Climate Change From Pole to Pole

BIOLOGY INVESTIGATIONS

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Juanita Constible, Luke Sandro, and Richard E. Lee, Jr.

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Part I—The Science of Climate Change

Part II—Climate Change Case Studies

How to Use This Book

"One of the biggest obstacles to making a start on climate change is that it has become a cliché before it has even been understood."
—Tim Flannery, *The Weather Makers,* 2005

"In order to understand scientific issues, you have to have a clear picture of what science is and what scientists do."
—Moti Ben-Ari, *Just a Theory: Exploring the Nature of Science,* 2005

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Topic: Nature of science, 9–12
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This book is about the *science* of climate change, not the political issues it has generated. Part of our goal in writing it is to help you and your students become more scientifically literate about an important global issue. In broader terms, we want to suggest ways you can use the topic of climate change to demonstrate the nature of science.

Part I, "The Science of Climate Change," includes four chapters of background information on climate and how it is changing. The chapters in Part I are suitable as reference material for busy instructors who just want "the basics" or as classroom readings for advanced high school students or nonscience majors. We have broken each chapter into short, relatively self-contained sections to make it easier to find specific topics. Chapter 1 introduces climate (including the natural greenhouse effect) and its importance to life on Earth. Chapter 2 outlines some of the methods and evidence used by scientists to detect and explain climate change. We focus on changes that have already occurred, rather than predictions of future change. Chapter 3 is an overview of the biological effects of climate change, from the responses of individual organisms to those of entire ecosystems. Chapters 2 and 3 also contain sidebars (Nature of Science boxes) about the nature of science that can help you integrate scientific processes and results in your classroom discussions about climate change. Chapter 4 is a student-friendly overview of the concepts in the first three chapters.

Part II, "Climate Change Case Studies" includes six classroom investigations for use in high school or college-level science courses. Each investigation is a case study of a well-documented biological response to climate change. Students solve real-life scientific problems using guiding questions, data tables and graphs, short reading assignments, and/or independent research. To emphasize the cooperative nature of science, all of the investigations require group work. Chapters 5 through 10 are each organized as follows:

- The introductory "At a Glance" comments give you a quick overview of the investigation.
- The teacher pages, which begin each chapter, include background information and teaching notes (i.e., materials, procedure, assessment, and extensions) specific to the investigation.
- The student pages, which follow the teacher pages, include copy-ready data sets, readings, and worksheets.

You can use as many or as few investigations as you want, and in any order. The table on page xiv can help you choose those that are most appropriate for your classroom. If you teach high school, you also can find how each activity addresses the National Science Education Standards (NRC 1996) in Connections to the Standards, page 74.

Key terms are defined in the Glossary. They appear in **boldface** at their first mention in the background text. In Chapter 4, and the student pages of Part II, especially important key terms appear in boldface a second time.

The study of how climate and its natural cycles affect biological systems is more than 150 years old. The study of how *human-dominated* climate affects biological systems is relatively new. The vast majority of scientific information on this topic has been published only since 2003 and so is not available in popular books and news articles. Most of our references, therefore, are from the primary literature (i.e., articles from scientific journals) and the Fourth Assessment Report of the International Panel on Climate Change (Parry et al. 2007; Solomon et al. 2007).

There is broad consensus among scientists on how the climate is changing and why. We regularly monitored the scientific literature and a range of climate change blogs (e.g., *http://blogs.nature.com/climatefeedback; www.talkclimatechange.com; www.globalwarming.org)* to stay abreast of scientific developments and arguments "for" and "against" human-dominated climate change. Although a few scientists are not convinced by the data or analyses presented by their colleagues, in writing this book we have attempted to provide you and your students with the most up-to-date, mainstream science available. As we write these words, however, a scientist somewhere in the world is revising or adding to the larger body of knowledge about climate change. It is our hope that you or one of your students will contribute to that body of knowledge in the future.

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Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. 2007. *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Climate Change Case Studies (Chapters 5–10): Their Focus, Use, and Curriculum Connections

	Chapter 5 "Now You 'Sea' Ice, Now You Don't"	Chapter 6 "Population Peril"	Chapter 7 "Carrion: It's What's for Dinner"	Chapter 8 "Right Place, Wrong Time"	Chapter 9 "Ah-Choo!"	Chapter 10 "Cruel, Cruel Summer"
Focal Organism and Location	Adélie penguins, Antarctica	Polar bears, Canadian Arctic	Wolves, Wyoming, USA	Pied Flycatchers, Spain	Humans (allergies), Northern Hemisphere	Humans (heat wave mortality), Pole to Pole
Classroom Time (hours)	1–3.5	1.5–3.5	1–2.5	1.5–3	Minimum 2–3.5	Minimum 3–4
Relative Difficulty Level (1 = easiest; 3 = hardest)	1	1	2	2	3	3
Science Connections						
Scientific Process Skills	◆	◆	◆	◆	◆	◆
Ecology/ Evolution	◆	◆	◆	◆		
Environmental/ Earth Science	◆	◆	◆	◆	◆	◆
Human Health					◆	◆
Interdisciplinary Connections						
Mathematics/ Statistics			◆	◆		◆
Technology/ Computers					◆	◆
Social Studies	◆	◆	◆		◆	◆
Language/ Visual Arts		◆			◆	

About the Authors

Juanita Constible is a coastal Louisiana outreach coordinator with the National Wildlife Federation in Baton Rouge, Louisiana. After graduating with her MS in biology from the University of Victoria, Constible worked as a wildlife biologist in California, North Dakota, and Louisiana. She then spent three years as a laboratory and outreach coordinator at Miami University, in Oxford, Ohio. In that position, she coordinated professional development activities and an Antarctic outreach program for K–12 science teachers. She is the author of six research articles in scientific journals and seven articles in science education journals. This is her first book.

Luke Sandro received his MAT in biological science education from Miami University after exploring various other fields. He has been teaching biology at Springboro High School, in Ohio, for seven years. He loves teaching adolescents because it is never boring and because he gets slightly better at it every year. He has enjoyed working with Lee and Constible on research and educational outreach for several years and has learned much about science and writing from both of them. He has authored three research articles about insect cryobiology and five science education articles.

Richard E. Lee, Jr., is distinguished professor of zoology at Miami University. He received his BA from the College of Wooster (1973), and an MS (1976) and PhD (1979) from the University of Minnesota. His research focuses on physiological and ecological mechanisms of cold tolerance, dormancy, and the winter ecology of temperate and polar insects and other ectotherms. This research includes field work on Ellesmere Island in the High Arctic and five field seasons on the Antarctic Peninsula. Lee has published more than 200 articles, reviews, and book chapters and is senior editor of two books. He currently teaches courses in general entomology, winter biology, and environmental science for elementary teachers. Lee also is active in providing professional development opportunities for teachers. For the past 15 years, he has co-directed an environmental science program at a field station in Wyoming for more than 1,200 Ohio elementary teachers.

