Chapter 2
Antarctica: The Continent

The area of Antarctica is 13.97×10^6 km^2 making it the fifth largest of the seven continents (Stonehouse 2002). It is conventionally oriented on maps as shown in Fig. 2.1 and is subdivided into East Antarctica, West Antarctica, the Antarctic Peninsula, and certain islands that rise more than 500 m above sea level (i.e., Alexander, Bear, Berkner, Roosevelt, Ross, and Thurston). In addition, Antarctica is surrounded by the Ross, Ronne, Filchner, Riiser-Larsen, Fimbul, and Amery floating ice shelves as well as by the Larsen ice shelf located along the east coast of the Antarctic Peninsula. Except for the northernmost tip of the Antarctic Peninsula, the continent lies within the Antarctic Circle at latitudes greater than 62.5° south.

The continuing exploration of Antarctica has uncovered several natural phenomena that have not been recognized elsewhere on the Earth. All of these phenomena, which are mentioned here in passing, are described in detail in the appropriate chapters of this book:

1. The stratosphere over Antarctica is depleted in ozone because of the release of chlorine-bearing gases (CFCs) by humans in the mid-latitudes of the Earth.
2. Large meltwater lakes that exist at the base of the East Antarctic ice sheet may be linked by subglacial streams of liquid water.
3. Subglacial evaporite deposits form as a result of refreezing of meltwater at the base of the East Antarctic ice sheet in response to decreases in pressure.
4. Numerous lakes and ponds occur in the ice-free regions of southern Victoria Land and in the Bunger Hills of East Antarctica. Some of these ponds contain highly concentrated brines that do not freeze even at −50°C.
5. Cold and unusually salty water forms in the circum-Antarctic oceans and then sinks to the bottom of the ocean basins where it flows north into the South Atlantic, South Pacific, and the South Indian oceans.
6. Meteorite specimens that land on the East Antarctic ice sheet are transported to the margins of the ice sheet and may be exposed on the bare-ice fields in the zone of ablation adjacent to the Transantarctic Mountains, and at the Yamato and Grove mountains of East Antarctica. In addition, several dozen rock samples from the Moon and from Mars have been collected in Antarctica.

The conventional orientation of the continent of Antarctica in Fig. 2.1 causes East Antarctica to be located *west* of an observer facing north anywhere within the Transantarctic Mountains. This contradiction arises because East Antarctica is positioned on the right-hand side of a map when the continent is oriented in the conventional manner as in Fig. 2.1. All geological maps in this book are oriented with north at the top in order to avoid any ambiguity about the directions of east and west.

2.1 Topography

The rocks that form the crust of Antarctica are almost completely hidden under a thick ice sheet that covers 97.6% of the entire land mass. The average elevation of the surface of the ice sheet is more than 2,000 m above sea level (a.s.l.). The highest elevations occur in a series of ice domes that are roughly aligned along a semi-circle in the interior of East Antarctica: Dome Fuji (3,807 m at 77°00′S, 046°00′E), Dome Argus

G. Faure and T.M. Mensing, *The Transantarctic Mountains: Rocks, Ice, Meteorites and Water*,
DOI 10.1007/978-90-481-9390-5_2,

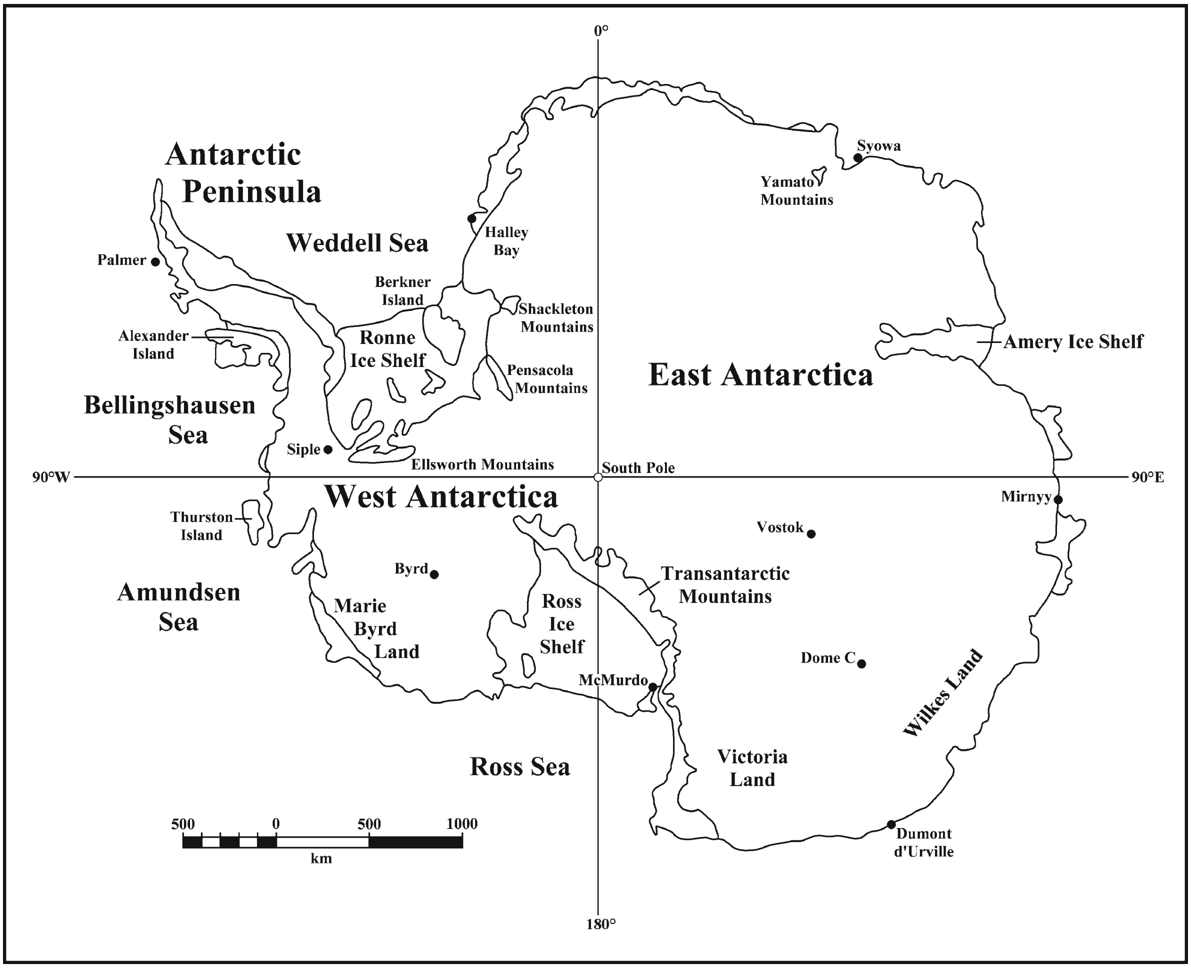

Fig. 2.1 Antarctica is conventionally oriented as shown and is subdivided into East Antarctica, West Antarctica, and the Antarctic Peninsula. The Transantarctic Mountains extend from northern Victoria Land along the Ross Sea and the Ross Ice Shelf toward the Pensacola Mountains adjacent to the Ronne Ice Shelf. Some of the research stations mentioned in the text are indicated on this map. A complete list of these stations is provided in Appendix 1.11.2 (Adapted from the Antarctic Journal of the US, volume 13, No. 4, October 1978)

(4,030 m at 81°00′S, 077°00′E), and Dome Charlie (3,206 m at 75°00′S, 125°00′E). The South Pole is located on the polar plateau at an elevation of 2,835 m. The average thickness of the Antarctic ice cap is 2,160 m and its volume has been estimated to be 30.11×10^6 km^3, which amounts to about 90% of the ice on the Earth (Stonehouse 2002). The greatest thickness of ice occurs in a small area in Wilkes Land at 69°30′S, 135°00′E where the bedrock is below sea level (National Geographic Society 1990). This site may be a large meteorite impact crater buried by the ice (Section 18.4.1).

The rocks of the Antarctic crust are exposed primarily on the Antarctic Peninsula, in the Transantarctic Mountains of East Antarctica, in the Ellsworth Mountains of West Antarctica, and in the extinct volcanoes of Marie Byrd Land. In addition, small mountain ranges project through the East Antarctic ice sheet in Queen (or Dronning) Maud Land, in Enderby Land, in Mac. Robertson Land, and in a few places in Wilkes Land (e.g., Gaussberg, Section 1.3.3).

The Sentinel Range of the Ellsworth Mountains in West Antarctica (Fig. 2.1) includes the Vinson Massif which contains the highest peak in Antarctica at 4,901 m (Stonehouse 2002). The highest peaks of the Transantarctic reach an elevation of 4,528 m in the Queen Alexandra Range along the north side of the Beardmore Glacier (National Geographic Society 1990).

Geophysical data indicate that the average thickness of the continental crust of East Antarctica is about 40 km. However, the crust thickens appreciably to about 55 km under the Transantarctic Mountains and under the subglacial Gamburtsev Mountains located in East Antarctica between 70° and 80°E longitude at about 80°S latitude (Bentley 1983; Kadmina et al. 1983).

The present elevation of the bedrock surface of some parts of East and West Antarctica is actually below sea level. For example, two large subglacial basins in Wilkes Land of East Antarctica lie below sea level. In addition, the surface of subglacial Lake Vostok at 78°28′S and 106°48′E is below sea level by about 200–300 m. The bedrock surface of most of West Antarctica is also below sea level partly because of the mass of the overlying ice sheet (Drewry et al. 1983; Bentley and Robertson 1982; Bentley et al. 1982). Consequently, the incursion of seawater into the subglacial basins could result in the break-up of the West Antarctic ice sheet and of the ice in the Wilkes basin of East Antarctica.

2.2 Volcanoes

Antarctica truly is the land of fire and ice because it contains a large number of volcanoes that were active during the Tertiary Period (LeMasurier 1990). At the present time only Mt. Erebus on Ross Island in Fig. 2.2a, b is still active. The summit of Mt. Erebus, which rises to a height of 3,794 m a.s.l., contains a large crater which intermittently fills with alkali-rich (basanite and kenyte) basalt lava (Kyle 1995).

