown in the bottom panel of Figure 4.3) and the claim of a global warming hiatus.

Can we do better than relying on visual inspection or artificial decadal averages? And how long is ‘long enough’ is one wants to be sure that one is looking at climate and not the short-term effects of weather?

The reader can analyze the GMST trends for oneself using an easy-to-use GMST-plotting tool that can access the 3 primary GMST data bases (NASA/GISS, NOAA/NCDC, HadCRUT4). The two HadCrut4 data subsets (krig v2 and hybrid v2) have had corrections applied due to gaps in the GMST data, particularly in the polar regions and parts of Africa.

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15 [Nine of the ten hottest years on record in the last decade:](http://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=53)

16 [Temperature trends:](http://www.ysbl.york.ac.uk/~cowtan/applets/trend/trend.html)

An analysis of the recent and long-term global land-ocean temperature record performed by the author can be found in Appendix B (Lies, Damn Lies, and Statistics). The analysis finds that the claim that global warming has paused since 1998 is unsupportable; the data shows that the existence of a pause is extremely unlikely (less than 1%). However, the data do support the claim that the rate of global warming has slowed since 1998 compared to that over the past half-century (although not compared to that since the start of the Industrial Age.) The existence of a pause or a slowdown in global warming over shorter time periods (a decade or less) is rendered moot because of the possibility of short-term weather variations.

The IPCC claims a warming slowdown, not a pause.

The 2013 IPCC report says that the global mean surface temperature (GMST) “trend over 1998–2012 is estimated to be around one-third to one-half of the trend over 1951–2012.” The same report, however, points out that 15-year hiatuses in the GMST are common in the recent historical record, and that they are typically followed by greater-than-average rises in the GMST during the succeeding 15-year periods. The report also points out that sea-level rise during this same time period has not shown a similar hiatus, but in fact has accelerated. See section 4.4.2.

Possible explanations for an apparent slowdown or pause in global warming.

The scientific climate community is not without explanations for a recent pause/slowdown in global warming (or for reasons why the pause/slowdown does not actually exist). The next few subsections explore some of these explanations. In identifying the cause(s) of changes in GMST, there are three bins in which to look:

(1) anthropogenic emissions of greenhouse gases. Because GHG emissions continue to rise unabated, these emissions can only account for increased warming. They cannot be responsible for any multidecade oscillations.

(2) external forcing agents [including volcanic emissions and similar pollution-produced aerosols (which generally give rise to cooling), and changes in solar irradiation]

(3) internal climate variations (including short-term weather patterns such as El Niño, La Niña systems or polar vortices, which maybe periodic or oscillatory in

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nature)

To explain a short-term pause/slowdown in global warming, only explanations from categories (2) and (3) above are viable. We now consider possible specific data-supported explanations that address this issue.

**Global-warming pause? There has been no pause.**

Some scientists maintain that, despite the IPCC’s 2013 pronouncement, there is no actual evidence for a recent pause in global warming. They argue, on statistical grounds, that the time period of interest for which a pause is claimed (7 years or fewer) is so short that it can easily be explained by chaotic or internal variations in Earth’s climate system or that some of the data, in particular, ocean temperatures, have been incorrectly measured or misinterpreted.

Stefan Rahmstorf at the website RealClimate argues that “the warming since 1998 is not significantly less than the long-term warming” and that ”while there has been a slowdown, this slowdown is not significant in the sense that it is not outside of what you expect from time to time due to year-to-year natural variability.”

A 2014 paper published in the *Quarterly Journal of the Royal Meteorological Society* goes further. It makes the case that the HadCRUT4 data has a coverage bias (coverage missing in the polar regions and Africa), that has resulted in an underestimate of the the global-warming trends during the period of the claimed pause. When the coverage bias is corrected for, the rate of rise in the GMSTs during this period is exactly the same as the long-term rise.

A 2015 paper published in the journal *Science* argues for a bias in the measurements of ocean temperatures. Sea temperatures were originally measured by passing commercial, military, and research ships retrieving water samples via buckets. This method is now perceived to be relatively unreliable due to differences in ships’ buckets, thermometers, and wait times between water retrieval and actual temperature measurement.

The 1980’s brought a shift to a newer technology: ocean temperature measurement by permanent in-situ buoys deposited by various governmental agencies.

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3. Karl, T. R. et al., Possible artifacts of data biases in the recent global surface warming hiatus: [http://www.sciencemag.org/content/early/2015/06/05/science.aaa5632.full?sid=5f6881f6-d98a-4ea3-ad8e-c3d05f95adf1](http://www.sciencemag.org/content/early/2015/06/05/science.aaa5632.full?sid=5f6881f6-d98a-4ea3-ad8e-c3d05f95adf1)
The authors find that buoy temperatures are colder than those measured in the same location by passing-ship bucket retrieval. As the measurement technology has shifted over the past thirty years, there has therefore been a shift to lower measured temperatures, the authors show. A 2015 *Science* paper\(^{22}\) shows the new corrected mean surface temperatures for oceans, land, and combined global averages compared to those previously measured. Note that the corrected ocean temperatures (square data points) are significantly higher than previous measurements (circles); global average temperatures also have risen accordingly.\(^{23}\) Figure 2 of that same article shows the authors’ corrected data for GMSTs since 1880, along with data uncorrected for bucket-buoy differences (Figure A) and data uncorrected for all known historical data-collection biases.

The authors also point out that although the new corrections eliminate the recent warming slowdown, the overall effect of the corrections is to raise the reported GMSTs of the late 19th and early 20th centuries by a substantial margin. Consequently, the rate of temperature increase since 1880 drops from a previous rate of 0.86 °C/century to a new corrected rate of 0.68 °C/century.

Unsurprisingly, some in the GWDL\(^{24}\) have questioned this new study by claiming that the corrections are simply too large to be believable and that even if the corrections are deemed valid, the corrected rate of warming is still slower than the collective average of IPCC’s 28 different predictive models.\(^{25}\)

**Global-warming pause? Its cause is a significant rise in aerosols that have been added to the atmosphere since 2000.**

A 2011 paper published in the journal *Science*\(^{26}\) uses data from four independent measurements to argue that the aerosol content of the stratosphere has increased significantly since 2000, and that this increase is responsible for an unexpected global cooling since then. Their measurements indicate that GMSTs have risen 25% less than they would have without the aerosol increase. Although the paper

\(^{22}\text{Figure 1 in Karl et al, “Possible artifacts of data biases in the recent global surface warming hiatus,” Science 26 (2015) 1469-1472.}\)

\(^{23}\text{The June 4, 2015 *Science* article being discussed also makes changes to the average land temperatures, by correcting for incomplete sampling over the Arctic – due to lack of regional weather-station coverage – which has experienced rapid recent warming. These corrections are responsible for changes in land temperature trends in Figures 1 and 2 of the Karl et al *Science* article referenced above.}\)

\(^{24}\text{Cato Institute: Is There No “Hiatus” in Global Warming After All? http://www.cato.org/blog/there-no-hiatus-global-warming-after-all}\)

\(^{25}\text{The claim that the new warming rates are smaller than the average of various predictive models is, of course, equivalent to comparing apples and oranges. Individual models have various degrees of reliability; the comparison should be between the data and the best predictive model(s).}\)

is focused on presenting evidence for the aerosol increase (rather than identifying the cause of the increase), the authors hypothesize that smaller and less intense volcanic eruptions have contributed more to the long-term stratospheric aerosol abundance than previously surmised. In addition, the authors do not rule additional explanations (e.g., solar variability, natural climate oscillations) for the pause/slowdown, and they are agnostic as to the warming/cooling effect of aerosols in 2020 and beyond.

Global-warming pause? Its cause is a temporarily lower solar irradiance.

A 2012 paper published in the journal *Surveys in Geophysics*\(^{27}\) presents evidence that the solar irradiance (or flux, in W/m\(^2\)) during the 2009 minimum of the recent 11-year solar cycle was measurably lower (by 0.29%) than that expected based on previous solar minima.

Global-warming pause? Its cause is equatorial Pacific surface cooling.

A 2013 paper in the journal *Nature*\(^{28}\) makes the case, via global-climate simulations, that the cooling of the eastern Pacific ocean surface can explain the recent global-warming pause. In their models, the authors constrain the surface temperatures of a region of the central/eastern Pacific ocean (with approximately 8% of the Earth’s surface area) to follow the observed (cooler) temperatures for that region. The consequences of applying this external constraint to their models results in an excellent fit to the GMSTs during the period of interest.

The same model also produces various seasonal warming and cooling patterns in specific regional areas which also match observations, thereby lending greater credence to this hypothesis. The authors conclude that "the current hiatus is part of natural climate variability, tied specifically to a La-Niña-like decadal cooling" and go on to warn that “Although similar decadal hiatus events may occur in the future, the multi-decadal warming trend is very likely to continue with greenhouse gas increase.” In other words, if CO\(_2\) emissions to continue to increase, their effects on planetary warming will inevitably swamp such internal variabilities in the climate system.

A 2015 paper published in *Science*\(^{29}\) (by, among others, Michael Mann, of hockey-stick and Climategate notoriety) provided supporting evidence for this hypoth-


esis by making the case that natural internal oscillations in the temperatures of the Atlantic and Pacific oceans - driven by large-scale circulations of ocean water - are responsible for the apparent global-warming pause at the beginning of this century. The authors deduced the magnitudes and phases of these internal oscillations by subtracting the global warming expected from external sources (e.g., greenhouse-gas emissions, volcanic dust emissions) from the global warming actually observed in years previous. These oscillations combine to produce a cooling effect during the first decade (and expected to continue into the second decade) of this century that has masked a greenhouse-gas-induced GMST rise during this period. Their data indicate that we are at or near the turnaround in the oscillation cycle. At that point, these oceanic oscillations will begin to produce warming on top of that due to the continuing human-caused greenhouse warming due to rising CO₂ levels.

The authors also make the prediction that “This pause is projected to end in the near future as temperatures resume their upward climb.”

**A pause or slowdown in global warming?: the take-away**

The claim that global warming has paused since 1998 is unsupportable; the data shows that the existence of a global-warming pause is extremely unlikely (less than 1%). (See Appendix B.)

It can be fairly claimed that there has been a slowdown in the rate of global warming since 1998 compared to that during the past half-century (although not compared to that during the overall period since the onset of the Industrial Age).

A definitive determination of the cause(s) of a slowdown in the rate of global warming will not be resolved in this writing. That multiple reasons have been proposed for its cause (and still others for its nonexistence) have been used by the GWDL to cast doubt not only any scientific evidence for a pause, but also as evidence for any global warming during the entire last century. On the other hand, most will recognize multiple scientific explanations for what they are: evidence that science is a messy process, particularly when applied to the complicated climate system. Science makes progress as new data confirm or disaffirm the various hypotheses that have been proposed to explain the old data.

**4.1.5 Paleoclimatology: finding the temperatures of the past**

Now that we have looked at the evidence for recent global temperature changes, let’s consider the historical context. What temperature ranges has Earth experienced in the past? We do this not only to put the magnitude of recent GMST
changes into perspective, but also to investigate the causes of historical GMST changes.

We begin with most distant past for which temperatures can be inferred (and for which the uncertainties are large) and move forward to the recent past (for which temperature records are presumably more accurate). Figure 4.4 shows reconstructed temperature variations from 500 million years through the present.

Climate Proxies: How we know temperatures in the distant past

Paleoclimatology is the use of various measurements and indicators to determine temperatures in the past. These indicators (called ‘climate proxies’) include ice cores, growth cycles in trees and coral, and the relative abundance of different oxygen and hydrogen isotopic compositions of water. The main method for determining temperatures hundreds of years ago involve the use of ice core proxies.

![Temperature of Planet Earth](https://commons.wikimedia.org/wiki/File:All_palaeotemps.png)

Figure 4.4: Reconstructed air temperature variations over the past 500 million years. Peaks correspond to interglacial warm periods; depths, to the colder glacial periods. Note the discontinuous horizontal scale changes. (CC BY-SA 3.0)

Glacial ice cores that can be extracted from subsurface ice contain air bubbles trapped within. The composition of the atmosphere in prehistoric times can be determined by measuring the relative concentrations of various gases and various isotopic forms of each gas in these trapped air bubbles. Both the air temperature and age of the air bubble sampled must be determined in order to produce a graph like that of Figure 4.4. One example each of air-temperature determination (from the relative abundance of the oxygen isotopes) and age determination (from the

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30 Paleotemperature graphs compressed: https://commons.wikimedia.org/wiki/File:All_palaeotemps.png
31 Paleoclimatology: https://en.wikipedia.org/wiki/Paleoclimatology
32 Climate Proxies: http://en.wikipedia.org/wiki/Proxy_(climate)

84
Age determination from carbon isotopic abundances

In order to determine the age of a trapped air bubble or a limestone skeleton formation, the isotopes of carbon (found in carbon dioxide) are often used instead. Carbon also has three isotopes found naturally, although only two of them ($^{12}$C and $^{13}$C) are stable. The third isotope ($^{14}$C) is radioactive and decays with a half-life of 5730 years. The current isotopic ratios in the atmosphere are $^{13}$C/$^{12}$C ≈ 0.01 and $^{14}$C/$^{12}$C ≈ $1.2 \cdot 10^{-12}$. The $^{14}$C/$^{12}$C atmospheric ratio is kept constant (despite the radioactive decay of $^{14}$C) by a continuing production of atmospheric $^{14}$C via the interaction of incoming cosmic rays with atmospheric nitrogen.

At the time that an air bubble becomes trapped in an ice core, its carbon dioxide composition reflects the $^{14}$C/$^{12}$C ratio of the atmosphere. However, as time passes, the ratio decreases as the $^{14}$C decays away exponentially in the CO$_2$ in the air bubble. Measurement of the $^{14}$C/$^{12}$C ratio in the trapped air therefore gives age of the ice core. A similar method can be used to determine the ages of discarded limestone skeletons. The details of this radiocarbon dating process are discussed in detail in Appendix C.

The carbon-dating method is limited to ages of 50,000 years or less; carbon-bearing matter older than that contains such a small amount of remaining $^{14}$C that calculated ages are unreliable. Other age indicators (not discussed here) must be used instead.
4.1.6 Temperature changes over the past hundreds of thousands or millions of years

Figure 4.5: Reconstructed temperature variations and ice volume variation - from oxygen isotope abundance variations - over the past 450,000 years. EPICA and Vostok are two Antarctica stations from which ice cores have been extracted. (Robert A. Rohde, Global Warming Art, CC BY-SA 3.0)

What does the temperature record of the past tell us about range of temperatures that Earth has experienced? Figure 4.5 shows that long-term temperature changes of 9 - 10°C accompany the quasi-periodic oscillation of glacial (when temperatures average 6-7°C below current norms) and interglacial periods (when temperatures are up to 3 - 4°C higher than current norms). These glacial-interglacial periods were experienced by humans.

When looking back even further into the past (Figure 4.4), it is clear that the range of temperatures Earth has experienced is even larger (up 10°C) than that experienced during relatively more recent ice-age oscillations.

We now have some historical perspective about climate changes in the distant past. The evidence clearly shows that these historical temperature fluctuations (up to 18°C; see Figures 4.4, 4.5) dwarf those (no more than 1°C; Figure 4.6) that have occurred in just the past millennium.

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4.1.7 How well have climate scientists predicted global warming?

We should not underestimate the difficulty of such modeling and its consequent predictions. The problem is twofold. One involves understanding and predicting human behavior. The second involves understanding the science of how GHGs interact, via physics (and chemistry and biology and geology) with the ocean, the atmosphere, and the various types of land masses.

