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1 An Introduction to the Climate Problem

In this chapter, we begin our tour through the climate problem by defining weather, climate, and climate change. We also discuss something that few textbooks address: why you should believe this book.

1.1 What Is Climate?

The American Meteorological Society defines *climate* as

> The slowly varying aspects of the atmosphere–hydrosphere–land surface system. It is typically characterized in terms of suitable averages of the climate system over periods of a month or more, taking into consideration the variability in time of these averaged quantities.[1]

Weather, on the other hand, is defined as

> The state of the atmosphere ... As distinguished from climate, weather consists of the short-term (minutes to days) variations in the atmosphere.[2]

Mark Twain, in contrast, famously summed it up a bit more concisely:

> Climate is what you expect; weather is what you get.

Put another way, you can think of weather as the actual state of the atmosphere at a particular time. Weather is what we mean when we say that, at 10:53 AM on November 15, 2014, the temperature in College Station, Texas, was 8°C, the humidity was 66 percent, winds were out of the southeast at 8 knots, the barometric pressure was 1,023 millibar, and there was no precipitation. Weather is also what we mean when we say that the temperature will be dropping this weekend when a cold front comes through the area.

Climate, in contrast, is a statistical description of the weather over a period of time, usually a few decades. This description would most frequently include quantities such as temperature, humidity, precipitation, cloudiness, visibility, and wind. Figure 1.1 demonstrates one example of a climate statistic: It shows the distribution of daily maximum temperatures in September at Ellington Field, southeast of Houston. During the 1970s, for example, the most likely daily maximum temperature was 31°C, which occurred on

[1] https://glossary.ametsoc.org/wiki/Climate, retrieved June 03, 2020.
[2] https://glossary.ametsoc.org/wiki/Weather, retrieved November 25, 2020.

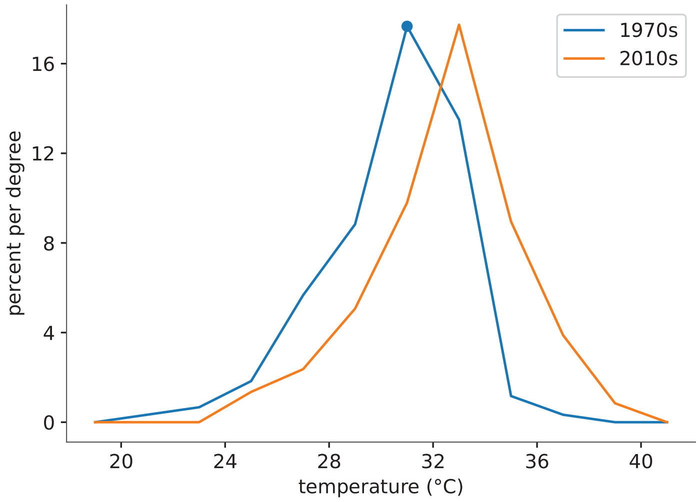

Figure 1.1 Frequency of occurrence of daily high temperature in September at Ellington Field, near Houston, TX, for two time periods: 1970–1979 (blue) and 2010–2019 (orange). HadISD [v3.1.1.2020f] data were obtained from www.metoffice.gov.uk/hadobs/hadisd on 2020-06-03 and are British Crown Copyright, Met Office [7 January 2021], provided under an Open Government Licence, www.nationalarchives.gov.uk/doc/non-commercial–government-licence/non commercial-government-licence.htm. This data set is described by Dunn (2019), Dunn et al. (2012, 2014, 2016), and Smith et al. (2011).

approximately 18 percent of the days (this point is indicated by the blue dot in the figure). In the 2010s, the most likely maximum temperature was 33°C, which also occurred on 18 percent of the days. The important thing about Figure 1.1 is that it tells us only the range of probable conditions over these two periods. It contains no information about what the actual high temperature was on any day – i.e., you cannot use Figure 1.1 to determine what the actual maximum temperature was on August 10, 1975.

In this book, I frequently use the Celsius scale, the standard temperature scale throughout most of the world (the Fahrenheit scale familiar to US readers is only used in the United States and a few other countries). For readers who may not be conversant in Celsius, you can convert from Fahrenheit to Celsius using the equation $C = (F - 32) \times 5/9$; or from Celsius to Fahrenheit, $F = C \times 9/5 + 32$. It is also useful to remember that the freezing and boiling temperatures for water on the Celsius scale are 0°C and 100°C, respectively. On the Fahrenheit scale, these temperatures are 32°F and 212°F. Room temperature is about 22°C, which corresponds to 72°F.