Mt. Erebus was discovered in January of 1841 by Captain James Ross who named it after the ship he and his crew had sailed to Antarctica (Section 1.1). The volcano was emitting plumes of steam when it was discovered and it was still active in March of 1908 when it was climbed by William E. David and his five companions of Shackleton's Nimrod Expedition. When it was climbed a second time in December of 1912 by Raymond Priestley and other members of Scott's Terra Nova Expedition, it was still active. The activity has continued into the modern era and actually intensified in 1982. The volcano became violent in December of 1984 when it ejected incandescent lava bombs accompanied by thunderous explosions and by the emission of colored steam and other gases.

The volcanoes of Antarctica occur not only in the Transantarctic Mountains and on the islands off the coast of Victoria Land, but also in Marie Byrd Land of West Antarctica, on the Antarctic Peninsula and on its off-shore islands, on the South Sandwich Islands, in East Antarctica, and on the islands of the Southern Oceans. All of these volcanoes were described in a book edited by LeMasurier and Thomson (1990). The descriptions of the volcanoes include photographs, maps, chemical analyses of the rocks, and interpretations of these analyses. Even the Gaussberg on the coast of East Antarctica (Section 1.3.3) is included in this compilation of Antarctic volcanoes. The book also

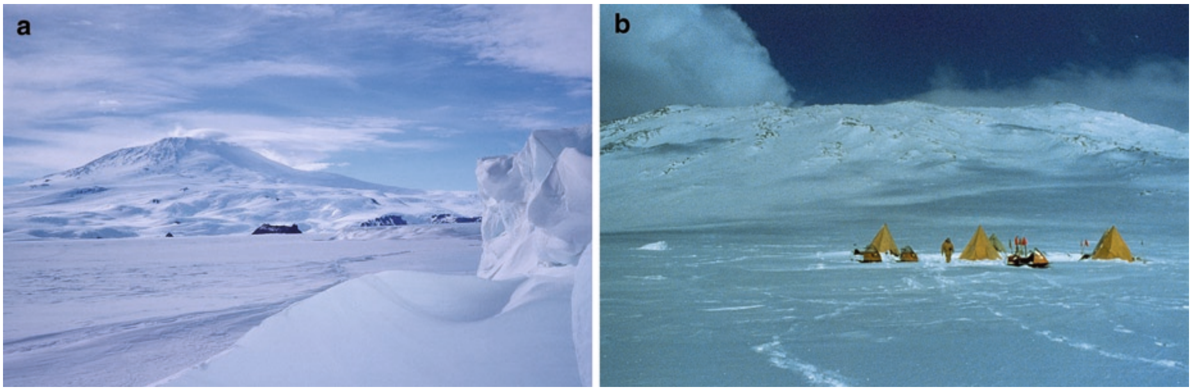

Fig. 2.2 (**a**) Mt. Erebus on Ross Island as seen from the Erebus Glacier tongue which projects into McMurdo Sound. A small plume of steam and other gases was rising from the summit of the volcano in January of 1985 (Photo by G. Faure) (**b**) Tent camp on the Fang Glacier below the summit of Mt. Erebus where scientists who need to work on the volcano spend at least one night in order to adjust to the high elevation (3,794 m above sea level). A large plume of steam was rising from the summit in the background during the 1982/83 field season (Photo courtesy of J.M. Palais)

contains references to the extensive literature on the volcanoes of Antarctica.

The volcanoes of the Transantarctic Mountains occur between Cape Hallett in northern Victoria Land and Mount Early (87°04′S, 153°46′W), which is located only 300 km from the South Pole. The volcanic mountains and cinder cones in the Transantarctic Mountains define the McMurdo Volcanic Province which is subdivided into four regions (Kyle 1990). These volcanoes were active in Late Tertiary time starting less than 25 million years ago and continuing to the present as in the case of Mount Erebus. All of them have extruded silica-undersaturated and alkali-rich lavas in marked contrast to the Ferrar Dolerite and Kirkpatrick Basalts of Middle Jurassic age both of which consist largely of silica-saturated tholeiites. These two suites of volcanic rocks are products of quite different petrogenetic processes that nevertheless occurred at different times in the lithospheric mantle underlying the Transantarctic Mountains. The petrogenesis of these different suites of volcanic rocks is the subject of Chapter 12 (Kirkpatrick Basalt) and Chapter 13 (Ferrar Dolerite), and Chapter 16 (Cenozoic Volcanoes).

The volcanoes in the Transantarctic Mountains and in Marie Byrd Land of West Antarctica erupted lava flows and pyroclastic ash that was deposited on the surface of the ice sheets. The ash was subsequently buried by snow and was thereby incorporated into the ice. The resulting ash layers now serve a useful purpose in the study of the ice sheets because they are unique "event horizons" whose age can be determined by isotopic methods (e.g., Folco et al. 2007). In addition, these horizons have preserved a record of the deformation of the ice sheets that is revealed by mapping their outcrop patterns on the bare-ice surfaces in the ablation zones. The chemical composition of the ash has been used to identify the volcanoes from which certain ash layers were erupted, while the sulfate concentration and the acidity (pH) of the ice above an ash layer provide clues to the amount of sulfuric acid that was injected into the stratosphere (Palais 1985). The volcanic dust and sulfuric acid in the stratosphere can cause temporary cooling of the global climate as demonstrated by the eruptions of Krakatau (Indonesia) in 1883, Mount St. Helens (Washington) in 1980, El Chichon (Mexico) in 1982, and Mount Pinatubo (Philippines) in 1992 (Holland and Petersen 1995; Thompson and Mosley-Thompson 1981; Kyle et al. 1981; Self et al. 1981).

2.3 Climate

The weather of Antarctica is proverbially hostile to life but actually varies widely depending on the season, the latitude, the elevation, and on local factors. The average monthly temperatures at McMurdo and South Pole stations in Fig. 2.3 display the range of seasonal temperature variations at these locations in relation to their latitude, elevation, and topographic setting:

McMurdo, 77°50′S, 24 m, coastal
South Pole, 90°S, 2,835 m, polar plateau

The highest average monthly temperature at the South Pole is only −32.3°C which occurs in December, whereas the highest average monthly temperature at McMurdo Station of −3.1°C occurs in December and January (Stonehouse 2002, p. 61). The highest average monthly temperatures at both locations in Antarctica are below the freezing temperature of water.

The "local conditions" that affect the weather alluded to above include the katabatic wind that blows from the polar plateau through the valleys of the outlet glaciers in the Transantarctic Mountains. The wind is generated when the layer of cold air that forms directly above the surface of the polar plateau drains downslope toward the coast. The speed of the wind on a gentle slope

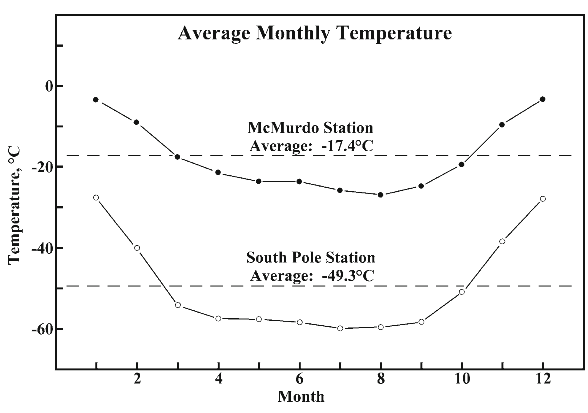

Fig. 2.3 The average monthly temperatures at McMurdo Station range from −26.9°C (August) to −3.1°C (December and January) compared to only −59.9°C (July) and −27.7°C (December) at the South Pole Station. The low seasonal temperature profile of the South Pole is partly attributable to its high southern latitude (90°S) and the high elevation of this site (2,835 m above sea level), whereas McMurdo Station is located at 77°50′S latitude at sea level on Ross Island. Nevertheless, the average annual temperatures at both sites are below the freezing temperature of water (Data from Stonehouse 2002)

is generally less than 36 km/h, but it can accelerate to hurricane strength when it is compressed in the narrow valleys through which ice from the plateau flows to the coast. For example, Mawson (1915) reported that on August 16, 1912, the katabatic wind at Cape Denison in Adelie Land of East Antarctica reached 129 km/h. Strong and long-lasting katabatic winds can cause frostbite in humans and can severely limit visibility because of the amount of snow that is transported in the atmosphere. Windy days during the summer months on the polar plateau and in the Transantarctic Mountains are, in many cases, accompanied by unusually low temperatures (e.g., −20°C to −30°C), clear skies, and low surface resolution because of blowing snow.

During cloudy weather a condition known as *whiteout* may occur when surface definition deteriorates because of the absence of shadows and because the horizon disappears. These conditions are dangerous because they can lead to accidents that result from poor visibility and associated disorientation. Whiteout conditions in Fig. 2.4 can also occur during dense fog and may be caused by ground blizzards when strong katabatic winds inject snow into the air. Travel on the polar plateau and in the mountains is "not indicated" under whiteout conditions.

Locations close to the coast on Ross Island and in Victoria Land occasionally do register temperatures above 0°C during the austral summer in December and

Fig. 2.4 During whiteout conditions in the Transantarctic Mountains the horizon becomes invisible and surface definition is lost. In the case shown here, the whiteout conditions resulted from high wind associated with snowfall near the coast of northern Victoria Land. The Scott tent, still used by geological fieldparties in the Transantarctic Mountains and on the polar plateau, is well suited for use in cold and windy weather, especially when it is set up in well-packed snow or névé. Mills Valley, Pain Mesa, northern Victoria Land, December 1982 (Photo by G. Faure)

January. In spite of such rare warm summer days along the coast, meteoric precipitation in the Transantarctic Mountains occurs in the form of snow rather than rain. However, the presence of morphologically preserved beech leaves and twigs in till of the Dominion Range less than 500 km from the South Pole indicates that during the Pliocene Epoch a temperate climate prevailed in that part of the Transantarctic Mountains (McKelvey et al. 1991; Hill et al. 1991; Mercer 1987; Webb and Harwood 1987). The meteorology of Antarctica is the subject of books by Rubin (1966), Businger (1977), Schwerdtfeger W. (1984), Bromwich and Stearns (1994), and King and Turner (1997).

