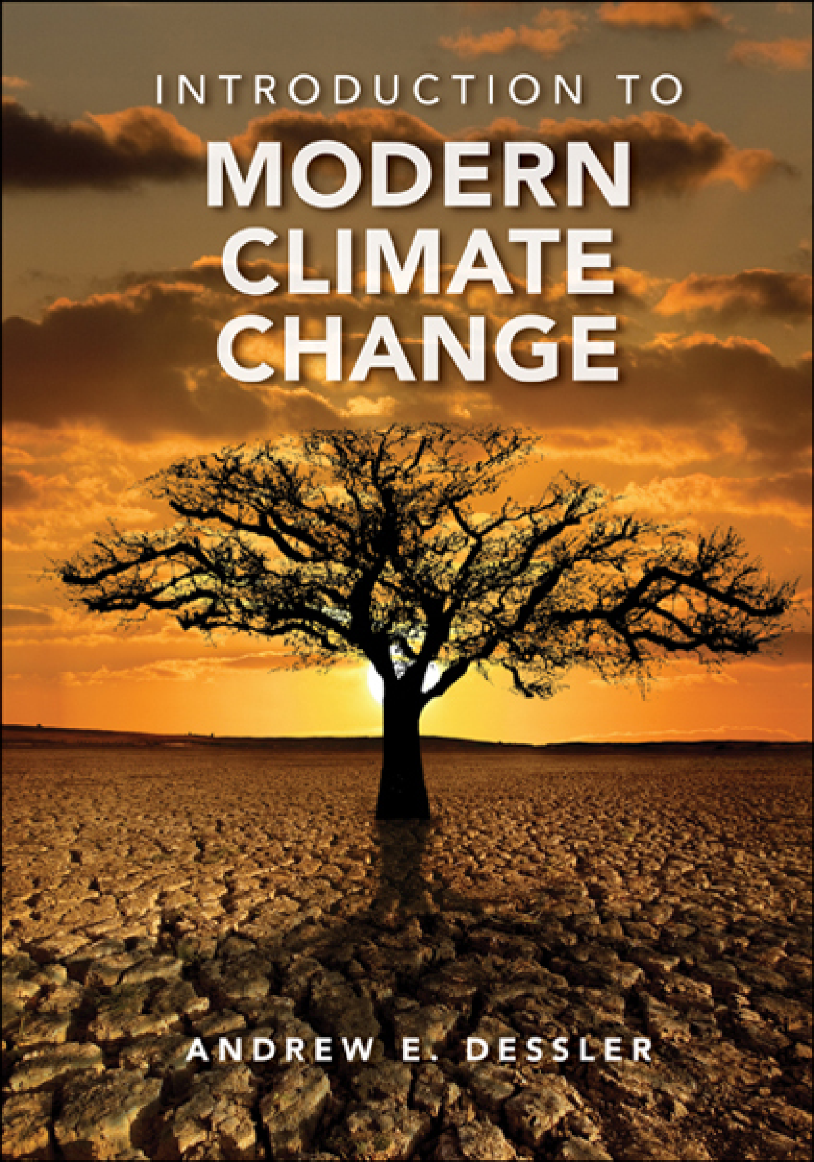
INTRODUCTION TO

MODERN CLIMATE CHANGE



ANDREW E. DESSLER

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Introduction to Modern Climate Change

This textbook gives students an entire overview of recent climate change – science, economics, and policy – enabling them to engage in informed debate of public policy. The focus is on the problems of anthropogenic climate change. The combination of science with economic and policy options makes this a unique introduction among climate change textbooks. Not just descriptive, it contains the quantitative depth that is necessary for a clear understanding of the science of climate change, with simple equations and problems for students to solve.

The first half of the book focuses on the science of modern climate change, including evidence that the Earth is warming and a basic description of climate physics. This section also covers the concepts of radiative forcing, feedbacks, and the carbon cycle. The second half of the book goes beyond the science to address economics and policy. Students will leave the class motivated to engage in this vital, controversial, and ongoing debate.