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Chapter 1
Climate and Life

CLIMATE BASICS

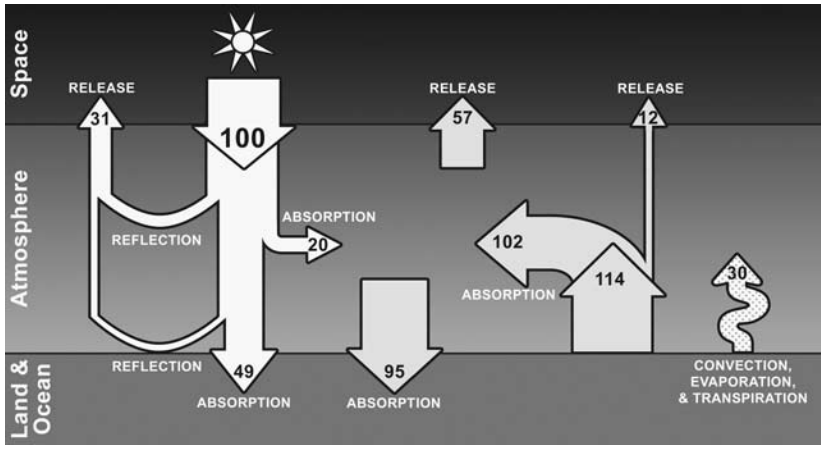
Climate is the state of the atmosphere over years or decades. Although *climate* is commonly defined as "average weather," the term encompasses more than a simple mean. It also refers to variability, seasonality, and extremes in climate elements such as temperature and precipitation (Hartmann 1994). Earth's climate is controlled by a complex, interactive system composed of land, water, snow and ice, organisms, and the atmosphere (Landsberg and Oliver 2005).

SCILINKS THE WORLD'S A CLICK AWAY
Topic: Radiation
Go to: *www.scilinks.org*
Code: CCPPO3

Earth's Energy Balance

The Sun powers Earth's climate system. Although the Sun emits **radiation** across the electromagnetic spectrum, the bulk of solar energy is visible, or **shortwave**, radiation (0.4–0.7 microns) (McArthur 2005). A fundamental property of the physical world is that the energy of a system remains constant. On an annual and global basis, solar energy entering Earth's climate system is balanced by reflection of shortwave radiation and eventual emission of **longwave**, or **far infrared, radiation** (4–100 microns) (Figure 1.1, p. 6). About 30% of incoming solar energy is reflected back to space by clouds, particles in the atmosphere, or light-colored substances on Earth's surface. The remaining 70% of incoming solar energy is absorbed by the climate system and eventually emitted back into space as longwave radiation (Landsberg and Oliver 2005).

Figure 1.1



Energy balance of Earth's climate system. The solid white arrows represent shortwave radiation emitted by the Sun. The solid gray arrows represent longwave radiation emitted by Earth's surface and atmosphere. The stippled arrow represents sensible and latent heat transfer (see "Global Circulation," p. 7). The numbers in the head of each arrow refer to the energy equivalent of a portion of solar radiation entering the atmosphere. Incoming solar radiation (100%) is balanced by the release of both shortwave (31%) and longwave (57%+12%) radiation. However, because energy is recycled between Earth and the atmosphere (see "The Natural Greenhouse Effect," below), the land and oceans emit the equivalent of 114% of incoming solar radiation.

Source: Course S250_3, The Open University, *http://openlearn.open.ac.uk/course/view.php?id=2805*. © 2007, The Open University. Modified with permission.

The Natural Greenhouse Effect

SCILINKS
THE WORLD'S A CLICK AWAY
Topic: Greenhouse gases
Go to: *www.scilinks.org*
Code: CCPPO4

Solar radiation travels unimpeded through space until it encounters matter such as dust or gas. When radiation encounters matter, it may change direction without a loss of energy (scattering or reflection), pass through the matter unchanged (transmission), or be retained by the matter (absorption). The behavior of radiation depends on the physical characteristics of the matter and the wavelength of the radiation itself (Mills 2005).

Each gas in the atmosphere has a different absorption profile for short- and longwave radiation. In broad terms, transparent gases transmit radiation and opaque gases absorb it. The dominant constituents of the atmosphere—oxygen, nitrogen, and argon—are transparent to most incoming shortwave and most outgoing longwave radiation. **Greenhouse gases**, such as water vapor and carbon dioxide, are relatively transparent to shortwave radiation but opaque to longwave radiation. This selective absorption of radiation causes the natural **greenhouse effect** (Hartmann 1994).

The greenhouse effect is a process by which radiation is "recycled" between Earth and the atmosphere. Greenhouse gases in the atmosphere absorb about 20% of incoming solar radiation and more than 90% of longwave radiation emitted by the planet's surface (Figure 1.1). Much of the absorbed energy is later emitted downward, again as longwave radiation (Mills 2005). The atmosphere and the Sun actually heat Earth in roughly equal measure. Without the greenhouse effect, Earth's mean temperature would be about 33°C cooler than it is now (Pitman 2005). It is important to note that the atmosphere slows the loss of energy to space but does not *permanently* trap energy.

The term *greenhouse effect* is not completely accurate because a greenhouse doesn't heat air the same way the atmosphere heats Earth. Greenhouse gases mainly warm the atmosphere by delaying the loss of outgoing longwave radiation to space. Glass greenhouses, by contrast, mainly warm air by preventing **convection** (i.e., mixing of warm air inside the greenhouse with cold air outside the greenhouse) (Allaby 1996). As we will see in the next section, air in the atmosphere is constantly on the move.

SCILINKS® THE WORLD'S A CLICK AWAY
Topic: Greenhouse effect
Go to: *www.scilinks.org*
Code: CCPPO5

Global Circulation

Although the loss and gain of radiation is balanced over the entire climate system, no one part of the planet's surface is in equilibrium at a given time (Lockwood 2005). Different areas of Earth's surface receive unequal amounts of solar radiation for a number of reasons. First, Earth is an oblate spheroid (a slightly flattened sphere). Solar radiation reaches the planet in essentially parallel lines, so it can only intersect the surface at a 90° angle near the equator. (The precise intersection varies between 23.5°N and 23.5°S over the year because of Earth's tilt and orbit.) The angle of solar rays becomes increasingly oblique at higher latitudes, reducing the intensity of radiation reaching the surface. Because rays near the poles are entering the atmosphere obliquely, they also have to travel farther through the atmosphere to get to the surface and are more likely to be absorbed by atmospheric gases (Trapasso 2005).

Second, Earth rotates on a tilted axis as it orbits the Sun. The Northern Hemisphere is tilted toward the Sun from March through September and away from the Sun the rest of the year. The hemisphere pointed toward the Sun receives more direct rays for a longer period each day (Alsop 2005).

Third, Earth's surface is composed of both liquids and solids. Water heats and cools two to three times more slowly than land because it has a high specific heat, is translucent so it can be heated more deeply, and is fluid so it can circulate heat energy (Trapasso 2005). The range of seasonal climate variability is smaller in the Southern than in the Northern Hemisphere because more of the Southern Hemisphere's surface is covered by ocean (Hartmann 1994).

SCILINKS THE WORLD'S A CLICK AWAY
Topic: Albedo
Go to: *www.scilinks.org*
Code: CCPPO6

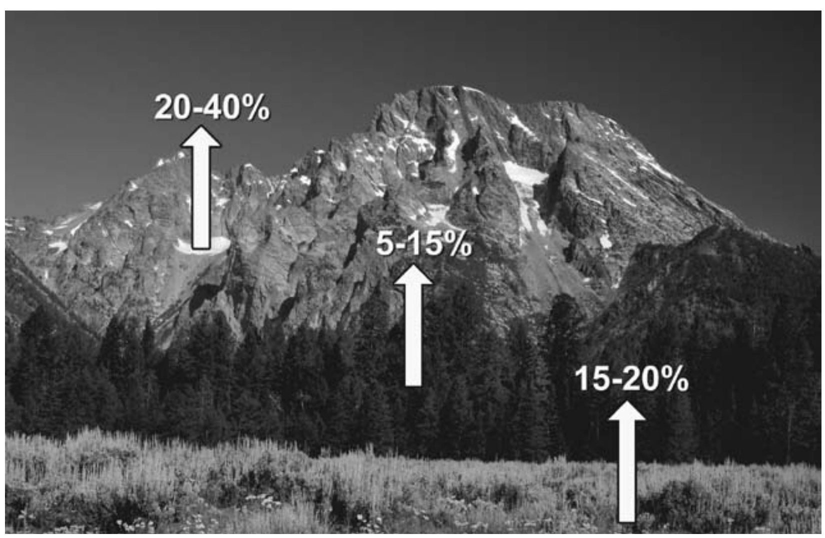
Finally, some surfaces are more reflective than others. The proportion of solar energy reflected by an object, called its **albedo**, is a function of the composition, roughness, and color of that object (Figure 1.2). The albedo of soil, for example, depends on characteristics such as particle size and water content (Goward 2005). The poles, which are covered by ice and snow for much of the year, have a higher albedo than tropical regions, which are covered by dark green vegetation (Hartmann 1994).