2.4 Cold-Weather Injuries

The effects of the low air temperatures in the Transantarctic Mountains are magnified by wind which accelerates the loss of heat from the human body. This phenomenon is expressed quantitatively by the *wind-chill scale* (Rees 1993) that converts the measured temperature into an equivalent wind-chill temperature. For example, the arrow in Fig. 2.5a indicates that the measured air temperature of −10°C at a wind speed of 8 m/s corresponds to a wind-chill temperature of −20°C. In addition, a wind speed of 8 m/s in Fig. 2.5b is equivalent to a speed of 28.8 km/h. The wind-chill temperature also permits the definition of the discomfort index in Table 2.1. Accordingly, a wind-chill temperature of −20°C is perceived as being "bitterly cold." Such conditions are not unusual during the austral summer on the polar plateau and in the Transantarctic Mountains, except along the coast.

The discomfort experienced by humans because of the cold and windy conditions that characterize the summer weather in the Transantarctic Mountains and on the polar plateau is aggravated by the extremely low humidity of the air. Humans working out-of-doors under these conditions must protect themselves by wearing appropriate cold-weather clothing. Their ability to cope with the stressful environmental conditions improves when they are physically fit, well rested, well nourished, healthy, and when they are highly motivated to accomplish their mission (Gunderson 1974).

The scientists who do research in Antarctica are, in most cases, highly motivated to accomplish their objectives and therefore can tolerate the adverse

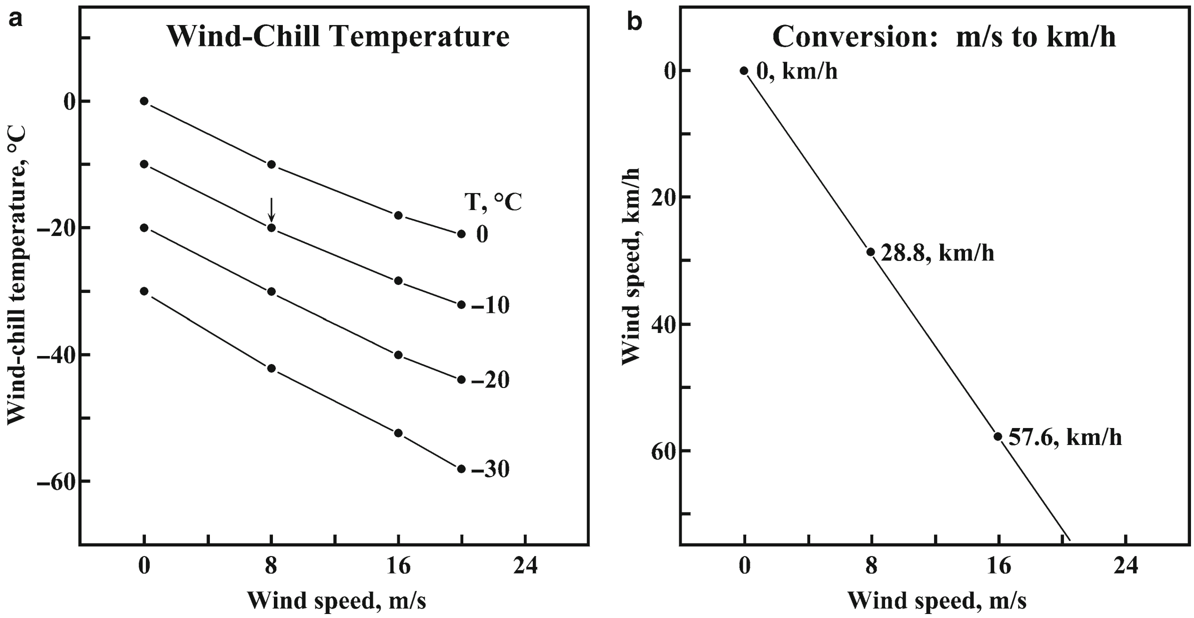

Fig. 2.5 (**a**) Conversion of the measured air temperature in degrees Celsius and the wind speed in meters per second into the wind-chill temperature which includes the effect of accelerated heat loss of the human body with increasing wind speed. The *arrow* indicates that a measured temperature of −10°C at a wind speed of 8 m/s corresponds to a wind-chill temperature of −20°C (**b**) Wind speeds measured in meters per second are converted into the equivalent unites of kilometers per hour by the relations: km/h = 3,600 m/1,000 s (Data from Stonehouse 2002, p. 293)

Table 2.1 Discomfort scale based on the wind-chill temperature derived in Fig. 2.5a from the measured temperature and the wind speed (Stonehouse 2002, p. 293)

Discomfort level	Range of wind-chill temperatures (°C)
Cool	+15 to +10
Very cool	+10 to 0
Cold	0 to −10
Very cold	−10 to −15
Bitterly cold	−15 to −25
Freezing cold	<−25

Table 2.2 Health hazards in Antarctica

(A) Weather-related
Hypothermia
Fire (burns and loss of shelter)
Frostbite
Snow blindness
Sunburn
Dehydration
Skin rashes
(B) Topographic hazards
Crevasses
Ice cliffs
Rock falls
Rock-climbing accidents
Drownings
Skiing/sledding accidents
(C) Aircraft and surface vehicles
Plane crashes[a]
Automobile accidents
Snowmobile accidents

[a]See Anderson (1974)

working conditions. However, some individuals may suffer emotional distress caused by loneliness, anxiety, sleeplessness, home sickness, constant daylight, anger, boredom, and the like. These kinds of emotional problems can also arise in individuals who are wintering over at one of the research stations which are cut off from the outside world for up to 6 months during the Antarctic winter.

The injuries caused by the harsh environmental conditions can be avoided in many cases by preventive measures taken in the field. If left untreated, minor bodily ailments can result in debilitating conditions that may require medical attention. The potential injuries and environmental hazards listed in Table 2.2 are not only weather-related but may also result from hazards associated with travel across mountainous terrain and on glaciers and sea ice.

Although hypothermia, sunburn, frostbite, and snow blindness do occur in Antarctica, these conditions rarely affect experienced field scientists. The most *common* weather-related health problems arise because of *dehydration* which not only affects kidney function and blood chemistry but also causes uncomfortable cracking and irritation of the skin. The most *dangerous* weather-related hazard is *fire* which can cause painful and potentially life-threatening burns and can also result in the loss of shelter, such as a dormitory building in McMurdo Station or a Scott tent in the field. The fire hazard is enhanced by the low humidity of the air and by the scarcity of liquid water with which to douse the flames.

The field manual that is issued by the Office of Polar Programs of the National Science Foundation to all groups that deploy through McMurdo Station contains the following admonition:

> Anyone deploying to remote locations in Antarctica should have a strong background in cold-weather survival or, at the very least, [should] employ a safety-survival guide with previous Antarctic experience. Antarctica is not a place to learn cold-weather skills. (Anonymous 1994)

2.5 The Ozone Hole

The hazardous working conditions in Antarctica arise not only from the harsh climate and the rugged surface environment, but also from exposure to excessive ultraviolet (UV) radiation caused by the destruction of ozone in the stratosphere above the continent (Appendices 2.11.2–2.11.5).

The seasonal loss of ozone from the stratosphere over Antarctica was first reported by Farman et al. (1985). Their data in Fig. 2.6 indicate that the amount of ozone in the atmosphere above the British Antarctic research station at Halley Bay on the east coast of the Weddell Sea (Appendix 1.10.2) declined from about 330 Dobson Units (DU) in October of 1957 to about 220 DU in October of 1984 (Appendix 2.11.4). In subsequent years, the average amount of atmospheric ozone in October over Antarctica continued to decline and approached 120 DU in 1989 followed by progressively lower values throughout the 1990s. The seasonal deficit in the amount of ozone over Antarctica is called the "Ozone Hole." The lowest amount of ozone of 90 DU was recorded in 1998 when the loss of ozone extended from about 12–24 km above the surface of the continent. In the same year, the ozone hole covered an area of 26.2×10^6 km^2 which is larger than the area of the North American continent.

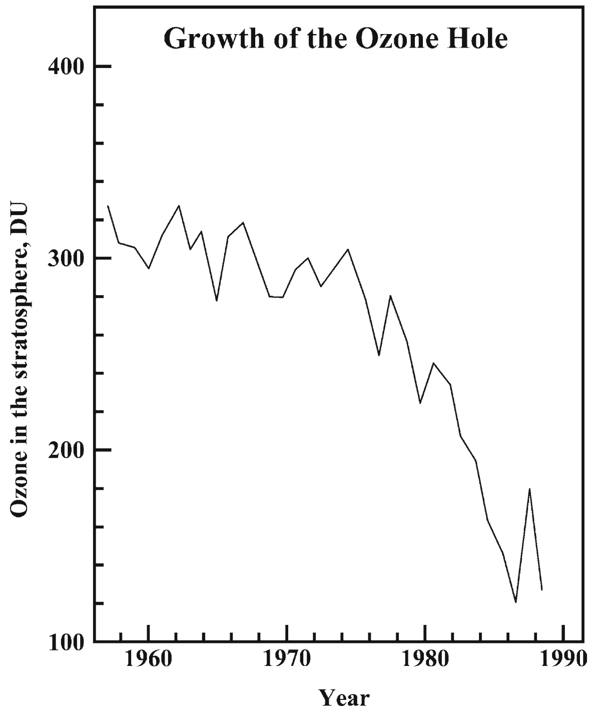

Fig. 2.6 Average ozone inventory in the stratosphere above the British research station at Halley Bay in October from 1957 to 1989. During that time interval the monthly averages for October decreased from about 320 Dobson units (DU) in the late 1950s to about 120 DU in the late 1980s. The decline of the average ozone inventory in October continued throughout the 1990s into the early twenty-first century (Adapted from Graedel and Crutzen 1993, Fig. 1.1)

Under normal circumstances, the oxygen molecules (O_2) of the air in the stratosphere, located 10–50 km above the surface of the Earth, are broken up by ultraviolet radiation emitted by the Sun and subsequently recombine to form ozone (O_3) (Appendix 2.11.4). The ozone of the stratosphere absorbs ultraviolet radiation thereby preventing it from reaching the surface of the Earth. This protection breaks down in Antarctica during September and October because, in the early spring, the stratosphere above the continent contains much less ozone than is present at other times of the year.

As the season progresses, the air in Antarctica warms up and the ozone hole gradually closes, but reappears in the spring of the following year. Measurements in

Fig. 2.6 demonstrate that this phenomenon has been occurring every spring since about 1970. It has been attributed to the release of anthropogenic chlorine-bearing gases such as chlorofluorohydrocarbons (CFCs) primarily in the northern hemisphere of the Earth.