Why do we care about weather and climate? Weather is important for making short-term decisions. For example, should you take an umbrella when you leave the house tomorrow? To answer this question, you do not care at all about the statistics of precipitation for the month, but rather whether it is going to rain *tomorrow*. If you are going skiing this weekend, you care about whether new snow will fall before you arrive at the ski lodge and what the weather will be while you are there. You do not care how much snow the lodge gets on average or what the average weather is for this time of year.

Climate is important for long-term decisions. If you are looking to build a vacation home, you are interested in finding a place that frequently has pleasant weather – you are not particularly concerned about the weather on any specific day. Plots like Figure 1.1 can help make these kinds of climate-related decisions; the plot tells us, for example, that a house in this location needs air-conditioning during the summer. If you are building a ski resort, you want to place it in a location that, on average, gets enough snow to generate acceptable ski conditions in most years. You do not care if snow is going to fall on a particular weekend, or even what the total snowfall will be for a particular year.

An example of the importance of both the climate and the weather can be found in the planning for D-Day, the invasion of the European mainland by the Allies during World War II. The invasion required Allied troops to be transported onto the beaches of Normandy, along with enough equipment that they could establish and hold a beachhead. As part of this plan, Allied paratroopers were to be dropped into the French countryside the night before the beach landing in order to capture strategic towns and bridges near the landing zone, thus hindering an Axis counterattack.

There were important weather requirements for the invasion. The nighttime paratrooper drop demanded a cloudless night as well as a full moon so that the paratroopers would be able to land safely and on target, and then achieve their objectives – all before dawn. The sky had to remain clear during the next day so that air support could see targets on the ground. For tanks and other heavy equipment to be brought onshore called for firm, dry ground, so there could be no heavy rains just prior to the invasion. Furthermore, the winds could not be too strong because high winds generate big waves that create problems for both the paratroopers and the small landing craft that would ferry infantry to the beaches.

Given these and other requirements, analysts studied the *climate* of the candidate landing zones to find those beaches where the required weather conditions occurred most frequently. The beaches of Normandy were ultimately selected in part because of its favorable climate, although tactical considerations obviously also played a key role.

Once the landing location had been selected, the exact date of the invasion had to be chosen. For this, it would not be the climate that mattered but rather the *weather* on a particular day. Operational factors such as the phase of the tide and the moon provided a window of three days for a possible invasion: June 5, 6, and 7, 1944. June 5 was initially chosen, but on June 4, as ships began to head out to sea, bad weather set in at Normandy, and General Dwight D. Eisenhower made the decision to delay the invasion. On the morning of June 5, chief meteorologist J. M. Stagg forecasted a break in the weather, and Eisenhower decided to proceed. Within hours, an armada of ships set sail for Normandy. That night, hundreds of aircraft carrying tens of thousands of paratroopers roared overhead to the Normandy landing zones.

The invasion began just after midnight on June 6, 1944, when British paratroopers seized a bridge over the Caen Canal. At dawn, 3,500 landing craft hit the beaches. Stagg's forecast was accurate and the weather was good, and despite ferocious casualties, the invasion succeeded in placing an Allied army on the European mainland. This was a pivotal battle of World War II, marking a turning point in the war. Viewed in this light, Stagg's forecast may have been one of the most important in history.

Temperature is the parameter most often associated with climate, and it is something that directly affects the well-being of the Earth's inhabitants. The statistic that most frequently gets discussed is average temperature, but temperature extremes also matter. For example, it is heat waves – prolonged periods of excessively hot weather – rather than normal high temperatures that kill people. In fact, heat-related mortality is the leading cause of weather-related death in the United States, killing many more people than cold temperatures do. And the numbers can be staggering: In August 2003, a severe heat wave in Europe lasting several weeks killed tens of thousands.

Precipitation rivals temperature in its importance to humans, because human life without fresh water is impossible. As a result, precipitation is almost always included in any definition of climate. Total annual precipitation is obviously an important part of the climate of a region. However, the distribution of this rainfall throughout the year also matters. Imagine, for example, two regions that get the same total amount of rainfall each year. One region gets the rain evenly distributed throughout the year, whereas the other region gets all of the rain in 1 month, followed by 11 rain-free months. The environment of these two regions would be completely different. Where the rain falls continuously throughout the year, we would expect a green, lush environment. Where there are long rain-free periods, in contrast, we expect something that looks more like a desert.