This is an invaluable textbook for any introductory survey course on the science and policy of climate change, for both nonscience majors and introductory science students.

Andrew E. Dessler is a climate scientist who studies both the science and politics of climate change. His scientific research revolves around climate feedbacks, in particular how water vapor and clouds act to amplify warming from the carbon dioxide that humans emit. During the last year of the Clinton Administration, he served as a Senior Policy Analyst in the White House Office of Science and Technology Policy. Based on that experience, he co-authored a book, *The Science and Politics of Global Climate Change: A Guide to the Debate* (Cambridge University Press, 2006; 2nd ed., 2010). He also authored a graduate textbook, *The Chemistry and Physics of Stratospheric Ozone* (2000). He is currently a Professor of Atmospheric Sciences at Texas A&M University. His educational background includes a B.A. in physics from Rice University and a Ph.D. in chemistry from Harvard University. He also undertook postdoctoral work at NASA's Goddard Space Flight Center and spent 9 years on the research faculty of the University of Maryland. In the mid-1980s, he worked in the energy group at The First Boston Corporation doing mergers and acquisitions analysis.

Advance Praise for *Introduction to Modern Climate Change*

"At last, a textbook about the scientific basis for global climate change that's well balanced, well written, highly illuminating, and accessible to non-science majors."

– Professor John M. Wallace, University of Washington

"Several years ago, Professor Andrew Dessler created an introductory course on climate change at Texas A&M University for freshmen and sophomores. This textbook is an outgrowth of the notes he used in teaching that course. Last year while Andy was away I taught the course using his first draft of the book, which was shared online with the students. Both the students and I very much enjoyed the course and the notes. Andy is a natural teacher and writer with such an ease of presentation that he makes complex subjects accessible by his clever use of everyday analogies. Climate change is a subject that Andy cares about passionately, and he really cares about his reader as well. The book provides an expert's exposition of climate change in all its facets, from ice sheets to options for public policy. While it is written primarily as a textbook, it also provides excellent reading for any layperson interested in the subject."

– Professor Gerald R. North, Texas A&M University

"Understanding the challenges of climate change requires an understanding of the relevant science, economics, and policy. However, existing introductory textbooks focus on only one of these disciplines, and there is a need for books covering all aspects. This textbook fills this void. Dessler has done an excellent job of clearly describing the different issues of climate change in a way that will be accessible to both science and non-science majors. I can see this book becoming the standard textbook for the growing number of introductory courses that discuss both the science and policy of climate change."

– Professor Darryn Waugh, Johns Hopkins University

"Professor Dessler's book is written for 'undergraduate non-science majors.' He must believe in the impossible – that he can bring a topic as complex as climate change into focus for students with little background in science. However, I must say that Professor Dessler has succeeded! Students who read this book will achieve a level of understanding of climate change that they may, first, 'engage in an informed debate of public policy'; second, understand the deep significance of Climategate; and third, explain and act upon the recent explosion of public interest in climate change (wide coverage by the media and huge UN conferences, with more than 20,000 persons attending). To put this in perspective, Lord King, a former scientific advisor to the British Prime Minister, is quoted as saying that 'No single issue, scientific or non-scientific, has ever received as much attention from world leaders as climate change.' Why this upwelling of interest? And how can society profit from it?"

– Professor Ted Munn, University of Toronto

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ANDREW E. DESSLER
Texas A&M University

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For Alex and Michael

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Preface

Future generations may well view climate change as the defining issue of our time. The worst-case scenarios of climate change are truly terrible, but even middle-of-the-road scenarios portend environmental change without precedent for human society. When future generations look back on our time in charge of the planet, they will either cheer our foresight in dealing with this issue or curse our lack of it.