The ozone hole in Fig. 2.7 is expected to fade away slowly and to disappear completely by the year 2068 because CFCs are no longer manufactured and therefore the amounts that are discharged into the atmosphere worldwide are decreasing annually (Cook-Andersen 2006).

We now know that the annual appearance of the ozone hole over Antarctica is caused by the circulation and low temperature of the stratosphere during the southern winter. The CFCs and other anthropogenic chlorine compounds, that are released into the atmosphere in the mid-latitudes of the Earth, are transported into the polar regions by the circulation of the atmosphere. During the winter in Antarctica (June, July, August, and September) the chlorine-bearing air of the stratosphere is isolated by strong westerly winds that form the circum-polar vortex. As a result, the temperature of the stratosphere within the vortex decreases to less than −80°C, which causes water vapor in the air to condense to form microscopic crystals of ice. Atoms of chlorine and other halogens are stored within the vortex by being sorbed to the surfaces of the ice crystals. When the vortex breaks down at the end of the Antarctic winter, warmer air enters the stratosphere and causes the ice crystals to sublime. The atoms of chlorine and other halogens that are thereby released accelerate the destruction of ozone in the stratosphere above Antarctica.

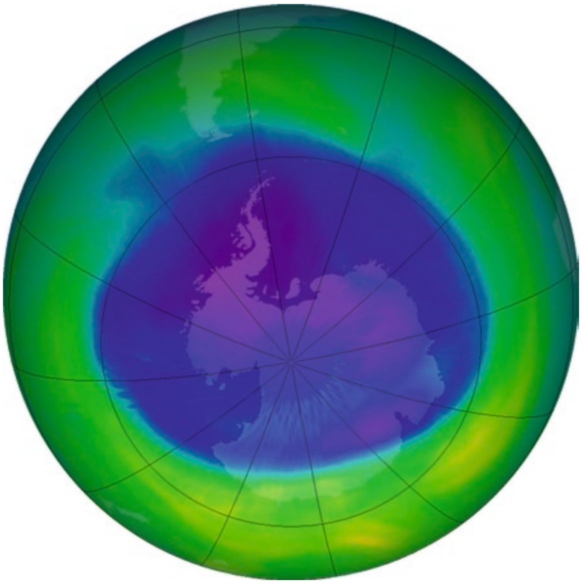

Fig. 2.7 The ozone hole over Antarctica in September of 2005 covered an area of more than 24 million square kilometers which is approximately equal to the area of North America. The ozone hole has been forming in the stratosphere over Antarctica since about 1970 as a result of the release of anthropogenic CFC gases into the atmosphere. Computer models now predict that the size of the ozone hole will begin to decline in 2018 and will stop forming altogether in 2068. This is good news because the ozone of the stratosphere absorbs ultraviolet radiation which can cause skin cancer and eye damage in humans and is harmful to marine organisms. The ozone content of the stratosphere over Antarctica has declined annually by about 70% below normal during September and October whereas the decline over the USA has only been between 3% and 6% (Cook-Andersen 2006; Photo courtesy of NASA)

The deterioration of the stratospheric ozone layer over Antarctica permits excessive amounts of solar ultraviolet radiation (UV) to reach the surface of the continent (Appendix 2.11.5). The increase in the intensity of UV radiation in Antarctica affects organisms on land and in the oceans as described in a book edited by Weiler and Penhale (1994). A summary by Graedel and Crutzen (1993) of the health effects of UV radiation indicates that it causes skin cancer in light-skinned individuals. Studies referred to by them indicate that a 1% reduction in the inventory of stratospheric ozone increases the effective UV dose by 2%, which causes a 4% increase in the incidence of the basal-cell carcinomas and about a 6% increase in the incidence of squamous-cell carcinomas. Therefore, unless special precautions are taken, geologists and other people who usually work out-of-doors in Antarctica during September and October may be exposed to higher doses of UV radiation than persons elsewhere on the Earth. The energy spectrum of solar UV radiation is discussed in Appendix 2.11.3.

Ozone also occurs as a contaminant in the air of large cities such as Los Angeles, and Mexico City. This low-altitude ozone persists for 25 days on average and can be transported for long distances by prevailing winds. The ozone in city smog is a byproduct of the combustion of gasoline and diesel fuel by automobile engines and can cause respiratory difficulties in humans. Ozone is also produced by lightning discharge in the air of the troposphere.

2.6 McMurdo Station

American scientists and support personnel who are scheduled to work in the Transantarctic Mountains or on the polar plateau of East Antarctica, in Marie Byrd Land in West Antarctica, and at South Pole Station will, in most cases, depart from Christchurch, New Zealand, and fly to McMurdo Station which is located at the tip of the Hut Point Peninsula on Ross Island in Fig. 2.8 (Section 1.2). This site was originally selected in 1955 by Admiral George J. Dufek as a logistics base for Operation Deep Freeze in preparation for research to be carried out by American scientists during the IGY (1957–1958). The site was chosen because it is located in a broad basin adjacent to a deep harbor where supply ships can unload cargo either onto a floating ice dock or directly to the shore. These favorable conditions also caused Robert Scott in 1901 to select this site for his winter-over base where he set up his Discovery Hut in Fig. 2.9 which still contains some of the equipment and supplies that he and his men left behind (Section 1.4.1).

During the IGY, McMurdo Station was operated by the US Navy in support of American civilian scientists and technicians. At that time and for several years thereafter, McMurdo Station consisted mainly of olive-green canvass-covered Jamesway huts that served as bunk houses for the enlisted men and for some of the transient scientists prior to their deployment. Neider (1974) wrote that in 1970/71 McMurdo Station looked like a military supply base. Partly for that reason female scientists were not allowed to work in Antarctica because the facilities in McMurdo were considered to be inadequate (Chipman 1986; Rothblum et al. 1995; Arnesen and Bancroft 2003). McMurdo, which is now administered by a civilian contractor, has evolved into a substantial village that can accommodate a summertime population of about 1,200 scientists, technicians, and field assistants who live in modern dormitory buildings. Women now make up more than one third of the population of McMudo Station. During the winter (March–August) the population of McMurdo drops to about 250. The support staff returns in mid-August on several special flights from New Zealand (Operation Winfly) in order to prepare for the arrival of scientists starting in October.

The US Antarctic Research Program (USAP) is administered by a representative of the National Science Foundation (NSF Rep) who occupies a prominent building called "The Chalet." The original Chalet in Fig. 2.10a was a Jamesway hut that had been painted red and had been dressed up by adding a wooden porch and gable. This hut was later replaced by a handsome wooden building in Fig. 2.10b that was built on the same site where it provides a spectacular view of the Royal Society Range across McMurdo Sound.

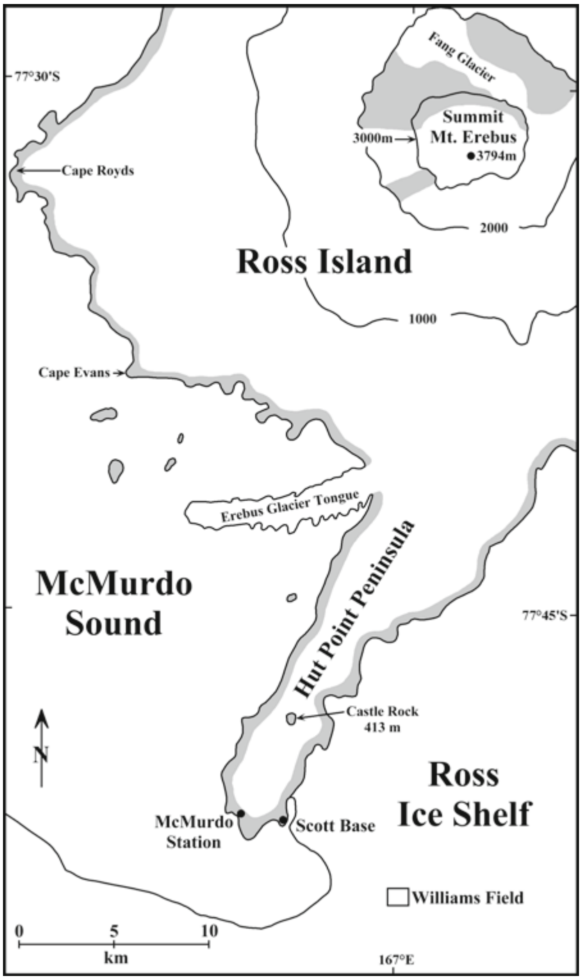

Fig. 2.8 McMurdo Station of the USA and Sott Base of New Zealand are both located at the southern tip of the Hut Point Peninsula on Ross Island. Castle Rock is a mass of hyaloclastite that rises to 413 m above sea level (a.s.l.) and is located about 6 km northeast of McMurdo Station. Cape Evans and Cape Royds contain the huts from which Robert Scott and Ernest Shackleton started their treks to the geographic South Pole, respectively. The Erebus Glacier Tongue is a prominent landmark for scientists traveling from McMurdo Station to Cape Evans and Cape Royds. The summit crater of Mt. Erebus is at 3,794 m a.s.l. (Adapted from the topographic map of Ross Island, Antarctica (ST 57–60/6, 1970, US Geol. Survey))

Fig. 2.9 View of McMurdo Station from Hut Point toward the Discovery Hut of Robert Scott (1901–1904) and Observation Hill in the background on the right. Arrival Heights is the basalt plateau on the left. The green building half-way up the slope of "Obs Hill" used to house the nuclear reactor that has since been dismantled and returned to the continental US (Conus). The sea ice in the "harbor" of McMurdo had not yet broken up when this picture was taken in January of 1983. Scott's ship, the RRS Discovery, was tied up next to the hut from 1902 to 1904 (Photo by G. Faure)