Other aspects of precipitation, such as its form (rain versus snow), are also important. In the US Pacific Northwest, for example, snow accumulates in the mountains during the winter and then melts during the following summer, thereby providing fresh water to the environment during the rain-free summers. If warming causes wintertime precipitation to fall as rain rather than snow, then it will run off immediately and not be available during the following summer. This could lead to water shortages during the summer.

As these examples show, climate includes many environmental parameters. What part of the climate matters will vary from person to person, depending on how each relies on the climate. The farmer, the ski resort owner, the resident of Seattle, and Dwight D. Eisenhower are all interested in different meteorological variables, and thus may care about different aspects of the climate. But make no mistake: We all rely on the stability of our climate for our continuing existence. I will discuss this in greater depth when I explore the impacts of climate change in Chapter 9.

1.2 What Is Climate Change?

The climate change that is most familiar is the seasonal cycle: the progression of seasons from summer to fall to winter to spring and back to summer, during which most non-tropical locations experience significant climate variations. The concern in the climate change debate – and in this book – is with long-term climate change. The American Meteorological Society defines the term *climate change* as:

> Any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer.[3]

In other words, we can compare the statistics of the weather for one period against those for another period, and if the statistics have changed, then we can say that the climate has changed.

Thus, we are interested in whether today's climate is different from the climate of a century ago, and we are worried that the climate at the end of the twenty-first century will be quite different from that of today. To illustrate this, we return to Figure 1.1 to examine how the distribution of daily maximum September temperatures near Houston, TX changed between the 1970s and 2010s. Clearly, the temperature distributions in these two periods are different – the temperature distribution in the 2010s is about 1.5°C warmer than in the 1970s. We also see that temperatures that rarely occurred in the 1970s occurred frequently in the 2010s. In the 1970s, for example, daily maximum temperatures above 34°C (93°F) occurred on only 3 percent of the days; in the 2010s, they occurred on 35 percent of days. In other words, *the climate of this region changed* between these decades. This plot doesn't tell us what caused the change – it may be due to human activities or any number of natural physical processes. All we have identified here is a shift in the climate.

The shift in the average daily maximum temperature in Figure 1.1 is only 1.5°C, and it may be tempting to dismiss this as unimportant. In Chapter 9, you'll see how small-seeming changes in temperature are associated with significant impacts on the environment and all of us who live in it. So you should not dismiss such a change lightly.

In Chapter 2, we will look at global data to determine if the climate of the entire planet is changing. Before we get to that, however, there are two things I need to cover. First, in the next section, I discuss the coordinate system I will be using in this book.

1.3 A Coordinate System for the Earth

I will be talking a lot in this book about the Earth, so it makes sense to define the terminology used to identify particular locations and regions on the Earth.

To begin, the *Equator* is the line on the Earth's surface that is halfway between the North and South Poles, and it divides the Earth into a northern hemisphere and a southern hemisphere. The *latitude* of a particular location is the distance in the north–south direction between the location and the Equator, measured in degrees (as indicated by the red arrow in Figure 1.2a). This means that the latitude of the Equator is 0°. Latitudes for points in the northern hemisphere have the letter N appended to them, with S appended to points in the southern hemisphere. Thus, 30°N means a point on the Earth that is 30° north of the Equator, whereas 30°S means the same distance south of the Equator.

[3] http://glossary.ametsoc.org/wiki/Climate_change, retrieved June 3, 2020.