Yet despite the stakes, the world has done basically nothing to address this risk. The reasons are obvious: The threat of climate change is really a threat to future generations, not the present one, so actions taken by our generation will mostly benefit them and not us. Moreover, such actions may be expensive – reducing emissions means rebuilding our energy infrastructure, and we have no idea how much that will cost. In such a situation, it is easiest to do nothing and wait for disaster to strike – which is why dams are frequently built after the flood, not before. Nevertheless, pushing this problem off onto future generations is a poor strategy. The impacts of climate change are global and mainly irreversible; by the time we have unambiguous evidence that the climate is changing and its impacts are serious, it will be too late to avoid these serious impacts. The only hope that future generations have to avoid serious climate change is us.

I fully believe that the cornerstone of good policy is an electorate that is educated on the issues, and this belief provided me the motivation for writing this book. The goal of the book is to cover the human-induced climate change problem from stem to stern, covering not just the physics of climate change but also the economic, policy, and moral dimensions of the problem. This sets it apart from most other books, which typically do not have a tight focus on human-induced climate change or do not cover the nonscience aspects of the problem.

Such complete coverage of the climate change problem is essential. The science clearly underlies all discussion of the problem, and an understanding of the science is essential to an understanding of why so many people are so worried about it. Climate change, however, is no longer just a scientific problem. Virtually every government in the world now accepts the reality of climate change, and the debate has, to a great extent, moved on to policy questions, including the economic and ethical issues. Thus, one must also understand nonscience aspects of the problem to be truly informed on this issue.

The first seven chapters of the book focus on the science of climate change. Chapter 1 defines the problem and provides definitions of weather, climate, and climate change. It also addresses an issue that most textbooks do not have to address: why the reader should believe this book as opposed to Web sites and other sources that give a completely different view of the climate problem. Chapter 2 explains the evidence that the Earth is warming. The evidence is so overwhelming that there is little argument anymore over this point, and my goal is for the readers come away from the chapter understanding this.

Chapter 3 covers the basic physics of electromagnetic radiation necessary to understand the climate. I use familiar examples in this chapter, such as glowing metal in a blacksmith shop and the incandescent light bulb, to help the reader understand these important concepts. In Chapter 4, a simple energy-balance climate model is derived. It is shown how this simple model successfully explains the Earth's climate as well as the climate of Mercury, Venus, and Mars. The carbon cycle is covered in Chapter 5, and feedbacks, radiative forcing, and climate sensitivity are all discussed in Chapter 6. Finally, Chapter 7 explains why scientists are so confident that humans are to blame for the recent warming that the Earth has experienced.

Chapter 8 begins an inexorable shift from physics to nonscience issues. Chapter 8 discusses emissions scenarios and the social factors that control them, as well as what these scenarios mean for our climate over the next century. Chapter 9 covers the impacts of these changes on humans and on the world in which we live. Chapter 10 covers exponential math. Exponential growth is a key factor in almost all fields of science, as well as in real life. In this chapter, I cover the math of exponential growth and explain the concept of exponential discounting.

Starting with Chapter 11, the discussion is entirely on the policy aspects of the problem. Chapter 11 discusses the three classes of responses to climate change, namely adaptation, mitigation, and geoengineering, and their advantages, disadvantages, and trade-offs. The most contentious arguments over climate change policy are over mitigation, and Chapter 12 discusses in detail the two main policies advanced to reduce emissions: carbon taxes and cap-and-trade systems.

Chapter 13 provides a short history of climate science and a history of the political debate over this issue, including discussions of the United Nation's Framework Convention on Climate Change and the Kyoto Protocol. Finally, Chapter 14 pulls the last three chapters together by discussing methods of deciding which of our options we should adopt, particularly given the pervasive uncertainty in the problem.

Overall, it should be possible to cover about one chapter in three hours of lecture. This makes it feasible to cover the entire book in one 15-week semester. At Texas A&M, the material in this book is being used in a one-semester class for nonscience majors that satisfies the University's science distribution requirement. Thus, it is appropriate for undergraduates with any academic background and at any point in their college career.