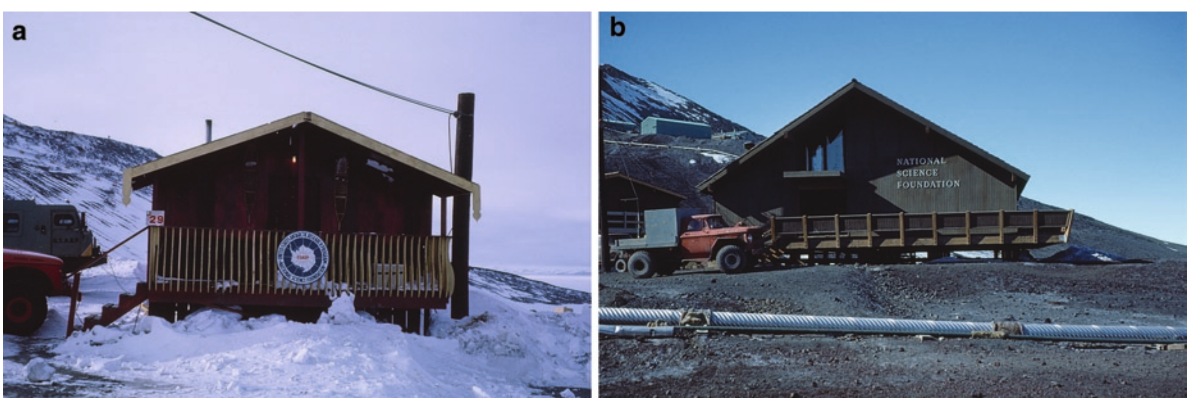

Fig. 2.10 (**a**) The Chalet in 1964 was a Jamesway Hut that had been painted red and that had the distinction of having a small porch (Photo by G. Faure). (**b**) Twelve years later in 1978, the offices of the NSF Rep were housed in a large permanent building that continues to be used for this purpose (Photo by G. Faure)

All activities related to on-going scientific research are supervised by the NSF Rep and his or her staff who have offices in the modern Chalet.

"Old Antarctic Explorers" (OAEs) will recall other landmarks of McMurdo such as Obs Hill (Fig. 2.9 and Section 1.4.3), the Berg Field Center (BFC), the Crary

Science and Engineering Center (Crary Lab), the Chow Hall, the Mammoth Mountain Inn (MMI), and the Hotel California (where you can check out anytime, but you can never leave). They will also remember Scott Base of New Zealand, Scott's second hut at Cape Evans, and Shackleton's hut at Cape Royds where the Adelie penguins come to incubate their eggs and to raise their chicks. Many OAEs have guided their field assistants to Castle Rock (Fig. 2.8) along the backbone of the Hut-Point Peninsula and have climbed to the top of this landmark in order to enjoy the view of Mt. Erebus and the Royal Society Range.

Former residents of McMurdo Station will also recall the windstorms that suddenly reduce visibility to less than 100 ft (30.48 m), with wind speeds in excess of 55 knots (101.9 km/h), and wind-chill temperatures that drop below −100°F (−73.3°C). Under these conditions, all personnel in McMurdo are required to remain in-doors (Condition I) and all travel is suspended for the duration of the storm that may last several days. The classification of weather conditions detailed in Table 2.3 is the responsibility of the McMurdo Weather Office (Mac Weather). Condition I storms can occur anywhere within the Transantarctic Mountains during the austral spring and fall especially on major outlet glaciers, such as the Reedy Glacier in Fig. 2.11, that channel the katabatic winds from the polar plateau to the Ross Ice Shelf or to the Ross Sea. Field parties that experience such storms learn first-hand that weather still rules in Antarctica.

A large base such as McMurdo Station requires a large amount of water for drinking, cooking, washing and, last but not least, for fighting fires. During the IGY and the years that followed, liquid water was obtained by melting snow that was scraped off the sides of the hills that surround McMurdo Station. The snow was trucked to the snow melter which was located adjacent to the original Chow Hall. This procedure was tedious, inefficient, and inadequate because, after a few years, the snow was used up and was not replaced by new snow.

In addition, the seasonal population of McMurdo Station continued to grow which increased the demand for water. For that reason, the US Congress in 1960 authorized the construction of a nuclear-fission reactor in order to provide power for the desalination of seawater. The components arrived on December of 1961 and were installed in a building that was erected at a site on the slope of Observation Hill above the station (Fig. 2.9). This reactor, which was put into operation in March of 1962, provided the power required to operate a desalination plant that converted seawater into fresh water (Neider 1974). However, in spite of the technological superiority of this process, water continued to be in short supply and had to be rationed. Matters came to a head when the representatives of the Antarctic Treaty Nations determined that the nuclear reactor violated the Treaty and therefore had to be shut down, dismantled, and all parts of it had to be removed from Antarctica. The Office of Polar Programs (OPP) did what was required and all radioactive waste was shipped to California. The nuclear installation was replaced by a desalination plant that is energized by fuel oil. The capacity of the present facility based on reverse osmosis is sufficient to provide an adequate

Table 2.3 Classification of weather emergencies at McMurdo Station and vicinity that are declared by the McMurdo Station weather office (Mac Weather) (Anonymous 1994)

Weather category	Description of weather conditions
Condition III	Wind speed up to 48 knots, wind chill down to −75°F, and visibility more than 1,320 ft (0.25 miles). Travel and all other activities are permitted although severe weather conditions may occur within 12 h.
Condition II	Wind speed between 48 and 55 knots, wind chill temperature between −75 and −100°F, and visibility between 100 and 1,320 ft (0.25 miles). Only pedestrian travel between buildings in McMurdo is permitted. Travel outside of McMurdo is restricted to marked trails and roads in radio-equipped vehicles.
Condition I	Wind speed in excess of 55 knots, wind chill temperatures less than −100°F, and visibility less than 100 ft. These parameters indicate extreme weather conditions. All personnel must remain inside buildings or in the nearest available shelter.

$$C° = \frac{F° - 32}{9} \times 5$$

1 mile = 5280 ft
1 ft = 12 in.
1 in. = 2.54 cm
1 knot = 1.852 m per h (Navy unit)
Wind-chill scale in Fig. 2.5

Fig. 2.11 Strong katabatic wind on the Reedy Glacier caused near whiteout conditions in this geological field camp in November of 1964 (Photo by G. Faure)

supply of water for the summer residents of McMurdo Station although shortages do occur and some of the water must be stored in case of fire.

The irony of the water shortage in McMurdo is that Antarctica contains 90% of the ice that exists on the Earth and 70% of the fresh water. However, mining of ice and snow on Ross Island for use in McMurdo Station is prohibitively expensive and may violate the Antarctic Treaty because of potential environmental issues. For these reasons, the demand for fresh water in the station continues to be met by desalination of seawater, although this process is also expensive and does impact the environment in McMurdo Sound because of the discharge of hypersaline brine by the desalination plant and of wastewater by the wastewater treatment plant.

Another way to make use of the fresh water that is stored in the glaciers of Antarctica is to tow icebergs to other regions of the world where water is in short supply. Each year large tabular icebergs break off from the Ross and Ronne ice shelves. These icebergs slowly disintegrate and melt as they are carried north by ocean currents. However, feasibility studies have demonstrated that icebergs cannot be towed because most of their volume is below the surface of the water and they tend to break apart by the stress of the tow cables (Husseiny 1978; Schwerdtfeger P. 1979; Holdgate 1980).

2.7 Amundsen-Scott South-Pole Station

The geographic South Pole was first reached in 1911 by Roald Amundsen and his companions and 1 month later in January of 1912 by Robert Scott and his team (Sections 1.4.3, 1.4.4). Nearly 17 years passed until 1929 when Admiral Richard Byrd flew over the South Pole in a Ford tri-motor airplane. Finally, in 1956 Admiral George J. Dufek landed at the South Pole in an LC-47 aircraft to prepare the way for the construction of an American research station to be used during

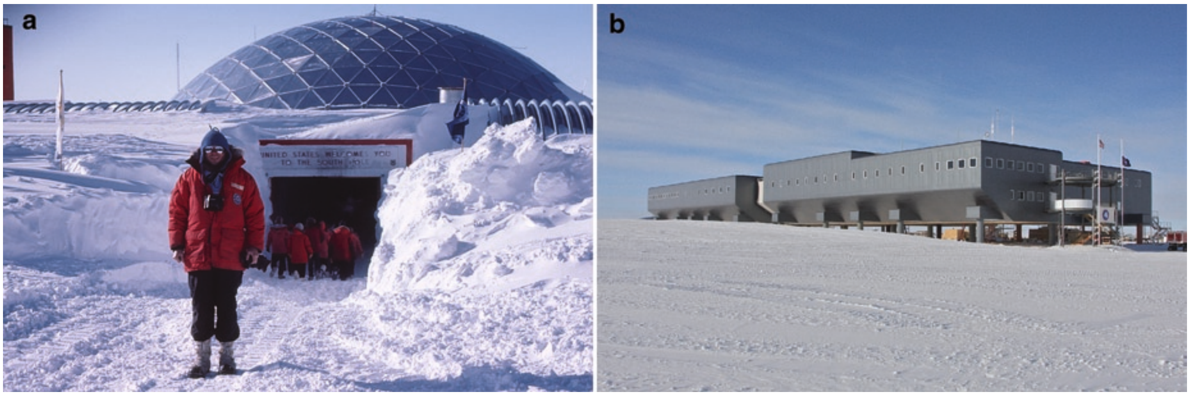

Fig. 2.12 (**a**) Entrance to the geodesic dome at Amundsen-Scott South Pole Station in December of 1982 (Photo by T.M. Mensing). (**b**) The new building at South Pole Station contains dorm rooms, laboratories, office space, a cafeteria, and recreational facilities. It is elevated above the surface to prevent snow drifts from accumulating (Photo by Keith Vanderlinde, National Science Foundation, taken on January 12, 2008)

the IGY (1957–1958). The first leader of Pole Station was Paul Siple who originally went to Antarctica as a Boy Scout with Byrd's first expedition in 1928 (Section 1.5.1).

The original building of South Pole Station was replaced in 1975 by a large geodesic dome located about 350 m from the actual pole. The dome in Fig. 2.12a, which was nearly 16 m high and 50 m in diameter, sheltered the science facilities, the galley, living quarters, communications equipment, and other essential services. The garage, the power plant, fuel bladders, and medical facilities were housed in a 252-m long tunnel covered by steel arches.