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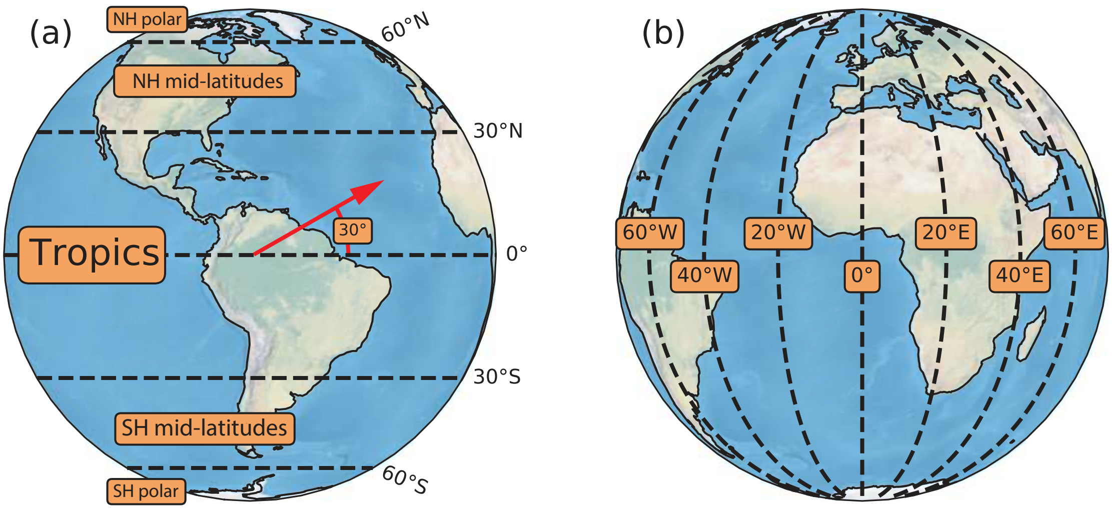

Figure 1.2 (a) A schematic plot of latitude showing the tropics (30°N to 30°S), the northern hemisphere (NH) and southern hemisphere (SH) mid-latitudes (30°–60° in each hemisphere), and the polar regions (poleward of 60° in each hemisphere). (b) A schematic plot of longitude.

The *tropics* are conventionally defined as the region from 30°N to 30°S, and this region covers half the surface area of the planet. The *mid-latitudes* are usually defined as the region from 30° to 60° in both hemispheres, and they occupy roughly one-third of the surface area of the planet. Most human population lives in the northern hemisphere, between the Equator and 60°N, because that's where most of the land is; the southern hemisphere is mainly ocean. The *polar regions* are typically defined to be from 60° to the pole, and together these regions occupy the remaining one-sixth of the surface area of the planet. The North and South Poles are located at 90°N and 90°S, respectively.

Latitude gives the north–south location of an object, but to uniquely identify a spot on the Earth, you need to know the east–west location as well. That is where *longitude* comes in (Figure 1.2b). Longitude is the angle in the east or west direction, from the prime meridian, a line that runs from the North Pole to the South Pole through Greenwich, England, which is arbitrarily defined to be 0° longitude. Locations to the east of the prime meridian are in the eastern hemisphere and have the angle appended with the letter E, whereas locations to the west are in the western hemisphere and have the letter W appended. In both directions, longitude increases to 180°, where east meets west at the international date line.

Together, latitude and longitude identify the location of every point on the planet Earth. For example, my office in the Department of Atmospheric Sciences of Texas A&M University is located at 30.6178°N, 96.3364°W (but please don't show up without an appointment). Knowing your location can literally be a matter of life and death – shipwrecks, wars, and other miscellaneous forms of death and disaster have occurred because people did not know where they were. Luckily for us, GPS (global positioning system) technology, which is built into your cell phone, can determine your latitude and longitude to within a few feet.

1.4 Why You Should Believe This Textbook

I now have to address an issue that generally does not come up in college textbooks: why you should believe it. Students in most classes accept without question that the textbook is correct. After all, the author is probably an authority on the subject, the publisher has almost certainly reviewed the material for accuracy, and the instructor of the class, someone with knowledge of the field, selected that textbook. Given those facts, it seems reasonable to simply assume that the information in the textbook is correct.

But climate change is not like every other subject. If you do a quick Internet search, you can find a website that disputes almost every claim made in this textbook. Your friends and family may not believe that climate change is a serious problem. They may even believe it is a hoax. You may agree with them. This book will challenge many of these so-called skeptical viewpoints, and you may face the dilemma of whom to believe.

This situation brings up an important question: How do you determine whether to believe a scientific claim? This is not just a philosophical question but one of great importance to you. When the coronavirus pandemic hit in early 2020, questions of science (how is it transmitted, do masks protect me, how many people around me are infected?) were literally matters of life and death. In fact, many important policy questions we face are built upon scientific claims.

For climate change, the case for action is built on scientific claims that the Earth is warming, humans are to blame for this, and future warming will bring with it risks of significant impacts. If you happen to know a lot about an issue, you can reach your own conclusions about the scientific claims relevant to that issue. But no one can be an expert on every subject; for the majority of issues on which you are not an expert, you need a shortcut.

