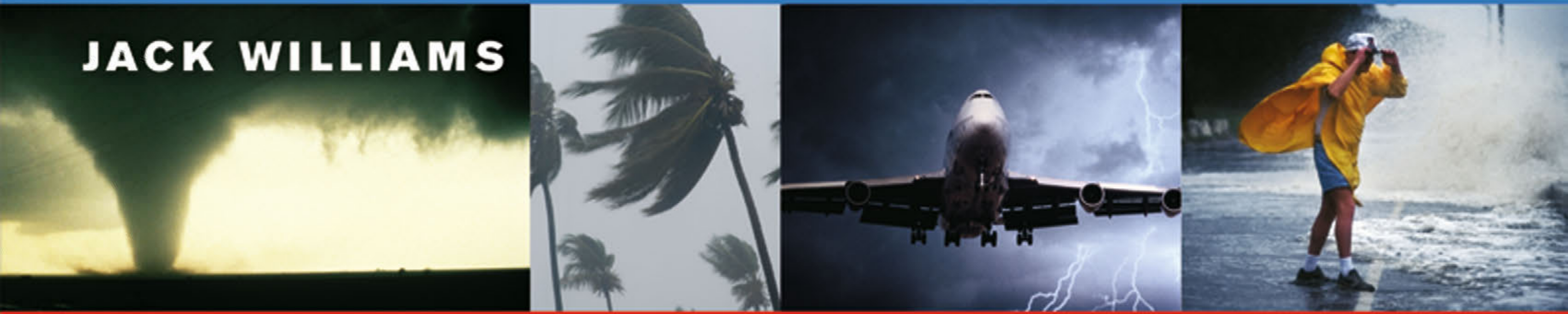
THE AMS WEATHER BOOK

JACK WILLIAMS



THE ULTIMATE GUIDE TO AMERICA'S WEATHER

The AMS Weather Book

The AMS Weather Book: The Ultimate Guide to America's Weather

Jack Williams

Copublished with the American Meteorological Society

The University of Chicago Press
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Jack Williams was weather editor of *USA TODAY* for twenty-three years before becoming public outreach coordinator for the American Meteorological Society in 2005. He has reported on weather and climate research from Antarctica, Greenland, a research icebreaker on the Arctic Ocean, flights into hurricanes, and tornado chases with scientists. He is the author of *The USA TODAY Weather Book*, *The USA TODAY Weather Almanac*, *The Complete Idiot's Guide to the Arctic and Antarctic*, and co-author with Dr. Bob Sheets of *Hurricane Watch: Forecasting the Deadliest Storms on Earth*.
He and his wife, Darlene, live in Falls Church, Virginia.

The American Meteorological Society seeks to advance the atmospheric and related sciences, technologies, applications, and services for the benefit of society.

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CONTENTS

FOREWORD

Weather is of interest to almost everyone, and it is important to all of us. It affects each of us on an everyday basis, and sometimes it threatens our health, property, and even our lives. More than 75 percent of natural disasters across the world are caused by weather, and roughly 25 percent of the U.S. economy is sensitive to weather. Severe weather—including hurricanes, tornadoes, blizzards, forest fires, floods, and droughts—affects every U.S. state and costs billions of dollars each year.

Not only is the weather itself constantly changing, but our relationship to it is changing as well. As the earth's population increases, its resources are becoming scarcer, and more people are settling in vulnerable areas, such as hurricane-prone coastal regions. These factors make adverse weather events more of a threat with each passing year. On top of this, the most rapid rate of climate change in human history is now unfolding. It will trigger important changes in weather patterns, frequencies, and intensities, involving many of the high-impact events described above. Destructive weather and uncertainty about future weather are increasingly challenging the sustainability of society through weather's effects on food, energy, transportation, water supplies, health, and defense. On the positive side, ever-improving weather predictions and warnings provide great opportunities across these same sectors of society.

There is much more to weather than statistics and impacts. Weather challenges our senses and inspires our imaginations, excites us with drama, awes us with its power, and edifies our lives with its beauty. Weather is much more than science: it is part of our art, literature, entertainment, and music. We love weather, even as we watch it warily for occasional misbehavior.

Although the workings of the atmosphere that create weather can seem complex and mysterious, a few basic principles explain a great deal. *The AMS Weather Book* is written in an accessible style and illustrated with superb color photographs and easily understandable graphics that explain weather systems and related optical phenomena, such as rainbows and halos, to readers of all ages. It provides the basic science behind the important questions: Will hurricanes get stronger and more frequent? What about blizzards and tornadoes? Droughts and floods? What is causing climate change?

Throughout the book, vignettes of people who are deeply involved in weather in their professional lives bring weather to the human level, giving readers a glimpse into what has become known as the **weather enterprise**, which spans public, private, academic, and military sectors. These diverse people—scientists, forecasters, emergency responders, pilots, broadcasters, wildfire fighters, and other providers and users of forecasts and information—tell fascinating stories about how weather events have affected them and their families.

It was a book about weather—the novel *Storm* by George Rippey Stewart—that triggered my own interest in hurricanes and my eventual career in atmospheric science. In this book, Jack Williams has done a masterful job in bringing weather and climate to life, and may well inspire those not already involved in the weather enterprise to consider a career in our exciting and vital discipline.

Richard Anthes
President
University Corporation for Atmospheric Research (UCAR)

Boulder, Colorado
Fall 2008

FOREWORD

What does every person alive on the planet have in common? We are all affected by the weather. It is a constant—sometimes good, sometimes bad, but always there. As a meteorologist who works at The Weather Channel, I have both experienced and explained numerous weather extremes. It is not only my job, but my passion.

My interest in weather started at a young age while growing up in south Florida. I wondered why thunderstorms so frequently popped up during the afternoon and why it would rain on one side of the street, but not the other. And then there was Andrew. The biggest weather event of my childhood and one of the most memorable hurricanes of all time, Hurricane Andrew is one of only three known Category 5 hurricanes to hit the United States. Though my family's property did not sustain damage in the storm, I vividly remember how it destroyed Homestead, Florida. I was curious to understand how hurricanes worked and how they caused such devastation. My memories from that hurricane stayed with me and helped set me on a path toward becoming a meteorologist.

It has been more than fifteen years since Hurricane Andrew, and I've lived through numerous devastating storms. Yet each time, I'm amazed at the powerful combination of wind and water—and how the pictures never do the weather, or the damage, justice. The damage wrought by Hurricane Katrina in Gulfport, Mississippi, was so extreme that while reporting on location in the days following its landfall, I felt as if I were on a movie set. It was hard to believe that wind, waves, and water could gut buildings, move mammoth casinos, and wash away people's homes, memories, and lives. It was hard to wrap my brain around the fact that much of the destruction along the coast had come from surge from the Gulf of Mexico, which by then had turned back into its more well-known sleepy and relatively motionless self. Indeed, less than twenty-four hours earlier, this calm body of water had been awakened and stirred, and it had annihilated nearly this entire community.

That's another reason weather is so captivating: it's a force of nature beyond our control. Severe weather is also intriguing because it's not something we live through on a daily basis. And yet, even when our region is calm, we can watch severe weather unfolding far beyond our lives, in another area of the world, on TV. And that's where this book comes in. *The AMS Weather Book* gives you the science behind your world—whether it's in your immediate environment or on screen.

Believe it or not, both what we think of as good and as bad weather are key to sustaining life as we know it on this planet. In simplistic terms, weather happens because temperature differences exist on earth. This book elegantly depicts weather as the process by which the atmosphere moves toward equilibrium, no matter if it's through an intense ice storm, severe flooding, or a basic sunny day. It includes personal stories of survival through which you can understand what it is like to live through severe weather—and learn what to do if you are in a similar situation.

Weather is always around us, ever changing, and often challenging to experience. From my perspective, it's important that everyone have an understanding of how weather works—when you gain knowledge, you gain power, the power to better protect yourself and your belongings when severe weather strikes your town. While the science of it all can sometimes seem intimidating, books like *The AMS Weather Book* make it easier to understand.

Stephanie Abrams
On-air meteorologist
The Weather Channel

Atlanta, Georgia
Fall 2008

A brief look at the topics and themes you'll find in the coming pages

"Everybody talks about the weather, but nobody does anything about it." How many times have you heard that saying? The first part of it is true. Everyone talks about the weather because it affects all of us all the time. But as you will read in the chapters ahead, there are many people who are doing a lot about the weather by conducting research, developing increasingly accurate computer forecasting models, and creating better and more sensitive instruments to monitor the atmosphere. Storms like Hurricane Katrina, as a recent and dramatic example, represent the violent side of the atmosphere and strike fear into our hearts, but the only remedy for fear is knowledge. This is the book for those who want to learn more about how the weather works and enjoy the process.

After Hurricane Katrina hit on August 29, 2005, the photograph on the previous two pages and others like it began popping up on Web sites and landing in e-mail boxes. The caption identified it as Hurricane Katrina making landfall. A few weeks later, while I was eating lunch in the National Center for Atmospheric Research (NCAR) cafeteria in Boulder, Colorado, someone mentioned these photos. We had a good laugh about how people will believe anything. The photo is obviously a powerful Great Plains thunderstorm, not a hurricane.

I realized later, however, that the misidentification is not really all that obvious unless you know more about weather than most people.

That realization helped crystallize one of my thoughts about this book, then just the glimmer of an idea I had discussed with the American Meteorological Society (AMS), and what it should accomplish. That is, it should help readers look at the sky (or photographs of the sky) with an informed appreciation of what they're seeing. It should also help readers understand news about weather and climate, cope with weather threats (including the different dangers presented by hurricanes and the storm in the photo), and learn how the atmospheric and oceanographic sciences are a part of the story of human understanding of the physical world.

This book is written for anyone who is curious and excited about weather and how the atmosphere works. Instead of writing a textbook that covers only hard science, we developed a book that focuses on the human side of the atmospheric sciences. It includes stories about people coping with weather events or working to improve understanding or forecasts of them, as well as a number of brief profiles of men and women whose professional lives focus on weather, oceanography, or climate. We also have 123 explanatory graphics, because the old saying about a picture being worth a thousand words applies to many scientific concepts.

The book uses a historical approach to explore topics, ranging from the blue sky in Chapter 1 to the ozone hole in Chapter 12, because the story of how scientists came to understand a phenomenon can help you understand it.

With a subject as big as Earth's atmosphere and oceans, we cannot go into immense detail on the many related topics addressed. To help you further these explorations, this book's accompanying Web site at http://www.amsweatherbook.com/ has links to other sites and recommendations for books and articles that further examine the topics in this book, as well as related topics that the book doesn't cover. Information usually found in footnotes is also on the Web site.