The first problem requires climate scientists to estimate the change in GHGs with time. Rather than a matter of science, this is a matter of human societal behavior. It involves population growth, the economics of and access to various types of energy, the level of technological development, not to mention history, among many other factors. It would be a major surprise (and triumph) if climate scientists managed to make such accurate predictions more than a year into the future. Fortunately, GHG concentrations can be measured in a straightforward manner and can be used to update predictions in almost real time.

The second problem, scientific modeling, given the GHG concentration, requires an understanding of how various biophysical systems (such as ocean, atmosphere, ice sheets) respond to the climate forcings of and sensitivities to various GHGs, as described in Section 3.7. This problem is the one that science is expected
to solve correctly despite the non-linearity of the problem, the lack of a control group (e.g., a second Earth), among the myriad other inconveniences.

Global-warming deniers have often claimed (by cherry-picking individual pieces of data or misusing model uncertainties) that climate models overestimate the temperature rise due to the increasing concentration of GHGs in the atmosphere. So it is particularly surprising that no long-term evaluation of climate scientists’ models was performed until 2019 \(^{34}\) (Plain-language summaries of the scientific paper can be found here \(^{35}\) and here \(^{36}\).) A small number of previous studies had evaluated a specific model, but this is the first large-scale study of multiple models spanning a nearly 5-decade time period.

The evaluation was performed on 17 models with active ranges that cover various portions of the years 1970 - 2017 (2017 is the last year for which temperature data was available to the authors). These models were evaluated according to 2 metrics:

1) how well the model did in predicting global mean surface temperatures as a function of time

2) how well the model did in predicting the rate of temperature change as a function of the rate at which GHGs are added to the atmosphere.

Metric 1 addresses the human-behavior prediction problem described in the first paragraph of this section. Metric 2 addresses the science problem described in that same paragraph.

The evaluations’ authors judge that 9 of the 17 models pass metric 1 (the human-behavior-based one), whereas 14 of the 17 models pass metric 2 (the scientific-based one). The low number of models passing the metric-1 test is a consequence of an early overestimate of the rate at which GHGs were added to the atmosphere in ensuing decades. In other words, even climate models from the early 1970s (although long since replaced by more sophisticated models) were accurate in predicting global warming, particularly when assumed future carbon emissions were retroactively replaced by actual measured carbon emissions.

For example, James Hansen’s 1988 model infamously predicted a warming that was 50% greater than the actual warming over the following two decades. How-

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\(^{35}\) Scientists have gotten predictions of global warming right since the 1970s: https://www.vox.com/energy-and-environment/2019/12/4/20991315/climate-change-prediction-models-accurate

\(^{36}\) Climate models got it right on Global Warming: https://www.scientificamerican.com/article/climate-models-got-it-right-on-global-warming/
ever, the problem was not in the physics of Hansen’s model, but rather in the assumption about future emissions of methane and chlorofluorcarbons (CFCs), which have a much higher climate forcing than does carbon dioxide. The overestimate of CH$_4$ and CFC emissions was in part a result of the failure to anticipate the Montreal Protocol (1989) which phased out CFCs in the successful attempt to repair the atmospheric ozone hole. Once the actual emissions of CO$_2$, CH$_4$, and CFCs are inserted in Hansen’s 1988 model, its predictions are indistinguishable from the warming actually observed.

### 4.2 Glaciers

Glaciers are found on every continent, and the evidence is that they have been retreating, on average, since monitoring began in the mid 1850’s. In order to understand how glacier scientists measure the extent and thickness of glaciers, we need to understand two quantities: glacier mass balance and the terminus.

Glacier mass balance is the difference between the ice-mass gain (by snowfall or condensation) and the ice-mass loss (by melting, sublimation, and by movement erosion). Figure 4.7 shows the mean annual mass balance of glaciers reported by the World Glacier Monitoring Service (WGMS). Figure 4.8 shows the cumulative mass balance for the same glaciers over the same time period. It is clear that glaciers have been in retreat over the past 35 years.

![Figure 4.7: Mean annual glacier mass balance (in equivalent millimeters of water) since 1980 as reported by WGMS. (Figure created from [data here](http://www.wgms.ch/), figure & data CC BY 4.0)](http://www.wgms.ch/)

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37 For glaciers where data is available for more than 30 years; no glaciers included from Antarctica or Australia

38 [http://www.wgms.ch/](http://www.wgms.ch/)
Glacier terminus measures the extent or length of a glacier and is the parameter that measures glacier or advance or retreat. Figure 4.9 shows the number of glaciers where the terminus is advancing (in blue) or retreating (in red). The preponderance of red bars indicate that mountain glaciers have been largely retreating since record keeping began. A significant number (but not a majority) of glaciers appear to have advanced from 1965 - 1985. This period which slightly lags that of the land-ocean global warming pause (Figure 4.3) that took place in the middle of the last century.

4.2.1 Glaciers: the take-away

Figures 4.9 summarizes the evidence that glacier ice has decreased worldwide since the 1880s, Figures 4.7 - 4.8 document quantitatively the striking glacier-ice loss since the 1980s. The water produced from the loss of glacier ice has contributed about 30% of the recent global sea-level rise that has occurred in tandem, as we shall see in section 4.4.


41www.grid.unep.ch/glaciers/pdfs/5.pdf as reported by the WGMS
4.3 Polar ice

4.3.1 Land ice vs. sea ice

Polar ice can be divided into two parts: land ice and sea ice. Antarctica is a continental landmass, surrounded by an ocean. The Arctic, on the other hand, is essentially an ocean surrounded by land, as there is no similar Antarctic-type
landmass located at the north pole. Ice does cover land within the Arctic circle (particularly Greenland, but also smaller portions of Canada, Russia, the US, and Scandinavia). The land ice is the accumulation of centuries of snowfall, kilometers or tens of kilometers thick and has been a permanent fixture in Greenland and Antarctica for millenia. On the other hand, much of the sea ice (no more than several meters thick) in both the Arctic and the Antarctic melts during their respective summers (although the Arctic has typically maintained a year-round ice cover for several tens of millenia) and re-forms during their winters.

Polar land ice can also go by the names ice sheet or continental glacier (particularly in research papers), whereas polar sea ice is alternatively termed an ice shelf. The land ice that is not polar – i.e., that exists at high altitudes and/or on mountains – usually goes by the name glaciers (or local glaciers, to distinguish it from the continental glaciers of Greenland et al.). To prevent confusion, this work will generally use the terms land ice, sea ice, and glaciers to represent polar land ice, polar sea ice, and non-polar land ice.

A very important distinction exists between the melting behavior of polar land ice and polar sea ice. When land ice melts, ocean levels rise in response. When sea ice melts, however, no sea-level rise takes place.\(^{42}\) (You can test this for yourself at home. Fill a large glass with roughly half water and half ice, and monitor the level of the liquid as the ice melts. The liquid level will not change as the ice melts.)

Despite this difference in the melting behaviors of polar land ice and sea ice, the extent of land ice and of sea ice can each tell us about temperature trends in the polar regions.

### 4.3.2 Land-ice extent

Figure 4.10\(^{43}\) shows the ice-mass loss from both the Antarctic and Greenland (land) ice sheets, along with that from (mountain, non-polar) glaciers. Note that polar ice, in both Greenland and Antarctica, appears to be melting at an accelerating rate. Also note their respective contributions to sea-level rise, a topic which we will examine in detail in the next section.

Beware of the GWDs raising the point that the ice cover on the Antarctica peninsula is increasing. That out-of-context statement is true. However, the ice cover over both western and eastern Antarctica is decreasing, and the ice

\(^{42}\)Technically, there is a tiny change in sea level due to changing amounts of sea ice because the density of the fresh water in the ice is slightly less than the density of the salt water in the oceans. However, this change is immeasurably tiny due to the small difference in densities and the vast extent of the oceans.

\(^{43}\)www.climatechange2013.org/images/report/WG1AR5_Chapter04_FINAL.pdf
cover decrease of these two areas dwarfs the ice-cover increase on the much tinier Antarctica peninsula.

Figure 4.10: Cumulative loss of Arctic (Greenland), Antarctic, and glacier land ice (since 1991) along with equivalent sea-level rise created from the ice melt. (IPCC AR5-WG1 report, Chapter 4, Fig. 4.25, p. 367, licensed for non-commercial use)

4.3.3 Sea-ice extent

Although sea ice in both polar regions melts during summer, and re-forms in the winter, much of the Arctic sea ice, unlike that of the Antarctic, remains year round. Although melting (or forming) sea ice does not directly raise (or lower) the level of the oceans, the extent of Arctic or Antarctic sea ice, monitored at a fixed time of the year, could serve as an indicator of the temperature of the polar regions.

Figure 4.11 shows the variation in extent of the Northern Hemisphere sea ice since 1900. All four seasons show a loss of sea ice extent during the latter half of the past century. However, the drop in extent is particularly noticeable (nearly 40%) for the summer season months of July - September (JAS). This dramatic

\[\text{Cumulative ice mass loss from glacier and ice sheets (in sea level equivalent)} = 1.0 \text{ to } 1.4 \text{ mm yr}^{-1} \text{ for 1993-2009 and } 1.2 \text{ to } 2.2 \text{ mm yr}^{-1} \text{ for 2005-2009.}

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47arctic.atmos.uiuc.edu/cryosphere/

Figure 4.11: Annual and seasonal sea-ice extent in the Northern Hemisphere over time. (IPCC AR5-WG1 report, Chapter 4, figure 4.3, licensed for non-commercial use)
What about Antarctic sea ice? Unfortunately, the polar sea-ice extent in the Southern Hemisphere was not well-monitored until the late 1970’s. Figure 4.12 shows both the variation in the sea-ice extent in both hemispheres since 1979. It is easy to see that there is little change (or perhaps a very slight increase) in the minimum extent of the Antarctic sea ice during the same period (1979 – 2010) during which the Arctic sea ice has dramatically decreased. Figure 4.12 clearly shows that the net polar extent (at the end of the polar summer) has decreased significantly since 1979.

Why might Antarctic sea ice be increasing if Earth is warming?

Because the GWDs often point to a recent increase in the amount of Antarctic sea ice as evidence refuting global warming (see next section), it is worth exploring the behavior of Antarctic sea ice in some detail.

The most obvious reason why sea ice can grow in extent on a warming planet is again related to the different densities (and therefore different melting temperatures) of fresh-water ice and sea ice. As polar land ice melts in Antarctica
due to GW, the freshwater melt decreases the salinity of the sea water. Because lower-salinity sea water freezes at slightly higher temperature, sea ice can grow in extent as the local Antarctic temperatures rise.

Other explanations\textsuperscript{51} have been proposed to explain the increasing extent of Antarctic sea ice on a global-warming planet. They include a local cooling triggered by the hole in the Antarctic ozone (remember that ozone is a warming greenhouse gas) and an increase in the local freezing temperature of water (due to the addition of fresh water from the melting land ice). No single explanation has yet gained scientific consensus.

\textbf{Why melting sea ice might be disastrous even though it cannot directly cause sea-level rise.}

Although the point has been made several times now that melting sea ice does not directly raise ocean levels, there are a number of reasons why climate scientists are concerned about melting sea ice.

First, a dramatic loss of sea ice is an indication of a warming planet. Like the canary in the coal mine, it is harbinger of danger ahead.

Second, sea ice can and does act like a stopper preventing land ice (in particular, major parts of both the Greenland and Antarctic ice sheets) from sliding into the ocean and raising sea level.

Third, sea ice is highly reflective (albedo = 0.5 to 0.7).\textsuperscript{52} Consequently, 50 to 70 percent of the sunlight hitting the sea ice is reflected back into space, without being absorbed and, therefore, without heating the atmosphere. Because the sea water is much less reflective (albedo = 0.06), a much greater portion (94%) of sunlight hitting sea water is absorbed in the ocean, thereby contributing to a greater local infrared emission and consequently higher atmospheric temperatures. The loss of the Arctic sea ice has been estimated to have the same effect on global temperatures as 20 years of man-made CO\textsubscript{2} emissions!

Finally, the Arctic warming associated with the albedo effect described in the previous paragraph threatens to melt the permafrost. This would lead to a release of presently-ground-trapped carbon dioxide and methane into the atmosphere, which in turn (via a positive feedback loop) raises temperatures still further, which will melt more permafrost, and so on.

\textsuperscript{51}Why is Antarctic sea ice growing?: http://www.skepticalscience.com/why-is-antarctic-sea-ice-growing.html
\textsuperscript{52}National Snow & Ice Data Center: https://nsidc.org/cryosphere/seaice/processes/albedo.html
Arctic and Antarctic sea ice: a typical case of climate-change-skeptic obfuscation

Although it is not possible to address every claim and objection that skeptics raise in their dismissal of global warming, the case of polar sea ice is typical of their efforts.

The GWDs often claim an increase in the extent of Antarctic ice (although it is certainly difficult to see any increase based on the data in Figure 4.12) and use it as a refutation of global warming. In using a claim of rising Antarctic sea ice as evidence against global warming, these GWDs conveniently (and dishonestly) ignore the overwhelmingly larger decrease in Arctic sea-level ice.

In 2013, NASA reported that Antarctic sea ice reached its greatest recorded maximum extent (since monitoring began in 1981) during that winter. Although much has made of this by climate-change skeptics, this maximum extent was less than 4% over the average maximum extent for the previous 32 years. Figures 4.13 and 4.14 show the annual variation of Arctic and Antarctic sea ice, respectively. A comparison of the two graphs shows that this much-vaunted 2013 increase (over the mean) in the maximal Antarctic sea-ice extent is dwarfed by the decrease (below the mean) in the maximal Arctic sea-ice extent in recent years. Once again, selective cherry-picking of the data by the GWDs leads to an incorrect conclusion.

53 Antarctic Sea Ice 50% Above Previous Record: [http://iceagenow.info/2014/05/antarctic-sea-ice-50-previous-record/](http://iceagenow.info/2014/05/antarctic-sea-ice-50-previous-record/) Note also therein the specious “50% above previous record” claim (perhaps due to a misreading of the graph’s vertical scale?). The maximum ice extent in actuality was a miniscule 0.15% over the previous record.

54 The claim is often accompanied by a past prediction by James Hansen (a renowned climate scientist, and an early and vocal advocate of the reality of global warming) that Antarctica sea-ice levels would decrease by 40% due to global warming. Hansen’s prediction was made in the early 1980s, just at the start of reliable Antarctica-ice measurements. Perhaps it also shows that climate scientists should be more cautious in communication, particularly when talking about predictions. See Chapter 7.


56 National Snow & Ice Data Center, Interactive Arctic Sea Ice Graph: [http://nsidc.org/arcticsaicenews/charctic-interactive-sea-ice-graph/](http://nsidc.org/arcticsaicenews/charctic-interactive-sea-ice-graph/)

Figure 4.13: Annual variation in Arctic sea ice for individual years 2007 - 2013. (Image courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder, licensed for non-commercial use.)

Figure 4.14: Mean annual variation in Antarctic sea for years 1981 - 2010. (NASA Earth observatory, public domain)
4.3.4 Polar ice: the take-away

The water produced from the loss of polar land ice (aka Arctic and Antarctic ice sheets) has contributed about 20% of the recent global sea-level rise that has occurred in tandem, as we shall see in the very next section.

4.4 Sea levels

4.4.1 How are sea levels measured?

Sea levels are directly monitored in two ways: (1) tidal gauge averages for a large number of stations worldwide, and (2) satellite altimetry (which has been available since the 1980s). During the time period for which both measurements have been in effect, the data for the two are in agreement.