When short- and longwave radiation gains exceed longwave losses on part of Earth's surface, the extra energy heats the air, evaporates water, or is temporarily stored by the surface (Figure 1.1). **Sensible heat transfer** occurs when energy is moved by **conduction** and convection from the surface to the atmosphere. The energy makes air molecules move faster, which we feel as an increase in temperature. **Latent heat transfer** occurs when water changes phase between a liquid, gas, or solid. When water on Earth's surface evaporates, the surface loses energy and cools—the planet is essentially "sweating." When vapor condenses in the atmosphere, the energy gained during evaporation is released and the air becomes warmer. The amount of

Figure 1.2

Albedo of glacial ice, conifer forest, and sagebrush.
Most landscapes are a patchwork of different surfaces, but overall, the albedo of polar regions is higher than that of equatorial regions.

Source: Data compiled from Goward 2005 and Mills 2005. Photograph courtesy of Ed Soldo.



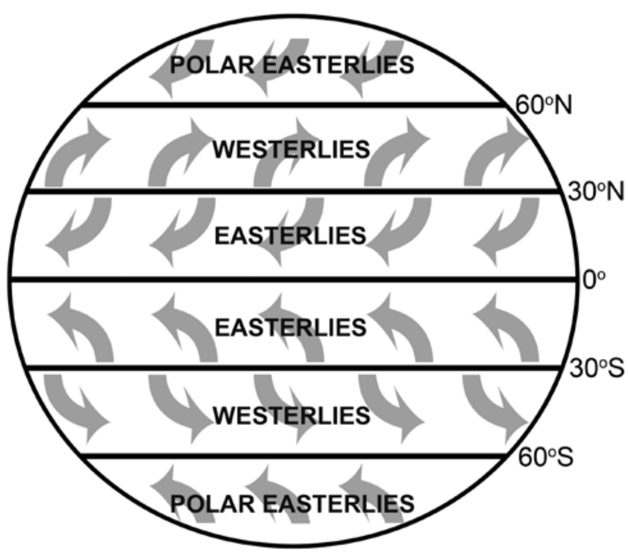
energy partitioned between heating, evaporation, and storage depends on the time of day, the availability of water, and the physical characteristics of the surface receiving the radiation (Pidwirny 2006; Ritter 2006).

Energy gradients (especially between the equator and the poles) drive the fluid motions of the atmosphere and oceans (Hartmann 1994). If our planet had a smooth, homogeneous surface and did not rotate, cells of warm air at the equator would rise, move straight north or south to the poles, and be replaced by cells of cold polar air. However, Earth's rotation causes the **Coriolis force**, which deflects wind to the right in the Northern Hemisphere and to the left in the Southern Hemisphere (Figure 1.3) (Lockwood 2005). Generally, as warm air moves poleward from the equator, it loses heat and moisture and settles near the surface at about 30°N and 30°S, the so-called **subtropical highs** (Akin 1991). On the poleward side of the subtropical highs, the **westerlies** blow air toward the poles from the southwest in the Northern Hemisphere and the northwest in the Southern Hemisphere. When the air moved by the westerlies cools and settles near the poles, relatively weak, irregular winds called the polar easterlies move air back toward the equator. On the equatorial side of the subtropical highs, the **easterlies** (also called trade winds) blow air toward the equator from the northeast in the Northern Hemisphere and the southeast in the Southern Hemisphere. The easterlies from the north and south meet in the **equatorial trough**, a belt of low pressure near the equator where winds are generally light. These global patterns of heat transport can be further distorted by the distribution of land and water and by barriers such as mountains (Akin 1991).

SCILINKS
THE WORLD'S A CLICK AWAY
Topic: Coriolis force
Go to: *www.scilinks.org*
Code: CCPPO7

Figure 1.3

Simplified model of global circulation (surface winds only).



The atmosphere moves about 60% of the heat that travels from the equator to the poles. The ocean moves the remaining 40% (Hartmann 1994). Ocean currents are driven by wind and atmospheric pressure gradients at the surface and by temperature and salinity gradients below the surface. Heat also is transported vertically in the ocean by upwelling (i.e., upward flows of cold, dense water) and downwelling. Currents flowing toward the poles, like the Gulf Stream, heat the eastern coasts of continents. Currents flowing away from the poles, like the California Current, cool the western coasts of continents (Hartmann 1994).

Some regional patterns in atmospheric and oceanic circulation can impact the global climate. The most important of these patterns is the **El Niño-Southern Oscillation** (ENSO), a cycle of sea surface temperatures and atmospheric pressure that occurs in the tropical Pacific but affects temperature and precipitation worldwide. **La Niña** and **El Niño** (the cold and warm extremes of ENSO) recur every two to seven years, although El Niño events tend to be more extreme. El Niño seems to be triggered by a weakening of the easterlies and a consequent rise in sea surface temperatures in the western and central Pacific (McPhaden, Zebiak, and Glantz 2006).

SCILINKS THE WORLD'S A CLICK AWAY
Topic: La Niña/El Niño
Go to: *www.scilinks.org*
Code: CCPPO8

The Water Cycle

The three main processes that move water between Earth's surface and the atmosphere are precipitation, evaporation from the surface, and transpiration from plants. On land, evaporation and transpiration are difficult to distinguish so they are often considered together as **evapotranspiration**. Precipitation and evapotranspiration are balanced globally: All the water that enters the atmosphere eventually leaves the atmosphere. However, factors such as variations in temperature and the distribution of land alter the relative importance of these processes and, therefore, the distribution of water in time and space (Hartmann 1994).

The distribution of water is critical to the climate system in three ways. First, as mentioned above in the discussion of latent heat transfer, the energy released by phase changes of water helps drive atmospheric circulation (Hartmann 1994). Second, water vapor is the most important and abundant greenhouse gas; in clear skies, it's responsible for about 60% of the natural greenhouse effect (Trenberth et al. 2007). This is because unlike other greenhouse gases, water vapor absorbs longwave radiation across the infrared spectrum instead of in a narrow band. Finally, water changes the albedo of the planet's surface through the deposition of snow and ice, distribution of vegetation, and structure of soils (Hartmann 1994).

Climate Classification

Climate can be classified in a number of ways. The simplest methods use a single physical variable such as latitude, average temperature, or variation in the balance between precipitation and evapotranspiration. Life scientists prefer to classify climate as a combination of physical and biological elements. One common, albeit not completely standardized, scheme is **biomes** (sometimes called zones in aquatic habitats). Biomes are defined by unique functional (i.e., morphological or physiological) groups of plants and animals adapted to a particular regional climate (Cox and Moore 2000). **Tundra**, for example, is a highly seasonal biome found around the Arctic Circle, on sub-Antarctic islands, and at high altitudes (Figure 1.4a). Tundra vegetation is typically low-lying and tolerant of extended periods of drought and cold. **Tropical rainforest**, on the other hand, is found near the equator and is characterized by hot, wet, and relatively stable conditions (Figure 1.4b). The vegetation in this biome is productive, diverse, and structurally complex (Begon, Townsend, and Harper 2006). Unless biomes are demarcated by a geographic barrier such as a mountain or a coastline, they tend to grade into one another (Cox and Moore 2000).