Now back to the photo in question. Two of my associates weighed in that day in Boulder: Peggy LeMone, an NCAR scientist profiled in Chapter 2, and Bob Henson, who's with NCAR media relations and author of the *Rough Guide to Weather 2* and the *Rough Guide to Climate Change 2*. Both agreed that in a hurricane, visibility wouldn't be as good as in this photo, because hurricanes are very humid, with haze, low clouds, and rain restricting visibility. Also, clouds in hurricanes don't have the structure of the cloud in the photo. The cloud that's shown almost touching the ground is a **wall cloud**. (Note that boldface type indicates the book's first use of a word or term that's defined in the Glossary in the back of the book.) It's attached to the bottom of a kind of long-lasting thunderstorm known as a **supercell**, which is characterized by an area of rotation known as a **mesocylone**, perhaps ten miles or so in diameter. Henson noted that the most obvious sign of a mesocyclone in the photo is the banded region with a corkscrew look above where the wall cloud meets the cloud above. Hurricanes are made of organized groups of smaller thunderstorms and do not contain supercells.

Henson knew that Mike Hollingshead, a storm chaser from Blair, Nebraska, shot the photo. According to Hollingshead's Web site, it was taken near Alvo, Nebraska, in the late afternoon of June 13, 2004, and soon after he took the photo, small tornadoes formed under the left side of the cloud. This brings us to the dangers from such clouds and how they differ from those posed by hurricanes.

Supercells can produce the strongest tornadoes. If you ever see a cloud that looks like this one, head for a place where you can find shelter from a tornado. As we discuss in Chapter 8, forecasters can predict where and when tornadoes are most likely to develop, but not exactly where and when one will hit. You have, at best, only minutes to take shelter from a tornado. With hurricanes, on the other hand, forecasters can almost always give you plenty of time to find a safe place.

As with almost every topic covered in this book, the Web site has more about this photo and links to other sites, including Hollingshead's. Use the "Comments and Questions" link on the site's home page to ask us about anything you can't find.

But first, join us in the chapters ahead as we unravel the mysteries of how the atmosphere and oceans produce the weather and climate that are a big part of our lives. We begin coverage of our weather topics in Chapter 1 by discussing science and the famous weather disasters that have caught the public's attention. In Chapter 2, we embark on a detailed exploration of the science of weather and oceanography, including how energy from the sun powers Earth's weather and how the atmosphere and oceans move energy around the Earth, creating its many different climates.

In Chapters 3 and 4, we cover the basic science of the forces that create winds, clouds, rain, snow, ice, and other aspects of weather. In Chapter 5, we put these pieces together to see how they create the global weather patterns that cause not only our daily weather but also the earth's overall climate, including changes in Earth's climate.

After seeing how weather is observed and forecast in Chapters 6 and 7, we turn to particular kinds of weather events, including thunderstorms and tornadoes in Chapter 8, middle-size weather systems such as clusters of thunderstorms in Chapter 9, hurricanes in Chapter 10, and some of the kinds of dangerous weather you seldom see on the evening news, such as dangerous heat, in Chapter 11.

Our exploration culminates in Chapter 12 with a look at the science related to one of the most important and often discussed issues of our time, a discussion without which this book would not be complete: how Earth's climate is changing.

—Jack Williams
Washington, D.C., Winter 2008


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How to cope with disaster, live with the weather, and enjoy the sky's wonders and science

CHAPTER 1

At 10:11 a.m., Sunday, August 28, 2005, Robert Ricks, a **meteorologist** at the National Weather Service (NWS) office in Slidell, Louisiana, sent an electronic bulletin reading: "Devastating damage expected…Hurricane Katrina…a most powerful **hurricane** with unprecedented strength…rivaling the intensity of Hurricane Camille of 1969. Most of the area will be uninhabitable for weeks…perhaps longer."

His bulletin warned: "Airborne debris will be widespread…and may include heavy items such as household appliances and even light vehicles. Sport utility vehicles and light trucks will be moved. The blown debris will create additional destruction. Persons…pets…and livestock exposed to the winds will face certain death if struck."

Ricks predicted the aftermath: "Power outages will last for weeks…water shortages will make human suffering incredible by modern standards."

Ricks, who was born in New Orleans, knew his audience: "People who were on the fence, trying to make the decision to finally leave. I grew up in this area, I know people who never leave the city; their lives are confined to their neighborhood. It disturbs their comfort zone when they are asked to leave." In fact, he said of his father, who died in June 2005, "Had he still been alive for the storm, it is uncertain if he would have stayed, as [he had] in past storms."

Previous pages: A helicopter carrying Federal Emergency Management Agency urban search and rescue workers flies over flooded New Orleans five days after Hurricane Katrina hit Louisiana and Mississippi.

During the forty-eight hours after Ricks sent his bulletin, Katrina moved inexorably inland with destructive power matched by few storms. The experiences of his extended family—uncles, aunts, cousins, their spouses, children, and grandchildren—mirror those of many of the more than a million men, women, and children in Louisiana, Mississippi, and Alabama. Ricks was fortunate in that none of his extended family members were among Katrina's estimated 1,600 fatalities.

Evacuation plans that Ricks and his immediate family made before Katrina threatened New Orleans ensured that his wife, Cynthia; their teenage son and daughter, Joshua and Lauren; and their miniature dachshund, Cocoa, would spend August 29 with relatives in Church Point, Louisiana. There they experienced generally sunny skies as Katrina wrecked New Orleans 100 miles to the east.

One of his aunts, Teresa Ricks, evacuated her home in Waveland, Mississippi before the storm. When Katrina's **eye**, with the storm's strongest winds swirling around it, came ashore at Waveland, the storm surge washed the house off its foundation, destroying it. Ricks' stepmother, Cathy Ricks, fled before the storm with her two sons and other family members to Millington, Tennessee, outside Memphis. Katrina destroyed her home in the New Orleans suburb of Poydras.

Other relatives decided to stay despite Ricks' calls urging them to flee. One of his aunts, Sylvia Guerin, argued that she had to stay to open her restaurant, Pudgy's Stuffed Potatoes in Chalmette, after the storm. She was among twenty relatives who stayed together at the two-story house of an uncle.

By the way, the restaurant that Ricks' Aunt Sylvia stayed behind to open the next morning blew up from a gas leak during the hurricane.

According to Ricks, "Shortly before Katrina's strongest winds hit, they were outside thinking, 'Man, is this all it's going to be?' Then they heard a roar and looked up the street to see a wall of water. They got inside and tried to shore up the door. Someone saw a wall bulging in. The house started to flood. I had told them to expect overtopping of levees, and they were well prepared with a boat." They shuttled everyone to a Mississippi River levee, about three blocks away, to ride out the storm.

Ricks says overtopping or failure of three levees allowed water from three directions to advance toward his uncle's house, putting it under fourteen feet of water. But the Mississippi River levee, in the area where the family found refuge, held. One thing that Ricks and his relatives know (as do most people who grow up in a flood-prone area) is that "if there's a flood, go to the levees. It's the high ground."

A success and a failure

It's hard to imagine that by Sunday morning, August 28, New Orleans had more than a few residents or visitors who didn't know that a Category 5 hurricane, with winds up to 160 mph and perhaps 20 feet of storm surge, was headed for them. The surge was bound to cause flooding when it washed into the marshes and waterways between the city and the Gulf of Mexico and into Lake Pontchartrain at the city's northern boundary. The National Hurricane Center had issued a hurricane watch Saturday morning that included metropolitan New Orleans. Hurricane Center forecasts every six hours since then had made it clear that Katrina would hit as a major storm with winds faster than 111 mph. In Chapter 10, we look at how meteorologists made these forecasts, which were extraordinarily accurate.

For decades, hurricane scientists and forecasters had been predicting a weather disaster for New Orleans that could match or exceed the 1900 Galveston, Texas, hurricane, which killed at least 8,000 people. Newspapers, including the *Times-Picayune* in New Orleans; magazines; television programs; and books had all described what could happen when—not if—a major hurricane hit New Orleans. As Ricks told NBC's Brian Williams on September 15, 2005, "We always prepare for the big one; we just didn't think it was going to come this soon."

Despite the knowledge of the potential for such a hurricane, and forecasts that gave more than two days' warning, Katrina turned out to be one of the deadliest natural disasters in U.S. history.

Katrina could have been much worse. Years of news stories about the consequences of a major hurricane and the Katrina warnings, including the one Ricks sent out that Sunday morning, prompted an estimated 85 percent of the approximately 1.2 million people in the storm's target areas to leave. Previous surveys and studies had concluded that perhaps 50 percent of New Orleans residents would leave. We have no way of knowing how many evacuees would have died had they not fled. Photos of the **flood** water and damage in New Orleans, and of entire Mississippi communities washed away by Katrina's storm surge, offer strong evidence that thousands more would have died had they stayed.

In the days after Katrina, the news media's focus wasn't on the success of prompting thousands to evacuate, but on the hundreds trapped in New Orleans. The paradox of Katrina is that the response both succeeded marvelously and failed miserably. Obviously, accurate weather forecasts aren't enough. Perhaps even more disturbing is that coastal residents can't always count on as much warning as the National Hurricane Center gave for Katrina, especially for a major hurricane. The 1935 Labor Day hurricane was the strongest ever to make landfall in the United States, and it haunts hurricane forecasters and emergency managers to this day. It grew from a **tropical storm** with winds slower than 65 mph in the Bahamas to a Category 5 hurricane hitting the Florida Keys in less than 48 hours.

Katrina intensified the debate in the United States about how lives can be saved and damage can be reduced in future weather catastrophes. As Jeff Rosenfeld, the editor in chief of the *Bulletin of the American Meteorological Society (BAMS)*, wrote in the November 2005 issue, "The death toll from Katrina…was indeed closer to that of 9/11 than any homeland disaster in the last 60 years. And the costs from Katrina will be several times that of the terrorist attacks."

Rosenfeld argued that, "For too many of us, a Katrina was too remote, too incomprehensible, or simply too gargantuan. A near-miss bombing in lower Manhattan in 1993 and mounting intelligence did not lead to enough prevention to avoid the destruction of the World Trade Center. Neither did the near miss of Hurricane Georges [in 1998] or countless scientific studies about every imaginable aspect of New Orleans' vulnerability save enough lives or prevent over $100 billion damage on the Gulf Coast."

Living with weather

Hurricanes are just one of the many weather and climate issues that nations and societies around the world will face in the coming years and decades. In this chapter and in the following chapters, we examine how weather and climate work and some of the things you can do to live more comfortably and safely with the weather.

Good sense says you should know about weather dangers whether you live along the U.S. Gulf of Mexico or Atlantic coasts, where a hurricane could hit; in the Southeast or Great Plains, where fierce tornadoes are most likely; or on a California hillside, which winter rain could turn into a slurry of sliding mud, rocks, and debris.