4.4.2 Recent sea level rise

Figure 4.15 shows a global average sea level rise of approximately 20 cm (8 inches) since the late nineteenth century. The average sea level rise over the past two decades is about 3.2 mm/year (0.12 inches/year).\(^5\)

4.4.3 Why are sea levels rising?

Three mechanisms are responsible for causing sea levels to rise as the global temperature rises: (1) the thermal expansion of water, and (2) the melting of glacier and polar ice, and (3) release of water formerly stored on land (or perhaps below ground). (Land water storage contributes to sea level rise if there is a net amount of water pumped out of the ground or released from dams that is then allowed to run off into rivers that eventually drain into the oceans.)

How well do we understand the origin of sea level rise? Table 4.1 shows the estimated contributions from these various mechanisms along with the measured sea level rise for three different time periods. The IPCC 5th Assessment Report (AR5, 2013) claimed considerable progress (over AR4, 2007) in matching the estimated and the observed sea level rise for the 1993 - 2010 measurement period. Glacier and ice melting contribute 50% of the rise; thermal expansion, just under 40%; and land water storage, just over 10%.

Estimated contribution to global mean sea level rise (all numbers in mm/yr)

<table>
<thead>
<tr>
<th></th>
<th>1901 - 1990</th>
<th>1971 - 2010</th>
<th>1993 - 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal expansion</td>
<td>0.80</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>mountain glaciers</td>
<td>0.54</td>
<td>0.62</td>
<td>0.76</td>
</tr>
<tr>
<td>Greenland glaciers</td>
<td>0.15</td>
<td>0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>Greenland ice sheet</td>
<td></td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Antarctica ice sheet</td>
<td></td>
<td></td>
<td>0.27</td>
</tr>
<tr>
<td>land water storage</td>
<td>-0.11</td>
<td>0.12</td>
<td>0.38</td>
</tr>
<tr>
<td>total contributions</td>
<td></td>
<td></td>
<td>2.9</td>
</tr>
<tr>
<td>observed mean sea level rise</td>
<td>1.5</td>
<td>2.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Table 4.1: Estimated and observed contributions to global mean sea level rise

Figure 4.15: Sea level rise since the late 19th century. Measurements are from tidal gauges (red) and from satellite altimetry (blue). The shaded gray area represents measurement uncertainty, which has decreased as more tidal gauges were employed. (EPA, public domain)
4.5 Ocean Heat, Acidification, and Deoxygenation

4.5.1 Ocean heat

There is a consensus (e.g., the 2013 IPCC AR5 report) that 93% of greenhouse-gas heating is deposited in the ocean. Approximately two-thirds of this ocean energy goes into the upper 700 m of the ocean, with only one-third deposited in depths below that. Nearly all of the remaining 7% of greenhouse-gas heating goes into melting ice (glaciers, sea ice, and land ice sheets over Greenland and Antarctica) and into heating the land surface. Of order 1% of the greenhouse heating energy goes into heating the atmosphere. The water content of Earth’s atmosphere has also increased (which results in increased rainfall intensity and, apparently, in a rise in the severity (if not the frequency) of water-driven chaotic surface storms such as hurricanes.

Why do the oceans absorb so much of this energy? First, water has an exceptionally high specific heat, i.e., it can absorb a large amount of energy without increasing its temperature substantially. Second, the oceans are both deep (up to 4 km) and broad (covering 71% of Earth’s surface area). Third, the oceans are dynamic, i.e., subject to currents, internal waves, and eddies that can easily exchange thermal energy as well as carbon dioxide and, to a lesser extent, oxygen.

Where are the consequences of ocean heating? They include (1) thermal expansion of ocean water (which in turn leads to rising sea levels, discussed in section 4.4), (2) thermal destruction of coral reefs (discussed immediately below), (3) the acidification of the oceans (section 4.5.2), and (4) the deoxygenation of the oceans (section 4.5.3).

Rising ocean temperatures and coral bleaching

A direct consequence of higher ocean temperatures (whether produced by long-term global warming or by temporary weather patterns such as El Niño) is coral bleaching. The warm temperatures cause the coral polyps to expel the algae that exist symbiotically with them and provide the bulk of their food and energy supply. The loss of the algae results in coral emaciation and/or death.

Corals are important because they support more than 20% of marine species, and the contribute in a major way to the food supply and economic livelihood.

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56 How fast are the oceans warming? Science (11 Jan 2019) Vol. 363, pp. 128-129: https://science.sciencemag.org/content/363/6423/128
60 There are other triggers of coral bleaching in addition to warmer ocean waters. These include ocean salinity changes, herbicides and other pollutants, and overfishing.
of hundreds of millions of people living in coastal communities.\textsuperscript{61}

Coral bleaching events (1998, 2002, 2014-2017) have been triggered by ocean warming and exacerbated by major El Niño warming events. During the worst bleaching event on record (2014 - 2017), more than 70\% of all oceanic corals were damaged. Hughes et al.\textsuperscript{62} report that 50\% bleaching can result from a temperature-time exposure of 4°C-weeks; nearly 90\% bleaching can happen with 8°C C-week exposure.

4.5.2 Ocean acidification

Carbon dioxide can dissolve in ocean water and form the slightly acidic carbonic acid, H$_2$CO$_3$. As the ocean warms, the solubility of CO$_2$ increases, and its pH level decreases.

The pH level is used to specify the relative acidity of a water-based solution. The pH scale is a logarithmic one, which measures (in an inverse sense) the concentration of hydrogen ions in the solution. The relative acidification level of two fluids is related to their pH levels by

$$\frac{A L_1}{A L_2} = 10^{(pH_2 - pH_1)} \quad (4.1)$$

A lower pH therefore indicates a more acidic solution.

\textsuperscript{61}Scientific American: Can We Save the Corals?, December 2017: https://www.scientificamerican.com/article/scientists-are-taking-extreme-steps-to-help-corals-survive/

Figure 4.16: Ocean data collected at Station Aloha in Hawaii shows increasing dissolved CO2 (green line), and decreasing pH (blue line; lower pH means higher acidity) over the past 30 years. These ocean CO2 and pH trends are caused by increasing atmospheric CO2 (red line). (NOAA, public domain)

Figure 4.16 shows the measured ocean pH at Hawaii’s Station Aloha (a deep-water station 100 km north of Oahu; it is thought to be free of coastal dynamics and terrestrial input). The change in station’s average pH level of -0.05 over 26 years is equivalent to a 12% increase in ocean acidification.

Although we don’t have direct measurements of ocean pH levels at the start of the Industrial Age (1850s), computer models tell us that ocean pH levels have dropped by 0.1 since then. Ocean acidification has correspondingly risen by 25%.

Consequences of ocean acidification

Another consequence of more dissolved CO2 in oceans is the decrease in carbonate ion (CO3^2-) concentration (figure 4.17). Because carbonate ions are...
important in building corals and shells of other marine organisms (e.g., clams, oysters, sea urchins, calcium-containing plankton), a decreased carbonate concentration means that those organisms will have greater difficulty in building and maintaining those shells.

Figure 4.17: How ocean carbonate chemistry and pH are related. (Figure 2 of S. Barker, A. Ridgwell, “Ocean acidification,” Nature Education Knowledge 3(10):21, licensed for non-commercial use; see also Figure 2 of “Climate change in the marine realm,” ed. A. Dummermuth, K. Grosfeld, licensed for non-commercial use.)

There are likely additional consequences (both favorable and unfavorable to ocean life) that are unknown at the present time. (Some known consequences include rate of rock weathering, predator and habitat detection by fish, echolocation by marine mammals.) Eventually, the ocean chemistry and life within will adapt to new conditions. But it is likely that these changes will take thousands of years.
4.5.3 Ocean deoxygenation

A final (belatedly-realized) consequence of the ocean heating is the decline of the oxygen concentration in Earth’s oceans. This ocean deoxygenation was first measured ocean-wide in the middle of the last century. The average drop is of order 2%\textsuperscript{65} but there are local concentrations of deoxygenation particularly in the Arctic and along the equator (with major secondary losses in the North Pacific and Southern oceans). Collectively, these aforementioned oceans are responsible for over 60% of the total oxygen ocean loss. Some individual tropical regions have suffered a 40% loss of their oxygen content.

The major cause of ocean deoxygenation\textsuperscript{66} is human-caused global warming. A secondary cause is nutrient changes introduced by humans that have altered the abundances and distributions of marine life. There is great concern that the rate of ocean deoxgenation will accelerate in this century due to the acceleration of warming (Figure 4.18). At present, climate models are underestimating the observed decline in ocean oxygenation. Such an accelerating decline of ocean oxygenation has major implications not only for the future of marine life and ocean productivity and for the usefulness of the ocean in carbon cycling, but also for human industries (fisheries, coastal economies) dependent on such.

\textsuperscript{65}Decline in global oceanic oxygen content during the past five decades, Nature 542, pp. 335–339 (16 February 2017) : https://www.nature.com/articles/nature21399.pdf

Figure 4.18: Simulated evolution of the models of the Fifth Assessment report of the IPCC with an average 0.6% decline during the 50-year period 1960-2010. The observational estimate for that same period amounts to 2%. (Carbon Brief CC BY-NC-ND 4.0)

The physics connecting warming ocean water and declining oxygen levels within is quite straightforward: the higher the temperature of a liquid, the less gas can be dissolved in it. It’s why your carbonated soda goes increasing flat as the liquid soda warms up.

But there is a second effect due to ocean warming. How oxygen enters and leaves the ocean is much more complicated. Oxygen from the atmosphere enters the ocean at the air-ocean boundary, gets mixed throughout the oceans via ocean currents (or is produced by phytoplankton dwelling near the surface). As polar sea ice melts, a layer of relatively buoyant water forms at the surface of colder, saltier ocean water. This stratification of the upper ocean boundary can prevent the mixing of oxygen-laden surface water with ocean water at greater depths.

A third effect results from a different set of human behavior. River sediments containing organic matter or nitrogen and phosphorus from farming fertilizers
and sewage drain into coastal ocean waters. The fertilizers cause algae and bacterial blooms which in turn deplete oxygen in the process breaking down dead marine life. These oxygen-depleted areas produce nitrous oxide (N\textsubscript{2}O), a potent greenhouse gas, producing a positive feedback to global warming\textsuperscript{67}.

The combined oxygen loss due to these three effects is problematic for life in the deep oceans. Impaired vision, difficulty in food finding due to an altered food web, a loss of biodiversity, and difficulty in thermal regulation are just a few of the many problems marine life faces with diminished oxygen. There is evidence that zooplankton (a major source of food in ocean mid-levels) are also affected by oxygen depletion. Many species move to greater ocean depths where the oxygen levels are appropriate to their needs. Further consequences to the marine food chain follow. As is typically the case, the financial and ecological costs of depleted ocean oxygen content are not figured in any real way as a cost of global warming.

### 4.6 Biological indicators and consequences of global warming

The indicators of temperature change previously discussed in this chapter have truly been global in nature: direct temperature measurements, ice cover, and ocean levels. And that’s as it should be. Prediction of global changes require global evidence. Temperature changes can also be inferred from changes to living systems. For example, temperature plays the major role in such things as the length of growing seasons for plants, migration patterns of birds, and the seasonal appearances of butterflies and insects.

Furthermore, few/no species of plants or animals cover the globe (except perhaps humans, who have mastered control of much of the environment). Still, global conditions can be deduced from the strongly overlapping trends of multiple local conditions.

However, for the reasons alluded to in the last two paragraphs, the evidence presented in the subsections to follow are sketchier and more disjointed then evidence in previous sections.

\textsuperscript{67}Declining oxygen in the global ocean and coastal waters, Denise Breitburg et al., Science 359, 46 (5 January 2018): https://science.sciencemag.org/content/sci/359/6371/eaam7240.full.pdf
4.6.1 Biological indicators of global warming: phenological changes

Seasonal timing

Phenology is the scientific study of periodic or time-sensitive biological phenomena, such as flowering, breeding, and migration, in relation to climatic conditions.

Length of growing season

The evidence from regional biological indicators points entirely one way. Table 4.x\textsuperscript{68} shows variety of biological indicators of regions temperature changes. The data is not meant to be exhaustive, but it is representative of the variety of indicators that have been studied. It has been culled from several large-scale collections\textsuperscript{68,69} of published papers of biological climate indicators.

4.6.2 Biological indicators of global warming: changes in plant or animal behavior

Bird migration: generic

Avian migration is complicated. The where and when of bird migration is believed to to species-dependent and is determined by seasonal plant growth, food availability, and precipitation patterns, all of which are sensitive to local temperatures.

A large scale study of bird migration\textsuperscript{70} (based on billions of birds over 24 years) found that rising temperatures have led to a gradual but measurable shift in spring avian migration by an average of nearly 2 days per decade.

The study used a neural network to differentiate between remote sensing observations of the flocking of hundreds of avian species and the simultaneous precipitation patterns that mimic the flocking behavior. It also found evidence of stronger phenological changes at higher latitudes in the spring. The study further found that the most rapid changes occurred in the western avian flyway (which has the largest number of species migrating the shortest distances – and therefore the most likely to respond to the changing availability of food resources). Shifts in

\begin{table}[h]
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Papers on Biological Indicators of Global Warming: & \cite{68} & \cite{69} \\
https://agwobserver.wordpress.com/2009/07/31/papers-on-biological-indicators-of-global-warming/ & \cite{70} & \cite{71} \\
Climate Change, Biological and Phenological Changes: & \cite{70} & \cite{71} \\
https://uknowispeaksense.wordpress.com/links-to-papers/ & \cite{70} & \cite{71} \\
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\end{tabular}
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fall migration were observed as well, although the connection to global temperatures was not as well established.

**Bird migration: hummingbirds**

Rising winter temperatures in the American South have made it an attractive alternative to previous winter habitats in Central America. Some of North America’s eastern hummingbird species have stopped making the thousand-mile migration trip to Central American and begun overwintering in the Carolinas, Georgia, or Florida instead. Other western NA species are migrating east. It is certainly possible that the changes in hummingbird migration habits is partly due to the loss of quality habitat and food resources in Central America in addition to newly attractive winter conditions in the American South.

**Insect migration: butterflies**

There has been great concern over the past two decades for the future viability of monarch butterflies due to various factors as habitat loss, unstable temperatures, and an increase in droughts and severe storms. All three of these factors can be negatively affected by climate change. Despite this concern, a comprehensive study of monarch decline did not take place until 2017.

The overwhelming number of monarchs spend summers in Eastern U.S./Canada, breed in the southern U.S. during fall or spring, and then migrate 1000+ miles to spend the winter at one of several small oyamel forest patches in central Mexico. The timing of their migration south is believed to be triggered by three factors: (1) a continuing decrease in the number of daylight hours, (2) a noticeable drop in nighttime temperatures (most likely to occur beginning in late August or September), and (3) a deterioration in the quality of the milkweed crop (which also occurs in northern mid-latitudes in August and/or September). Each of these factors causes a physiological change in butterflies that results in the suspension of reproductive activity, in preparation for the migration.

Migration is also quite sensitive to temperature (55 - 70°F is strongly preferred during migration) and stable weather patterns (an absence of storms and unusual or rapid changes in climate). There are instances this century on record

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71 Forget the migration. Hummingbirds are making NC their winter home.: https://www.newsobserver.com/living/article238366508.html
73 How Monarchs Know When to Migrate, Debbie Hadley, November 4, 2019: https://www.thoughtco.com/monarchs-know-when-to-migrate-1968175
of greater-than-75% monarch loss during storms. Global warming is not only responsible for rising temperatures and increasing the frequency and severity of storms (the opposite of the stable weather patterns conducive to monarch migration), but also for changes the late-summer deterioration of the milkweed crop. Additionally, there is also loss of monarch habitat in Mexico due to forest logging and in mid-western U.S. by chemical spraying (particularly by glyphosate) and prairie loss.