The famous geodesic dome that had sheltered the South-Pole Station for 30 years was replaced in 2007 because it was buried by snow that drifted around it. The new building in Fig. 2.12b is elevated on stilts in order to avoid the problems caused by the accumulation of snow. The geodesic dome will be dismantled and its parts will be returned to the continental US (Conus). The new station can accommodate a population of about 200 persons working on research projects in astronomy, upper atmosphere studies, meteorology, geophysics, and glaciology during the austral summer (October-February). Most of the scientists and technicians return home at the end of the summer. Only a small group of scientists and technicians stays to maintain the station during the winter.

Although Pole Station is more than 1,600 km south of Ross Island, it continues to be resupplied during the summer by ski-equipped C-130 aircraft flying out of McMurdo Station. The winter-over crew at Pole Station is resupplied only once in August by Winfly when mail and other supplies are dropped by parachute from a C-130 aircraft circling overhead in total darkness. Occasionally, aircraft have landed during the winter to evacuate persons requiring emergency medical treatment.

In addition to other science facilities, the South Pole Station includes a seismological observatory that has operated since 1957. This facility was greatly improved in January of 2003 when a new observatory was placed into service about 8 km from the main building. The sensor of the seismograph at the new facility is located in a borehole at a depth of 300 m below the surface where it is not affected by vibrations caused by the diesel-powered electric generators and other activities at the main station. As a result, the South Pole seismological observatory is now virtually free of locally-generated seismic noise and therefore is ideally suited to detect earthquakes that occur elsewhere on the Earth.

Visitors to Pole Station like to have their picture taken beside a barber pole topped by a silver globe surrounded by the flags of the Treaty Nations (Fig. 2.13). This "pole" is not at the precise location of the geographic South Pole because the East Antarctic ice sheet is sliding on its base which means that the true position of the South Pole must be redetermined annually.

Fig. 2.13 Gunter Faure (*left*) and Teresa M. Mensing (*right*) at Amundsen-Scott South Pole Station in December of 1982 (Photo by G. Faure)

2.8 Fieldwork in Antarctica

A voyage to Antarctica in a wooden sailing ship used to be a dangerous undertaking that lasted 2 years in most cases. Even steam-powered ships exposed travelers to severe wind storms, high waves, as well as to potentially dangerous icebergs and to the pack-ice that forms around the continent as the sea ice breaks apart in the spring.

The early explorers also used dogsleds to travel in Antarctica (Sections 1.3–1.5) which required skill in the handling of dogs and caused many dogs to die of malnutrition and exhaustion. In addition, dogs were routinely killed during extended trips in order to feed the remaining dogs. For example, in 1911 Roald Amundsen and his men left their base at the Bay of Whales (Framheim) with 55 dogs, but when they returned 89 days later after a journey of 2,976 km (1,860 miles), only 14 dogs remained alive (Section 1.4.4). Robert Scott and Ernest Shackleton also used dogs on their expeditions but preferred ponies and attempted to use primitive tractors to pull sleds (Sections 1.4.1, 1.4.2). Even Richard Byrd took a large number of dogs to Antarctica in addition to tractors and fixed-wing aircraft (Sections 1.5.1, 1.5.2). After the end of World War II, New Zealanders continued to use dog teams in Antarctica where they maintained a group of specially bred huskies (Fig. 2.14) at Scott Base on Ross Island (e.g., Herbert 1962, Figs. 4 and 5). However, the dog teams were gradually replaced by snowmobiles, helicopters, and fixed-wing aircraft. All sled dogs had to be removed from Antarctica prior to

Fig. 2.14 Antarctic huskies who were bred at Scott Base on Ross Island were used by New Zealand fieldparties to travel on the glaciers and snow fields of the Transantarctic Mountains. All dogs were removed from Antarctica in 1994 (Photo by G. Faure, November 1964)

April 1, 1994, in compliance with the Antarctic Treaty (Walton and Atkinson 1996; Stonehouse 2002).

In the modern era, most American scientists fly to Christchurch, New Zealand, on commercial airliners and are then transported to McMurdo Station by ski-equipped C-130 and wheeled C-141 cargo planes. A one-way trip from Christchurch to McMurdo Station takes 6–8 h depending on the type of aircraft, on the amount of cargo being transported, and on weather conditions. Most of the flight path crosses the open water of the South Pacific Ocean and of the Ross Sea where the water temperature is close to −2°C. Immersion in water at this low temperature is survivable by humans for only 2 or 3 min. Even though thousands of flights have crossed this dangerous stretch of water in the 50 years since the IGY, none have had to ditch in the ocean. However, several flights from Christchurch to McMurdo Station each year are forced to turn back before passing the point-of-no-return because of adverse weather conditions in McMurdo.

During the stop-over in Christchurch the Antarctic travelers are issued their cold-weather clothing at the Clothing Distribution Center (CDC) located near the airport. All Antarctic travelers need to try on the clothing they are issued to make sure that all items fit

Fig. 2.15 A helicopter of the New Zealand Air Force on Shapeless Mountain of southern Victoria Land is being loaded with the camping gear of an American fieldparty in December of 1994. This example of international cooperation is characteristic of operations in Antarctica (Photo by G. Faure, December 1994)

Fig. 2.16 This ski-equipped C-130 aircraft, flown by pilots of the US Navy, landed on Evans Névé in northern Victoria Land in 1982 to drop off a geological fieldparty (Photo by T.M. Mensing)

comfortably. Some OAEs prefer to wear their own clothing in Antarctica, but first-timers should use the clothes they are issued and should learn how to wear them correctly.

Geologists preparing to work in the Transantarctic Mountains or on the polar plateau spend about 10 days in McMurdo checking out camping equipment and food at the Berg Field Center (BFC). In addition, all persons who intend to live and work outside of the station are required to attend a 2-day snow-craft course taught by experienced American mountaineers (Yankielun 2007). Although helicopter support such as in Fig. 2.15 is available to field parties working within about 240 km (150 miles) of McMurdo Station, groups that work on the polar plateau, in most cases, prefer to use snowmobiles which can be transported into the field in the cargo holds of ski-equipped C-130 aircraft shown in Fig. 2.16 or suspended from helicopters. Field parties also receive a short-wave radio which they are required to use for daily check-ins with the field-party communications center in McMurdo or at South Pole Station. Most groups use two-burner Coleman stoves to heat their tents and to cook their food. Great care and skill in the use of these and other kinds of stoves is required to avoid burns and to prevent fires.

After field parties have checked out all of the necessary equipment from the BFC in McMurdo, including snowmobiles, they are ready for an overnight "shakedown trip" to a location of their choice on Ross Island,

Fig. 2.17 Most geological field parties take an overnight trip to Cape Evans or Cape Royds on Ross Island in order to practice driving snowmobiles, setting up their Scott tents, cooking a meal, and communicating with McMurdo Station on their short-wave field radio (This photo was taken at Cape Royds with Mt. Erebus in the background in 1992 by T.M. Mensing)

such as Cape Royds or Cape Evans. This trip, illustrated in Fig. 2.17, is the first opportunity for the members of a group to practice their skills in loading Nansen sleds, driving snowmobiles, setting up tents, preparing food, sleeping in their tents, and communicating with McMurdo Station by short-wave radio.

The large displacement of the magnetic south pole from the geographic pole (i.e., 2,820 km in 1990) and the steep inclination of the magnetic-field lines detract from the utility of the magnetic compass in Antarctica. The angle subtended by the magnetic and geographic poles for an observer at McMurdo Station is 130°. In other words, the magnetic-compass needle points 130° east of the geographic south pole. Therefore, the *magnetic declination* at this location is 130° east. In addition, the needles of magnetic compasses used in Antarctica must be specially balanced in order to allow them to swing freely because of the steep inclination of the magnetic field in the vicinity of the magnetic pole. The use of the magnetic compass for travel within the continental area of Antarctica and in the adjacent oceans has been superseded by the Global Positioning System (GPS) which is based on a set of satellites the positions of which are known precisely.

2.9 Preservation of the Environment

The large number of persons who annually pass through the American research stations at McMurdo, South Pole, and Palmer as well as those who live and work outside of these stations, generate large amounts of waste that must be collected, sorted, packaged, and removed from the continent. The disposal of waste generated in Antarctica was originally mandated by the Antarctic Treaty which came into force in 1961 and is now required by US Public Law 95–541 also known as the Antarctic Conservation Act (ACA) of 1978. This Act specifically protects all mammals, birds, and plants in Antarctica, as well as designated historical sites and other places of interest. In addition, the Protocol on Environmental Protection of the Antarctic Treaty, which was signed by 26 nations in 1991, has guided the activities of the US Antarctic Program (USAP) ever since. The *rules* by means of which USAP assures compliance with the Protocol were published in 1993. Beginning on August 15 of 1993, all American citizens working in Antarctica are required to follow these rules. Violators can be fined or charged in courts of law in the state where they reside (Anonymous 1993).

The basic rule concerning waste disposal is that anything that is shipped or flown in must eventually be shipped out. Accordingly, the amount of material that is brought in must be *reduced* to the essentials, items that are no longer needed should be *re-used* if possible, and the rest must be collected for shipment to Conus for *recycling* and/or safe disposal. These guidelines are essential for the preservation of the environment in Antarctica because the cold and dry conditions prevent most materials from decomposing such as organic waste, paper, metals, wood, plastics, clothing, etc. Certain items are banned from Antarctica altogether:

1. Polystyrene chips (called peanuts) that are used as filler in packing boxes
2. Nonindigenous plants and animals such as house plants, flowers, pets, tropical fish, and nonsterile soil
3. Pesticides (except for hygienic or scientific use), and
4. Polychlorinated biphenols (PCBs)

Certain other substances are considered to be hazardous pollutants that must be handled safely in order to prevent injury to humans. These hazardous materials are generally labeled as being flammable, corrosive, reactive, toxic, or radioactive. Any waste that contains these kinds of materials is labeled "Antarctic hazardous waste." Pollutants that are required for research purposes either at one of the stations or in the field require a permit before they can be imported to Antarctica. Therefore, USAP each years applies for a comprehensive permit to import such potentially hazardous materials.

The rules concerning the disposal of waste in Antarctica are implemented by requiring that it be sorted at the source into the appropriate waste streams. USAP has defined 16 different kinds of waste and provides separate color-coded containers for each including not only glass, paper, plastics, and metal cans, but also batteries, cardboard, clothing, construction debris, domestic combustibles, food-contaminated waste, hazardous waste, heavy metals, light metals, wood, and miscellaneous waste. As a result, of these efforts, the three American research stations have become models of environmental preservation and even remote field camps are required to participate. Everything that is taken into the field must eventually be removed and they really do mean *everything*.