During television interviews in Katrina's aftermath, some residents compared the dangers of living near the Gulf of Mexico with the **tornado** danger on the Great Plains. Such comments reflect a stunning lack of comprehension of the relative dangers. Even the worst tornado outbreak cannot lay waste to hundreds of square miles the way that Katrina and many smaller and weaker hurricanes have done.

Most places have their particular weather dangers. Floods kill people in areas that are normally wet as well as those that are normally dry. Lightning is a danger anywhere you hear thunder.

While dramatic storms might be frightening, weather in general need not be feared. As with many things that inspire fear, knowledge can be the antidote, especially if you use that knowledge wisely. Ricks, for instance, used his meteorological knowledge and bought a house high enough and far enough away from the water to avoid storm-surge flooding. It's on the north side of Lake Pontchartrain, across the lake from New Orleans and 39 feet above sea level. "I have a love for the water," he says, "and would have loved to live closer to the lake," but he didn't want to worry about flooding. He was worried, however, about trees falling on the house. Ricks says his family doesn't regret evacuating even though 100 mph winds and a nearby tornado did no serious damage to the house; staying would have been frightening.

His family's evacuation plan exemplifies the preparations that anyone who lives along the U.S. Gulf or Atlantic coasts should make before the hurricane season begins each year. The plan had options of going east, north, or west depending on where Katrina seemed likely to head. They had a reservation at a hotel in Biloxi, Mississippi, if east were the way to go, and arrangements to stay with a Weather Service colleague near Jackson, Mississippi, if north were the safest direction. Based on the forecast, they decided that the third option, heading west to stay with relatives in San Antonio, Texas, was the best choice. Cynthia Ricks and their children left on Sunday morning a couple of hours before her husband sent the bulletin. He had gone to work at 4 a.m. at the Slidell NWS office, forty miles northeast of downtown New Orleans on the north side of Lake Pontchartrain, for the twelve-hour shift that everyone there works during emergencies. Ricks brought with him five days' worth of food and clothing because everyone at the office knew he or she could be stuck there for days in Katrina's aftermath.

Even though Cynthia Ricks and the children didn't wait until the last minute to leave, evacuees were clogging highways heading west. What should have been a three-hour drive to the area of Church Point, Louisiana, took nine hours. With Church Point unlikely to be in Katrina's path, Cynthia Ricks elected to stay with relatives there rather than risking another twelve or more hours in traffic trying to reach San Antonio.

More than disasters

Fortunately for most of the world, especially the more populated areas, the weather is good much more often than bad, even considering disagreements about what constitutes good and bad weather. Think back on your life and how often you had to take special precautions (or wish you had) because of weather. Unless you've gone looking for trouble, days when the weather required precautions were almost certainly rare.

Most bad weather days aren't caused by extreme events, such as Hurricane Katrina, but are what Roger Pielke Jr. of the Cooperative Institute for Research in Environmental Sciences (CIRES) and Richard Carbone of the National Center for Atmospheric Research (NCAR), both in Boulder, Colorado, refer to as "routinely disruptive weather." In their article, "Weather Impacts, Forecasts, and Policy" in the March 2002 issue of *BAMS*, they define such weather as "not extreme, but significant enough to warrant behavioral adjustments." Such events could include snow that requires you to shovel your driveway before driving to work on roads that have been plowed.

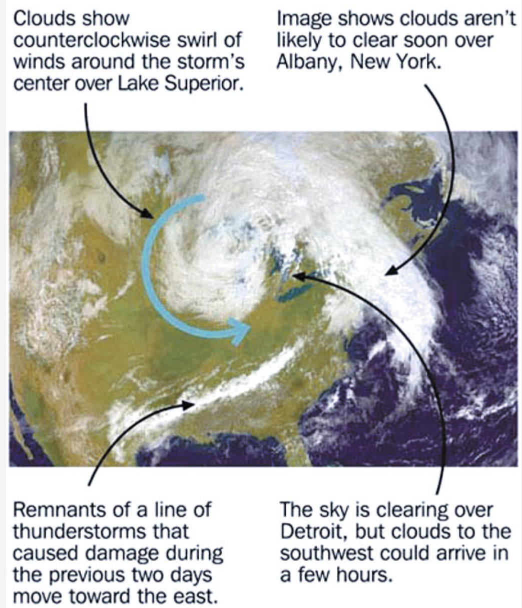
If the **atmosphere** is behaving the way most people would like, and you've decided how to dress to go outdoors today, you might be finished thinking about the weather for that day. In fact, maybe you think that only meteorologists and a few hobbyists with backyard weather instruments really care about the weather.

That's not the case, however, because weather, good and bad, is a part of the economy. Exactly how big a part is an open question because, as Pielke and Carbone write in their 2002 article, "There is no centralized collection of data and no standardized methodology" for assessing weather's economic effects.

Even though the costs of weather and benefits of forecasts are hard to pin down, economists and others try to do just that. For instance, The National Oceanic and Atmospheric Administration (NOAA) says in its 2006 report *Economic Statistics for NOAA* that industries affected the most by weather and climate account for about one-third of the nation's gross domestic product, or $4 trillion in 2005 dollars. Such industries include finance, insurance, real estate, retail and wholesale trade and manufacturing, agriculture, construction, energy distribution, and outdoor recreation.

Satellites give the big picture

This weather satellite image shows a storm that formed over the western Plains and moved into the Midwest with high winds and tornadoes. The worst was over at the time of this image, 11 a.m. on April 12, 2001. The image shows that clouds over most of the eastern United States are part of the same system—Chapter 5 explains how this works.



In this book, capitalized "Weather Service" and "NWS" refer to the U.S. National Weather Service.

If you're a regular air traveler you're sure to have experienced weather effects on aviation. The Air Transport Association reports that air-traffic delays cost the airlines $6 billion a year, with weather causing 70 percent of these delays. Major disasters such as Katrina, which closed airports in New Orleans and some nearby places for weeks, add to aviation's weather costs. But routine weather, such as small **thunderstorms**, fog, and low clouds that cause flight delays and cancellations, are much more frequent than major disasters, and their total cost is higher than the costs of disasters to individual airlines. Weather also adds to the costs of traveling or shipping on highways and railroads. NOAA says clearing snow from streets, roads, and highways costs $2 billion a year in the United States. A big Northeastern U.S. snowstorm that shuts down cities from Washington, D.C., north to Boston, can cost $10 billion a day in lost retail business, wages, and tax revenues.

Weather and climate forecasting and research are large enterprises. The federal government spends approximately $3 billion a year for meteorological operations and research. While the NWS is the government's main forecasting agency (it also conducts some research), several other agencies, including the Defense Department, have large weather operations. Federal agencies, colleges and universities, and other institutions conduct weather research using government, foundation, and other funds. In addition, about 400 private companies provide weather forecasts and other weather-related products with annual revenues estimated to be in the $500 million range.

The book *Railroads and Weather* by Stan Changnon, published by the American Meteorological Society in 2006, provides a comprehensive account of the effects of weather on the American railroad industry.

Statistics and dangerous weather. Statistics on the number of deaths and amount of damage from different kinds of weather help officials decide what types of forecasts are most needed and where research funds should be spent. Such statistics show you what kinds of weather you should worry about. But weather death statistics aren't as reliable as we'd like.

Nine geographers at Arizona State University and the University of Arizona spotlighted this problem with a study in the July 2005 *BAMS*. It points out that the U.S. National Climatic Data Center's *Storm Data* monthly bulletin lists "excess heat" as killing many more people than cold weather, while figures from the National Center for Health Statistics show four times more people dying from "excessive cold" than from heat. The article says the discrepancies arise from different ways of collecting data and different standards for determining the major cause of death. With heat deaths, for example, someone who dies of heat stroke is obviously a victim of hot weather. But when an 85-year-old man with several health problems who's taking a half dozen medications dies in his nursing home that's not air conditioned—as happened to many victims of the 2003 heat wave in France—is he a victim of advanced age or of the heat?

Weather-related traffic accidents are the biggest U.S. weather-related killers. The Federal Highway Administration and the National Oceanic and Atmospheric Administration (NOAA), which includes the NWS, estimate that weather- related road accidents kill 7,000 people and injure more than 600,000 each year in the United States.

Another complication arises from trying to determine whether someone is a direct or indirect victim of an event. A woman killed by flying debris during a hurricane is a direct victim. But how about someone killed in an accident at an intersection where the traffic light is still dark three days after the hurricane knocked out power? A medical examiner could decide that the death was caused by the hurricane or that it was an ordinary traffic accident.

Unclear distinctions between direct and indirect deaths usually account for discrepancies in news media reports. The NWS usually lists only direct victims, while other officials might include indirect victims, with differing criteria for determining who was a victim. The chart, below, shows U.S. weather deaths reported by the NWS. While the exact figures, especially for heat and cold deaths, can be disputed as we saw above, they give you a sense of the relative dangers of various kinds of weather. Katrina and other 2005 hurricanes changed the U.S. ten-year average annual hurricane death rate from 21 for the ten-year period from 1995 to 2004, to 117 for the ten years ending in 2006.

Not all gloom, doom, and economics. Understanding weather and forecasts involves more than avoiding disasters and saving or making money. Knowing about the weather helps you appreciate the world around you. The weather is also an accessible way to develop at least some appreciation for science and how scientists work. To study the weather as an amateur you don't need to buy expensive equipment; all you need to do is walk outdoors, or even look out the window as people have always done. But you also have ways of looking at the weather that your ancestors could have only dreamed of.

Average yearly U.S. weather-related deaths 1997–2006

Heat	170
Floods	74
Tornadoes	62
Winds	47
Lightning	44
Winter storms	41
Cold	18
Hurricanes	117

We are living in a golden age for those who consider themselves weather weenies (those for whom weather is a passion bordering on obsession). Computer and Internet access brings you weather data that only researchers and forecasters saw a quarter of a century ago, such as minutes-old **weather satellite** images of all parts of the earth, current weather in places as remote as the South Pole and as near as the school down the street, and regularly updated weather charts of current and forecast conditions for both the surface and aloft from around the world.

Folklore and science

Of course, long before computers, Internet access, and ubiquitous satellite coverage, weather had a profound influence on human lives and activities, and people struggled to make sense of how the atmosphere behaved with only the most basic information.

Indeed, earlier in human history, people ascribed weather events, good and bad, to spirits, gods, or other mysterious causes beyond human understanding. In one way or another, many people saw the weather in terms of "theological **meteorology**," as David Laskin puts it in his book *Braving the Elements: The Stormy History of American Weather*. Laskin describes how the Puritan settlers of New England saw the weather from their arrival in 1620 until well into the eighteenth century: "Drought, flood, severe cold, unbearable heat, deadly blizzard, and life-giving spring rain: these were all taken without question as the work of God—or the devil."