Monarch breeding is uniquely dependent on the milkweed plant which is used both as an egg repository and as the sole source of food during the monarch larval stage. In late summer, the milkweed plants undergo yellowing, mold covering (produced by most commonly aphids), and dehydration. The 2017 study concluded that spraying by the chemical glyphosate had been a major factor in monarch decline earlier in this century, but that further negative impacts from spraying alone were not likely.

The U.S. Fish and Wildlife Service (FWS) announced a $3.2-million fund in 2015 to help restore milkweed habitat, including spring breeding habitats in Texas and Oklahoma. The fund included money to seed the Monarch Conservation Fund, which is administered by the FWS and used to solicit additional financial contributions. In 2018, a consortium of Fish and Wildlife agencies developed a detailed 20-year strategy[74] for butterfly conservation.

**Miscellaneous behavior changes**

Leatherback turtles face a doubling in their journey time from nesting on shore to cooler feeding grounds[75]

Kemp’s Ridley turtles, on the other hand, have incurred a 40-fold increase over 35 years in beach strandings in coastal New England, due to climate-change-caused warming in the Gulf of Maine.[76]

Puffins in the Gulf of Maine normally eat hake and white herring. However, these fish have now moved north due to global warming. The puffins have tried feeding their young butterfish instead, but the young are unable to swallow them. Fledgling survival rates have declined by over 25-30% over the past two decades.

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4.6.3 Biological consequences of global warming: biodiversity and habitat loss

Miscellaneous

Pikas require a cool, moist, rocky habitat. It has become hotter, drier, and snowier. Because they currently live in high-altitude mountainous terrain, such changes leave them nowhere else to go.\footnote{Pika (Ochotona princeps) losses from two isolated regions reflect temperature and water balance, but reflect habitat area in a mainland region, E. A. Beever, Journal of Mammology, Volume 97, Issue 6, December 5, 2016: https://academic.oup.com/jmammal/article/97/6/1495/2628942}

4.6.4 Biological consequences of global warming: extinction risk

A 2015 synthesis of 131 selected studies, published in the journal Science\footnote{Urban, M. C., Accelerating extinction risk from climate change, Science, 348, pp. 571-573 (1 May 2015)} suggest that “extinction risks will accelerate with future global temperatures, threatening up to one in six species under current policies.”

Although hundreds of studies published over the past two decades have yielded various predictions regarding the number of extinctions that will be caused by global warming, the studies differ greatly in the number and type of species studied, the geographical range involved, and the assumed future rise in GMSTs. Not surprisingly, the extinction levels predicted in these varied studies ranged widely, from 0 to 50%.

In this 2015 synthesis, Urban revisited every extinction study published. He threw out all the studies that examined just a single species, on the grounds that the results of such studies might inflate the result of his meta-analysis. (Individual species are often chosen for study because they already suspected of being vulnerable to climate change.)

Despite the substantial differences in the modeling assumptions used in the individual 131 studies remaining, Urban found that the magnitude of future climate change was, by far, the most important predictor of extinction risk. As with other effects of global warming (ice loss, sea-level rise, and frequency of extreme weather), the magnitude of the extinction risk accelerates with GMST rise. Urban further found that loss of biodiversity is projected to be greatest in Australia, New Zealand, and South America, regions where a large fraction of the species are confined to a narrow geographic range, and/or face disappearing habitats or barriers to migration.
Overall, his study finds that up to 2.8% of all species could become extinct in the unlikely event that the GMST rise since the Industrial Revolution remains at the present 0.8°C level. If the eventual GMST rise is limited to 2°C (a target suggested by GWAs as the largest tolerable increase in GMSTs that would prevent a runaway greenhouse effect), the extinction rate rises to 5.2%. For IPCC climate models RCP 6.0 and RCP 8.5 (both of which involve an increase in GHG release over the present; these models are discussed in Chapter 7), the extinction rates are 7.7% and 16%, respectively. It is likely that these extinction rates are underestimates, as the studies analyzed under-represent tropic zones, where many of the biological species are endemic, and therefore highly susceptible to habitat change.

However, it is also true that another of the major findings of Urban’s meta-study is that major uncertainties still plague any study of extinction risk. Among the many questions that remain mostly unanswered are: Can adaptive behavior ameliorate the impact of climate change? How rapidly does extinction (a non-instantaneous process) take place? Are slow-to-migrate species subject to greater risk from climate change effects? Does extinction take place before suitable habitats disappear completely? Do associated effects of climate change (e.g., the rise of invasive species or the altered interaction of species in an ecosystem) accelerate or reduce the impact of global warming?

The consequences of climate change for biodiversity seem far more uncertain than, say, those for ice loss or sea-level rise. Consequently, studies that predict extinction risk should be regarded with more skepticism until many basic questions (some listed above) are researched and answered. And, as for other predicted consequences of climate change such as ice loss and sea-level rise, the magnitude of the effects remain highly dependent on any future steps that humans take to reduce or magnify global-warming trends.

4.6.5 Biological consequences of global warming: the human comfort range

The evidence that global warming is already changing where and how humans live comfortably is already overwhelming. Consider the following

Killer Heat

The Union of Concerned Scientists produced a 52-page report[79] on the future of dangerously hot days in the United States.

The authors consider the physiological consequences of changes in the heat index experienced by humans under various RCP scenarios. Even under a rapid-action climate plan, the authors conclude that 200 of the U.S.’s 481 urban regions would experience more than 30 days with dangerous heat index above 100°F. (Recent historical averages indicate that only 29 urban areas experienced similar number of heat-index-days at present.)

**Human comfort level**

Another recent paper examined the history of the human comfort range over the past 6000 years and found it to be in the temperature range of 11 °C to 15 °C (= 52 °F to 59 °F), mean annual temperature. The authors speculate that this range represents some fundamental constraint on human living (along with accompanying crop production and livestock raising).

The authors also show that (in a business-as-usual mindset: climate scenario RCP8.5) the geographical locus of this climate niche is likely to shift geographically more in the next 50 years than during any similar period since 4000 BC. The authors estimate that 1 - 3 billion humans will be moved out of this traditional ‘human climate niche’ and experience hotter temperatures than virtually anywhere today.

The authors further conclude that the stability of this human climate niche is likely intrinsic to humans (despite technical innovations over past millennia). They also document historical examples connecting temperature changes outside this niche and subsequent human migration, and they further discuss the implications for new human migration paths in the near future. They suggest that 30% of the world’s population would need to migrate in order to maintain life within this traditional human climate niche. It should be emphasized again that the ground assumption for this work is climate projection RCP8.5.

**4.6.6 Biological consequences of global warming: human migration**

Documenting and reporting of the climate effects on human migration has exploded recently. The following articles give a flavor of what has already happened and what might be expected to come.

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The Great Climate Migration, New York Times (July 25, 2020)\textsuperscript{81}

How Climate Migration Will Reshape America, New York Times (September, 2019)\textsuperscript{82}

Climate migration myths; International migration and climate adaptation in an era of hardening borders; Meeting the looming policy challenge of sea-level change and human migration; Sea-level Rise and Human Migration and more, in Nature Climate Change (November/December 2019)\textsuperscript{83}

The Climate Crisis, Migration and Refugees, The Brookings Institution (July, 2019)\textsuperscript{84}


The first two articles (written for the NY Times) summarize current and future prospects for human migration. The next two articles are much more scholarly and document the research behind such popular expectations. The last reference, also scholarly, revisits the research in addition to suggesting 6 priorities for policy prescriptions to avoid large-scale climate-induced human-migration effects and suggestions for further research.

It is impossible to present a confident summary of where the issue of climate-change-induced effects on human migration is going. The uncertainties are too great. The main ones are

(1) how the world will respond to the climate crisis (i.e., which RCP scenario the world chooses to follow): will the Paris accords change government behaviors?

(2) the economics of switching from carbon-based energies to renewable energies

(3) the personal behavior of the world’s relatively well-off population: will there will a switch in diet (from carbon-intensive meat to a mostly plant diet)? will drivers choose electric or hybrid cars?

\textsuperscript{81} The Great Climate Migration: https://www.nytimes.com/interactive/2020/07/23/magazine/climate-migration.html


\textsuperscript{83} Several articles on the connection between climate change and human migration in late 2019: https://www.nature.com/collections/dagebcjja

\textsuperscript{84} The climate crisis, migration, and refugees: https://www.brookings.edu/research/the-climate-crisis-migration-and-refugees/

\textsuperscript{85} Human Migration in the Era of Climate Change: https://academic.oup.com/reep/article/13/2/189/5522922
4.6.7 Biological consequences of global warming: human behavior and evolution

Carbon dioxide and human cognition

Humans evolved while breathing an atmosphere than contained much less carbon dioxide than currently. [The atmospheric concentration of CO\textsubscript{2} exceeded 400 ppm (parts per million) for the first time in human history in 2015.]

In closed environments (e.g., homes, classrooms, scientific conference rooms), CO\textsubscript{2} concentrations can exceed outdoor concentrations.

Previous research had shown, in a longitudinal study of Chinese individuals of both transitory and cumulative exposure to air pollution, that long-term exposure to air pollutants impedes cognitive abilities on both math and verbal tests. It was already well known that air pollution had harmful effects on human health, including lowered life expectancy and increased illness, hospitalization, and cases of dementia.

The authors of this most recent study take pains to note that there are as yet no studies looking at prolonged effects of, or effects on young children and the elderly.

Climate change and human health

“Ensuring that the health of a child born today is not defined by a changing climate” (11/13/2019)

“Preventing and mitigating health risks of climate change”

4.7 Extreme weather as a consequence of global warming

A lengthy discussion of the connective causes between extreme weather (e.g., extreme changes in precipitation or temperature, changes in the frequency or severity of storms, hurricanes, etc.) is beyond the scope of this work. However,
there is great confidence in the science community that higher GMST result in greater extremes in temperatures (both high and low) and greater extremes in precipitation.

On the other hand, there is some confidence in a connection between higher GMST and water-driven cyclonic events (hurricanes and typhoons) but relatively little confidence in a connection between higher GMST and non-water-driven cyclones (tornadoes). Physics suggests that the higher the GMST, the greater the water evaporation from oceans, and the more water vapor available to drive water-driven cyclones.

4.7.1 Daily temperature and rainfall extremes and global warming

A recent study\textsuperscript{89} focusing just on temperature and precipitation extremes, uses computer analyses of what the climate would be like if the Industrial Revolution had never happened. The models calculate the changes in the frequency of weather extremes that would be likely to occur in any given location on Earth as a function of GMST rise.

The authors conclude that 75\% of the moderate\textsuperscript{90} daily hot extremes over land are attributable to the 0.85\degree C-rise in GMSTs since pre-industrial times. Put differently, these once-in-three-year temperature extremes have increased four- to five-fold since 1880.

The frequency of temperature extremes depends in a highly nonlinear manner on GMST rise. If the GMST rise reaches 2\degree C (a level that environmental activists consider a goal within reach if humans actively curtail GHG emissions), the frequency of these temperature extremes is expected to increase by a further factor of 3 over today’s. If, however, the GMST reaches 3\degree C (a level suggested as inevitable by a number of climate models in the latest IPCC report, AR5), the frequency of such extremes increases instead by a factor of 15 over those of today.

Increased precipitation is a well-understood physical consequence of rising temperatures. Warmer air takes up more moisture from oceans and therefore results in increased rainfall (a variation on 'what goes up, must come down'), although the excess rainfall is not evenly distributed geographically. Some areas may be subjected to increased drought instead.


\textsuperscript{90} Moderate’ daily temperature extremes are considered to be those exceeding the 99.9th percentile. These extremes are expected to occur approximately once every three years.
The authors’ computer models predict that rainfall increases will be less severe than those in temperature. The occurrence of heavy daily precipitation\textsuperscript{91} days under present-day warming is only slightly higher (20\%) than in pre-industrial conditions. If the warming rises to 2°C, the probability of the most extreme precipitation events increases by a factor of 1.5 to 3 depending on geographic location.

4.7.2 Extreme weather events and global warming

Although extremes in daily temperatures and precipitation are easily attributable to global warming, the connection of overall planetary warming to individual and seasonal events such as hurricanes or El Niño/La Niña is somewhat more tenuous.

4.7.3 Is there an evidentiary connection between global warming and extreme weather events?

The Union of Concerned Scientists has prepared a 11-page summary\textsuperscript{92} of extreme weather research through June 2018. The extreme conditions covered include cold, heat, precipitation, drought, wildfire, and storm surge.

\textsuperscript{91}Heavy’ daily precipitation is considered to be an event exceeding the 99.9th percentile. Such extremes are expected to occur approximately once every 30 years.

\textsuperscript{92}The Science Connecting Extreme Weather to Climate Change, Union of Concerned Scientists, June 2018: https://www.ucsusa.org/sites/default/files/attach/2018/06/extreme-weather-Appendix-A2.pdf
The rising costs of extreme weather

Figure 4.19 displays the number of billion-dollar (adjusted by the Consumer Price Index) disasters in America. Although there is a clear increasing trend in the number of these events with time (and, therefore, with average GMST), some words of caution are in order.

First, correlation does not imply causation. Second, accounting methods have changed with time (probably by becoming more cost-inclusive).

Extreme weather attributions

In an attempt to disentangle science from statistics, Carbon Brief analyzed 260 recent extreme weather events covered by 234 scientific papers. The great majority of these weather events involved extreme heat waves, heavy rain (and flooding), and severe drought, as displayed in Figure 4.20.
Of the attribution studies associated with heat-wave events, 95% of them concluded that the events were either made more likely or more intense by global warming.

On the other hand, attribution studies concerned with extreme rainfall, 57% of them judged the events were made more likely or more severe by global warming (whereas 25% of them found no link to climate change; 6% found climate change made the events less severe or less likely; 12% of the studies were inconclusive).

Finally, for the third kind of extreme event (drought, 65% of attribution studies found that extreme drought events were made more intense or more likely by global warming (whereas 20% of the studies found not link or warming) 13% of the studies were inconclusive).

A graphical summary of the understanding and attribution of climate change impacts on extreme events can be found at the blog[^95] and in the text[^96].

[^95]: http://blogs.reading.ac.uk/weather-and-climate-at-reading/2016/can-specific-extreme-weather-or-climate-events-be-attributed-to-climate-change/
4.8 Warming up to Climate Tipping Points

4.8.1 What’s a climate tipping point?

A climate tipping point is a threshold value of some parameter that, once exceeded, results in a large and/or long-term change in the climate system. It’s often associated with a positive feedback mechanism that amplifies the initial change in the threshold parameter.

For example, there may be some value of Earth’s temperature that, once exceeded, will result in an unbridled runaway heating of Earth. If the temperature rises above some threshold value, it may be impossible for current weathering cycles to put sufficient CO$_2$ into rocks (via weathering) or back into the ocean (through acidification). Consequently, the extra CO$_2$ in the system will warm Earth further, which in turn amplifies the effect of the initial warming. We have only to be reminded of the runaway greenhouse effect that apparently happened long ago on the planet Venus to see an extreme consequence of a climate tipping point threshold exceeded.

4.8.2 Permafrost melting

Permafrost and methyl hydrates

Permafrost consists of ground or soil that has been frozen for two consecutive years. It can vary in thickness from less than 1 meter to over 1 kilometer. It is generally found below an active layer of ground/soil that is not permanently frozen (but may thaw and refreeze every year). Both permafrost and active layers may contain organic material, the remains of dead microbes, plants, and animals.