Figure 1.4

(a) Alpine tundra (b) Tropical rainforest

Photo (a) courtesy of Juanita Constible.
Photo (b) courtesy of Ashley Richmond.

(a) Alpine tundra (Rendezvous Mountain, Wyoming)
(b) Tropical rainforest (Amazon Conservatory, Peru)

SCILINKS THE WORLD'S A CLICK AWAY
Topic: Biomes
Go to: *www.scilinks.org*
Code: CCPP09

THE BIOLOGICAL ROLE OF CLIMATE

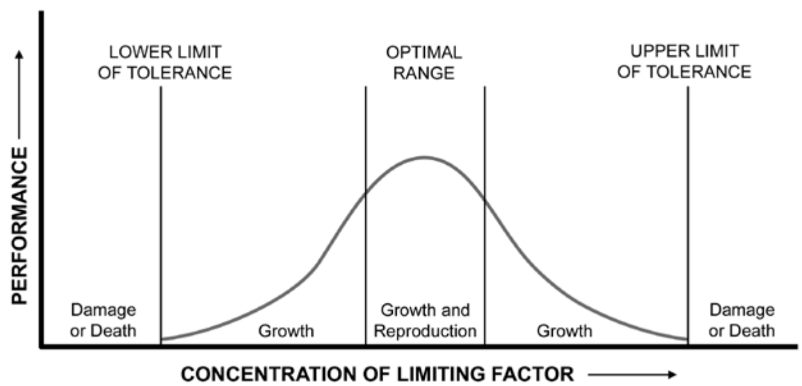
Climate is a major force shaping the distribution, abundance, and structure of life at every level of organization, from subcellular structures to biomes.

Physiological Limits

An abiotic **limiting factor** is a physical factor that constrains an organism's life processes (Figure 1.5). Within the optimal range of a limiting factor, growth is maximized and reproduction can occur. Outside the optimal range, growth is slower and reproduction ceases. Beyond the upper and lower limits of tolerance, growth ceases and the organism may suffer irreversible damage or death (Begon, Townsend, and Harper 2006).

Figure 1.5

Generalized model of effect of limiting factors on organismal survival, growth, and reproduction.



Temperature is the most important limiting factor imposed by climate because it affects nearly every aspect of an organism's physiology. At the most basic level, temperature affects how fast molecules move and, therefore, the rate of biochemical reactions (Hochachka and Somero 2002). When temperatures are too low, reactions may proceed too slowly to support life. When temperatures are too high, the pace of reactions may outstrip the availability of energy or chemical substrates (Allaby 1996).

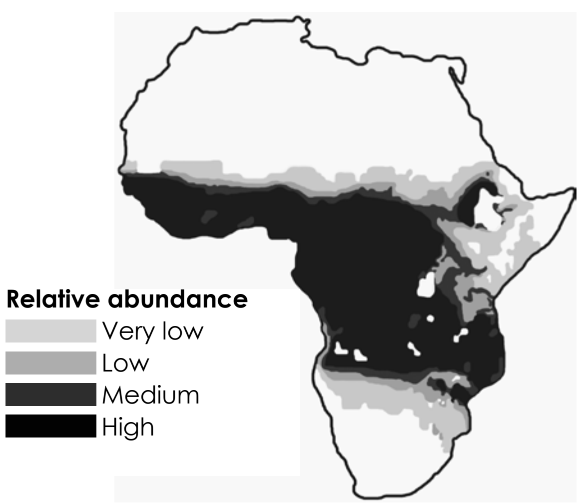
Temperature also affects the structure and function of cellular components. Extreme heat or cold can irreversibly damage enzymes and membranes and disrupt coordination among interdependent biochemical reactions (Levinton 2001). In cases of sublethal temperature stress, organisms may have to use extra energy to repair damaged cells or tissues (Hochachka and Somero 2002).

Finally, temperature can alter the water balance of an organism's cells and tissues. Water is critical to life. It is the primary constituent of organisms and acts as a chemical reagent, coolant, and transport mechanism (Akin 1991). The rate of evaporation—and therefore water loss—depends on both the temperature and relative humidity of the surrounding air. Organisms lose more water in extreme heat. They also lose more water in extreme cold, because the water content of the air is lower than that of their bodies (Begon, Townsend, and Harper 2006).

Precipitation is another critical limiting factor controlled by climate. Precipitation both directly affects the availability of water and indirectly affects the intensity of other physical limiting factors. For example, precipitation can change the salinity, sediment load, and nutrient levels of coastal systems by increasing discharge from rivers (Kaiser et al. 2005). Furthermore, precipitation can change the pH of streams and lakes via acid rain (Begon, Townsend, and Harper 2006).

The distribution and abundance of a species depends in part on the physiological limits of its individuals (Spicer and Gaston 1999). Consider, for example, the mosquito *Anopheles gambiae sensu stricto*, a major vector of malaria (Figure 1.6). The potential geographic range of this species is defined by both temperature (5–42°C) and precipitation (33–332 cm per year). The abundance of the species, however, varies across its range depending on how favorable the conditions are. Although the mosquito *can* develop outside its optimal range, it is most abundant where conditions are warm and wet (Figure 1.6) (Lindsay et al. 1998).

Figure 1.6



Approximate distribution and relative abundance of *Anopheles gambiae sensu stricto* in Africa.

Source: Lindsay, S. W., L. Parson, and C. J. Thomas. 1998. Modified with permission.

Evolution

No one species can withstand the full range of physical conditions found on Earth (Spicer and Gaston 1999). In part, this is because adaptive evolution can occur only in response to local conditions (Begon, Townsend, and Harper 2006). Most organisms live within **microclimates**, small areas that experience significantly different physical conditions than those of the regional climate or **macroclimate** (Figure 1.7). Microclimates vary in size, from a tiny bubble of air to an entire hillside or valley, and are formed by variations in geometric position, shading, and other physical and biological factors (Bailey 2005).

Figure 1.7

Microclimates in a valley on Santa Catalina Island, California.
The relatively cool and wet north-facing slope of the valley (left side of the picture) is dominated by oak trees and a variety of herbs. The relatively warm and dry south-facing slope is dominated by grasses and drought-resistant plants such as sagebrush and cactus.

Photograph courtesy of Lauren Danner.

Earth's climate is always changing because of astronomical, geological, and biological processes. If a particular change is correlated with variation in reproductive success, a **population** (group of individuals of one species) may adapt to that change. Adaptation to a new climate regime can occur relatively rapidly (i.e., a few generations to a few hundred years) in large, genetically variable populations (Stearns and Hoekstra 2005). Climatic change also can trigger the evolution of new species. Both extreme events and gradual trends over time can increase the chance of speciation by isolating populations, forcing populations to relocate, or presenting new selection pressures. In mammals, at least, it seems climatic changes must be unusual over a period of hundreds of thousands of years to cause the evolution of new species (Barnosky and Kraatz 2007).

Structure and Function of Ecosystems

An individual organism—no matter how solitary its lifestyle—constantly interacts with other organisms. Within populations, individuals may compete for resources, prey on one another, or cooperate to raise young. The strength of interactions within and between populations helps shape the structure and function of **communities** (groups of populations of different species) (Begon, Townsend, and Harper 2006).