Farmers and sailors had practical reasons for trying to forecast the weather, and close observations of the clouds, the winds, and other weather elements allowed for some success. Often these observations were the basis for weather proverbs, which can at times offer some guidance about what to expect, especially in the next few hours.

Weather proverbs. Before technology advances changed the science dramatically, weather "forecasts" were based on simple observations of the sky and pattern recognition. This led to the development of weather proverbs, or "rules," that helped provide some idea of weather to come.

For example, a proverb such as "ring around the moon, we'll have rain soon" can sometimes work. High clouds made of ice crystals cause the thin rings you see around the moon or the sun. Such high clouds are often the leading edge of a large storm system, which could bring rain or snow in the next day or two. Proverbs like this one, which have to do with the kinds of clouds combined with the direction the wind is blowing, are most likely to have at least a little value.

Sayings involving animals are generally useless unless they refer to the weather in the near future. Changes in humidity and air pressure that precede some storms can affect animal behavior. When it comes to predicting what a coming season will be like, we have no reason to think animals have any worthwhile weather information. As an example, let's consider the winter prediction folklore about woolly bear caterpillars. These caterpillars, if they survive, will emerge from their cocoons as Isabella tiger moths. The caterpillars are a couple of inches long and mostly black but with a brown band around their middle. Folklore holds that if the brown band is narrow, the coming winter will bring deep snow. But this has no basis in science, which is based on observable phenomena governed by physical laws. In attempting to confirm that woolly bears have some forecasting skill, a scientist would have to collect data over at least a few winters and compare the width of woolly bear bands and snowfall during the subsequent winter. At the least, statistics for such a study would have to show the woolly bears' "forecasts" are better than those you would produce by flipping a coin and predicting a snowy winter when heads comes up. For future winter weather to affect a woolly bear's coloration the previous fall, something would have to happen in the atmosphere that fall to cause heavy snow in the caterpillar's location the following winter. The caterpillar would have to receive a signal that the atmospheric phenomenon is occurring that fall and this would somehow have to trigger growth of color bands.

Some global weather patterns do affect future weather events, and researchers have learned how to detect and use these signals. For example, some of the best-understood patterns involve changes in summer and fall Pacific Ocean temperatures, which forecasters use to predict the odds of North American weather patterns during the coming winter.

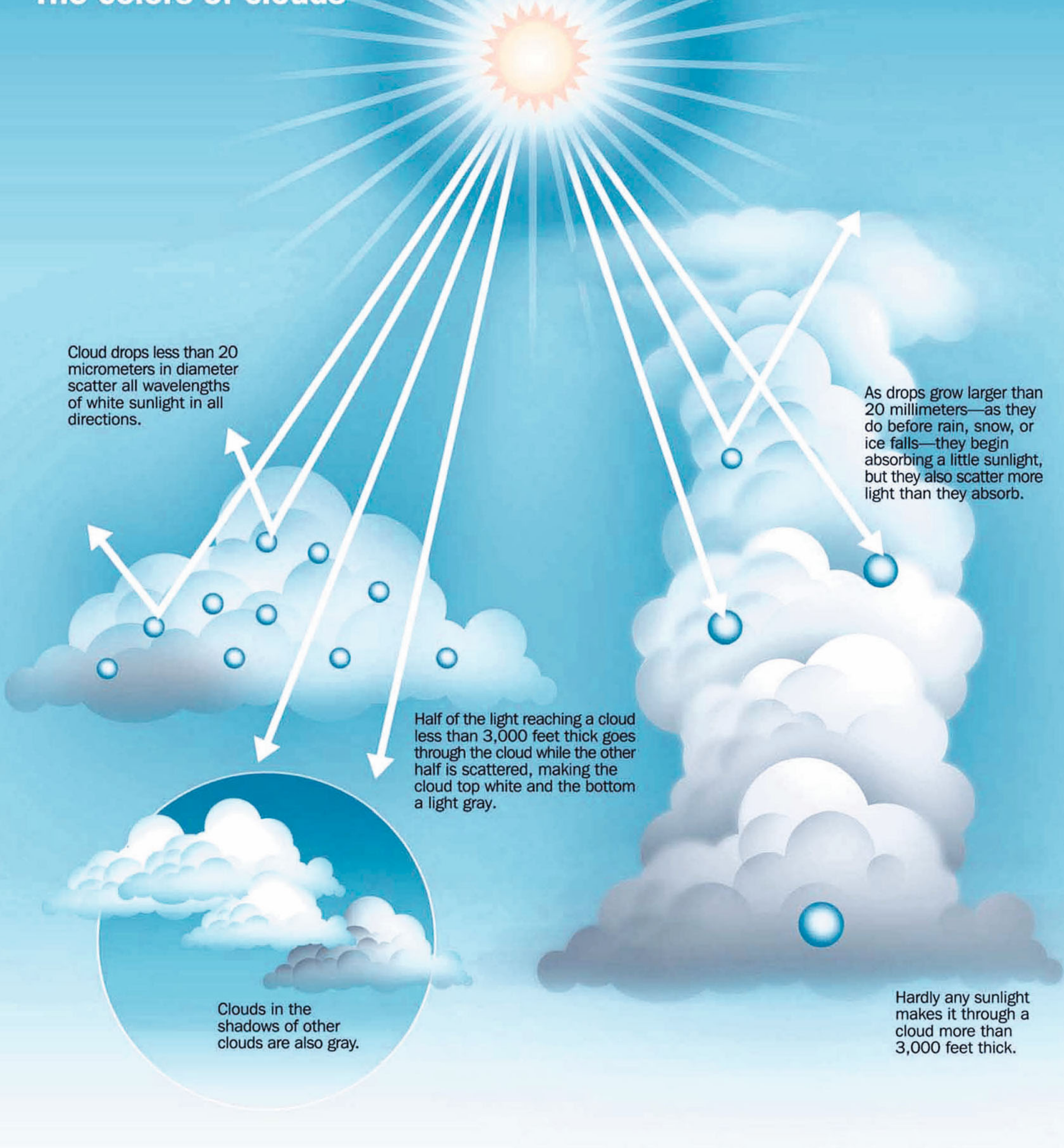
Sky and science

If we are going to understand how the atmosphere actually works and how storms such as Hurricane Katrina behave, it is necessary to go beyond weather proverbs and woolly bears. The sky is a good place to begin. It is always changing. In the sections below, we'll briefly introduce the science

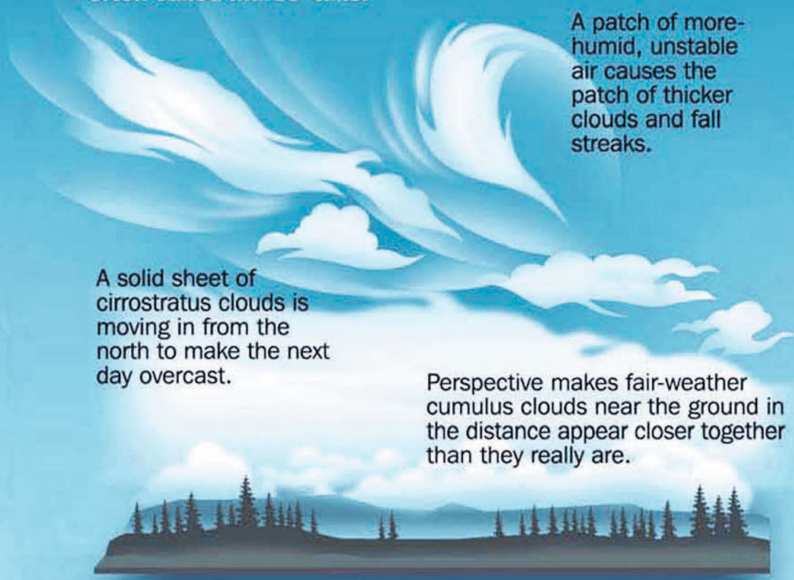
A gallery of clouds

Clouds form and stay in the sky only when the air is rising—sometimes only inches per hour, at other times at 100 mph. In Chapter 4, we see how clouds form and sometimes produce rain, snow, or ice and why some clouds are flat stratus clouds, while others are piled-up cumulus clouds.

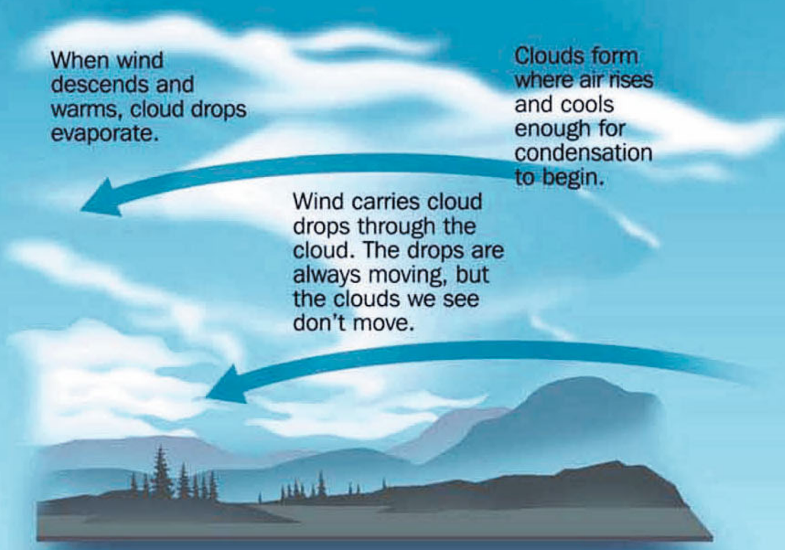
The colors of clouds



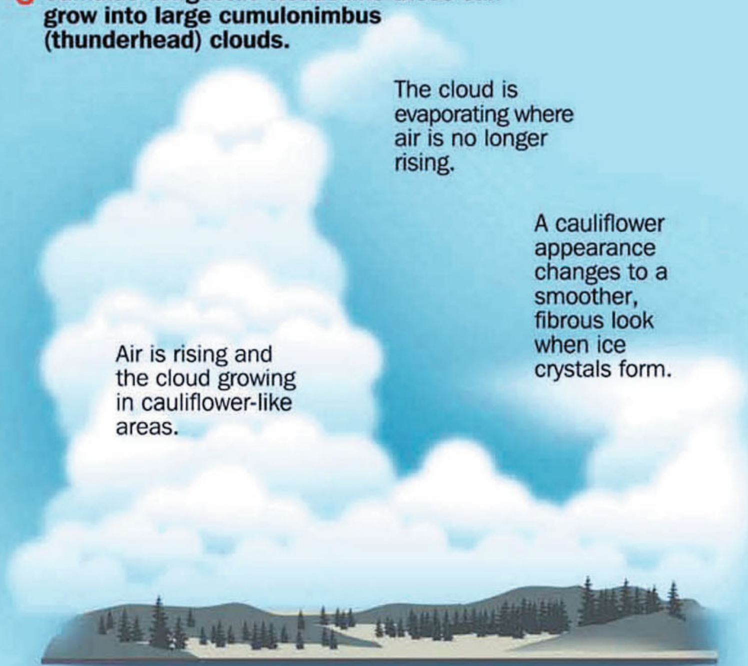
1 Fall streaks are ice crystals that are being pushed by high-altitude winds as they fall from tiny, puffy clouds, which are hardly visible at the tops of the streaks. Fall streaks are often called mares' tails.