The transformation of McMurdo Station from a temporary military supply base to its present squeaky-clean appearance did not happen overnight and required a change in the local culture. However, after the problems were graphically described and condemned in the popular press (e.g., Lemonick 1990) and with prodding from Greenpeace (e.g., May 1988; Anonymous 1990), the activities of the US Antarctic Program continue to comply with ACA and the rules arising from it.

2.10 Summary

Antarctica is a large continent with a highly diversified topography and weather conditions. Sweeping generalizations about its weather have little value because the conditions on the surface of Antarctica depend critically on the latitude, the elevation above sea level, the distance to the nearest coast, the time of year, and the local topography. Similarly, the topography of Antarctica includes large and elevated continental ice sheets, rugged mountains, magnificent valley glaciers, ice-free valleys containing meltwater streams and lakes filled with brine, and coastal regions where primitive plants grow on land during the austral summer and where an abundant fauna and flora thrive in the ocean (Mastro and Wu 2004). In spite of the cold and dry conditions that characterize the Transantarctic Mountains, primitive plants such as algae, lichens, and mosses have been found there (Williams 1995).

The low temperatures and high winds that commonly occur in the Transantarctic Mountains and on the adjacent polar plateau of East Antarctica combine to cause wind-chill conditions that can result in injury to humans. Cold-related injuries are avoided by the excellent polar clothing and shelters that USAP provides to groups living and working in the field. Injuries may also result from dehydration in the extremely dry air and from fires that cause burns and the loss of shelter. Other sources of injuries include accidents related to mountaineering, travel on glaciers and sea ice, as well as plane crashes, and accidents that occur during construction and repair of buildings, and from accidental immersion in seawater. Work in Antarctica is not without risk. The motto is: “Plan ahead, stay alert, keep in touch, and never walk alone.”

Another potential source of personal injury arises from the high flux of solar ultraviolet radiation that reaches the surface of Antarctica in September and October because of the destruction of ozone in the stratosphere. The loss of ozone results from CFCs and other chlorine-bearing anthropogenic gases that are primarily released by people in the northern hemisphere. These gases are temporarily trapped by the south-polar vortex that develops over Antarctica during the austral winter. When the vortex breaks down in the spring, the chlorine atoms are released and convert ozone (O_3) back into its diatomic form (O_2). The destruction of up to 70% of the ozone in the stratosphere over Antarctica causes the so-called ozone hole and permits excessive UV radiation to reach the surface. Prolonged and unprotected exposure to UV radiation can cause skin cancer and cataracts in humans. However, no acute cases have been reported that are attributable to the depletion of ozone in the stratosphere over Antarctica.

The USA maintains three research stations in Antarctica: at McMurdo on Ross Island, at the South Pole, and Palmer Station on Anvers Island in the Palmer Archipelago. These stations are a major component of the US Antarctic Program that is administered by the Office of Polar Programs of the National Science Foundation which is funded directly by the Congress of the USA. McMurdo and South Pole stations have been operated continuously since the IGY on a year-round basis, whereas Palmer Station opened in 1965. These stations provide facilities for research to scientists who either work at the stations or in the field outside the stations.

The large number of people that annually pass through McMurdo or live and work at South Pole and Palmer stations generate large amounts of waste of different kinds that must be removed from Antarctica in order to avoid contamination of the continent. The emphasis on the protection of the pristine environment of Antarctica has greatly reduced the impact American scientists and technicians have had on the areas where they have worked since the IGY.

2.11 Appendices

2.11.1 Exploration of Antarctica by Tractor Train

On November 1, 1958, a tractor train left Byrd Station in West Antarctica for a systematic study of snow stratigraphy, seismic profiling of the ice and underlying crust of Antarctica, and for a geological reconnaissance of the Horlick Mountains (Schulthess 1960). The group of six was led by Dr. Charles Bentley of the University of Wisconsin in Madison and included William E. Long, William Chapman, Fred Darling, Jack Long, and Leonard LeSchack. The departure of the tractor train was preceded in October of 1958 by a reconnaissance flight from Byrd Station to the Wisconsin Range of the Horlick Mountains where the

Fig. 2.18 The tractor train of the Marie-Byrd-Land oversnow traverse left Byrd station in West Antarctica on November 1, 1958, as part of the exploration of Antarctica during the IGY. The tractor train consisted of three Sno-cats each of which pulled a sled. The leading tractor, which was driven by Willam E. Long, carried a crevasse detector that projected from the front of the vehicle. The tractor train stopped at regular intervals to carry out glaciological and geophysical research. In addition, four members of the research team, including Bill Long, climbed Mt. Glossopteris in the Ohio Range and collected samples of rocks and fossils (Photo by Emil Schulthess reproduced by permission of Matthias Kamm, administrator of the photo archive of Emil Schulthess)

flight path turned east to the Ohio Range and continued to the Thiel Mountains where the aircraft turned northwest to the Whitmore Mountains in West Antarctica before returning to Byrd Station. Bill Long who was on this plane noted that a thick sequence of stratified rocks occurred in the Ohio Range and decided to make a collection of the stratified rocks he had seen in the Ohio Range.

The tractor train that left Byrd Station in Fig. 2.18 consisted of three Sno-cats each of which pulled a sled. The leading tractor, known as the "Sally Jeanne," was driven by Bill Long assisted by Fred Darling. This tractor carried a crevasse detector that is visible in Fig. 2.18. Occasional mechanical breakdowns of the vehicles, bad weather, and difficulties with crevasses limited the daily progress of the tractors to less than 36 km. The tractor train was resupplied from Byrd Station by a Dakota R4D aircraft that brought fuel for the tractors, food and mail for the crew, and, at least once, a dentist who treated one of the scientists. The elevation of the polar plateau in the path of the tractor train was in excess of 2,100 m above sea level and the weather was cold and windy most of the time with temperatures ranging from −20°C to −25°C.

Eventually the tractor train arrived at Station 414 at the foot of the Horlick Mountains and was delayed there by lack of fuel. The resupply plane from Byrd Station had to turn back several times because of bad weather, problems with radio transmissions, and mechanical problems. While the group waited for several days for the plane, Bill Long and three of his companions decided to climb Mt. Glossopteris which is one of the highest mountains in that part of Antarctica at 2,867 m above sea level.

In spite of bad weather, the group consisting of Bill Long, Fred Darling, Charles Bentley, and Jack Long set out in the morning and disappeared into the blowing snow and swirling clouds on the mountain. During the day a fog bank obscured the tractors parked about

Fig. 2.19 This picture taken by Emil Schulthess, a Swiss photographer who spent some time in the field with the Byrd-Station traverse group, captures the moment Bill Long returned to the Sno-cats at Station 414 after he and his companions had successfully climbed Mt. Glossopteris in the Ohio Range. The climbers were exhausted but unhurt after spending 12 h on the mountain shrouded in fog at this time (Photo by Emil Schulthess. Reproduced by permission of Matthias Kamm, administrator of the photo archive of Emil Schulthess)

2 miles from the foot of the mountain. After 12 h, Bill Long suddenly appeared out of the fog in Fig. 2.19 carrying a large backpack full of rock samples and a variety of fossils including marine invertebrates and fossilized Glossopteris leaves. The other climbers also returned utterly exhausted but unhurt.

This episode in the exploration of Antarctica had positive consequences for Bill Long whose study of the samples he collected on Mt. Glossopteris earned him a Master's Degree in geology at The Ohio State University (Long 1959, 1961). The results of his work gained the support of the Office of Polar Programs of the National Science Foundation in Washington, D.C. which provided the logistical support for geological fieldwork in the Ohio Range in 1960/61 and 1961/62. Several other scientists who joined Bill Long contributed their expertise to the study of all aspects of this remote mountain range, including: G.A. Doumani, J.H. Mercer, J.M. Schopf, S.B. Treves, R.L. Oliver, A.J. Boucot, L.L. Lackey, M.D. Higgins, J. Ricker, and C.J. Skinner. Bill Long earned a Ph.D. in Geology at The Ohio State University for his dissertation on the stratigraphy and environment of deposition of the sedimentary rocks in the Ohio Range (Long 1965).

The geology of the Ohio Range as it is presently understood is presented in this book in Section 7.5.1 (basement rocks) and in Section 10.5.2 (Beacon Supergroup). In addition, Fig. 10.22 depicts the adit of the Dirty Diamond Coal Co. from which Bill

Long and his companions extracted an unweathered sample of coal from a seam in the Mt. Glossopteris Formation.

2.11.2 Structure of the Atmosphere

The structure of the atmosphere of the Earth in Fig. 2.20 is defined in terms of the variations of pressure and temperature that occur with increasing altitude above the surface of the Earth. The major structural units are:

Troposphere, 0–10 km
Stratosphere, 10–50 km
Mesosphere, 50–100 km
Thermosphere, >100 km

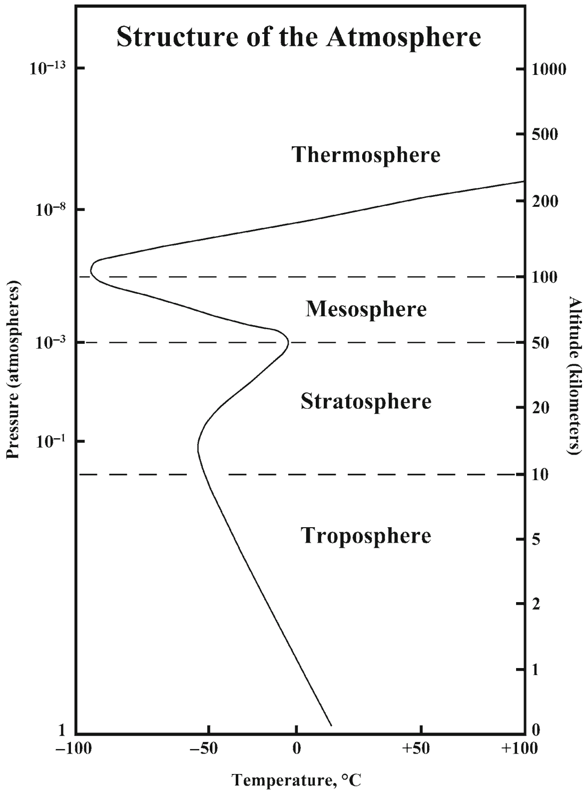

Fig. 2.20 The structure of the atmosphere of the Earth is based on the systematic variation of temperature (in degrees Celsius) and pressure (in atmospheres). The major subdivisions are the troposphere (0–10 km), stratosphere (10–50 km), mesosphere (50–100 km), and thermosphere (>100 km). Ozone (O_3) occurs in the lower part of the stratosphere between 10 and 25 km above the surface of the Earth (Adapted from Graedel and Crutzen 1993, Fig. 3.5)