The relationship between climate and the structure and function of communities is complicated. On one hand, the internal dynamics of a community may override the climatic suitability of a habitat for a given species. In New England, for instance, the northern limit of the little gray barnacle (*Chthamalus fragilis*) is set by competition, not climate. In the absence of competition from northern acorn barnacles (*Semibalanus balanoides*), little gray barnacles could live 80 km farther north than they currently do (Wethey 2002). On the other hand, climate mediates species interactions—for example, by controlling the rate at which energy flows through a food web. Seasonal and annual variations in temperature, precipitation, and the number of cloudless days regulate the amount of new tissue produced by plants (Begon, Townsend, and Harper 2006). Climate also affects interactions at the top of the food chain. On the western coast of North America, the ochre sea star (*Pisaster ochraceus*) consumes more of its primary prey (i.e., mussels) when temperatures are high. Under consistently high temperatures, sea stars can extensively damage mussel beds, eliminating the habitat of hundreds of intertidal species (Harley et al. 2006).

Another layer of complexity is added when we consider the relationship between **ecosystems** (communities and their associated physical environments) and climate. Climate influences local soil types, decomposition rates, and the turnover of nutrients between soils and living organisms. Ecosystems also affect local climate, however, through their surface properties (e.g., albedo) and exchanges of energy, water, and gases. For example, crops and grasses can enhance the effects of wetter-than-average summers. In the Mississippi River Basin of North America, increased soil moisture leads to increased plant growth. More plants mean more leaf surface area and, in turn, higher evapotranspiration rates. The rapid cycling of water from the soil to the atmosphere increases water vapor and, therefore, precipitation (Kim and Wang 2007). The cyclic magnification of a regional climate trend is called a **feedback**. We will discuss feedbacks further in Chapter 2.

THE ENHANCED GREENHOUSE EFFECT

Humans have had a significant impact on Earth's climate system despite its size and complexity. The natural greenhouse effect, which keeps the planet livable, has been enhanced globally by fossil fuel emissions and regionally by feedbacks. In the next chapter, we will discuss how scientists study climate change. We also will examine the types and causes of changes that have occured in the last 100 years.

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Part II: Climate Change Case Studies

CONNECTIONS TO STANDARDS

In this section of the book, we present six classroom investigations that use the case study method. The use of real-life stories makes science more understandable and engaging to students. Furthermore, open-ended cases illustrate the nature of science better than cookbook "experiments" with a predetermined right answer (Herreid 2007). In this collection of investigations, students analyze data from recent scientific research, solve realistic problems, and communicate their interpretations and decisions to their peers in a variety of ways.

As we discussed in Chapter 3, scientists have detected the effects of anthropogenic climate change in nearly every taxa and in all biomes. To engage student interest, however, we focused on charismatic species such as penguins and polar bears. Because relatively little research has been done on the effects of climate change in South America, Africa, and Asia (Parmesan 2006), most of the case studies are from North America and Europe.

Each case study corresponds to multiple National Science Education Standards (NRC 1996). You can use the table on the next page to help you choose the case most relevant to your instructional needs.

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Connections to the National Science Education Standards

◆ Primary focus of lesson; ◈ Secondary focus of lesson

National Science Education Standards	**CH. 5:** Now You "Sea" Ice, Now You Don't	**CH. 6:** Population Peril	**CH. 7:** Carrion: It's What's for Dinner	**CH. 8:** Right Place, Wrong Time	**CH. 9:** Ah-Choo!	**CH. 10:** Cruel, Cruel Summer
Content Standard A: Science as Inquiry						
Design and conduct scientific investigations						◆
Use technology and mathematics to improve investigations and communications					◆	◆
Formulate and revise scientific explanations and models using logic and evidence	◆	◆	◆	◆		◆
Recognize and analyze alternative explanations and models	◆	◆		◆		◆
Communicate and defend a scientific argument	◆	◆	◈	◆	◆	◆
Understand that mathematics is essential in scientific inquiry			◆			◆
Content Standard C: Life Sciences						
Biological evolution	◈	◈		◈		
The interdependence of organisms	◆	◆	◆	◆		
Matter, energy, and organization in living systems	◆	◆	◆	◈		
Behavior of organisms		◈		◆		◈
Content Standard E: Abilities of Technological Design						
Propose designs and choose between alternative solutions					◆	
Implement a proposed solution					◆	
Communicate the problem, process, and solution					◆	◈
Understand that many scientific investigations require contributions of individuals from different disciplines	◆					
Content Standard F: Science in Personal and Social Perspectives						
Personal and community health					◆	◆
Natural and human-induced hazards					◈	◆
Science should inform active debate about how to resolve certain social challenges, but cannot resolve challenges alone		◆				◈
Humans have a major effect on other species	◈	◆	◆			
Content Standard G: History and Nature of Science						
Scientists have ethical traditions					◈	
Scientific explanations must meet certain criteria	◆	◆	◆	◆	◆	◆

Chapter 5
Now You "Sea" Ice, Now You Don't

Penguin communities shift on the Antarctic Peninsula

Teacher Pages

AT A GLANCE

Increasing air temperatures in the last 50 years have dramatically altered the Antarctic Peninsula ecosystem. In this interdisciplinary inquiry, learners use a cooperative approach to investigate changes in the living and nonliving resources of the Peninsula. The activity stresses the importance of evidence in the formulation of scientific explanations. (Class time: 1–3.5 hours)

This chapter has been modified from the following article: Constible, J., L. Sandro, and R. E. Lee. 2007. A cooperative classroom investigation of climate change. *The Science Teacher* 74(6): 56–63.

"For many, [the Antarctic Peninsula] is the most beautiful part of the Antarctic, unlocked each year by the retreating ice.... It is on this rocky backbone stretching north that most of the continent's wildlife survives.... Almost every patch of accessible bare rock is covered in a penguin colony. Even tiny crags that pierce the mountainsides are used by nesting birds."
—Alastair Fothergill, *A Natural History of the Antarctic: Life in the Freezer,* 1995

INTRODUCTION

At the global level, strong evidence suggests that observed changes in Earth's climate are largely due to human activities (IPCC 2007). At the regional level, the evidence for human-dominated change is sometimes less clear. Scientists have a particularly difficult time explaining warming trends in Antarctica—a region with a relatively short history of scientific observation and a highly variable climate (Clarke et al. 2007). Regardless of the mechanism of warming, however, climate change is having a dramatic impact on Antarctic ecosystems.

By the end of this lesson, students should be able to do the following:

- Graphically represent data.
- Use multiple lines of evidence to generate scientific explanations of ecosystem-level changes on the Antarctic Peninsula.
- Describe ways in which climate change on the Antarctic Peninsula has led to interconnected, ecosystem-level effects.
- Participate in an interdisciplinary scientific investigation, demonstrating the collaborative nature of science.

WARMING CLIMATE, WANING SEA ICE

Air temperature data indicate that the western Antarctic Peninsula (Figure 5.4, p. 82) has warmed by about 3°C in the last century (Clarke et al. 2007). Although this relatively short-term record is only from a few research stations, other indirect lines of evidence confirm the trend. The most striking of these proxies is a shift in penguin communities. Adélie penguins, which are dependent on sea ice for their survival, are rapidly declining on the Antarctic Peninsula despite a 600-year colonization history. In contrast, chinstrap penguins, which prefer open water, are dramatically increasing (Figure 5.1). These shifts in penguin populations appear to be the result of a decrease in the amount, timing, and duration of sea ice (Figure 5.2).