Any serious understanding of climate change must be quantitative. Therefore, the book assumes a knowledge of simple algebra. No higher math is required. The book also assumes no prior knowledge of any field of science, just an open mind and willingness to learn. To aid in the student's development of a numerate understanding of the climate, there are quantitative questions at the end of many of the chapters, and every chapter also has more open-ended, qualitative questions. In addition, there is a chapter summary at the end of each chapter that reviews and summarizes the most important take-away messages from the chapter. A list of important terms is also provided at the end of each chapter.

This is not a book of advocacy. This is not to say that I do not have opinions. I do, and strong ones. I recognize, though, that shrill advocacy is frequently less effective than a dispassionate presentation of the facts. Thus, my strategy in this book is to just explain the science and then lay out the possible solutions and trade-offs among them. I firmly believe that an unbiased assessment of the facts will bring the majority of people to see things the way I do: that climate change poses a serious risk and that we should therefore be heading off that risk by reducing our emissions of greenhouse gases.

Every year that our society does nothing to address climate change makes solving the problem both harder and more expensive. I am still optimistic, though, because problems often appear intractable at first. In the 1980s, as evidence mounted that industrial chemicals were depleting the ozone, it was not at all clear that we could avoid serious ozone depletion at a reasonable cost. The chemicals causing the ozone loss, namely chlorofluorocarbons, played an important role in our everyday life – in refrigeration, air conditioning, and many industrial processes – just like the main cause of climate change, fossil fuels, also play an important role in our society. But the cleverness of humans prevailed. A substitute chemical was developed and it seamlessly and cheaply replaced the ozone-destroying halocarbons – all at a cost so low that hardly anyone noticed when the substitution took place.

I realize that solving the climate change problem will be much harder than solving the ozone depletion problem – how much harder, no one knows. I am confident, though, that the ingenuity and creativeness of humans is so great that we can solve this problem without damaging our standard of living. However, there is only one way to find out – and that is to try to do it.

Acknowledgments

Many people have helped me write this book. I thank Rob Korty, John Nielsen-Gammon, Jerry North, R. Saravanan, Russ Schumacher, Debbie Thomas, Andrew Wang, and Shari Yvon-Lewis, for reading and commenting on various parts of the book. Much of this book was written while I was on faculty development leave from Texas A&M University during the fall of 2010, and I thank the university for this support.

1 An introduction to the climate problem

This chapter begins our trip through the climate problem by defining what climate and climate change are, and how we use latitude and longitude to describe locations on the Earth. This chapter also addresses a question that most textbooks do not have to address: Why you should believe it.

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.

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, *weather* refers to the actual state of the atmosphere at a particular time. We are referring to the weather when we say that the low and high temperatures on August 8, 1993 in College Station, TX, were 24 °C and 37 °C, respectively, and there was no precipitation.

Climate, in contrast, is used for a statistical description of the weather over a period of time, usually a few decades. It could include the average temperature, for example, as well as a measure of how much the temperature varies about this average value, such as the record high and low temperatures. Figure 1.1 shows the distribution of daily high and low temperatures in August in Fairbanks, AK between 1975 and 2008. It shows, for example, that the most likely high temperature is 23 °C, which occurred on approximately 5% of the days during this period. It also shows that extremes occur less frequently; for example, the probability of high temperatures above 30 °C or below 8 °C are quite small. The climate tells us only the range of probable conditions on a particular day; it contains no information about what the temperature was on August 8, 1993.

In this book I frequently use the Celsius scale, the most widely used temperature scale in the world (the Fahrenheit scale more familiar to U.S. readers is only used in the United States and a few other countries). Celsius is also used by scientists, and because this book is foremost a science textbook, I have adopted the Celsius scale. In Chapter 3 I discuss the Kelvin scale, which is also widely used by scientists.