2.11.3 Energy Spectrum of UV Radiation

Electromagnetic radiation emitted by the Sun is subdivided into three types defined by their wavelength (λ):

Infrared, $\lambda > 750$ nanometers (nm)
Visible light, $\lambda = 400–750$ nm
Ultraviolet, $\lambda < 400$ nm

Ultraviolet light (UV) in Fig. 2.21 is itself subdivided into:

UV-A, $\lambda = 400–320$ nm
UV-B, $\lambda = 320–290$ nm
UV-C, $\lambda < 290$ nm

The energy (E) of electromagnetic radiation is inversely proportional to its wavelength according to the equation:

$$E = hc/\lambda \qquad (2.1)$$

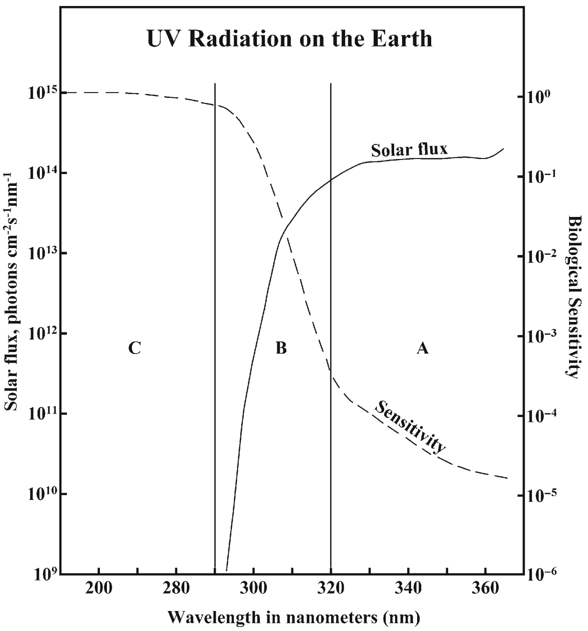

Fig. 2.21 Flux (*solid line*) and biological sensitivity of DNA (*dashed line*) of solar ultraviolet (UV) radiation on the surface of the Earth. UV radiation is subdivided into UV-A, UV-B, and UV-C with decreasing wavelength expressed in nanometers (nm). The solid line represents the UV-flux that reaches the surface of the Earth when the Sun is at a zenith angle of 39° and is expressed by the number of UV photons/cm²/s/nm. The biological sensitivity is scaled in terms of factors of 10^{-1} starting at 1.0 which is the maximum sensitivity and lowest tolerance of DNA molecules for UV radiation of different wavelengths (Adapted from Graedel and Crutzen 1993, Fig. 13.7)

where h = Planck's constant = 6.62517×10^{-27} erg/s and c = speed of light = 2.99792×10^{8} m/s

Accordingly, UV radiation is more energetic than visible light and UV-C is the most energetic form of UV radiation.

2.11.4 Formation and Destruction of Ozone

The most energetic UV radiation (i.e., UV-C) causes O_2 molecules in the stratosphere to dissociate:

$$O_2 + E \rightarrow O + O \quad (2.2)$$

The free oxygen atoms react with diatomic molecules of O_2 to form ozone (O_3):

$$O + O_2 + M \rightarrow O_3 + M \quad (2.3)$$

where M is a neutral molecule such as N_2 or O_2 which absorbs the energy released by reaction 2.3 and disperses it into the environment.

The ozone molecules preferentially absorb UV-C with a wavelength of $\lambda = 250$ nm (Hartley absorption band) and are dissociated in the process:

$$O_3 + E \rightarrow O_2 + O \quad (2.4)$$

$$O_3 + O \rightarrow 2O_2 \quad (2.5)$$

for a net reaction of:

$$2O_3 \rightarrow 3O_2 \quad (2.6)$$

Reactions 2.2–2.6 produce and destroy ozone and thereby maintain its inventory in the atmosphere. However, when certain trace constituents are introduced into the stratosphere, such as: NO, HO, Cl, Br, etc., the natural balance is disturbed because, in the presence of these catalysts, ozone is destroyed more rapidly than it is produced (Holland and Petersen 1995).

The amount of ozone in the atmosphere is expressed in terms of the Dobson Unit (DU) which is the number of ozone molecules that would form a layer of pure ozone that has an area of 1.0 cm^2 and is 0.01 mm thick at a pressure of 1.0 atmosphere and a temperature of 0°C. According to this definition, a column of air with an ozone concentration of 1 DU would contain 2.69×10^{16} molecules of O_3 per square centimeters. Correspondingly, an ozone concentration of 100 DU represents a layer of ozone that is 1.0 mm thick and has an area of 1.0 cm^2 at the temperature and pressure specified above. The average amount of ozone in the stratosphere of the equatorial region of the Earth is about 250 DU.

The principal anthropogenic contaminants that contribute to the destruction of ozone are the chlorofluorocarbons (CFCs) that were once widely used as propellants in aerosol cans containing hair spray and as coolants in refrigerators and air conditioners. These compounds are related to methane (CH_4) in which hydrogen has been replaced by the halogens fluorine, chlorine, and bromine. Therefore, the molecules of CFCs have formulas such as: $CFCl_3$, CF_2Cl_2, and CF_3Cl. Most of these compounds are gases at room temperature and their solubility in water is very low.

When CFC gases are released into the atmosphere, they gradually rise into the lower stratosphere because they are not washed out of the troposphere by rain. In the stratosphere the chlorine atoms are released when the CFC molecules are broken up by energetic UV-C radiation as indicated by the reaction:

$$2CFCl_3 + E + \frac{3}{2}O_2 + H_2O \rightarrow 2CO_2 + 2HF + 6Cl \quad (2.7)$$

The chlorine permits reactions to occur that destroy the ozone of the stratosphere:

$$Cl + O_3 \rightarrow ClO + O_2 \quad (2.8)$$

$$O_3 + E \rightarrow O + O_2 \quad (2.9)$$

$$ClO + O \rightarrow Cl + O_2 \quad (2.10)$$

When reactions 2.8–2.10 are summed, they add up to:

$$2O_3 \rightarrow 3O_2 \quad (2.11)$$

which is identical to Eq. 2.6. In this way, chlorine atoms in the stratosphere act as "ozone killers" and thereby decrease the ozone inventory of the global stratosphere.

Although the production of CFCs has been halted and they are no longer released into the atmosphere, these compounds continue to be the principal source of chlorine in the stratosphere. Natural sources, such as: sea spray, volcanic eruptions, and methyl chloride gas (CH_3Cl) released by plants are minor sources of atmospheric chlorine. Even though CFCs were outlawed, the chlorine concentration of the stratosphere is still five times higher than normal because of delayed releases of anthropogenic CFCs and other volatile halogen-bearing industrial compounds such as the cleaning solvent methyl chloroform (Graedel and Crutzen 1993, p. 143).

Although both the area and the depth of the ozone hole over Antarctica have varied annually, the size of the hole has not *decreased* appreciably even after the manufacture and release of the ozone-destroying gases were prohibited in 1987 by the Montreal Protokol. However, the computer models predict that the area and depth of the ozone hole will begin to decline in 2018 and that it will disappear by the end of the present century. If that happens, we will have successfully reversed the effects of this case of anthropogenic contamination of the atmosphere (Morell 2007; Stonehouse 2002; Faure 1998; Holland and Petersen 1995; Graedel and Crutzen 1993; Stolarski 1988; Molina and Rowland 1974).

2.11.5 Effect of UV Radiation on the Biosphere

The reduction of the ozone content of the stratosphere of the Earth as a whole, and of the Antarctic stratosphere in particular, has significantly *increased* the amount of UV radiation that reaches the surface of the Earth. The ozone layer in the stratosphere shields the Earth from the most energetic UV-C radiation ($\lambda < 290$ nm) by means of the ozone-destroying reaction of equation 2.4 (i.e., the Hartley absorption band). In addition, N_2O and O_2 also adsorb UV-C and prevent it from reaching the surface of the Earth. The amount of UV-B ($\lambda = 290$–320 nm) that passes through the atmosphere in Fig. 2.21 rises with increasing wavelength (and decreasing energy), whereas the low-energy UV-A radiation ($\lambda = 320$–400 nm) is not absorbed by the atmosphere and therefore all of it reaches the surface. Consequently, plants and animals have evolved a tolerance for UV-A and for the low-energy part of the UV-B spectrum. However, the decrease of the ozone content of the stratosphere of the Earth has caused an undesirable increase in the flux of energetic UV-B and UV-C radiation that reaches the surface. The problem is especially acute in Antarctica during the early spring in October.

Biological organisms on the surface of the Earth cannot survive prolonged exposure to UV-C ($\lambda < 290$ nm) because it destroys organic molecules. The relation between the solar flux of UV radiation and the wavelength of that radiation in Fig. 2.21 indicates that the flux of UV-C at the surface of the Earth is less than 10^{-5} times the flux of UV-B at $\lambda = 320$ nm. The flux of UV-B that reaches the Earth increases by a factor of more than 10^5 as the wavelength increases from 290 to 320 nm. In contrast to UV-B, the flux of UV-A is nearly independent of the wavelength from $\lambda = 320$ to 400 nm.

The biological sensitivity of DNA molecules also depends on the wavelength of the UV radiation. According to the data in Fig. 2.21, the sensitivity of DNA to UV-C radiation is 1.0 (i.e., UV-C is lethal). The sensitivity of DNA molecules to UV-B radiation decreases with increasing wavelength from 290 to 320 nm (i.e., long-wavelength UV-B radiation is tolerated better than short-wavelength UV-B radiation). DNA molecules tolerate UV-A best of all because organisms that did not adapt to this radiation did not survive on the surface of the Earth.

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