Figure 5.1

Adélie penguin

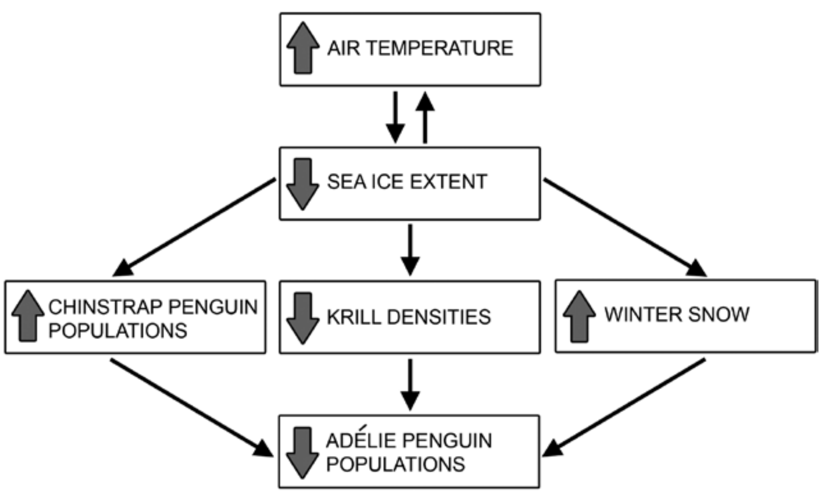
Chinstrap penguin

Adélie and chinstrap penguins. Adélie penguins *(Pygoscelis adeliae)* breed on the coast of Antarctica and surrounding islands. They are named after the wife of French explorer Jules Sébastien Dumont d'Urville. Adult Adélies stand 70–75 cm tall and weigh up to 5 kg.

Chinstrap penguins *(Pygoscelis antarctica)* are primarily found on the Antarctic Peninsula and in the Scotia Arc, a chain of islands between the tip of South America and the Peninsula. Their name comes from the black band running across their chins. Adult chinstraps stand 71–76 cm tall and weigh up to 5 kg.

Photographs courtesy of Michael Elnitsky.

Figure 5.2

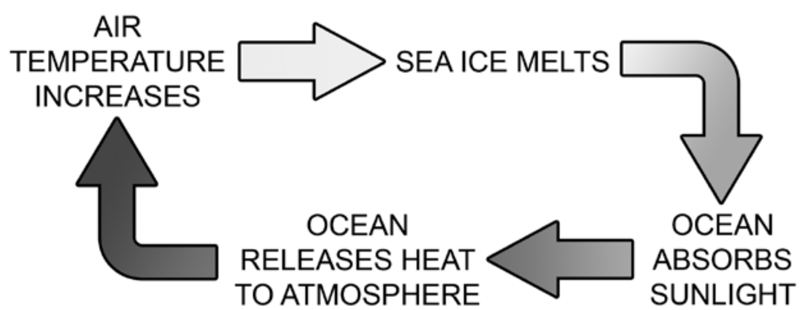


Effects of climate change on sea ice, krill, and penguin communities of the Antarctic Peninsula.

Why is sea ice so important to Adélie penguins? First, sea ice is a feeding platform for Adélies. Krill, the primary prey of Adélies on the Peninsula, feed on microorganisms growing on the underside of the ice (Atkinson et al. 2004). For Adélie penguins, which are relatively slow swimmers, it is easier to find food under the ice than in large stretches of open water (Ainley 2002). Second, sea ice helps control the local climate. Ice keeps the Peninsula cool by reflecting solar radiation back to space. As air temperatures increase and sea ice melts, open water releases heat and amplifies the upward trend in local air temperature (Figure 5.3) (Wadhams 2000). Finally, ice acts as a giant cap on the ocean, limiting evaporation. As sea ice declines, **condensation nuclei** (aerosols that form the core of cloud droplets) and moisture are released into the atmosphere, leading to more snow. This extra snow often does not melt until Adélies have already started nesting; the resulting melt water can kill their eggs (Fraser and Patterson 1997).

Figure 5.3

Melting sea ice amplifies the effects of climate change.



Activity Overview

This directed inquiry uses the jigsaw technique, which requires every student within a group to be an active and equal participant for the rest of the group to succeed (Colburn 2003). To begin, students are organized into "Home Groups" composed of five different specialists. Specialists from each Home Group then reorganize into "Specialist Groups" that contain only one type of scientist (e.g., Group 1 could include all of the Ornithologists and Group 2 all of the Oceanographers). Each Specialist Group receives a piece of the flowchart in Figure 5.2, in the form of a data table. With only a few facts to guide them, the Specialist Groups create graphs from the data tables, brainstorm explanations for patterns in their data, and report results back to their Home Groups. Finally, Home

Groups use the expertise of each specialist to reconstruct the entire flowchart (Figure 5.2).

TEACHING NOTES

Prior Knowledge

Before starting this activity, students should have at least a rudimentary knowledge of Antarctica. You can find a collection of links to our favorite Antarctic websites at *www.units.muohio.edu/cryolab/education/AntarcticLinks.htm*. You can also engage student interest in this inquiry by showing video clips of penguins, which are naturally appealing to students of all ages. We have short movies of Adélies feeding their young and battling predators on our website at *www.units.muohio.edu/cryolab/education/antarcticbestiary.htm*, and National Geographic has a video called "Rocky Parenting" at *http://news.nationalgeographic.com/news/2006/11/061117-adelie-video.html*.

Materials

- Specialist Fact Sheet (Student Page 5.1; one for each student, or one overhead for the entire class)
- Temperature data (Figure 5.4; one overhead for the entire class)
- Data sets for each Specialist Group (Student Pages 5.2–5.6: Adélie Penguins, Sea Ice, Winter Snow, Chinstrap Penguins, and Krill)
- Specialist Group Report Sheets (Student Page 5.7; one for each student)
- Sheets of graph paper (one for each student) or computers connected to a printer (one for each Specialist Group)
- Sets of six flowchart cards (one complete set for each Home Group; before the inquiry, you can make flowchart cards by photocopying Figure 5.2 and cutting out each box [i.e., "Air Temperature," "Sea Ice Extent," etc.])
- Paper, markers, and tape for constructing flow charts

Procedure: Graphing and Interpretation

1. Split the class into Home Groups of at least five students each. (Optional: Assign the name of a different real-life research

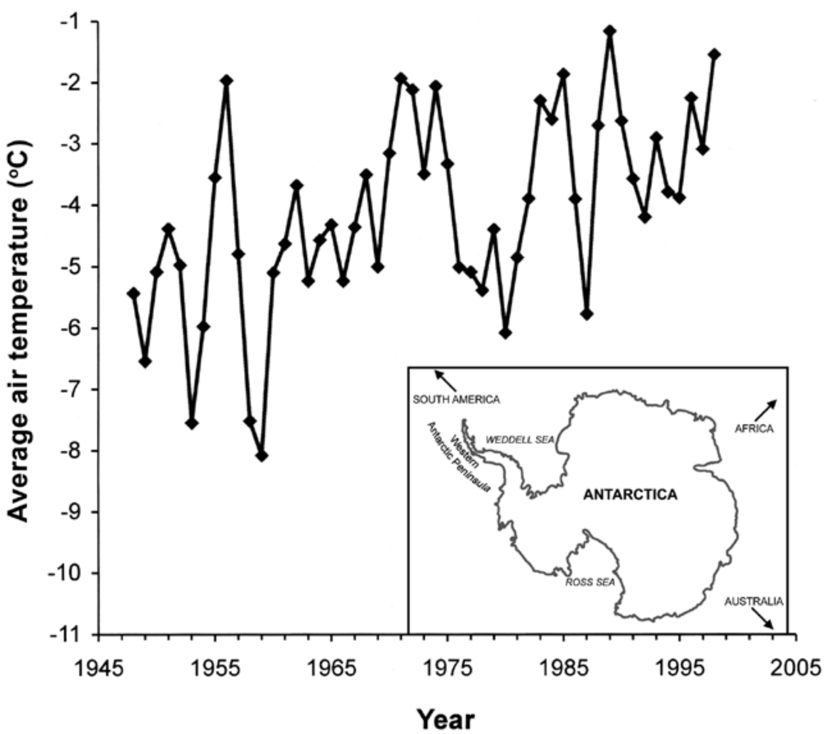
agency to each group. See *www.units.muohio.edu/cryolab/education/AntarcticLinks.htm#NtnlProg* for examples.)