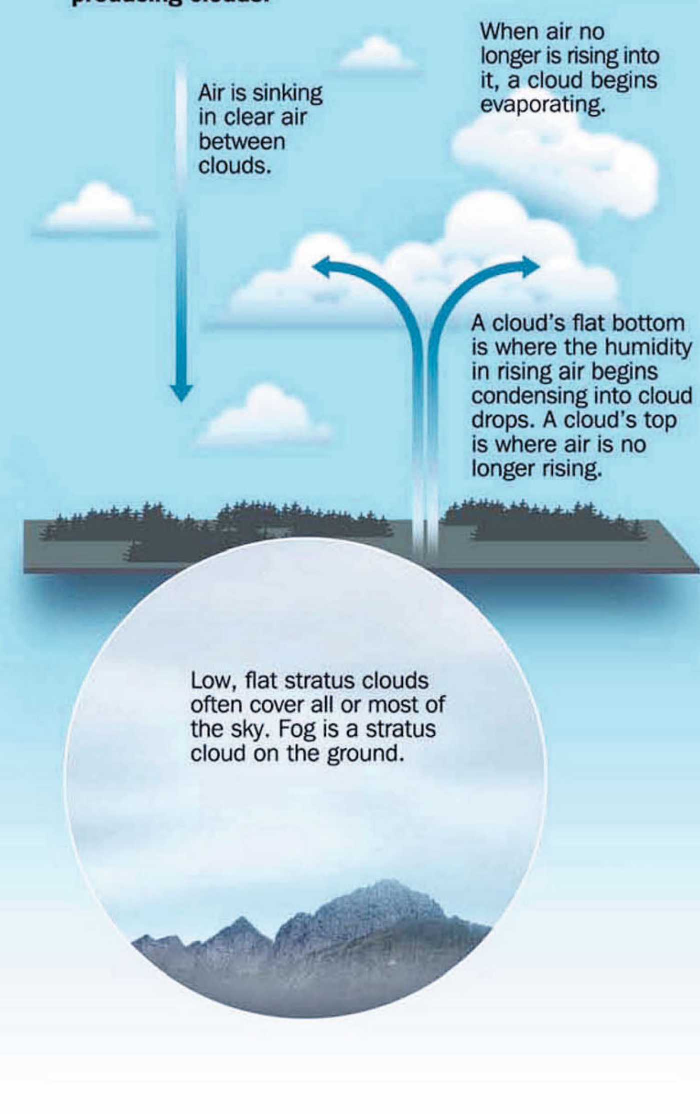
2 Lenticular clouds like the ones below are commonly seen downwind from mountains. Wind blowing over the mountains from the right continues rising and then descends as shown by the arrow on the drawing.



3 Cumulus congestus clouds like these can grow into large cumulonimbus (thunderhead) clouds.



4 Fair-weather cumulus clouds like these don't produce rain or snow. Sometimes, however, clouds that look like fair-weather cumulus grow into larger, precipitation-producing clouds.



of the sky by taking a look at clouds and displays of light in the sky such as rainbows, and we'll also answer the age-old question of why the sky is blue.

A focus on clouds. Richard Hamblyn's book *The Invention of Clouds* is a biography of Luke Howard (1772–1864). His system of naming clouds is still in use today, with only a few modifications. He first presented his system to the public at a December 1802 evening lecture in London, which was an immense success.

By that time, scientists were developing the general picture of clouds being formed when water vapor condenses into drops of water or turns into ice crystals, but the science of clouds and precipitation was just beginning. Howard's talk included his watercolors of clouds as illustrations. With Howard's lecture, Hamblyn says, "Nineteenth-century meteorology took off with a public conversation set high amid the region of the clouds. It was a bold beginning both for a new century and a new science."

Rainbows. When most people see a rainbow, its beauty strikes them. There's more than meets the eye, however, namely the science of optics and even the wider science of physics and the general history of science.

Our very brief history of rainbow science begins with the Greek thinker Aristotle, who thought that rainbows were reflections from clouds. The obvious problem with this concept is that you often see a rainbow with no cloud behind it. And it doesn't explain the colors of rainbows.

As with most of the learning of the Greeks, the Islamic world's scholars preserved and added to Greek science during Europe's Dark Ages. One of the key contributions Islamic scientists made toward understanding the rainbow is the concept of **refraction**, or the bending of light as it passes from air into water and then back into air, as light hitting a raindrop does to form a rainbow.

In *The Rainbow Bridge: Rainbows in Art, Myth, and Science,* Raymond L. Lee Jr. and Alistair B. Fraser note that one of the key contributors to the Islamic science that leads directly to today's understanding of rainbows was the mathematician, physicist, and physician known in the West as Alhazen (Abu Ali al-Hasan ibn al-Haytham in full), who lived from 965 to 1040. They describe how he blended meticulous optical experiments and mathematical analysis to lay the foundations of later rainbow science.

As Europe emerged from the Dark Ages and more and more works of Islamic science were translated into Latin, European scientists continued adding to the understanding of many phenomena, including rainbows. In the 1630s, the French philosopher René Descartes (1596–1650) carefully measured the angles of light rays as they passed through a glass sphere filled with water. He derived what we know as Snell's law of refraction, without knowing that the Dutch physicist Willebrord Snell (1580–1626) had derived it mathematically in 1621. Descartes also calculated that the light rays that cause a primary rainbow reflect once from the back of a water drop and are also refracted as they enter and leave the raindrop, and that light rays that cause a secondary rainbow are actually reflected twice. While Descartes' explanation of the rainbow's shape holds up well, it doesn't explain the colors. In the mid-1660s, Isaac Newton (1643–1727) filled in that gap with experiments showing that a prism breaks sunlight into several colors. Each color is refracted by a different amount as it enters the prism or enters and leaves a water drop. Newton, who believed that light is made of particles, argued that different colors are different kinds of particles, but that idea wasn't satisfactory because it couldn't explain other aspects of light.

Other scientists of Newton's time thought that light moved as waves, not particles. Both theories explain most aspects of light, but by early in the nineteenth century, experiments had shown that some light phenomena can be understood only if light travels as waves. In the 1860s and 1870s, the British scientist James Clerk Maxwell (1831–1879) demonstrated that light can be understood as a combination of electric and magnetic waves, which helped make the wave **theory** of light dominant. Even more importantly, light waves are only a part of the much larger **electromagnetic spectrum**, which includes radio waves, **infrared energy**, ultraviolet waves, microwaves, and more. The light waves responsible for rainbows are related to the waves used for weather radar; satellite observations, which include more than visible light images; and microwave technologies that help scientists collect vital measurements of phenomena from the winds in a hurricane to the ice floating on the Arctic Ocean.

Meteorology and meteors

Today the word meteorology refers to the study of atmospheric phenomena. It comes from a Greek word that referred to all phenomena in the sky.

English speakers use the word **meteor** for the streak of light—often called a shooting star—seen as an object traveling through space enters the earth's atmosphere and friction heats the object to a burn. Unless the object is a spacecraft, it's called a **meteoroid** once it enters Earth's atmosphere. Any part of a meteoroid that doesn't burn and reaches the earth's surface is a meteorite.

Meteorologists talk about **hydrometeors**, wet things in the air such as raindrops; **electrometeors**, any visible or audible indicator of atmospheric electricity including lightning, thunder, and auroras; **lithometeors**, anything in the air made of mostly solid, dry particles such as dust and volcanic ash; and **photometeors**, any luminous optical phenomena in the atmosphere such as a rainbow.

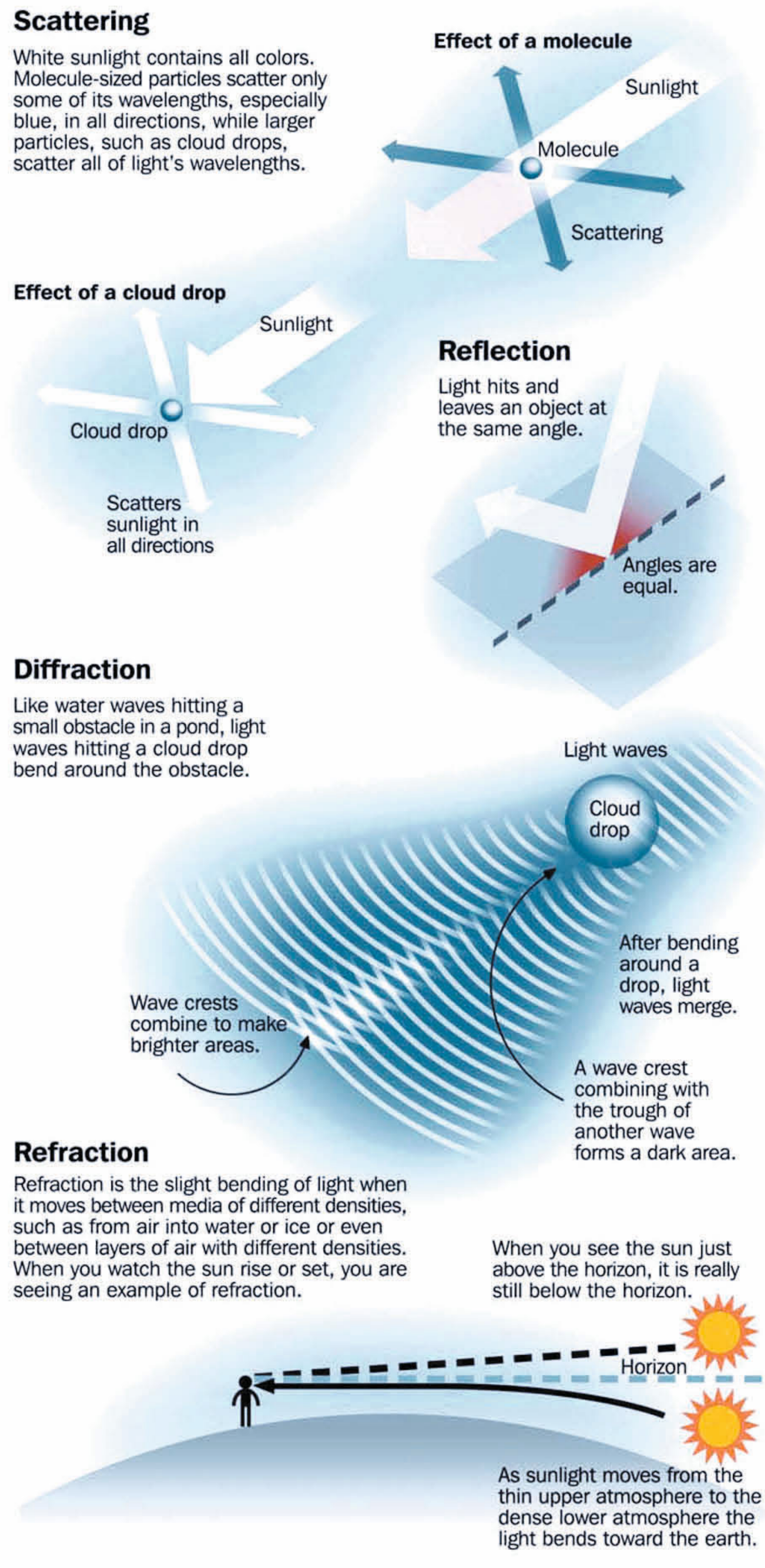
While equations and experiments treating light and other electromagnetic phenomena as waves led to theoretical and practical advances, including radio, television, and radar, the particle theory of light didn't die. Scientists continued to face the apparent paradox that light has properties of both waves and particles. The development of quantum mechanics early in the twentieth century resolved this apparent paradox. We won't get into that in this book, but it does illustrate that looking at the sky can be a purely aesthetic experience, or it can provide a window into the physical principles underlying many scientific disciplines.