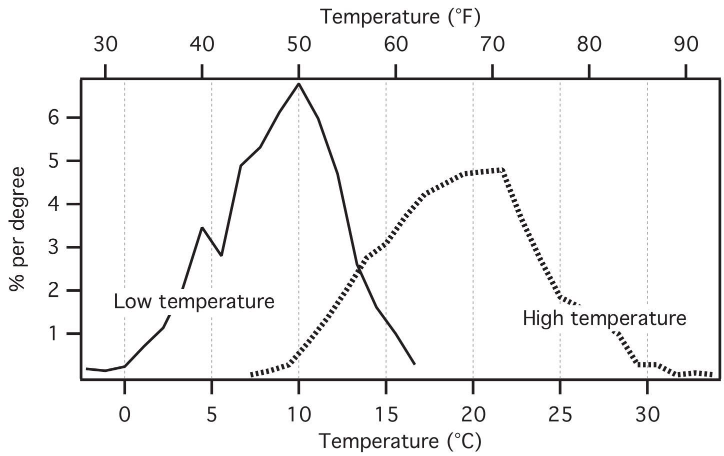

Fig. 1.1 Frequency of occurrence of daily high and low temperatures in August in Fairbanks, AK between 1975 and 2009 (data obtained from the National Climatic Data Center; http://cdo.ncdc.noaa.gov).

It is useful to remember that the freezing and boiling temperatures for water in the Celsius scale are 0 °C and 100 °C, respectively. In the Fahrenheit scale, these temperatures are 32 °F and 212 °F. Room temperature is approximately 72 °F or 22 °C. And to convert from Fahrenheit to Celsius, use the equation $C = (F - 32) \times 5/9$; to convert from Celsius to Fahrenheit, use the equation $F = C \times 9/5 + 32$.

Why do we care about weather and climate? Weather, on one hand, 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 don't care at all about the average 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.

Climate, on the other hand, is more 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 interested in the weather on any specific day. If you are building a ski resort, you want to place it in a location that, on average, gets enough snow to produce acceptable ski conditions. You do not care if snow is going to fall on a particular weekend, or even what the total snowfall will be for particular year; you are interested in the long-term statistics of snowfall.

A good example of the importance of both the climate and 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 thousands of 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, thousands of Allied paratroopers were to be dropped into the French countryside in the middle of the night before the beach landing in order to capture strategic towns and bridges near the landing zone, thus hindering a German counterattack.

There were important weather requirements for the invasion. The nighttime paratrooper drop required 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 required firm, dry ground, so there should 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 the Navy, particularly for the small landing craft that would ferry infantry to the beaches.

Given these and other weather requirements, Allied 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 because of its favorable climate and other tactical considerations.

Once the landing location had been selected, the exact date of the invasion would have to be selected. 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 3 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 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 carrying tens of thousands of soldiers 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 key turning point in the war. And analyses of both weather and climate played a key role in the success of this mission.

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 (it kills many more people than cold-related mortality). And the numbers can be staggering: In August of 2003, a severe heat wave in Europe lasting several weeks killed tens of thousands of people.

Precipitation rivals or even exceeds 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 vs. snow), are also important. In the U.S. Pacific Northwest, for example, snow that accumulates in the mountains during the winter melts during the following summer, thereby providing fresh water to the environment during the otherwise dry 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 can 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 he or she relies on the climate. The farmer, ski resort owner, 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. In particular, food production and freshwater availability, two of the most important things we rely on to survive, are greatly affected by the climate. I will discuss this in greater depth when I explore climate impacts in Chapter 9.

A final difference between weather and climate is how easy they are to determine. Measuring the weather is pretty easy – just walk outside and look around.[1] If you need a higher level of accuracy, you can buy reasonably cheap instruments to measure the temperature, precipitation, or any other variable of interest. Climate, in contrast, is much harder to measure; it requires the gathering of decades of data so that we have sufficiently good, robust statistics, such as I plotted in Figure 1.1. I will discuss this challenge in greater detail in Chapter 2.