2. Instruct students to read the Specialist Fact Sheets (Student Page 5.1). Within a Home Group, each student should assume the identity of a different scientist from the list.
3. Introduce yourself: "Welcome! I'm a climatologist with the Palmer Station, Antarctica Long-Term Ecological Research project. In other words, I study long-term patterns in climate. My colleagues and I have tracked changes in air temperatures on the peninsula since 1947. We have observed that although temperature cycles up and down, it has increased overall [show Figure 5.4]. We think this is occurring because of an increase of greenhouse gases, but we are unsure of the impacts on the Antarctic ecosystem. Your team's job is to describe the interconnected effects of warming on Antarctica's living and nonliving systems."

Figure 5.4

Climatologists: Air temperature data set.

Source: Data compiled from the Palmer Station, Antarctica Long-Term Ecological Research (LTER) data archive. Data from the Palmer LTER archive were supported by the Office of Polar Programs, NSF Grants OPP-9011927, OPP-9632763, and OPP-021782.



4. Direct the specialists to meet with their respective Specialist Groups. Specialist Groups should not interact with one another.

5. Distribute the data sets and Specialist Group Report Sheets (Student Pages 5.2–5.7) to each Specialist Group. The specialists should graph their data set and interpret the graph.

Procedure: Flowchart and Class Discussion

1. Reconvene the Home Groups.
2. Hand out a complete set of flowchart cards to each group. Each specialist should make a brief presentation to his or her Home Group approximating the format on the Specialist Group Report Sheet (Student Page 5.7). Home Groups should then construct their own flowcharts using all of the flowchart cards. Remind the students throughout this process that they should use the weight of evidence to construct the flowcharts. In other words, each idea should be accepted or rejected based on the amount of support it has.
3. Consider these discussion questions during the flowchart process (do this as a class, by Home Group, or as homework for each student):
   - How has the ecosystem of the Antarctic Peninsula changed in the last 50 years? What are the most likely explanations for these changes?

Figure 5.5

Performance rubric.

Student Name:

Criteria	Points	Self	Teacher	Comments
Active participation in the group process.	5			
Appropriate graph is used to display data. All required elements (labels, titles, etc.) are present. Data are graphed accurately.	5			
Data and interpretations from Specialist Groups are clearly communicated to Home Groups by individual specialists.	10			
Alternative explanations are weighed based on available evidence and prior scientific knowledge.	10			
Conclusions are clearly and logically communicated.	10			
Report Sheet is complete.	5			
TOTAL	**45**			

- Is there sufficient evidence to support these explanations? Why or why not? What further questions are left unanswered?
- Did your Specialist Group come up with any explanations that you think are not very likely (or not even possible!), based on the complete story presented by your Home Group?

Assessment

To assess student learning, you can use a simple performance rubric that focuses on group work and the nature of science (Figure 5.5, p. 83). Depending on the unit of study in which this inquiry is used, a variety of specific content standards also may be assessed. In an ecology unit, for example, you could determine student knowledge of interactions between populations and their environments; in an Earth science unit, you could check student understandings about weather and climate.

Modifications

Some students have initial difficulties with the construction and interpretation of flowcharts. Once students have connected their flowchart cards with arrows, it may be useful to have them label each arrow with a verb. For instance:

↓ Sea Ice Extent —*causes*→ ↑ Winter Snowfall

For lower-level students, you can construct a worksheet with a "skeleton" of the worksheet (e.g., the general shape of the flowchart and some of the text within the boxes).

You can shorten this lesson by starting immediately with Specialist Groups, rather than with Home Groups. Another option is to provide premade graphs of the data rather than having Specialist Groups create their own.

To make this lesson more open-ended, students may do additional research on the connections between sea ice, krill, and penguins. Note, however, that the majority of resources on this topic are research articles in scientific journals. If you have access to a university library, you might wish to make a classroom file of related journal articles. A more engaging extension would be for students to generate ideas for new research studies that would address questions left unanswered by the current inquiry. This type of activity could range from asking students to formulate new hypotheses to asking students to write short proposals that include specific research questions and plans to answer those hypotheses.

CONCLUSION

Many students have trouble comprehending how just a few degrees of atmospheric warming (in this case, 3°C) could make a difference in their lives. The decline of a charismatic species such as the Adélie penguin is an example of how a seemingly minor change in climate can pose a major threat to plants and animals. Beyond the effects of climate change, however, the activity illustrates the multidisciplinary, international, and, above all, cooperative nature of science. We want social teenagers to realize that they do not have to sit alone in a lab to do science.

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OTHER RECOMMENDED RESOURCES

These additional resources were used to create the Student Pages, but are not cited in the text:

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Chapter 5
Now You "Sea" Ice, Now You Don't

Penguin communities shift on the Antarctic Peninsula

Student Pages

Note: Reference List for Students

For more information on references cited in the Chapter 5 Student Pages, go to teacher references on page 85.

STUDENT PAGE 5.1

Specialist Fact Sheet

Each Home Group contains five different specialists:

1. *Ornithologist:* A scientist who studies birds. Uses visual surveys (from ship or on land), diet analysis, bird banding, and satellite tracking to collect data on penguins.
2. *Oceanographer:* A scientist who studies the ocean. Uses satellite imagery, underwater sensors, and manual measurements of sea-ice thickness to collect data on sea-ice conditions and ocean temperature.
3. *Meteorologist:* A scientist who studies the weather. Uses automatic weather stations and visual observations of the skies to collect data on precipitation, temperature, and cloud cover.
4. *Marine Ecologist:* A scientist who studies relationships between organisms and their ocean environment. Uses visual surveys, diet analysis, and satellite tracking to collect data on a variety of organisms, including penguins.
5. *Fisheries Biologist:* A scientist who studies fish and their prey. Collects data on krill during research vessel cruises.

STUDENT PAGE 5.2

Ornithologists (Adélie Penguin Data Set)

YEAR	# BREEDING PAIRS OF ADÉLIE PENGUINS
1975	15,202
1979	13,788
1983	13,515
1986	13,180
1987	10,150
1989	12,983
1990	11,554
1991	12,359
1992	12,055
1993	11,964
1994	11,052
1995	11,052
1996	9,228
1997	8,817
1998	8,315
1999	7,707
2000	7,160
2001	6,887
2002	4,059

Source: Data compiled from Smith, Fraser, and Stammerjohn. 2003. Photograph courtesy of Richard E. Lee, Jr.

- Adélie penguins spend their summers on land, where they breed. They spend winters on the outer extent of the sea ice surrounding Antarctica, where they molt their feathers and fatten up.
- Adélies are visual predators, meaning they need enough light to see their prey. Near the outer part of the pack ice, there are only a few hours of daylight in the middle of the winter. There is less sunlight as you go farther south (closer to land).
- On the western Antarctic Peninsula, Adélie penguins mostly eat krill, a shrimplike crustacean.
- Several countries have been heavily harvesting krill since the mid-1960s.
- Adélie penguins need dry, snow-free places to lay their eggs. They use the

same nest sites each year and at about the same time every year. Heavy snowfalls during the nesting season can bury adult Adélies and kill their eggs.

- Female Adélies lay two eggs, but usually only one of those eggs results in a fledged chick (fledged chicks have a good chance of maturing into adults). The two most common causes of death of eggs and chicks are abandonment by the parents (if they cannot find enough food) and predation by skuas (hawklike birds).
- In the water, Adélies are eaten mostly by leopard seals and killer whales.
- Adélies can look for food under sea ice because they can hold their breath for a long time. They are not as good at foraging in the open ocean, because they cannot swim very fast.
- Adélie penguins have lived in the western Antarctic Peninsula for at least 644 years.