It is estimated that world permafrost contains roughly 1500 GmT (Giga metric Tons) of carbon, which is approximately twice the amount of carbon present in atmospheric carbon dioxide and methane.$^{[97]}$

Related to permafrost soil are the methyl hydrates (also known as clathrates), which are found below glacial ice sheets, continental ocean shelves, or permafrost layers. Methyl hydrates consist of biologically-produced methane trapped in a crystalline water ice structure and formed at low temperatures and high pressures. The amount of carbon deposited in methyl hydrates is less certain that in permafrost. Estimates range from 500 - 400 GmT (= 1 - 5x the amount of carbon currently in the atmosphere).

The danger of permafrost melting

The Arctic regions have recently been warming more than 2x faster than the planet as a whole. If permafrost begins to melt, that can awaken microbes that will then decompose other organic material in the soil and release CH$_4$ or CO$_2$ in the process. Methane is of greater immediate concern because it is 86x more potent as a greenhouse gas than CO$_2$ over a 20-year period (or about 30x more potent over a 100-year period). Over the long term, the CH$_4$ will oxidize to CO$_2$. Given the long-term trend of warming temperatures, melting of the permafrost seem to be irreversible.

The uncertainties of permafrost melting

Permafrost melting has now been observed in several locations in the Arctic. The recent IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) reports that Arctic permafrost temperatures have reached record-high levels and have increased 0.29 °C (± 0.12 °C) from 2007 - 2016. Given current warming trends, the loss of near-surface permafrost extent would be 2 - 66% in (the slowest-warming) scenario RCP2.6 and 30 - 120% in (the fastest-warming) scenario RCP8.5. The latter increases could potentially add tens to hundreds of GmT of carbon to the atmosphere.

How can we obtain more certain estimates? Some questions that still need to be answered definitively include

Does permafrost release more CH$_4$ or CO$_2$?

Can permafrost release of CO$_2$ stimulate plant and tree growth which then offsets total carbon release?

Does permafrost melting happen from the top down or in abrupt or random ways?

Consequences of permafrost melting during a previous warming episode

A recent study of permafrost melting during the last deglaciation (8000 - 18,000 years ago) may hold some good news. During this period, global temperatures rose by 4 °C.

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99 Old carbon reservoirs were not important in the deglaciation methane budget, M. N. Dyonisius et al., Science, 21 Feb 2020: 367, pp. 907-910: https://science.sciencemag.org/content/367/6480/907

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During this past temperature rise (greater than the likely global temperature during the remainder of our century), methane emissions from old cold-region carbon, such as permafrost and methyl hydrates, were minor. The authors examined the isotopic carbon composition of air bubbles trapped in Antarctic ice and found that the consequent global warming was small. The authors hypothesize that any CH$_4$ or CO$_2$ released in permafrost melting may have been used instead to stimulate plant growth during the glaciation. Consequently, the net carbon emissions were much smaller than expected during the early Holocene.

The authors argue that methane emissions due to permafrost melting during this century may be smaller than what others suggest.

4.9 The Take-Away: Is the Planet Warming?

Substantial evidence exists for global warming over the past 130 years. The evidence includes direct measurements of air, land, and ocean temperatures, the loss of mountain glacier ice mass, the retreat in the extent of the great majority of mountain glaciers, the diminution of both the Greenland and Antarctica land ice sheets, the net loss of polar sea ice, and the currently accelerating sea-level rise due to the melting of both glacier and polar land ice and the thermal expansion of ocean water. The fact that the sea-level rise expected from warming ocean temperatures and the melted glacier and polar ice runoff matches very nearly the rise directly measured from tidal gauges and satellite altimetry lends credence to our overall understanding of the overall consequences of global warming.

Loss of biodiversity and the rising frequency of extreme weather also appear to confirm the existence of global warming. However, the connections between biodiversity or extreme weather and climate change are somewhat less direct and more complicated (and in need of much more data and better modeling). Nevertheless, the consequences of increased planetary warming for species extinction and extreme weather could well be dire unless we take the rise of GHG emissions seriously.
Chapter 5

Are Humans Responsible for Global Warming?

The main claims presented so far in this work are virtually unimpeachable. Chapter 2 presented the incontrovertible evidence that a greenhouse effect (due primarily to water, carbon dioxide, and methane in the atmosphere) warms Earth by roughly 40°C over the temperature that would be expected by direct solar heating alone. Chapter 2 also presented the well-documented evidence that abundance of atmospheric carbon dioxide has increased continuously since the mid-1850’s. Chapter 3 presented various lines of evidence that the mean global temperature of Earth has increased over the past century by roughly 0.6°C.

This intent of this chapter is to shed light on two questions: (1) Is the rising CO₂ abundance (and of other GHGs) the proximate cause of the global temperature rise? and, if so, (2) Are human activities responsible for the observed increase in atmospheric GHGs?

GWDs/GWSs will often point to some natural variability in Earth’s internal processes or to secular changes in solar irradiation as alternative causes of terrestrial surface heating. After all, Earth has experienced significant temperature changes in the past without significant human contribution. And our Sun is clearly variable, both in appearance (e.g., sunspots, flares, and prominences over hundreds or thousands of years), and in luminosity. The variance in luminosity is much smaller in amplitude than the variance in appearance, and has been detected only with satellites over the past several decades. The variations in luminosity are different in different parts of the electromagnetic spectrum: infrared, visible, and ultraviolet. So we will also examine evidence for terrestrial and/or solar causes for climate change.

In order to answer the two overarching questions above, we address several more specific questions. First, are CO₂ concentrations and global temperatures correlated? And if so,
how do we know that the recent rise in global temperatures is not the cause of
the recent rise of atmospheric CO$_2$, rather than vice versa? Can the issue be
settled by looking at the records of the past to see if global temperature changes
lag CO$_2$ concentration changes rather than lead them?

Second, what about the most extreme climate change that Earth has experienced
in the recent past without apparent human intervention? Can we pin down the
cause(s) for the rise and fall of the ice ages? Is there any connection of ice ages
to GHGs? Are there any other lessons to be learned from understanding the
cause(s) of the ice ages?

5.1 Are global temperatures correlated with atmospheric CO$_2$ levels?: the recent ice-age record

To begin the discussion, we start with one tantalizing set of data. Over the
past half million years, Earth has experienced a number of ice ages separated by
warmer periods (called interglacial periods). Figure 5.1 shows both temperature
changes (determined via an oxygen-isotope proxy) and CO$_2$ concentrations (from
ice-core measurements) as a function of time.

Figure 5.1: Variations in the atmospheric concentration of CO$_2$ (in parts per
million by volume) shown in dark blue and mean global temperatures shown in
light blue. (NOAA public domain)

1www.ncdc.noaa.gov/paleo/globalwarming/temperature-change.html
5.1.1 A strong correlation exists between temperature and CO₂ concentration

There are a number of noticeable features in Figure 5.1. The main one that stands out is the very tight correlation between temperature and CO₂ concentration. They rise and fall in a similar fashion. We can use the scales on the axes of the graph to quantify the relative changes in temperature and CO₂ concentration: for every 10° C change in the temperature, there is an equivalent change of 80 ppm (parts per million) in the CO₂ concentration.

5.1.2 Is the increasing CO₂ abundance the cause (or effect) of global warming?

In order to make a convincing case for CO₂-caused global warming, the CO₂ abundance changes must lead (rather than lag) global temperature changes. What does the historical evidence show? We’ll return to this important question of which variable leads the other in section 5.3 below.

5.1.3 Earth’s temperature changes and global ice cover in the recent past seem to have been periodic

A second feature of Figure 5.1 to note is the apparent periodicity in the data. Both the minimum temperatures (which correspond to glacial periods) and the maximum temperatures (which correspond to the warm interglacial periods) have a period of about 100,000 years plus or minus 20,000 years.

Although the correlation between global temperatures and CO₂ abundance changes in Figure 5.1 is striking, our present understanding of the periodic rise and fall of the ice ages is related to cyclic changes in parameters related to Earth’s orbit as we will discuss shortly.

It may be that the effects of CO₂ abundance changes and orbital changes are entangled, perhaps even with additional factors. The path forward is not particularly clear.

But I have chosen to first explore the topic that we know most about: the origin of the most dramatic temperature changes the planet has experienced: the quasiperiodic rise and fall of the ice ages. Perhaps we can glean some useful information that will help us answer the questions of whether GHGs have any involvement in the cyclic ice ages and whether or not such temperature changes

²Although popularly called ‘ice ages,’ these periods of low temperatures and advancing glaciers should more properly be termed ‘glacial periods.’
lead or lag CO₂ concentrations.

5.2 The ice ages and their causes

5.2.1 A history of ice-age hypotheses

The first suggestion that significantly more glaciation existed at cyclic intervals in Earth’s past was made by Louis Aggasiz (1840), who correctly deduced that (1) the polishing and scratching of rock surfaces and (2) the deposition of sand, rock, and even large boulders could be explained by the advance and retreat of large ice sheets or glaciers.

Although other scientists had previously suggested astronomical hypotheses for the origin of this glacial periodicity, Milutin Milankovic (1941) was first to surmise that glaciation eras got their start when four variations in Earth’s orbital parameters conspired to significantly change the amount of sunlight received at high northern latitudes during summer.

Milankovic’s calculations suggested that a reduced solar insolation in summer allowed a greater amount of the ice that formed during the previous winter to survive. Year by year, during these periods of reduced solar energy, the ice slowly grew into large sheets that covered significant portions of the planet. The opposite, ice-sheet collapse, would occur when these same orbital parameters worked together to produce many years of high solar insolation at these same northern latitudes.

The observations that convinced the scientific community that Earth’s ice ages were rooted in variations of its orbital parameters were published in 1976.

5.2.2 Orbital variations that affect solar insolation

Milankovic suggested that the following four periodic variations in the Earth’s orbit could be collectively responsible for the rise and fall of glacial epochs:

1) A variation in the shape (or eccentricity) of Earth’s orbit (Figure 5.2) Such a variation would not change the average Earth-Sun distance over the course of a year, but during eras of high orbit eccentricity, Earth would be closer to the Sun at its nearest point and farther from the Sun at its most distant during the year. The eccentricity \(^3\) varies from 0.003 - 0.06 over a period of about

\(^3\)Each of these orbital variations is caused by the gravitational interaction of Earth with other objects in the solar system.

\(^4\)A perfect circle has an eccentricity of 0.0; as eccentricity approaches 1, the ellipse shape becomes more and more elongated. An ellipse with eccentricity 0.06 would be visually difficult
100,000 years.

The present value of Earth’s orbital eccentricity is 0.017, which means that the nearest and farthest Earth-Sun distances during the year are 1.7% smaller and larger than the mean distances. In turn, the amount of sunlight Earth receives would be 3.4% larger and smaller, respectively, at those extremes. Although variations in Earth-Sun distance are not the cause of the seasons a smaller orbit eccentricity might cause more extreme seasons in the Northern Hemisphere (hotter summers and colder winters) but less extreme seasons in the Southern Hemisphere.

Figure 5.2: The shape of Earth’s nearly circular orbit varies slightly in shape over a period of 100,000 years. Consequently the smallest and largest Earth-Sun distances over the course of a year vary slightly. (Contributed by C. Law, public domain)

2) **A variation in the obliquity of Earth’s rotation axis (currently 23.4°)**

This is a fancy way of saying that the angle between the plane of Earth’s equator and the plane of Earth’s orbit around the Sun varies periodically (Figure 5.3). This variation causes the Northern Hemisphere (or the northern end of Earth’s rotation axis) to tilt sometimes more than its average value of 23.0° and sometimes less. A larger value of the obliquity results in more extreme seasons in both hemispheres. The amplitude of this axial-tilt variation is approximately 1.0°; the period is 41,000 years.

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5the Northern Hemisphere has just started summer on July 5, when Earth is farthest from the Sun; Earth is closest to the Sun on January 4
The current obliquity of 23.4° is the main cause of Earth’s seasons. When the northern end of Earth’s rotation axis is tilted toward the sun, the Northern Hemisphere begins its summer, whereas, simultaneously, the south end of the rotation axis points away from the sun, which causes the Southern Hemisphere to experience its winter.

3) **A variation in the direction of Earth’s rotation axis, the precession of the equinoxes** Over the course of the precession period (23,500 years), the average obliquity angle remains approximately 23.4° (subject to the slight variation described in (2) above), but the axis undergoes a conical motion shown in
Figure 5.4 We can understand this motion by comparing the spinning Earth with a spinning top. The spinning of the top corresponds to Earth’s rotation. However, the axis of the top can wander around in direction (and becomes especially large as the top slows down) as it spins. This type of precession will also result in a change in direction of the ‘North Star’ (as the direction of the rotation axis changes) by an angle of $47^\circ$ over nearly 12,000 years (half of the precession period).

4) A variation in the orientation of the long axis of Earth’s orbit Unfortunately, this motion is also sometimes called a precession. However, we will use its alternate, fancier name: 'the advance of the perihelion’ to forestall any
confusion between it and the previously-described precession.

The period of Earth’s perihelion advance is 19,000 years.

The mathematics of combining cyclic events effects of different periods is straightforward. First-year physics students encounter one of the simplest, the phenomenon of beats, when two pure musical tones of the same amplitude but slightly different period are added together. The varying sound amplitude created by the constructive and destructive interference of the sound waves in audible and quite easy to demonstrate. In principle, the mathematical combination of four different cycles, each of different period and amplitude, should be straightforward, although the results would not be as simple and symmetrical as the case of musical beats.

It would be empowering to announce that, during the 75 years since Milankovic’s suggestion, the calculated solar-insolation effects have been combined, paleoclimatologists have found a similarly-varying record in sediment and ice cores, and that science has identified the evidence for the likely mechanism(s) by which ice ages begin and end. It would also be untrue. But ... perhaps a smoking gun has been found.

In 1976, Hays, Imbrie, and Shackleton presented evidence from marine sediment cores in the southern Indian Ocean. Imbrie’s statistical analysis of Hays’s radiolaria counts and Shackleton’s measurements of the oxygen-isotope ratio in foraminifera (remember that this ratio is a climate proxy for both global ice volume and surface temperatures; see Section 4.1.5) found periodicities in the data of 42,000, 23,500, and 19,000 years. These periods match, nearly exactly, the periods of the Earth’s orbital variations 2, 3, and 4 described above.

In addition, the authors found that the dominant periodicity in their data was approximately 100,000 years, a match for the period of Earth’s eccentricity cycle (variation 1 described above). Calculated solar insolation (based on the four orbital effects and paleoclimatic data) is shown in Figure 5.5. (See also\textsuperscript{6} ) 'Smoking gun', yes?

Figure 5.5: Shown are the Milankovitch cycles, both past and predicted into the future. The top (blue) graph shows axial tilt (obliquity $\epsilon$, the green curve is eccentricity ($e$), the purple curve is longitude of perihelion ($\sin(\omega)$), the red curve is precession index ($e \sin(\omega)$), the black curve is the daily average insolation at the top of the atmosphere on the summer solstice ($Q_{\text{top}}^{\text{day}}$), followed by benthic forams and Vostok ice cores at the bottom. The vertical gray line indicates the present day. (Source, CC BY 3.0)

But data coincidences are no substitute for scientifically-linked, cause-and-effect mechanisms. For one thing, the almost negligible effect of the orbital eccentricity on the solar insolation at Earth means that the eccentricity variation could not directly account for the large amplitude of temperature variations present with the 100,000-year period. Moreover, how do small changes in any of the orbital parameters get amplified into large changes in climate? Put differently, how do tiny shifts in solar insolation at the top of our atmosphere drive such drastic
changes in ice volume on Earth’s surface?