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 locations experience significant temperature variations. Precipitation can also vary by season. In fact, almost any climate variable can vary over the course of the year.

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 follows:

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

[1] There are, of course, siting issues in measuring the weather. Depending on your location, the weather you measure when you walk outside may not be terribly representative of the weather of the larger areas.

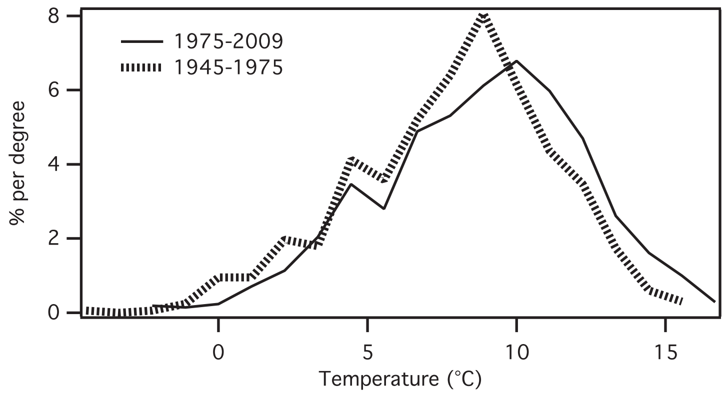

Fig. 1.2 Frequency of occurrence of daily low temperature in August in Fairbanks, AK for two periods, 1945–1975 and 1975–2009 (data obtained from the National Climatic Data Center; http://cdo.ncdc.noaa.gov).

In other words, we can compare the climate for one period against the climate 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 (defined over the past few decades) is different from the climate of a century ago, and we are worried that the climate at the end of the 21st century will be quite different from that of today. As an example, Figure 1.2 plots the August minimum temperature in Fairbanks, AK for two periods, 1945–1975 and 1975–2009. The distribution of daily minimum temperature has clearly shifted, from an average of 7.6 °C in the early period to an average of 8.5 °C in the later period. In addition to the shift in average temperatures, we can see that warm temperatures became more frequent and cold temperatures became less frequent. It should also be noted that there is no information on the cause of the change in this plot – it may be due to global warming or one of any number of other physical processes. All we have identified here is a shift in the climate.

The increase in daily minimum temperature is only 0.9 °C, and it might be tempting to dismiss this as unimportant. However, as I discuss in Chapter 9, seemingly small changes in climate are associated with significant impacts on the environment. Do not dismiss such a change lightly.

In Chapter 2, we will pick up this theme and look at data to determine if the climate is indeed changing. Before we get to that, though, there are two things I need to cover. First is the coordinate system I will be using in this book. The second is a more general discussion about why you should believe the science in this textbook.

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 describe the terminology used to identify particular locations and regions on the Earth.

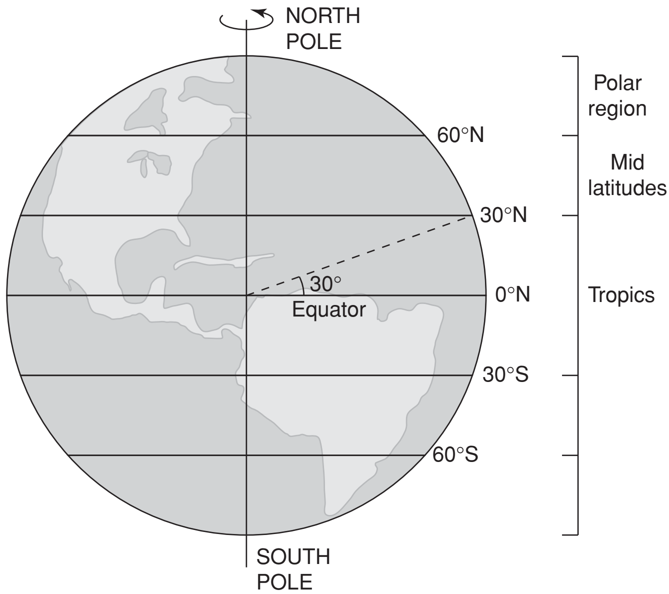

Fig. 1.3 A schematic showing of latitude.