Not all splotches or arcs and lines of color you see in the sky are rainbows. In fact, most of them are not. You can't see a rainbow unless the sun is behind your head and drops of water are in the air where you see the rainbow. These drops can be a distant rain shower, a waterfall, or even from a lawn sprinkler.

If the sun isn't directly opposite the "rainbow," you are looking at a **halo**, a **corona**, or maybe **iridescence** in a cloud. The term corona can be con-

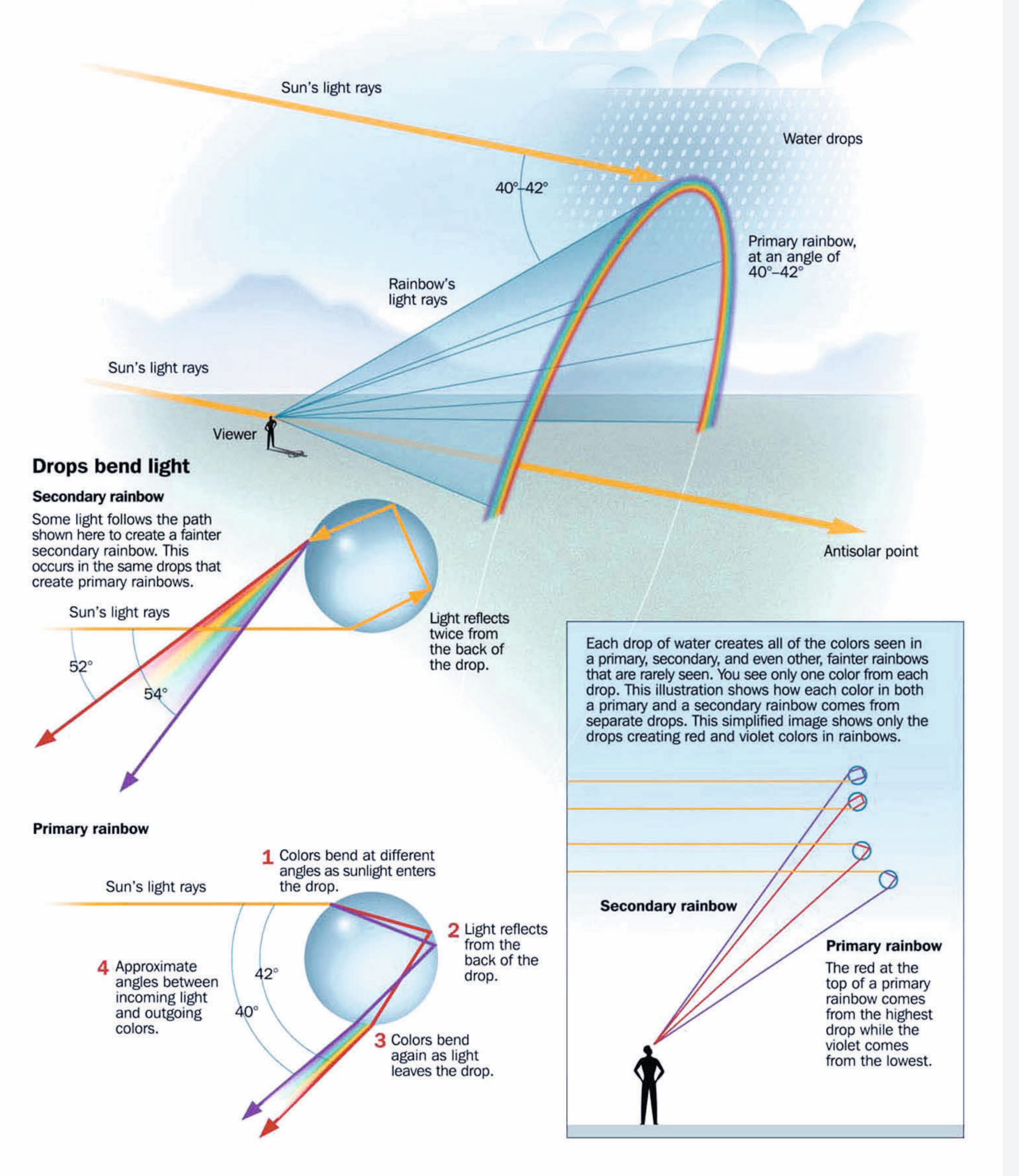
How the atmosphere bends light

The air's gas molecules plus particles in the air, such as dust, pollution, drops of water, and ice crystals, bend light in several ways, as this graphic shows. Most of this chapter's other graphics show some of the effects of bending light.



How water drops make rainbows

You see a rainbow only when the sun is behind you, as you look toward water drops in the air. Light is refracted (slightly bent) as it enters a drop, reflected from the back of the drop (sometimes more than once) and refracted again as it leaves the drop.



fusing because it refers to both the sun's outer atmosphere, which can be seen during eclipses, and to a disc of light surrounding the moon or the sun. Light being diffracted as it passes through clouds causes coronas and iridescence. If a circle of colored light (the colors could be faint) looks like it is touching the moon or sun it is a corona. A corona is usually the ring around the moon that can be a sign of coming rain.

Omens and wonders in the sky. Once you learn a little about meteorology and start looking at the sky, you'll find you can amaze others by pointing out phenomena such as halos and sun dogs, which are caused by sunlight being refracted, or bent, by ice crystals.

Sun dogs—their more formal name is parhelia—on either side of the sun are the most common kind of halo. Across most of North America you might see at least one sun dog every few days when high, thin clouds cover at least part of the sky.

To see if a narrow streak of light circling or partly circling the sun is a 22-degree halo or a splotch of light is a sun dog, extend your arm and spread your fingers. If your thumb is over the sun, the tip of your little finger will touch or be very close to a 22-degree halo or a sun dog.

When you see a sun dog or sun dogs and the sun is about 15 to 25 degrees above the horizon, look straight up. If the cloud causing the sun dog stretches to the zenith—the sky directly above you—you have a good chance of seeing a circumzenith arc as well, as Warren Tape and Jarmo Moilanen say in their book *Atmospheric Halos and the Search for Angle X*. If you watch the sky, you have a good chance of seeing a circumzenith arc maybe twenty-five times a year.

On rare occasions, conditions are right for displays of several kinds of halos at the same time. In the distant past, when people saw anything out of the ordinary in the sky, such as a comet or a display of several halos, they often interpreted the phenomenon as omens. Such events could cause consternation. In their book, Tape and Moilanen show a seventeenth-century engraving of a halo display over Nuremberg, Germany, on April 19, 1630. The engraving's text warns: "God threatens through word and deed, and God threatens through Nature."

While many in the seventeenth century likely felt uneasy at the sight of halos in the sky, a few were seeking what caused them, including Descartes. In 1637, Descartes suggested that giant rings of ice in the sky caused sun dogs. While we know now that Descartes was wrong, we have to realize that neither he nor anyone else in his time had any way of knowing that rings of ice do not form in the sky or that cirrus clouds are made of tiny ice crystals that cause halos. In 1662, the Dutch mathematician and astronomer Christian Huygens (1629–1695) worked out a theory of halos. Using the geometry of how light rays could be bent, he showed that transparent cylinders of water or ice with opaque cores could create a display that looked somewhat like a sun dog. He extended his idea to show how such cylinders could cause other halos.

It's time to retire Roy G. Biv

In addition to their scientific and cultural interest, rainbows are also a prime example of how students, even in primary school, should develop a scientific attitude that asks "is this true?" when what they see doesn't agree with what they are told.

For years, American school children have been told that the name "Roy G. Biv" will help them remember the colors of the rainbow. If you search the Web for "rainbow colors" you'll find sites, including some purporting to be educational, selling the idea of Roy G. Biv for the colors red, orange, yellow, green, blue, indigo, and violet as the "colors of the rainbow."

But anyone who looks at a real rainbow will tell you that Aristotle's idea that the rainbow has three colors comes closer to being the case than Roy G. Biv. Lee and Fraser write in *The Rainbow Bridge*, "The number seven derives not strictly from visual observation but also from Newton's belief that sight and hearing are related. Because each musical octave contains seven tones and semitones, he reasoned that the spectrum should have seven colors."

Here the halo science story takes a turn that shows science is far from being as straightforward as you might think from reading science textbooks. In 1681, the French scientist Edme Mariotte (1620–1684) proposed that small ice crystals, which act like prisms, could bend light to cause halos. He even showed how a particular kind of crystal could form a 22-degree halo and, when turned in a different direction, could create sun dogs.