Second, if the obliquity effect (41,000-year period) and, in particular, the precession effects (21,000-year average period) produce such large changes in solar insolation - the variation in which would appear to be the primary cause of the Ice Ages - why is the dominant period in the climatic data currently 100,000 years? Is this period a multiple of the smaller periods of the other orbital variations?

Third, how is the gradual changeover in the period of the calculated solar-insolation periods from 41,000 years to the current 100,000 years from roughly 1.2 Myr ago to 0.8 Myr ago to be explained?

5.2.3 Ice ages: the take-away

Although more than 80 years have passed since Milankovitch’s initial hypothesis - and 40 years since the pioneering measurements of Hays, Imbrie, and Shackleton, much remains to be understood about the specifics of the the orbital regulation of the ice ages. Paleoclimatologists are confident that variations in Earth’s orbital parameters affect glaciation. The evidence is more than circumstantial but less than that needed for a complete understanding of cause.

5.3 Do global temperatures lead or lag atmospheric CO₂ levels?

We now return to the original question: Do temperature variations in the historical ice-age record lead or lag the CO₂ concentration changes? It appears from Figure 5.1 that CO₂ concentration changes lag the temperature changes, which seems contrary to expectations if climate scientists are attributing global warming to CO₂. However, the question of lead or lag is quite nuanced and tied up in the ultimate causes of both temperature and CO₂ changes: the Earth’s orbital changes that we discussed in the previous section.

The current understanding of temperature-CO₂ cause-and-effect relationships at the end of an ice age reveals a complicated picture. The short answer is that the CO₂ concentration initially lags the temperatures rise (which is caused by the orbital effects discussed above). However, the initial temperature rise triggers an atmospheric CO₂ increase (due to its decreased ocean solubility) that in turn amplifies and broadens the original temperature rise.
Because this issue of lag-lead is often raised by global-warming skeptics as clear evidence against present-day CO$_2$-triggered warming, we consider the issue in some detail. But, first, a reminder about what follows. The evidence to be discussed applies to the temperature rise associated with an interglacial period following a glacial period (or ice age). (A reverse argument presumably applies at the start of an ice age, but is not considered here). The evidence and the understanding that follow are based on recent research by Shakun et al.

The subtle interplay of ice, temperature, and CO$_2$

Let’s look at a key piece of their detailed data first (Figure 5.6). It is clear from Figure 5.6 that temperature lags the CO$_2$ concentration once a large temperature increase sets in (at about 18 kyr ago). During the initial onset of the temperature rise, the temperature, CO$_2$ concentration, and ice data are indistinguishable.

![Temperature and CO$_2$ over the last deglaciation](source)

Figure 5.6: The global temperature (green) (measured relative to the mean of the early Holocene, 11.5–6.5 kyr ago), an Antarctic ice-core composite temperature record (red), and atmospheric CO$_2$ concentration (blue dots). (Source, permission granted by J. Shakun for non-commercial use)

So what’s going on? Shakun et al.

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7Shakun et al., Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation: Nature 484, pp. 49–54 (05 April 2012)

8Shakun et al., ibid., Not all of Shakun et al.’s data that bear on their interglacial heating scenario is presented here. Refer to their article in Nature for details

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start of an interglacial period unfold in the following order:

(1) Changes in Earth’s orbital parameters (see the ‘cause of the ice ages’ section above) conspire to start a warming trend in the northern hemisphere (particularly in Greenland and the rest of the Arctic). [19 kyr ago]

(2) This warming melts ice and floods the oceans with a large supply of fresh water.

(3) This fresh water injection reverses the hemispheric heating trends. Southern hemisphere oceans now warm [18 kyr ago]

(4) Southern hemisphere oceans release CO$_2$ as higher temperatures decrease CO$_2$ concentration in water. [17.5 kyr ago]

(5) This dramatic rise in CO$_2$ concentration in turn triggers a similar rise in temperatures. Shakun et al estimate that 7% of the interglacial warming occurs before the CO$_2$ rise, whereas 93% occurs after the CO$_2$ concentration rises. [17 kyr]

The interplay between ice, global temperature, and CO$_2$ concentration is clearly a subtle one. And unfortunately it does not lend itself to a simple and short explanation in a world of television sound bites and short newspaper or magazine articles.

5.3.1 Global mean surface temperatures and atmospheric CO$_2$ concentrations: the take-away

Global mean surface temperatures and atmospheric CO$_2$ concentrations are strongly correlated over the past half-million years. Detailed investigation of the start of interglacial warming period indicates that a small temperature increase (triggered externally, presumably by Earth orbital changes) happens first. This in turn triggers a sharp increase in the CO$_2$ concentration which drastically amplifies the original temperature increase.

What implications does this study have for today? The global temperature increase over the past 100 - 150 years was not triggered by orbital effects (which operate on a significantly larger time scale), but rather by the increase in CO$_2$ concentration due to the onset of increased fossil-fuel use starting in the Industrial Age. However, the lesson of post-ice-age global warming is that even a small temperature increase can drive a dramatic rise in CO$_2$ concentration which, in turn, can amplify greatly the initial warming. This temperature amplification is what most climate scientists are concerned about in the near future.
5.4 Is human activity the cause of increasing CO₂ abundance?

By the end of this section, there are several questions we would like answered. Can the rising CO₂ abundance can be traced to human activities? If the rising CO₂ abundance does not have a direct human cause, then what is the cause? Can we blame it on the Sun? Are geologic processes responsible? Could there be a biological explanation?

To make a convincing argument for human-activity-caused global warming, we will certainly need to find evidence for a correlation between the carbon humans add to the atmosphere and the rise in CO₂ concentration. But the mere presence of a correlation is not necessarily evidence of causation. How do we prove causation? It would be best if the science available could make a predication about some facet of the rising CO₂ concentration that would point the way to one certain cause (whether it be humans’ activity, solar, geologic, biological, or whatever) and, simultaneously, away from each of the others. Of course, if such strong evidence were to exist and be agreed upon, then there would be little need for this work.

5.4.1 The fossil-fuel use and atmospheric-CO₂ connection

Global-warming supporters basic claim is that the rise in the atmospheric CO₂ abundance since the mid-1800’s (Figure 3.7) is the natural consequence of the post-industrial age. In particular, the rise is due to the burning of fossil fuels to meet the energy needs of an increasingly mechanized society. A secondary reason for the rise is the clearing of large forest areas (forests are CO₂ sinks due to the use of CO₂ in photosynthesis) for agricultural purposes.
Figure 5.7: Atmospheric CO\textsubscript{2} concentration (thick black line) and prorated cumulative emissions from fossil fuel use (thin red line) as a function of time.\footnote{Mauna Loa Seas Adjusted Fossil Fuel Trend: http://scrippsc02.ucsd.edu/graphics_gallery/mauna_loa_record/mauna_loa_seas_adj_fossil_fuel_trend.html} (Scripps CO\textsubscript{2} program, licensed for non-commercial use)

Figure 5.7 shows the same rise in the atmospheric CO\textsubscript{2} abundance as shown in Figure 3.7, but now also with the cumulative emissions from fossil-fuel use reduced by fixed percentage. The correlation between these two quantities is stunning. But we need to remind ourselves that correlation is not causation.

### 5.4.2 The evidence of \textsuperscript{13}C

For evidence supporting the claim that the rising atmospheric CO\textsubscript{2} abundance is due to human-driven fossil-fuel burning, climate scientists point to recent changes in the relative amounts of two different isotopes of carbon, carbon-12 (\textsuperscript{12}C) and carbon-13 (\textsuperscript{13}C). Both isotopes exist in nature, and \textsuperscript{12}C version is typically 100 times more abundant than the \textsuperscript{13}C isotope (see section 4.1.4). Rather than quoting directly the relative abundance of these isotopes (i.e., $\frac{\text{\textsuperscript{13}C}}{\text{\textsuperscript{12}C}}$ ratio), scientists unfortunately use a slightly different quantity, $\delta^{13}C$, in their publications. The
relationship between these two quantities is given in equation (5.1).

\[
\delta^{13}C \equiv 1000\% \left[ \frac{\left(\frac{^{13}C}{^{12}C}\right)_{\text{sample}}}{\left(\frac{^{13}C}{^{12}C}\right)_{\text{standard}}} - 1 \right]
\]  

(5.1)

The quantity \(\left(\frac{^{13}C}{^{12}C}\right)_{\text{sample}}\) represents the relative isotope abundances for the sample being measured. The quantity \(\left(\frac{^{13}C}{^{12}C}\right)_{\text{standard}}\) represents the relative isotope abundances for the ‘reference standard’ against which all measured samples are compared.

Table 5.1\(^{11}\) shows current average \(\delta^{13}C\) values\(^{12}\) and the corresponding \(\frac{^{13}C}{^{12}C}\) values present in a variety of carbon-containing materials found on Earth. Note that current \(\delta^{13}C\) values are all negative, which simply indicates that the isotopic ratios in each of these carbon-containing materials are less than the equivalent ratio in the reference standard. Unfortunately, the values of \(\delta^{13}C\) and \(\frac{^{13}C}{^{12}C}\) of a given sample are not linearly related. Fortunately, however, a decrease in \(\delta^{13}C\) is equivalent to a decrease in \(\frac{^{13}C}{^{12}C}\) in the sample.

<table>
<thead>
<tr>
<th>Material</th>
<th>(\delta^{13}C)</th>
<th>(\frac{^{13}C}{^{12}C})</th>
</tr>
</thead>
<tbody>
<tr>
<td>atmosphere</td>
<td>- 8 %</td>
<td>0.992</td>
</tr>
<tr>
<td>land plants (C3 metabolism)</td>
<td>-28 %</td>
<td>0.972</td>
</tr>
<tr>
<td>land plants (C4 metabolism)</td>
<td>-22 %</td>
<td>0.978</td>
</tr>
<tr>
<td>land plants (CEM metabolism)</td>
<td>-16 %</td>
<td>0.984</td>
</tr>
<tr>
<td>coal</td>
<td>-25 %</td>
<td>0.975</td>
</tr>
<tr>
<td>oil &amp; petroleum deposits</td>
<td>-30 %</td>
<td>0.970</td>
</tr>
<tr>
<td>ocean water</td>
<td>- 7 %</td>
<td>0.993</td>
</tr>
<tr>
<td>algae</td>
<td>-15 %</td>
<td>0.985</td>
</tr>
</tbody>
</table>

\(^{10}\)The ‘standard’ is that found in Bellemite, a fossilized limestone skeleton from the Cretaceous Period.

\(^{11}\)Data from Park and Epstein, Plant Physiology, March 1961, 36, No. 2, (1961)

\(^{12}\)Values of \(\delta^{13}C\) have fairly large ranges, from about 10% to 50% of the average values, depending on the geographical location of the sample. The ranges in the associated \(\frac{^{13}C}{^{12}C}\) values, however, are less than 2%.
The data in Table 5.1 shows that live plants (which actively take in CO$_2$ from the atmosphere via photosynthesis) and their dead by-products (e.g., coal and oil) produce a lower value of the $\delta^{13}C/\delta^{12}C$ ratio in their biomass than that present in the atmosphere from which they draw their carbon.

---

Figure 5.8: The $\delta^{13}C$ values present in the atmosphere (reconstructed from ice core samples) and both shallow and deep water as a function of time. Also plotted is the concentration of atmospheric CO$_2$ abundance. (Fig. 4 of Böhm et al. Geochemistry Geophysics Geosystems 3 (2002) 1-13, licensed for non-commercial use)

Let’s now look at the behavior of $\delta^{13}C$ atmospheric ratio since the onset of rising CO$_2$ abundance in the 1850’s. Figure 5.8 shows the decrease in atmospheric $\delta^{13}C$ (and therefore in the $\delta^{13}C/\delta^{12}C$ ratio) since the mid-1800’s. The data is extracted from ice cores in the manner described in section 4.1.1. Note that the drop in $\delta^{13}C$ tracks very well the atmospheric abundance which is also plotted in the same figure. Figure 5.9 shows similar data from atmospheric samples measured at Mauna Loa and the South Pole since 1980. Figure 5.10 shows a similar data

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18Figure 4 of Evidence for preindustrial variations in the marine surface water carbonate system from coralline sponges, Böhm et al. Geochemistry, Geophysics, Geosystems 3 (2002) 1-13, (March 2002)

19Isotopic data at Mauna Loa and the South Pole: https://scrippsco2.ucsd.edu/graphics_gallery/isotopic_data/mauna_loa_and_south_pole_isotopic_c13_ratio.html

for sea coralline sponges formed at various times. Similar data have been measured in sea coral in the Great Barrier Reef since 1800, see\textsuperscript{16}

Figure 5.9: The drop in $\delta^{13}C$ (and therefore in the $^{13}C/^{12}C$ ratio) measured in the atmosphere at Mauna Loa, Hawaii (black dots, fit by black curve) and at the South Pole, Antartica (red dots, fit by red curve) since 1980. (Scripps CO\textsubscript{2} Program, licensed for non-commercial use)

\textsuperscript{16}Wei et al: Geochimica et Cosmochimica Acta, vol. 73, issue 8, 15 April 2009, p. 2332
Table 5.1 suggests that the burning of fossil fuels (coal and oil products, which have a relatively low $^{13}C/^{12}C$ ratio) adds carbon dioxide (with that same relatively low $^{13}C/^{12}C$ ratio) to our current atmosphere that has a relatively high value of the $^{13}C/^{12}C$ ratio. Consequently, the overall $^{13}C/^{12}C$ ratio in the atmosphere ought to fall as more and more fossil fuels are burned. And this is exactly what is documented by the data in Figures 5.8, 5.9, and 5.10. Figures 5.8 and 5.10 in particular suggest that the drop in the atmospheric $^{13}C/^{12}C$ ratio begins at exactly the same time that the CO$_2$ concentration begins to rise due to industrial expansion.
Does the carbon-isotope-ratio evidence just presented nail the case shut in favor of human-driven rise (via fossil-fuel burning) in the atmospheric CO$_2$ abundance? Not quite, but it makes the case far more convincing than mere speculation. Although we have no evidence of any other mechanism that produces both an increase in the atmospheric CO$_2$ abundance and a decrease in the $\left(\frac{^{13}C}{^{12}C}\right)$ ratio in atmosphere CO$_2$, absence of evidence is not necessarily evidence of absence of an alternative method.

To understand why the arguments above are not nail-in-the-coffin evidence of human-driven global warming, suppose, for the sake of argument, that the rising atmospheric CO$_2$ abundance were due to some natural process, say, emission of CO$_2$ produced by some chemical reactions occurring in the oceans. Perhaps this imaginary CO$_2$ oceanic emission were due to CO$_2$ somehow leaking out of the limestone (present in fossilized marine shells) in oceanic deposits. Let me emphasize again that I am making this up for purposes of discussion. We have no evidence whatsoever that leakage of CO$_2$ from oceanic limestone is actually occurring. If these shells’ limestone were of recent formation, it would contain carbon isotopes in the same ratio as that present in Table 5.1 and which, in turn, is smaller than the isotopic ratio in the current atmosphere. Consequently, the continuous addition of the limestone-emitting CO$_2$ would also result in a decreasing $^{13}C/^{12}C$ ratio in the atmosphere with time.

The point here is that any present-day leakage of CO$_2$ into the atmosphere from plant (or animal) life that previously took in atmospheric CO$_2$ and incorporated it into its biomass (by some process that reduces the $^{13}C/^{12}C$ ratio relative to that of the atmosphere) could mimic the decrease in the atmospheric $^{13}C/^{12}C$ ratio that we currently attribute to fossil-fuel burning. But it should be emphasized again that we know of no such other process.