One type of shortcut is to rely on your firsthand experience about how the world works. Claims that fit with your own experience are easier to accept than those that run counter to it. People do this sort of evaluation all the time, usually subconsciously. Consider, for example, a claim that the Earth's climate is not changing. In your lifetime, climate has changed very little, so this seems like a plausible claim. However, a geologist who knows that dramatic climate shifts are responsible for the wide variety of rock and fossil deposits found on Earth might regard the idea of a stable climate as ludicrous, and in turn might therefore be less likely to accept a human origin for climate change. The problem with relying on firsthand experience about the climate is that your experience might not be relevant to our present situation. For climate change, that is the case. Our present situation is unique – people have never changed the composition of the global atmosphere as much or as fast as is currently occurring. Thus, whatever the response will be, it will be outside the realm of our and the Earth's experiences.

Another type of shortcut is to rely on your values: You can accept claims that fit with your overall worldview while rejecting the claims that do not. For example, consider the scientific claim that secondhand smoke has negative health consequences. If you are a believer in unfettered freedom, you might choose to simply reject this claim out of hand because its truth implies that governments should regulate smoking in public places to

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protect public health. If, on the other hand, you are skeptical about corporate power, you may uncritically accept any claim that implies corporations are engaged in behavior that is bad for consumers.

Yet another shortcut is to rely on an *opinion leader*. Opinion leaders are people who you trust because they appear to be authoritative or because you agree with them on other issues. They might include a family member or influential friend, a media figure such as talk show hosts Tucker Carlson or John Oliver, or an influential politician such as Barack Obama or Donald Trump. In the absence of a strong opinion of your own, you can simply adopt the view of your opinion leaders. The problem with this approach is that many opinion leaders promote scientific viewpoints carefully screened to lend support to their preferred policies. Because of this, much of what you hear from opinion leaders is absolute nonsense.

1.4.1 How Science Works

Where should you turn to find out whether science supports a particular scientific claim? To answer this, let's discuss how science actually generates knowledge. Science begins with the process that most of you learned in high school, which may have been described to you as the "scientific method." It describes a process whereby an individual scientist generates a hypothesis, performs experiments to test the hypothesis, and then reaches a conclusion about the hypothesis.

In reality, this is only the first step of the true scientific process. Before the conclusion of this experiment can be considered "true," it must first be judged valid by the rest of the scientific community. This begins with the experimenter writing up a detailed description of exactly how the experiment was performed, the data that was collected, and the calculations or other methods of analysis that were done, all in enough detail that someone knowledgeable in the field could reproduce the work.

The resulting manuscript is then submitted for publication in a scientific journal. The first formal control that the scientific community exercises on the quality of scientific work comes at this point. Scientific journals will not publish the paper until it has been critically reviewed by other experts in the field. In this process, known as *peer review*, the reviewers' job is to look for errors or weaknesses in the analysis that might cast doubt on the conclusions. The identity of the reviewers is typically not revealed to the author, so that the reviewers can give their unvarnished opinion of the work without fear of later retribution.

If the reviewers do not identify any problems in the paper, then it gets published in the peer-reviewed literature. Peer review is a highly effective filter that stops many errors from being published, but it cannot catch every problem. Reviewers occasionally fail to notice an obvious mistake, and there are some types of error that reviewers cannot catch. They cannot tell if the author misread observations of an instrument, wrote a number down wrong, had a bug in their computer code, or if the chemical samples used in an experiment were contaminated.

But peer review is only the first level of quality control applied to scientific claims. When an important or novel claim passes peer review and is published in the peer-reviewed literature, it then gets tested in what I call the "crucible of science." This is the process whereby important conclusions get re-tested by the scientific community. This might mean having other scientific groups replicate the original experiment by re-doing the process described in the original peer-reviewed paper. This is important because, while one scientist might make a mistake, do a sloppy experiment, or have a bug in their computer code – and peer reviewers might fail to catch it – it is unlikely that multiple independent groups will make the same mistakes. Consequently, as other scientists confirm the results of the original experiment, the scientific community increasingly comes to accept the claim as correct.