STUDENT PAGE 5.3

Oceanographers (Sea Ice Data Set)

YEAR	AREA OF SEA ICE EXTENDING FROM THE ANTARCTIC PENINSULA (KM^2)
1980	146,298
1981	136,511
1982	118,676
1983	88,229
1984	85,686
1985	78,792
1986	118,333
1987	142,480
1988	90,310
1989	44,082
1990	79,391
1991	111,959
1992	110,471
1993	94,374
1994	103,485
1995	95,544
1996	86,398
1997	100,784
1998	73,598
1999	79,223
2000	79,200
2001	69,914

Source: Data compiled from the Palmer Station, Antarctica Long-Term Ecological Research (LTER) data archive. Data from the Palmer LTER archive were supported by the Office of Polar Programs, NSF Grants OPP-9011927, OPP-9632763, and OPP-021782. Photograph courtesy of Marianne Kaput.

- In August or September (the middle of winter), sea ice covers over 19×10^6 km^2 of the Southern Ocean (an area larger than Europe). In February (the middle of summer), only 3×10^6 km^2 of the ocean is covered by sea ice.
- Sea ice keeps the air of the Antarctic region cool by reflecting most of the solar radiation back into space.
- Open water absorbs solar radiation instead of reflecting it and converts it to heat. This heat warms up the atmosphere.
- Sea ice reduces evaporation of the ocean, thus reducing the amount of moisture that is released to the atmosphere.
- As sea ice melts, bacteria and other particles are released into the

atmosphere. These particles can form condensation nuclei, which grow into rain or snow.
- Rain helps to stabilize the sea ice by freezing on the surface.
- Sea ice can be broken up by strong winds that last a week or more.
- An icebreaker is a ship with a reinforced bow to break up ice and keep channels open for navigation. Icebreakers were first used in the Antarctic in 1947 and have been commonly used to support scientific research for the last 25 years.

STUDENT PAGE 5.4

Meteorologists (Winter Snow Data Set)

YEAR	% OF PRECIPITATION EVENTS THAT ARE SNOW
1982	49
1983	67
1984	72
1985	67
1986	81
1987	80
1988	69
1989	69
1990	68
1991	72
1992	70
1993	70
1994	83
1995	77
1996	74
1997	81
1998	81
1999	83
2000	77
2001	90
2002	82
2003	76

Source: Data compiled from Antarctic Meteorology Online, British Antarctic Survey *(www.antarctica.ac.uk/met/metlog)*. Photograph courtesy of Luke Sandro.

- In the winter, most of the precipitation in the western Antarctic Peninsula occurs as snow. There is an even mix of snow and rain the rest of the year.
- It is difficult to accurately measure the amount of snowfall in the Antarctic because strong winds blow the snow around.
- The Antarctic Peninsula has a relatively warm maritime climate so it gets more rain and snow than the rest of the Antarctic continent.
- Most of the rain and snow in the western Antarctic Peninsula is generated by cyclones from outside the Southern Ocean. Cyclones are areas of low atmospheric pressure and rotating winds.
- When there is less sea ice covering the ocean, there is more evaporation of the

ocean and, therefore, more moisture in the atmosphere.

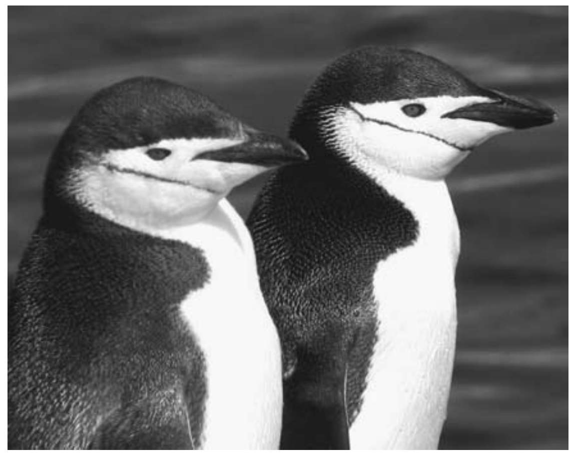
- As sea ice melts, bacteria and other particles are released into the atmosphere. These particles can form condensation nuclei, which grow into rain or snow.

STUDENT PAGE 5.5

Marine Ecologists (Chinstrap Penguin Data Set)

YEAR	# BREEDING PAIRS OF CHINSTRAP PENGUINS
1976	10
1977	42
1983	100
1984	109
1985	150
1989	205
1990	223
1991	164
1992	180
1993	216
1994	205
1995	255
1996	234
1997	250
1998	186
1999	220
2000	325
2001	325
2002	250

Source: Data compiled from Smith, Fraser, and Stammerjohn. 2003. Photograph courtesy of Michael Elnitsky.



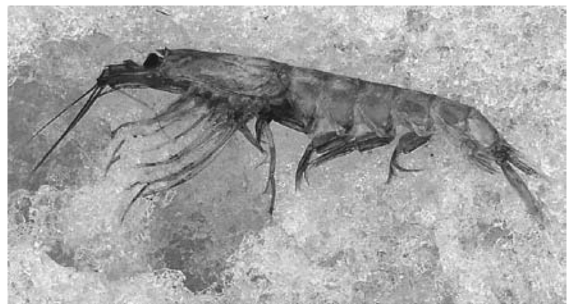
- Chinstrap penguins breed on land in the spring and summer and spend the rest of the year in open water north of the sea ice. The number of chinstraps that successfully breed is much lower in years when the sea ice does not melt until late in the spring.
- Chinstraps mostly eat krill, a shrimp-like crustacean.
- Whalers and sealers overhunted seals and whales, which also eat krill, until the late 1960s.
- Chinstraps hunt primarily in open water because they cannot hold their breath for very long.
- The main predators of chinstraps are skuas (hawklike birds), leopard seals, and killer whales.
- Chinstraps will aggressively displace Adélie penguins from nest sites in order to start their own nests and may compete with Adélies for feeding areas.
- Although chinstrap penguins have occupied the western Antarctic Peninsula for over 600 years, they have become numerous near Palmer Station (one of the three U.S. research stations in Antarctica) only in the last 35 years.

STUDENT PAGE 5.6

Fisheries Biologists (Krill Data Set)

YEAR	DENSITY OF KRILL IN THE SOUTHERN OCEAN (# KRILL/M^2)
1982	91
1984	50
1985	41
1987	36
1988	57
1989	15
1990	8
1992	7
1993	22
1994	6
1995	9
1996	31
1997	53
1998	46
1999	4
2000	8
2001	31
2002	8
2003	3

Source: Data compiled from Atkinson et al. 2004. Photograph courtesy of Richard E. Lee, Jr.



- Krill, a shrimplike crustacean, is a keystone species, meaning it is one of the most important links in the Antarctic food web. All the vertebrate animals in the Antarctic either eat krill or another animal that eats krill.
- Krill eat mostly algae. In the winter, the only place algae can grow is on the underside of sea ice.
- Several countries have been harvesting krill since the mid-1960s.
- Ultraviolet radiation is harmful to krill and can even kill them. Worldwide, ozone depletion is highest over Antarctica.
- Salps, which are small, marine animals that look like blobs of jelly, compete with krill for food resources. As the salt content of the ocean decreases, salps increase and the favorite food species of krill decrease.

STUDENT PAGE 5.7

Specialist Group Report Sheet

Name: ______________________________

Specialist Group: ______________________________

In your own words, summarize the general trends or patterns of your data. Attach a graph of your data to the back of this sheet.

List possible explanations for the patterns you are seeing.

With the help of the facts on each data sheet, choose the explanation that you think is most likely. Why do you think that explanation is most likely?

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