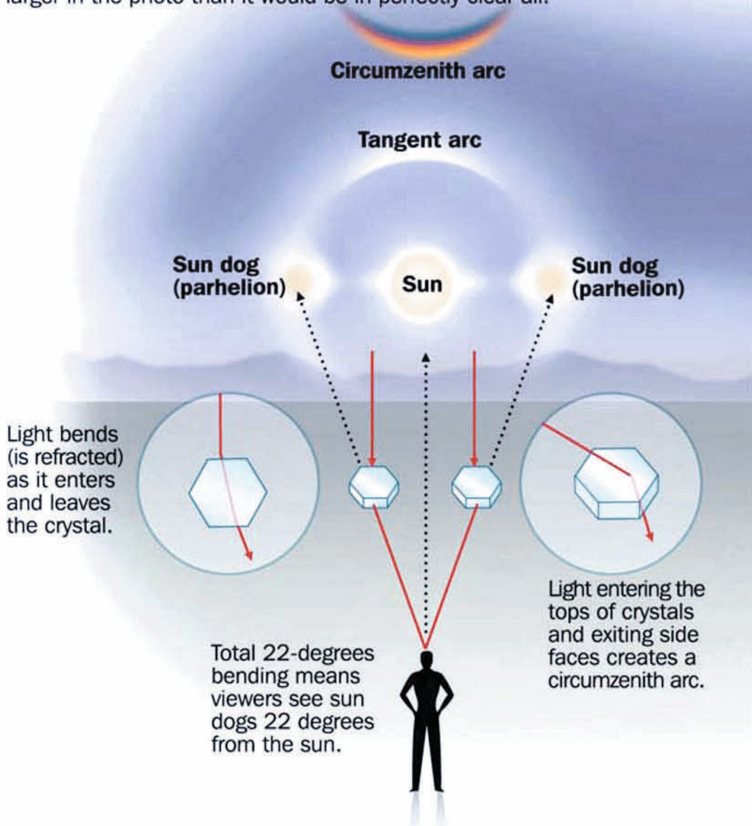
Through the centuries, artists have depicted rainbows in myriad ways that offer a window on the artist's culture. For an interesting look at this topic, see Lee and Fraser, *The Rainbow Bridge: Rainbows in Art, Myth, and Science*.

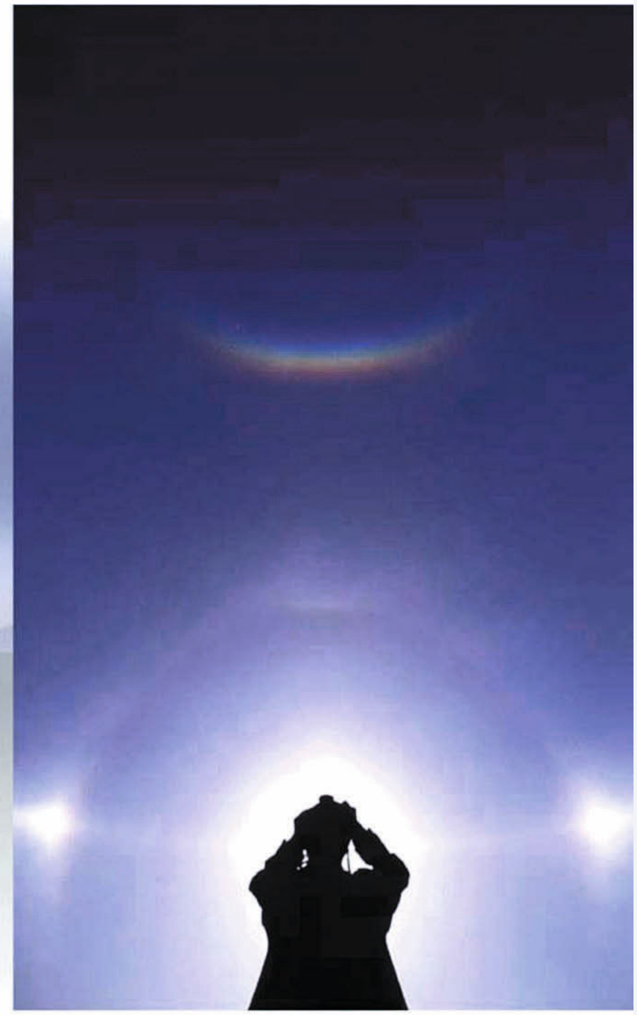
Today we know Mariotte was on the right track, but he was ignored until early in the nineteenth century because no one had any way of testing the differing hypotheses of Huygens and Mariotte. Both made fairly good predictions for 22-degree halos and sun dogs, which were the only kinds of halos scientists considered. However, at the beginning of the nineteenth century when scientists began trying to explain less-common kinds of

Ice crystals create halos

Flat ice crystals falling with their hexagonal faces down form the sun dogs on both sides of the sun and also the circumzenith arc overhead in the photo. Crystals with different shapes and orientations create other kinds of halos, including the 22-degree halo around the sun and the tangent arc.

Because of space constraints, the sun dogs and circumzenith arc below are drawn closer to the sun than in the photo. Forward scattering of sunlight by tiny particles in the air creates a solar aureole that makes the sun look larger in the photo than it would be in perfectly clear air.





Ken Tape takes a picture of his father, Walter, observing a halo in northern Alaska; Ken used his father's head to block the sun and capure the display on camera.

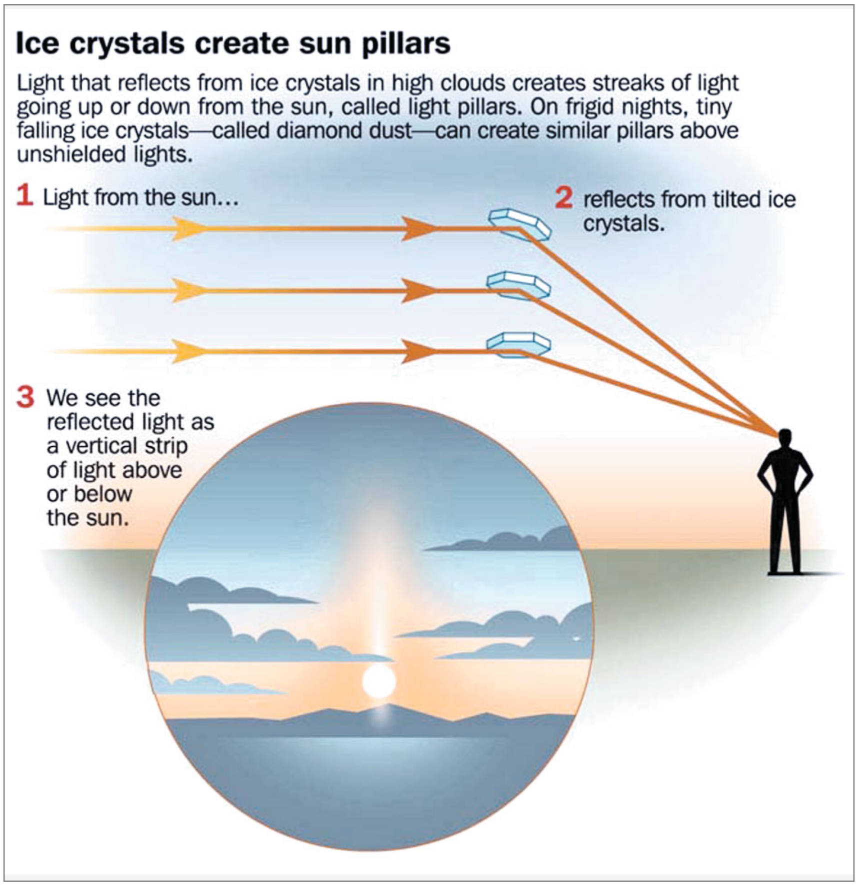
halos, they recognized the superiority of Mariotte's hypothesis. The evidence for Mariotte's hypothesis has continued to grow. For instance, scientists now make direct observations of high clouds by going up in airplanes to capture ice crystals, which they examine under microscopes. (We will read about one of these scientists in Chapter 4.)

Generally, when you see a 22-degree halo or a sun dog, the ice crystals responsible are more than 20,000 feet up. If you live, or have ever lived in a place with cold winters, you've surely seen evidence that ice crystals that create halos can float in the air very near the ground.

One of the kinds of halos you sometimes see high in the sky is a sun pillar, which looks like a streak of light coming down from the sun toward the earth or, if the sun is low in the sky, a streak shooting up from the sun. On a still night when the temperature is well below freezing, the air can be filled with tiny ice crystals known as diamond dust. On such nights, you sometimes see narrow beams of light going up from the uncovered tops of lights such as streetlights.

To see really spectacular halo displays, you should head for the polar regions, to places such as the U.S. Amundsen-Scott Base at the South Pole, where the highest temperature ever recorded is 8 degrees above zero Fahrenheit. Tape notes that while "the polar regions tend to have better halos than elsewhere, nobody really knows why. Cold by itself is not an explanation since high clouds in **temperate climates** are plenty cold."

Unlike the men and women of seventeenth-century Europe who feared that God was sending warnings, the men and women at the South Pole on January 11, 1999, relished the spectacle when



at least twenty-two different forms of halo graced the sky during a display that lasted fifty minutes.

"We knew we were witnessing something extraordinary. Of course, every moment at the bottom of the earth is extraordinary, but this was more exciting than usual," says Mary E. Hanson, a National Science Foundation public affairs officer.