Scientists can also test the implications of a scientific claim. For example, if someone claims the Earth is warming, we would expect that ice all over the world should be melting. That's a testable hypothesis, and if it turns out to be true (it is), then that would increase our confidence in the conclusion that the Earth is warming. Naturally, all of these replications and other tests of the original claim will themselves be published in the peer-reviewed literature, so the peer-reviewed literature contains both the original claim as well as all attempts to re-test it.

Over time, as the peer-reviewed literature fills up with replications and other tests of a claim, some claims become well-verified enough that they come to be regarded simply as scientific truth. When this happens, we say that a *scientific consensus* on that claim has emerged. For example, we now accept as scientific truth that the structure of DNA is a double helix, that atoms obey the laws of quantum mechanics, and that burning fossil fuels has increased the abundance of carbon dioxide in the atmosphere. At this point, further investigation into these claims attracts little attention from the scientific community. If the evidence supporting a claim is mixed, with some evidence supporting it while other equally persuasive evidence contradicts it, then we would conclude there is no consensus on whether the claim is true or false.

The road to scientific consensus is not a clean, straight line. When a claim is novel, the peer-reviewed evidence is often mixed, with some peer-reviewed papers confirming and others dissenting. However, over time, as our understanding of a phenomenon grows, the scientific community may resolve these differences and develop a strong scientific consensus about the claim. It is important to point out that this is not a formal process. There are no meetings or votes where it is determined what the consensus is. Every scientist working in the field has their own ideas about what is well known and what is yet to be resolved in their field. Scientific consensus emerges organically when most scientists working in an area independently conclude that a particular scientific claim can be confidently categorized as either true or false.

Scientists who continue to dispute the consensus – and who can't advance a good reason for doing so – become marginalized and ignored by their colleagues. In climate science, these people are sometimes referred to as *climate skeptics* or, less charitably, climate deniers. This latter term gains rhetorical power by comparing them to people who cast doubt on the reality of the Holocaust.

The messy development of scientific consensus gives dishonest advocates the opportunity to selectively cite out-of-date, discredited, or unrepresentative peer-reviewed studies in an attempt to claim that "scientists disagree" on important questions, even when there is actually widespread agreement in the scientific community. In Chapter 13, we'll talk in more detail about strategies advocates use to attempt to cast doubt on solid, well-understood science. These strategies were pioneered by the tobacco industry in the 1960s during their attempt to cast doubt on the solid science connecting smoking to various health impacts.

It is important to reiterate that a scientific consensus is not based on a poll or vote of the opinions of scientists, but rather an analysis of the published peer-reviewed literature. These should be similar because it is the scientists who are writing the papers, but it is nevertheless an important operational distinction. If I ask whether there is a consensus among scientists on some issue, how do you determine if consensus exists, and whose opinion counts? If, on the other hand, I ask whether consensus exists in the peer-reviewed literature, then it's easy to determine what the consensus is – just read the scientific literature.

1.4.2 Scientific Assessments

While this sounds simple in theory – all you have to do is read the scientific peer-reviewed literature! – anyone who has ever tried to read a peer-reviewed journal article knows that it is extremely difficult. Scientific papers are densely written and full of jargon because they are written for other experts, so they assume a deep technical background and knowledge of the issue. Because of this, reading and understanding the peer-reviewed literature takes years of study, so it is impractical to expect non-experts to do that.

What we therefore need is a reliable summary of the peer-reviewed literature that is understandable to non-experts. The summary should focus on questions that are important to policymakers – for example, is the Earth warming, are humans to blame, what are the impacts? The report should then summarize what the peer-reviewed literature tells us about each one. It should also evaluate how confident we are about each conclusion, based on the level of consensus in the peer-reviewed literature, and communicate this to the assessment's readers.

Such a summary of the peer-reviewed literature is what is known as a *scientific assessment*. Policymakers can turn to these assessments in order to determine what the science says on any particular scientific claim. These assessments do not perform new science – their job is simply to summarize and analyze the peer-reviewed literature in language that non-experts can understand.

Assessments start with policymakers defining the questions they want answered. Then, a writing team with relevant scientific expertise is assembled. The reliance on large writing groups reduces the possibility that an erroneous minority opinion will make it into the report, much like getting multiple opinions in medicine reduces the chance of a bad diagnosis. After the writing team produces its assessment, the assessment is then itself peer reviewed by other experts in the field. This provides an additional check to ensure that the assessment accurately summarizes the peer-reviewed literature.