To begin, the *equator* is the line on the Earth's surface that is halfway between the North and South Pole, 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 (Figure 1.3), measured in degrees. 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.

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 these regions occupy roughly one third of the surface area of the planet. The *polar regions* are typically defined to be 60 ° to the pole, and 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 also need to know the east–west location. That is where *longitude* comes in (Figure 1.4). 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, and 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.

Fig. 1.4 A schematic showing of longitude.

Together, latitude and longitude identify the location of every point on the planet Earth. For example, the Department of Atmospheric Sciences of Texas A&M University is located (approximately) at 30.6 °N, 96.3 °W. 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, for around $100 you can buy a GPS (global positioning system) receiver that will give 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 a college textbook: 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 basically correct.

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

This situation brings up an important and interesting question: How do you determine whether or not to believe a scientific claim? If you happen to know a lot about an issue, you can reach your own conclusions on the issue. However, 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 unconsciously. Consider, for example, a claim that the Earth's climate is stable. 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, but in turn might be less likely to accept a human origin for climate change. The problem with relying on firsthand experience about the climate is that 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 may be outside the realm of our and the Earth's experiences.

Another type of shortcut is to rely on your values: You can accept the claims that fit with your overall world view while rejecting the claims that do not. For example, consider the scientific claim that second-hand 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 it implies that governments should regulate smoking in public places to protect public health.

Yet another shortcut is to rely on an *opinion leader*. Opinion leaders are people that 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 conservative talk show host Rush Limbaugh or comedian Jon Stewart, or an influential politician such as Barack Obama or George W. Bush. 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 there is no guarantee that the opinion leaders have a firm grasp of the science.

The best approach is to rely on the opinion of experts. When the relevant experts on some subject have high confidence that a scientific claim is true, that is the best indication we have that the claim actually is true. This is not just my view; I am willing to bet it is something you believe in, too. If a friend tells you that she thinks she may be sick, what would you recommend? Your recommendation is likely to be that she should go see a doctor – and not just any doctor, but one who is an expert in that particular ailment.

This is also the view of the U.S. legal system. Many court cases involve questions of science (e.g., what was the cause of death, does a particular chemical cause cancer, does a DNA sample match the defendant). To settle those cases, the court will frequently turn to expert witnesses. These expert witnesses are, as their name suggests, experts on the matter that they are testifying about, and they provide relevant expertise to the court to help evaluate the important scientific questions that a case may revolve around.

To be an expert witness, one must demonstrate expertise in a particular subject. I have served as an expert witness on climate change in lawsuits over the permitting of coal-fired power plants, and the court qualifies me as an “expert” by using my research in climate change as well as the textbooks I have authored as evidence. Other members of my department have served as expert witnesses in lawsuits that have weather-related aspects to them. For example, in a lawsuit involving a car wreck, an expert on weather may testify about the weather conditions at the time, about the visibility, about the possibility that there was ice on the ground, and so on.

It should be emphasized that one must demonstrate specific, recent expertise in the exact area under consideration to be an expert witness. Showing expertise in general technical matters or in a related field is not sufficient. For example, one might consider anyone with a Ph.D. in physics to have a credible opinion about the science of climate change. This is not so, and a person with a Ph.D. in physics without specialized knowledge of the climate would not be qualified to be an expert on matters of climate. That also goes for weather forecasters – climate and weather are different, and being an expert in weather would not qualify someone to be an expert witness on climate. The reverse is also true, so I, despite being a professor of atmospheric sciences, would not qualify as an expert in weather. The requirement for the expertise to be recent rules out those who were experts, say, a decade ago but who have not kept up with the latest discoveries in the field.