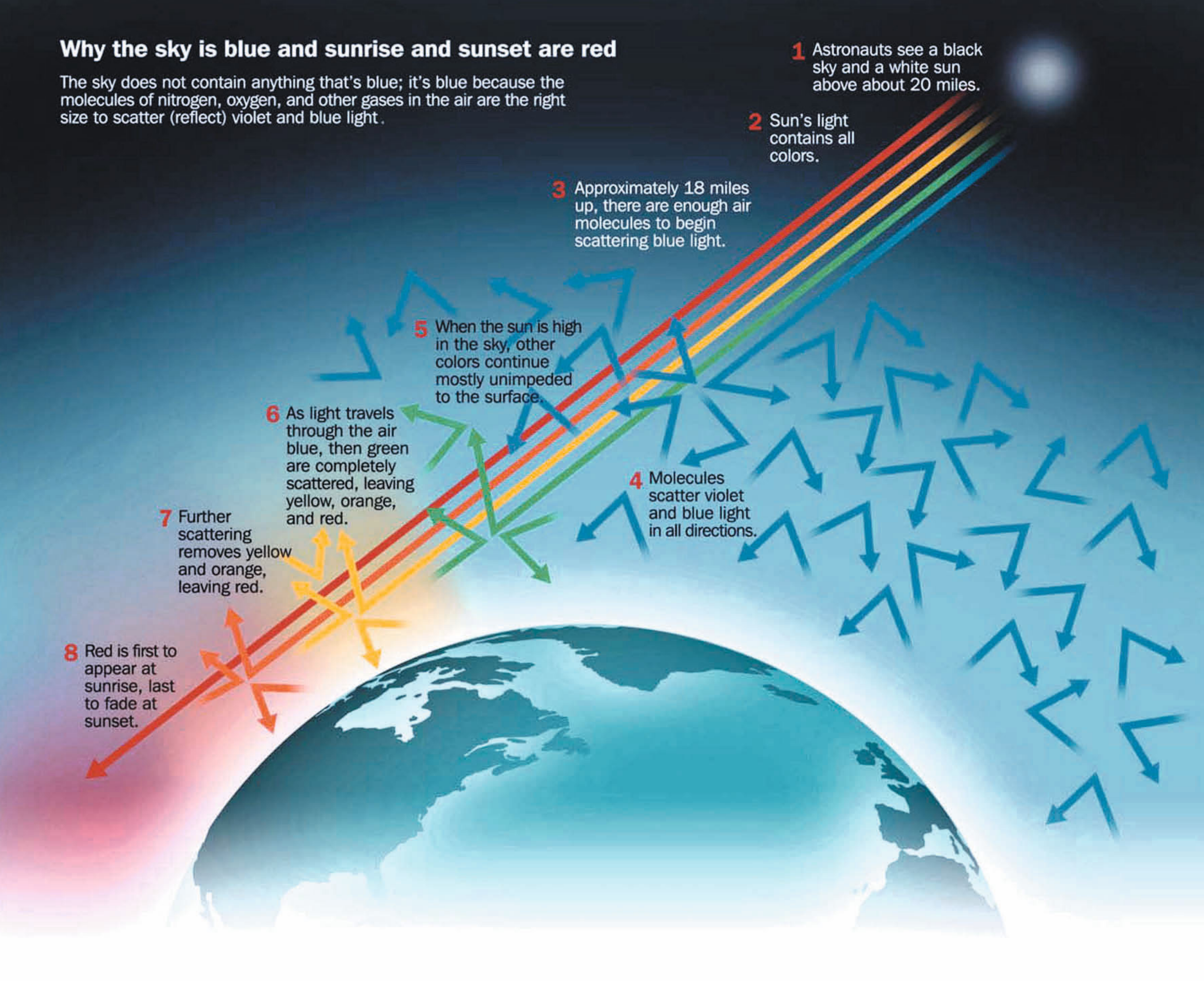
"It was one of those crispy-clear days, and the sky and ground both seemed sprinkled with diamonds. Then these bands of translucent shimmer started to appear in the sky…lots of them. If you were a religious person, you might have thought they were heavenly beings or angels. We didn't know what they were until the Finnish scientists told us. They were as excited as the typically reticent Finns are likely to get. (I'm a Finnish-American so I can say that.) That's how I knew it was a true scientific phenomenon."

Jarmo Moilanen (co-author of *Atmospheric Halos),* Marko Riikonen, and Marko Pekkola were the three Finnish scientists studying halos at the South Pole that year. In addition to taking hundreds of photographs of the displays they saw, the Finns captured crystals from the air to study under a microscope. Riikonen explains, "relating the halos and ice crystals is nowadays pretty much computer business. You take photos of the display and simulate it by experimenting with differently shaped crystals in different orientations until you get a result that matches the display. Taking ice crystal samples can further confirm that the crystal shapes used in simulations are roughly correct."

Scientists in the nineteenth and early twentieth centuries worked out the mathematics of the shapes and orientations of ice crystals needed with the sun at various altitudes above the horizon to form certain kinds of halos. But many of the formulas were too complex to easily calculate until scientists started using computers. The fact that computers can churn out different representations of halos for various crystals and sun angles doesn't mean, however, that discoveries aren't waiting to be made. Tape and Moilanen say that researchers still have much to learn. "We have no doubt," they write, "that with increased awareness new halos will be seen and photographed." They say that "anyone who has modest camera equipment and is alert for what to watch for can make a contribution." Their book includes a guide to halo photography.

In common use a halo is circular in shape, but scientists who study atmospheric optical phenomena have extended the term to refer to all photometeors, including rings, arcs, pillars, or bright spots, around the sun or moon that are caused by clouds made of ice crystals or by ice crystals floating in the air.

Why is the sky blue? Scientists know now that molecular scattering of blue light turns the sky blue, but this knowledge was not easily gained. The British physicist John William Strutt (1842–1919), who was the Third Baron Rayleigh and is usually referred to as Lord Rayleigh, developed the theory of electromagnetic scattering in the 1870s. To scatter **electromagnetic radiation**, particles have to be much smaller than the wavelength of the radiation. The amount of scattering depends on both the wavelength of the radiation, such as light, and the



size of the particles. As it turns out, the molecules of nitrogen and oxygen, which account for 99 percent of the air's molecules, are more efficient for scattering the wavelength of blue light than the wavelengths of other colors.

The discovery of Rayleigh scattering explained why the sky is blue, a question that scientists had been trying to answer since the time of the Greeks with no success. Previous ideas based on the scattering of light by water drops, water vapor, or dust particles in the air did not stand up to scientific scrutiny.

Even more importantly, the discovery that the sky is blue because the molecules of the air scatter blue light more efficiently than other wavelengths helped confirm the hypothesis that all matter is made of extremely tiny atoms and molecules (which are made of atoms). Rayleigh's theory also enabled scientists to calculate the size of the air's molecules (since earlier experiments had established the wavelengths of different colors of light). The idea of atoms had been around since the time of the Greeks, but nineteenth-century scientists were making an increasingly compelling case for it. For instance, Maxwell, whose electromagnetic theory we discussed above in relation to rainbows, also helped develop the theory that the heat we feel results from the motion of molecules.

Maxwell's suggestion to Rayleigh that scattering by the molecules of the air could explain why the sky is blue, led him to consider the problem over several years and eventually do the calculations showing that molecules are the right size to scatter blue light, making the sky blue. Over the years, laboratory experiments and other evidence have confirmed this. A blue sky is more than a blue sky; it helps tell the story of how scientists go about understanding the physical world.

Summary and looking ahead

If you can't imagine yourself becoming a scientist or meteorologist, you are likely a daily consumer of weather information. This information could be as simple as what you see when you look out the window before leaving home each day. Most people also obtain weather information from radio, television, the Internet, or a newspaper.

Many people preparing to make a major purchase, such as a new car or house, or an investment decision, first research the topic, often at great length. They want to become educated consumers. Becoming an educated consumer of weather information isn't likely to save you a lot of money, but it can make your life easier and could even help you avoid disaster. This book will guide your efforts to become an educated weather consumer.

As an educated weather consumer, you'll be able to make better use of weather forecasts, because you'll know what they can and can't tell you. For instance, reliable, detailed predictions of which days will be wet and which will be dry more than a week or so in advance aren't possible.

Another important aspect of using weather forecasts is that you often have to make decisions, perhaps life and death decisions, based on probabilities, not categorical facts such as "the winds ARE going to blow faster than 100 mph tomorrow." The Hurricane Katrina forecasts for New Orleans are a perfect example of how your responses to forecasts have to be based on probabilities, not a firm statement that 100 mph winds will hit your neighborhood tomorrow. At 10 a.m. on Saturday, August 27, 2005, when the Hurricane Center issued the hurricane watch that included New Orleans, the odds were only 19 percent that Katrina's eye would pass within seventy-five miles of the city.

When Ricks issued his bulletin at 10 a.m. on Sunday (as described at the beginning of this chapter), the odds of Katrina's center passing within seventy-five miles of New Orleans had risen to "only" 35 percent.

Landfall of a major hurricane over a particular area on a particular day is an extremely rare event. For the sake of argument, let's say that such an event occurs every 50 years during the hurricane season at a specific location vulnerable to hurricanes. Given that the hurricane season is roughly 150 days, the observed probability for the event would be approximately 1 in 7,500, or 0.013 percent. When the forecast probability (in this case 35 percent) vastly exceeds the observed probability of a rare and potentially catastrophic event, be prepared to take cover.

Next we will begin our detailed exploration of the science of weather and oceanography by discussing, in Chapter 2, how energy from the sun powers Earth's weather and how the atmosphere and oceans move energy around the earth, creating its many different climates.

At meteorology's center

No history of the atmospheric sciences since World War II is complete without the stories of Joanne and Bob Simpson.

When forecasters said Katrina was a "Category 5" hurricane, the number referred to the scale that Herbert Saffir created in the 1960s and Bob Simpson modified in the early 1970s when he was director of the National Hurricane Center (NHC). Research flights that scientists made into Katrina were carrying on work he had initiated in 1945.

Bob and Joanne Simpson at the Roosevelt Roads Naval Air Station in Puerto Rico in 1964 after a Project Stormfury flight in the Navy WC-121 Super Constellation behind them.

In Chapter 5, we will see how the Hadley circulation in the tropics helps drive the atmosphere's global circulation. Today's meteorologists consider the work of Joanne Simpson and Herbert Riehl, published in 1958, the basis of our current understanding of the Hadley circulation.

In addition to being the first scientist to conduct hurricane research from airplanes, Bob proposed, organized, and initially ran the National Hurricane Research Project, which began in 1956. It is the forerunner of today's NOAA Hurricane Research Division. In 1964, when he was the Weather Bureau's deputy director of research, Bob established the National Severe Storms Laboratory in Norman, Oklahoma, which among its many accomplishments developed Doppler weather radar.

Bob began his meteorological career in 1939 with a $1,440-a-year, entry-level job at the U.S. Weather Bureau but quickly advanced, working as a forecaster in New Orleans and Miami and studying at the University of Chicago. In 1945 the Bureau sent him to Panama to help the Army Air Forces establish a tropical weather forecasting school. While there, he organized and flew on the first hurricane research flight.

Joanne began her meteorological career after earning her bachelor's degree at the University of Chicago in 1943. She taught weather to aviation cadets at the University of Chicago and New York University while completing her master's degree in meteorology at Chicago. When World War II ended, she, like other women who had been doing "men's work," was expected to get married and settle down as a housewife. But, "I didn't want to go home and mop the floor." Instead, in 1947 she became the first woman in the world to earn a PhD in meteorology. Her dissertation was about tropical clouds, a topic then considered outside the meteorological mainstream.

At the time, Bob was one of the few other scientists interested in tropical weather. He headed Bureau operations in Hawaii and the Pacific from 1948 until 1952 and was assigned to the Bureau's Washington, D.C., Headquarters before and after that. When he could get away from his other duties, he hitched rides on military hurricane reconnaissance flights. These convinced him that scientists needed focused research flights to learn how hurricanes work.

Neither the Eisenhower administration nor Congress saw a need for hurricane research until hurricanes Carol, Edna, and Hazel hit the East Coast in 1954, doing at least $750 million (in 1954 dollars) in damage and killing more than 150 people. The resulting outcry led Congress to fund the National Hurricane Research Project, which the Weather Bureau appointed Bob to organize and run.

The Bureau asked leading atmospheric scientists to advise and participate, including Riehl and Joanne. By the mid-1950s, Joanne had become internationally known for her work on tropical weather and clouds.