5.4.3 The evidence of $^{14}C$

Additional evidence that the rising CO$_2$ abundance is driven by fossil-fuel burning comes from another isotope of carbon, carbon-14 ($^{14}C$) that was previously discussed in section 4.1.1. Unlike $^{12}C$ and $^{13}C$, $^{14}C$ is not stable. $^{14}C$ is a radioactive isotope, and it decays (by emitting an electron and an antineutrino) with a half-life of 5730 years. However, $^{14}C$ does exist in low concentration in the atmosphere (along with living plants and animals). It is produced when nitrogen atoms in the atmosphere are struck by cosmic-ray electrons and converted to $^{14}C$. Plants that ingest $^{14}CO_2$ during photosynthesis – along with animals that then eat the plants – acquire the same $^{14}C/^{12}C$ abundance ratio as the atmosphere.

\[\text{the } \frac{^{14}C}{^{12}C} \text{ abundance ratio } \approx 10^{-12} \text{ in the atmosphere and living systems}\]
However, once a plant (or animal) dies, it stops ingesting $^{14}$C, and radioactive decay causes the $^{14}\text{C}/^{12}\text{C}$ ratio to fall exponentially thereafter. After approximately 35,000 years (6 half-lives) the $^{14}$C abundance will be reduced to a level less than 2 % of that presently in the atmosphere.\footnote{Measuring the $^{14}\text{C}/^{12}\text{C}$ ratio in an object that contains carbon once present in a living organism allows the object to be dated.}

Using an argument similar to that in the previous section, we should be able to make a prediction about how the $^{14}\text{C}/^{12}\text{C}$ ratio should have changed with increased fossil-fuel burning. Fossil fuels (e.g., coal, formed from plants that died long ago) will have a much lower $^{14}\text{C}/^{12}\text{C}$ ratio than that in the present atmosphere. When burned, they will therefore produce $^{14}$CO$_2$ with a lower-than-atmospheric $^{14}\text{C}/^{12}\text{C}$ ratio. As more and more fossil-fuel carbon is added to the atmosphere, the atmospheric $^{14}\text{C}/^{12}\text{C}$ ratio should also decrease.

A figure showing the drop in the fractional change in $^{14}$C abundance\footnote{$\Delta^{14}$C is defined in the same manner as that of $\delta^{13}$C (See equation (5.1).) I am clueless as to why a lower-case delta is used with $^{13}$C, whereas the upper-delta is used with $^{14}$C.} found in trees as a function of time can be found at\footnote{archiv.ub.uni-heidelberg.de/volltextserver/volltexte/2006/6862/pdf/LevinRAD2000.pdf}. Remember that the abundance of $^{14}$C in living trees reflects the $^{14}$C abundance in the atmosphere. As just predicted, $^{14}$C abundance in trees (which reflects atmospheric $^{14}$C abundance) has decreased since the 1850’s, the onset of the Industrial Age. (The use of $\Delta^{14}$C as an indicator of fossil fueling ceases to be useful after 1950 when atmospheric testing of nuclear bombs added significant amounts of $^{14}$C to the atmosphere. Once atmospheric nuclear testing ended in the 1960s, the atmospheric $^{14}\text{C}/^{12}\text{C}$ ratio again began to drop.)

\subsection{5.4.4 The Take Away: Is human activity the cause of global warming?}

The substantial observed increase in atmospheric CO$_2$ abundance due to human activity correlates nearly exactly with anthropogenic emissions from combustion and other industrial processes. The increase of both atmospheric CO$_2$ and anthropogenic emissions commenced at exactly the same time, the onset of the Industrial Age.

These changes have also been accompanied by well-correlated decreases in both the $^{13}\text{C}/^{12}\text{C}$ and $^{14}\text{C}/^{12}\text{C}$ ratios in atmospheric CO$_2$. These decreases match those expected if the rise in atmospheric CO$_2$ is caused by the increased burning of $^{13}$C-deficient and $^{14}$C-deficient fossil fuels.
What could be wrong with current climate models that have led to the conclusion that GHG emissions are responsible for the observed rate of global warming? First, our understanding of the effects of increasing CO$_2$ (and other greenhouse gases) on climate would have to be in error. In addition, a mechanism would have to exist that is not included in these climate models. (The two most obvious external factors that arrive on Earth and could produce an influence on Earth are sunlight and cosmic rays. These effects were ruled out in section 5.4.4 and 5.4.5.) But since the models include all known climate-changing processes, this mechanism must presently be unknown to climate science. Finally, this (unknown) mechanism must have produced a warming only since the industrialization age began (and when greenhouse-gas emissions began their rise).

There is certainly some probability that each of the three unlikely conditions mentioned in the previous paragraph is true, but the probability that all three are true does seem remote. It is not surprising that the 2013 IPCC AR5 judges that it is more than 95% probable that “human influence has been the dominant cause of the observed warming since the mid 20th century.”
Appendices

A The Greenhouse Effect in a Greenhouse

How did the greenhouse effect originally get its name? In a greenhouse, visible light passes through the transparent glass (the analogy of Earth’s atmosphere) and (as in the case of a planetary-atmosphere ‘greenhouse’) some visible light is reflected back out through the glass and some is absorbed by the ground, plants, etc. in the interior of the greenhouse. And (again, as in the case of a planetary-atmosphere greenhouse) the warming ground, plants, etc. re-emit any absorbed light back, but in the infrared, which the glass (heavily absorbs). The glass traps this infrared radiation in the same way that the atmospheric greenhouse gases trap the infrared radiation emitted by the planet.

So maybe you have never actually been in a greenhouse. The same effect happens in a car left out in the sun with the windows closed. Even if the car is left out in the sun for an hour, when you return it is almost impossible not to notice that the air inside the car is hotter than the air outside the car. The steering wheel, the dashboard, and other surfaces in the car feel warm, and often uncomfortably hot, to the touch.

So it seems reasonable to think that this inside-the-car air- and surface-warming phenomenon is equivalent to the greenhouse-warming effect for planets, right? As far as I can tell, that question is still open to some debate. There are scientists who consider the logic presented in the two previous paragraphs sound.

But perhaps an equal number of scientists disagree and blame the high temperatures inside greenhouses or inside closed cars on a totally different cause: the closed-ness of the system and the inability of the air to convect with other air outside of the closed system.

To understand this argument, let’s imagine what happens in the same car left in the sun, but with the windows open. As before, the interior surfaces of the car (and to a lesser extent the air inside the car) absorbs sunlight and rises in temperature. The hotter air expands (due to the ideal gas law) and then rises (because it relatively buoyant compared to cooler air). Cooler air sinks. If the windows are open, however, some of the rising air leaves the car, and this air is
replaced by air not originally in the car. This continuous mixing of air inside and outside of the car is further facilitated if there is a horizontal crosswind blowing.

According to this view, the higher temperatures inside a closed car are simply due to the continual heating of both air and solid surfaces, without the chance to exchange that thermal energy with a cooler system. (The most likely possibility for thermal exchange with air exterior to the closed car is through the car’s windows, which are a relatively good insulator.

the take-away

The greenhouse effect that heats a greenhouse or a car with closed-windows does not appear to operate in exactly the same manner as a planetary-atmosphere greenhouse. There are two competing mechanisms that attempt to explain why a greenhouse or closed-window car heat up in sunlight. Both mechanisms (the one claiming the high interior car temperatures are due to the infrared radiation produced by the hot interior and trapped inside by the air and the glass and the other claiming that the high temperatures are due to continued direct solar heating but without the possibility of convection with an outside system) can claim support from mathematical models. It is quite likely that both heating mechanisms are operating simultaneously in a greenhouse or car.

B Lies, Damn Lies, and Statistics

B.1 The GWDL claims of a recent global warming 'pause'

One of the most contentious controversies in recent climate change 'political' discussion is about whether or not there has been a recent pause in global warming (which is often confused with a slowdown in the rate of global warming). See section 4.1.4.

"...Earth’s temperature has not budged for 18 years." [21]

"The satellite data demonstrate that there has been no significant warming whatsoever for 17 years." [22]

"There has been essentially no global warming since 1998." [23]

Typically (and as in the cases above), the claims come without reference to or display of any relevant temperature data. Their power seems to lie in their repetition.

It is curious that the GWDL would point to a warming pause for the period 1998 - 2013. The pause in warming (or possibly even a decline in mean temperatures) from the late 1940s through 1970s seems much more apparent in Figures 4.1 - 4.3. However, based on the GWDL claim of a pause only from 2000 - 2012, tt would seem unfair to characterize this group of people as global-warming deniers. (Claiming a pause seems to require an admission that there is a temperature rise to begin with, doesn’t it?)

**Calculation choices**

In performing statistical calculation, I employ an easy-to-use GMST-plotting tool [24] that can access the 3 primary GMST data bases (NASA/GISS, NOAA/NCDC, HadCRUT4).

First, there is the question of which category of temperature trends to look at: ’Land/Ocean’, ’Land’, or ’Satellite’. ’Land/Ocean’ is superior to ’Land/ simply because ’Land’ cover less than 30% of Earth’s surface. ’Land/Ocean’ is superior to ’Satellite’ for two reasons: (1) satellites measure the temperature in the tropopause [25] and (2) satellite observations have only been available since 1979, thereby precluding any study of temperature trends before that time.

Another choice must be made as to which of the databases to use. Although there are differences in methodology and ..... among the databases, they all give approximately the same results. I have chosen to use the (NASA) GISTEMP data. This is the same data that is plotted in Figure 4.2.

**Least-squares fits**

I performed linear least-squares fits to the temperature-vs-time data just described on a TI calculator and checked the results with additional software. A linear least-squares curve fit (a fit that minimizes the sums of the squares of the differences between the actual individual temperature values and the temperature values predicted by the linear fit to the time-temperature data) returns

---


[25] The tropopause is the atmospheric layer in which most weather occurs, and its maximum height ranges from 10 - 18 km above Earth’s surface, depending on latitude. It lies just above the 100-200-km-thick planetary boundary layer, the layer in immediate contact with Earth’s surface and subject to rapid variations in physical conditions. The temperature and moisture level both decrease with height throughout this layer.
several quantities of interest:

\( m, b \) the \textit{slope} and \textit{intercept} of the fit, respectively,

\( \sigma_m, \sigma_b \) the \textit{standard deviation} for each of the these two fit parameters; the standard deviation is the square root of the average of squares of the differences between actual data and fit data described above; the standard deviation is a measurement of the uncertainty of the fit parameter.

\( r \) the \textit{correlation coefficient}; the correlation coefficient is a quantity between 1 and -1, which is a measure of the reliability of the fit; for \( r = \pm 1 \) a complete correlation exists, and the points lie exactly on a straight line; for \( r = 0 \) there is no correlation, and it makes little sense to fit a linear function to the data; for a reasonable correlation, \( r \) should be greater than 0.9.

Interpreting the standard deviation of the fit is a matter of taste. For physicists, using 3 standard deviations is the gold standard, although often 5 standard deviations are often considered necessary for important discoveries. In climate science, however, 2 standard deviations often seems to be the norm.

The standard deviation is related to the likelihood that the most likely value of a fit parameter lies within a certain range, as the table below shows.

<table>
<thead>
<tr>
<th>range of parameter ( (p - \sigma_p, p + \sigma_p) )</th>
<th>probability that parameter lies in the given range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p - 2\sigma_p, p + 2\sigma_p )</td>
<td>95.4%</td>
</tr>
<tr>
<td>( p - 3\sigma_p, p + 3\sigma_p )</td>
<td>99.7%</td>
</tr>
</tbody>
</table>

**Reference periods**

In order to decide whether there has been a warming 'slowdown' or 'pause' in global warming, it might help to have a standard of 'warming'. For reference, we can use the entire period (1880 - 2015) over which GMST data exists to establish a comparison period for looking at recent global warming trends. The rate of global warming for this period is

\[
\frac{\Delta T}{\Delta t} (1880 - 2014) = 0.067 \ (\pm \ 0.007; r = 0.88) \ ^\circ C/\text{decade}
\]  \( (2) \)

The number preceded by the \( \pm \) in parentheses is the standard deviation; it is followed by the correlation coefficient.

However, the temperature-time graphs show a plateau from roughly the late 1930s through the early 1960s. From then, until the present, the rate of temperature rise with time is clearly much higher. (Might this be a consequence of the
economic disruption of World War II? An effect of some other climate forcer? It is curious that this plateau and its possible causes are the subject of so little comment in the global-warming discussion.) So perhaps it is more appropriate to use this more recent time period as a reference baseline. We find

\[
\frac{\Delta T}{\Delta t} (1963 - 2014) = 0.155 \pm 0.024; r = 0.93 \text{ } ^\circ C/\text{decade}
\] (3)

which represents a rate of temperature rise with time that is more than 2x that for the 1880 - 2015 period (along with a significantly higher uncertainty).

B.2 A Recent 'Slowdown' or 'Pause'?  

Let’s go back to the claims made at the top of this appendix. Did you notice what the three quotes above have in common? Each quote claims, in slightly different language, (1) that there has been no temperature rise during a certain time period, and (2) that time period seems to begin around 1998.

Why 1998? If you look at the temperature data in any of Figures 4.1 - 4.3. 1998 stands out as an anomalously warm year. It was certainly the hottest year on record at that time, and there is some probability (due to uncertainties in the measurements) that it has been the hottest year in temperature-recorded history (although 2014 has a more likely claim for that honor\textsuperscript{26}. Clearly, selecting high-temperature year of 1998 to be the start of our time interval will prejudice the result in favor of a small rate of global warming.

But let’s go with claimants’ best shot. The result is

\[
\frac{\Delta T}{\Delta t} (1998 - 2014) = 0.084 \pm 0.038; r = 0.51 \text{ } ^\circ C/\text{decade}
\] (4)

Even for this supposedly best-case (for the GWDL) scenario, it is fair to say that (1) the rate of warming is, in fact, greater than the average over the last 135 years (although with greater uncertainty; also note the very low value of the correlation coefficient), (2) the rate of warming has not paused. A pause \((\frac{\Delta T}{\Delta t} = 0)\) is more than 2\sigma removed from the rate of temperature rise given by the least-squares fit, which means the probability that there is no warming for this period is less than 2.5%, less than 1 in 40.

**Temperature trends depend on the time period selected**

It should be apparent in advance (from the two calculated rates of warming in the past section) that the rate of warming is likely to depend crucially on the

\textsuperscript{26}NASA/NOAA Annual Global Analysis for 2014, slide 5 of http://www.ncdc.noaa.gov/sotc/briefings/201501.pdf
time range selected. What if the time interval is changed to begin with the year on either side of 1998? The results are

\[
\frac{\Delta T}{\Delta t} \quad (1997 - 2014) = 0.090 \ (\pm 0.032; \ r = 0.57) \ ^\circ C/\text{decade} \quad (5)
\]

and

\[
\frac{\Delta T}{\Delta t} \quad (1999 - 2014) = 0.110 \ (\pm 0.031; \ r = 0.63) \ ^\circ C/\text{decade} \quad (6)
\]

Not surprisingly, these results are even less supportive of the claim that global warming has paused. The likelihood that there is a pause in global warming, based on these two time intervals, is less than 1%. And keep in mind the relatively large values of the correlation coefficients and the relative standard deviations in each of the last three least-squares fits.

On the other hand, it would be fair to say that there has been a slowdown in the rate of global warming during this time period (circa 1998 - 2014), relative to the rate of warming in the past half-century. But also note two other points: (1) the warming rate over the past 18 years is nevertheless higher than the average warming rate since the onset of the industrial age, and (2) the warming rate over the past 18 years is within 2 standard deviations of the rate over the past 50 years (and, therefore, that there is roughly a 10% probability that there has been no slowdown at all in the rate of global warming during this time period).