There are many more examples that demonstrate that, as individuals and as a society, we have decided that expertise counts when one is evaluating competing claims on matters of science. That is probably a good thing, too, because on a planet with almost 7 billion people, you can always find someone who will contest any claim, no matter how well established it is. For example, it would be relatively easy to find someone somewhere who would dispute the claim that cigarettes cause health problems. So if everyone’s opinion counted equally, then it would be impossible to ever settle any dispute over a scientific claim – even one as simple as whether the Earth goes around the Sun.

Nonetheless, you also know that experts are not all equal. If one of your friends needs to see an endocrinologist for treatment of a serious endocrine disorder, you are not going to recommend that he open the yellow pages and call the first one he finds. Rather, you will suggest that he try to find the best one, perhaps by asking friends, family, or their family doctor for recommendations, or do research online to find someone with outstanding credentials.

For important medical decisions, though, even finding a doctor you trust is not enough. After all, anyone – even the most trusted expert – can make a mistake. Moreover, some people have biases that may be undetectable. One way to gain additional confidence in a particular diagnosis is to get a second opinion. If you have the time and resources, you may even get more opinions. If all of the experts agree, then you would have justifiably high confidence that the recommendations are the best advice that modern medicine can provide.

Climate change is really no different. It is obvious that the relevant experts are the community of climate scientists. However, there are thousands of climate scientists out there, so which ones should we to listen to? One approach would be to ask all of the world's climate scientists what they think – and if the vast majority agree on a particular point, then we can have high confidence that point of view is correct.

This is, in fact, what has already been done. In 1988, as nations began to acknowledge the seriousness of the climate problem, the Intergovernmental Panel on Climate Change (IPCC) was formed. The IPCC assembles large writing teams of scientific experts and has them write, as a group, a report detailing what they know about climate change and how confidently they know it. The reliance on large writing groups reduces the possibility that the erroneous opinions of an individual or a small group make it into the report, much like getting multiple opinions in medicine reduces the chance of a bad recommendation.

To further minimize the possibility that the group of scientists writing the report are biased in some direction, the scientists making up the writing teams are not drafted by a single person or organization; they are nominated by the world's governments. Thus, the only way the IPCC's writing groups would be biased in some direction is if all of the world's governments nominated biased individuals. This seems very unlikely, particularly because some of the world's governments are very concerned about climate change whereas others would be very happy if climate change disappeared completely as a political issue.

After being written by experts, the IPCC's reports are then reviewed by other expert scientists, and they undergo a public review and a separate review by the world's governments. In the end, the IPCC's reports[2] are widely regarded as the most authoritative statements of scientific knowledge about climate change, and as such they carry enormous weight in both the scientific and policy communities. The reports are not perfect (no complex document written by humans can be), but they are really quite good. In 2007, the IPCC shared the Nobel Peace Prize in recognition of its work on the climate.

In addition to the IPCC's reports, you can also examine reports from other assessment organizations, such as the United States National Academy of Sciences. Or you can look at the statements put out by the scientific societies that climate experts belong to. For example, in October of 2009, a collection of U.S. scientific organizations sent a letter to the U.S. Senate stating that climate change is a serious problem facing the entire human race and that emissions of greenhouse gases have to be dramatically reduced for us to avoid the most severe impacts.[3] Signatories of this letter include the American Association for the Advancement of Science, the American Chemical Society, the American Geophysical Union, the American Institute of Biological Sciences, the American Meteorological Society, the American Society of Agronomy, the American Society of Plant Biologists, the American Statistical Association, the Association of Ecosystem Research Centers, the Botanical Society of America, the Crop Science Society of America, the Ecological Society of America, the Natural

[2] These reports can be downloaded (available at http://www.ipcc.ch).

[3] This letter is available online (see http://www.aaas.org/news/releases/2009/media/1021climate_letter.pdf).