B.3 When does weather become climate?: How long is ‘long enough’?

It should also be clear from an examination of the time-temperature data (or any data) that reducing the time interval sampled can easily produce a warming rate that is approximately zero or even negative. Consider the interval beginning in 2003,

\[
\frac{\Delta T}{\Delta t} \quad (2003 - 2014) = 0.044 \ (\pm 0.048; \ r = 0.28) \ ^\circ C/\text{decade} \quad (7)
\]

It can certainly be claimed that the rate of warming for this interval is essentially zero (or, perhaps more appropriately, that there is no discernible trend in the data). But now a question arises as to whether we have narrowed the range of sampling to such a small interval that the effects of short-term weather have overwhelmed the effects of long-term climate. Unfortunately, there is no definitive answer to whether a sampling time period is ‘long enough’.
B.4 the take-away

The claim that global warming has paused since 1998 is unsupportable; the data shows that the existence of a global-warming pause is extremely unlikely (less than 1%).

It can be fairly claimed that there has been a slowdown in the rate of global warming since 1998 compared to that during the past half-century (although not compared to that during the overall period since the onset of the Industrial Age).

Although the data do support the possibility of a global-warming pause over the past 10 years, this time period is also so small that short-term weather variations may temporarily be hiding the long-term pattern. Clearly we will have a much better perspective on what happened during this period in another ten years.

C Radioactive Dating

Radioactive dating is a technique for establishing the age of a material that relies on the physics of radioactive decay of certain nuclei. Which nucleus is selected for use in the age measurement is dependent, among other things, on the estimated age of the object and whether the object was at some point alive. Each radioactive dating method has its own particular idiosyncracies.

The most familiar radioactive isotope used for dating purposes for the general reader is most likely carbon-14 \(^{14}_{6}C\). Consequently, we will describe the details of the \(^{14}_{6}C\) dating process.

C.1 The \(^{14}_{6}C\) decay process

The \(^{14}_{6}C\) nucleus decays according via the following process:

\[
^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e + ^{0}_{0}\nu
\]  

The symbols \(C\), \(N\), \(e\), and \(\nu\) stand for carbon, nitrogen, electron, and antineutrino\(^{27}\), respectively. The subscript preceding each symbol represents the electric charge on the particle. The superscript preceding the symbol represents the 'baryon number'\(^{28}\) of the particle. Both electric charge and baryon number have

\(^{27}\)The antineutrino is an electrically uncharged lepton. Its presence in the decay is necessary to preserve a third conserved quantity, the weak nuclear charge. It also carries away some of the energy and momentum of the decaying nucleus.

\(^{28}\)The baryon number is not particularly easy to define in layman terms. For our purposes here, it is sufficient to say that protons and neutrons are the only common baryons that are encountered in everyday experience. Each proton and each neutron have a baryon number of
the virtue of being conserved in any radioactive decay (or any other physical process, for that matter).

C.2 The radioactive decay equation

Given an ensemble of radioactive nuclei, one cannot predict which particular nuclei will decay after a certain amount of time passes. However, each radioactive nucleus is characterized by a 'half-life' which gives the time period over which half of the nuclear ensemble will decay. The half-life of $^{14}{_6}C$ is approximately 5700 years. In other words, if one started with a sample of $^{14}{_6}C$ nuclei today, half of these nuclei would remain after 5700 years (with the other half having decayed to $^{14}{_7}N$, along with electrons and antineutrinos). Similarly, after another 5700 years (now 11,400 years from the start), half of the half that remained after the first 5700 years are now left; i.e., only $\frac{1}{4}$ of the original $^{14}{_6}C$ sample are still $^{14}{_6}C$ after 11,400 years.

An equation can be developed to predict the fraction of a radioactive sample remaining after a time $t$ after the clock starts (at time = 0):

$$\frac{N(t)}{N(0)} = 2^{-\frac{t}{T}}$$  \hspace{1cm} (9)

where $N(t)$ represents the number of nuclei at time $t$ and $T$ is the half life. Note that the equation correctly predicts that the fraction of an initial sample that remains [$\frac{N(t)}{N(0)}$] after a times $t = T$, $2T$, $3T$, ... is $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, ... as described in the paragraph previous to equation (2).

Mathematicians generally prefer to use an equivalent equation with base $e$ rather than base 2. So you will more likely encounter equation (2) in the form of

$$\frac{N(t)}{N(0)} = e^{-0.693\frac{t}{T}}$$  \hspace{1cm} (10)

C.3 Details of and assumptions behind the $^{14}{_6}C$ process

A number of assumptions are implicit in the working of this method:

(1) The carbon-14 dating method works only on an object that was once living (plant or animal), but, at some point, ceased living and died. The age obtained

Abstract: The carbon-14 dating method is a radiometric dating method that relies on the decay of $^{14}{_6}C$ nuclei. It is used to determine the age of organic materials up to about 50,000 years old. The method is based on the principle that all living organisms absorb carbon-14 from the atmosphere, and once they die, the carbon-14 begins to decay at a known rate. By measuring the ratio of carbon-14 to carbon-12 in a sample, scientists can determine the age of the sample.

In the context of carbon-14 dating, the half-life of $^{14}{_6}C$ is approximately 5700 years. This means that after 5700 years, half of the original $^{14}{_6}C$ nuclei will have decayed into $^{14}{_7}N$ and other products, releasing energy in the process. The rate of decay is exponential, and the proportion of remaining $^{14}{_6}C$ nuclei decreases by half with each passing half-life.

There are several assumptions made in the carbon-14 dating method:

1. The carbon-14 dating method is based on the assumption that the decay rate of $^{14}{_6}C$ is constant over time. This is necessary because the stability of the decay rate allows for accurate age estimation. However, slight variations in the decay rate can occur due to changes in solar activity and other factors, which can introduce errors in the dating process.

2. The initial amount of $^{14}{_6}C$ in the sample is assumed to be accurately known. This is because the method depends on comparing the current amount of $^{14}{_6}C$ to the expected amount based on the known decay rate.

3. The environment in which the sample was found must not have significantly altered the proportion of $^{14}{_6}C$ to $^{12}{_6}C$. This is because the presence of additional carbon-12 (from other sources) can cause inaccuracies in the age estimation.

4. The sample must be completely mixed before measurement. This ensures that the sample contains a representative concentration of $^{14}{_6}C$ and avoids potential errors due to non-uniform mixing.

5. The sample must be free from contamination by modern carbon sources. This is important because modern carbon can disrupt the accurate dating of ancient samples.

Despite these assumptions, the carbon-14 dating method remains a reliable and widely used technique for determining the age of organic materials. However, it is important to be aware of the limitations and potential errors associated with the method.
from the radioactive-decay method will be the time since the object died.

Living objects contain $^{14}\text{C}$ because they either ingest $^{14}\text{C}$ (in the form of carbon dioxide) directly via photosynthesis (if a plant) or indirectly via plant-eating (if animal). In other words, the abundance of $^{14}\text{C}$ in living plants or animals is identical to that in the atmosphere because the atmosphere, plants, and animals are all in $^{14}\text{C}$-equilibrium because of real-time plants’ photosynthesis and animals’ plant-eating and digestion.

After the plant or animal expires, the object no longer ingests $^{14}\text{C}$ from the atmosphere (if plant) or from eating (if animal). From then on, the $^{14}\text{C}$ nuclei decay according to equations (2), (3).

(2) The abundance of $^{14}\text{C}$ in Earth’s atmosphere is assumed to have remained constant over time.

$^{14}\text{C}$ in the atmosphere is produced through the interaction of atmospheric nitrogen with incoming cosmic-ray electrons. Clearly, the $^{14}\text{C}$ atmospheric abundance will remain constant with time only if the incoming cosmic-ray electron flux remains constant with time, as was initially assumed. It has recently been realized that the incoming cosmic-ray flux has not been constant over long periods of time. However, scientists have found independent markers of this cosmic-ray flux in ancient trees, particularly bristlecone pines, whose ages can be independently determined from the their tree ring structure. Therefore, corrections can be made as needed to the assumption that the cosmic-ray flux, and thereby the atmospheric $^{14}\text{C}$ abundance, has remained constant with time.

This allows the value of $N(0)$ (equivalent to the $^{14}\text{C}$ abundance in the sample, and equal to the $^{14}\text{C}$ abundance in the atmosphere, when the object died) to be ‘known’. The present ratio of $^{14}\text{C}$ to $^{12}\text{C}$ abundance in the atmosphere is $1.2 \cdot 10^{-12}$.

(3) In practice, the current abundance of $^{14}\text{C}$ in the sample under consideration is not directly measured. Instead, the abundance of $^{14}\text{C}$ is measured relative to the abundance of a different carbon isotope which is not subject to radioactive decay in the same sample. This ‘non-radioactive’ or reference carbon isotope is typically $^{12}\text{C}$.

Because the abundance of $^{12}\text{C}$ in the sample is assumed to remain constant over time (unlike that of decaying $^{14}\text{C}$), or

$$N(C12, t) = N(C12, 0)$$

(11)
Equation (3) applied to $^{14}\text{C}$ becomes

$$\frac{N(C_{14},t)}{N(C_{14},0)} = e^{-0.693\frac{t}{T}}$$  \hspace{1cm} (12)$$

Combining equations (4) and (5) results in

$$\left(\frac{N(C_{14},t)}{N(C_{12},t)}\right) \div \left(\frac{N(C_{14},0)}{N(C_{12},0)}\right) = e^{-0.693\frac{t}{T}}$$  \hspace{1cm} (13)$$

Equation (6) is then inverted to solve for the age of the object (or, equivalently, the time since the object died and stopped ingesting atmospheric $^{14}\text{C}$):

$$t = 1.44 \cdot T \cdot \ln \left(\frac{N(C_{14},t)}{N(C_{14},0)} \div \frac{N(C_{12},t)}{N(C_{12},0)}\right)$$  \hspace{1cm} (14)$$

One can then measure the isotopic ratio in the sample at present, $\frac{N(C_{14},t)}{N(C_{12},t)}$ and then assume an isotopic ratio of $\frac{N(C_{14},0)}{N(C_{12},0)} = 1.2 \cdot 10^{-14}$ (or, alternatively, a slightly different number corrected for variations in the cosmic-ray flux of the past, as described above). These numbers can then be used in equation (7) to determine the present age $t$ of the object under consideration.

(4) The accuracy of the $^{14}\text{C}$ dating method clearly becomes problematic if the object is older than many multiples of the half-life. For example, consider an object is 10 half-lives old. This means that the $^{14}\text{C}$ abundance in the object has been reduced by a factor of $2^{10} \approx 1000$ compared to its value at the object’s death. At some point, the measurement uncertainty in the $^{14}\text{C}$ abundance value becomes a significant fraction of the actual value. At this point, the derived age becomes significantly uncertain and therefore unreliable.

C.4 Other radioactive dating methods

As was expressed above, the choice of radioactive nucleus used for dating is dependent on the age of the sample to be dated. And for reasons just mentioned (having to do with an abundance-degraded sample), it should be clear that the half-life of the radioactive nucleus used should be comparable to the age of the object.

If one wants to date the oldest terrestrial rocks (or meteorites or lunar rocks), that likely have ages of several billions of years, it would be appropriate to use a radioactive nucleus with a half-life of several billions of years. Fortunately,
there are such isotopes [uranium-238 (half-life $\approx 4.5 \cdot 10^9$ years ), thorium (half-life $\approx 1.4 \cdot 10^{10}$ years), or potassium (half-life $\approx 1.3 \cdot 10^9$ years )] that can be found in many such rocks.

As for the case of the $^{14}_6$C dating process, a reference nuclear isotope must be found, in each case, that is relatively uncontaminated by nuclear decay processes (similar to the $^{12}_6$C reference isotope described above). In addition, some method must found to establish the ratio of the abundance of the decay isotope to that of the reference isotope at the time that the nuclear-decay clock starts (i.e., $t = 0$). For the age-dating of terrestrial rocks, the nuclear-decay clock starts at the time of rock solidification (as solidification traps the parent, decay, and reference nuclei in place).

If one wants to date an object of recent origin, for example an expensive fine wine (it should not be a surprise that wine forgery is a thriving industry), one would use an isotope with a half-life of tens or a few hundred years. Here, the heaviest isotope of hydrogen, tritium, fills the bill. It has a half-life of approximately 13 years, and hydrogen, because of its abundance in water, is a significant component of wine.
Notes

a John did not finish (4) and (5).

b John intended for this work to have two components: “The second part of this work would deal with topics that are far more speculative, includ[ing] climatic model predictions for the future, the choices of what types of energy we humans rely on, and public policy choices for reducing the global carbon atmospheric content or living with the consequences.” There some pieces of the latter in the original manuscript (“chapter 6”), but it was incomplete and is not included here.

c John had several paragraphs here with the comment “Why is this here.” Given our own difficulty following its purpose, we have removed it in this version; it is available with the original manuscript.

d After John died and as this manuscript was being edited, the IPCC AR6 was released, which updates the certainty of causal relationships and predictions. “Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5.”

e We verified all of the hyperlinks at the time we reviewed the manuscript, in some cases updating or replacing them.

f John’s original graphic in the figure below was replaced with a functionally-equivalent version with a clean copyright license explicitly allowing our use, and better graphics.

g Replaced figure of unknown copyright with a handwritten table and citation.

h Figure above replaced with an equivalent with clean copyright license.

i Replaced original figure for vibration modes of carbon dioxide with new figure created by Colin Law.

j Replaced the figure above with one with a clean use license. The original figure is available at the Royal Society link in the updated caption.

k Replaced original figure for H2O vibrational modes with new version.

l John began writing this manuscript in 2014.

m Original version included figures from the article that were removed as we do
not have permission to reproduce *Science* magazine figures here and could not find a replacement.

*a* Replaced original figures 4.7 and 4.8 with ones with cleaner copyright and more data.

*b* Figure 4.11 replaced with alternate with cleaner copyright.

*c* The original figure 4.12 replaced with new version with clean copyright and extra data.

*d* John originally had placeholders for sections on “historical perspective,” “land water storage,” and “sea levels: the take-away,” that he did not complete.

*e* Original figure 4.15 replaced with new version with clean copyright and extra years of data.

*f* John did not finish compiling this table from the underlying papers referenced below.

*g* John appears to have only started this section.

*h* John appears to have been in the middle of working on this section, with notes to himself to write more in multiple places in the original document.

*i* John included another figure here, from the Carbon Brief work, for which we were unable to secure permissions.

*j* John had placeholders at the end of this section for subsections on Amazon forest dieback, shutdown of the Atlantic meridional overturning current, and melting of the West Antarctic ice sheet. He did not complete any text in these sections.

*k* Figure 5.1 replaced with new figure with clean copyright.

*l* Figure 5.2 replaced by public domain version.

*m* Figure 5.3 replaced by public domain version

*n* Figure 5.4 replaced by public domain version

*o* Figure 5.4 replaced by public domain version

*p* Replaced figure 5.5 to avoid copyright issues, in both figure and in caption.

*q* Figure 5.6 replaced to avoid copyright issues.

*r* Figure 5.7 updated with more recent version, that includes extra 5 years of data.

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Figure 5.7 updated with more recent version, that includes extra 5 years of data.

Figure 5.9 replaced with alternate with extra data and clean copyright.

Figure 5.10 replaced with alternate with clean copyright.

Omitted figure 5.11; copyright issue and no replacement found.