Chapter 14
Glaciers and the Latest Ice Age

Abstract The cryosphere consists of glacial ice, sea ice, ice shelves, ice caps, continental glaciers, valley glaciers, permafrost, and ice in rivers and lakes. Some of the cryosphere is temporary, such as sea ice near the North Pole and elsewhere, and it melts in warm months and re-freezes during colder months. Glacial ice on land represents a vast store of fresh water. It also is directly tied to sea level. For example, as glacial ice melts, sea level is raised worldwide. As glaciers expand, sea level is lowered worldwide. The two most important areas on Earth for freshwater storage are Greenland and Antarctica. Greenland's glaciers are receding faster than Antarctica's because global warming is affecting the Northern Hemisphere glaciers more so than those in the Southern Hemisphere. Sea ice is disappearing in the Northern Hemisphere and is sometimes expanding in the Southern Hemisphere. The rate of Greenland's ice loss is accelerating. Ice cores from the cryosphere tell scientists a great deal about the history of the atmosphere from gas bubbles trapped within them. Isotope studies tell us about past atmospheric compositions and temperatures. Glaciers were more extensive in the recent geologic past in what is generally known as the Pleistocene "ice age." Carbon dioxide and global temperatures have been correlated throughout the past 800,000 years from ice cores.

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Sea Ice	Precession
Permafrost	Deuterium
Mean Sea Level	Tephrochronology
Dansgaard-Oeschger Events	Glacial Lake Outbreak Floods (GLOFs)
Ice Shelves	Insolation
Ice Albedo	Methane
EPICA	Bipolar Seesaw
Calve, Calving	Iceberg
Carbon Dioxide	Greenland Ice Cap
MODIS	Mountain Glaciers
GPS	Sea Ice Extent
GRACE	Ross Ice Shelf
Milankovitch Cycles	Ice Volume
Isostatic Rebound	Southern Ocean
Petermann Glacier	Vostok Station
Larsen B Ice Shelf	Moraines
NASA	Rock Flour
Oxygen-18	Mid-Pleistocene Transition

14.1   Introduction

The cryosphere is that part of the Earth that is frozen throughout most of the year. Glaciers, ice caps, icebergs, sea ice, ice shelves, and permafrost make up the cryosphere and each is treated in the following chapters.

Glacial ice stores a large amount of fresh water and represents the largest reservoir of fresh water on the planet. Glacial ice is found today at or near both poles and in many of the highest mountain areas of the world. There is a direct relationship between glacial ice and sea level. When glaciers expand sea level is lowered. When glaciers retreat sea level is raised. Over the past several decades sea level has risen and glaciers have retreated, in some areas more so than in other areas.

Much of this frozen world, the cryosphere, is melting as a result of global warming and it is causing a world-wide rise in sea level and a release of methane

(CH_4) to the atmosphere as we have seen earlier in this text. The potential for sudden methane release will be treated in the following chapter, Chap. 15.

The cryosphere consists of those regions of the globe, both land and sea, covered by snow and ice. These include Antarctica, the Arctic Ocean, Greenland, parts of Northern Canada, parts of Northern Siberia, icebergs, sea ice, and most of the high mountain ranges throughout the world where sub-zero temperatures persist throughout the year.

The cryosphere plays an important role in the regulation of the global climate system. Snow and ice have a high albedo; they reflect much of the solar radiation they receive; as much as 90%. This results in cooling of the Earth and as glaciers expand they provide a negative feedback to global warming. But the overall extent of glacial ice throughout the world is diminishing, not expanding. Some glaciers may be expanding depending on local conditions, but worldwide glacial ice is becoming less and less and represents a classic example of a positive feedback to global warming. As the ice recedes, less sunlight is reflected and more absorbed by the bare, darker Earth causing another positive feedback loop.

Some parts of the Antarctic reflect as much as 90% of the incoming solar radiation, compared to a global average of 30%. Without the cryosphere, the global albedo would be considerably lower causing more energy to be absorbed at the Earth's surface rather than reflected, and consequently the temperature of the atmosphere would be much higher. Indeed, during the Cretaceous Period (120–65.5 million years ago) evidence suggests there was little or no snow and ice cover even at the poles and global temperatures were at least 8–10°C warmer than today and inland seas covered much of the continents. These inland seas greatly moderated the climate. The Cretaceous Period was a time of reining dinosaurs who roamed Earth largely from pole to pole on land, sea, and air.

The cryosphere also decouples the atmosphere and oceans which reduces the transfer of moisture and stabilizes the energy transfers within the atmosphere. The formation of sea ice in Polar Regions can initiate global thermohaline circulation patterns in the oceans (see Chap. 12, Fig. 12.6). The thermohaline circulation greatly influences the global climate system. The lack of sea ice may also shut down the thermohaline circulation, which may have a major negative effect on energy distribution on Earth. The presence of the cryosphere markedly affects the volume of the oceans and global sea levels, changes to which can affect the energy budget of the climate system. The climate system has a high degree of sensitivity to changing conditions within the system.

14.2   Greenland Ice Sheet

Greenland has the last remaining ice cap or ice sheet in the Northern Hemisphere and it is rapidly diminishing in volume (Figs. 14.1 and 14.2). Although the glacial ice in Greenland has often been considered as a single ice sheet, as more ice melts
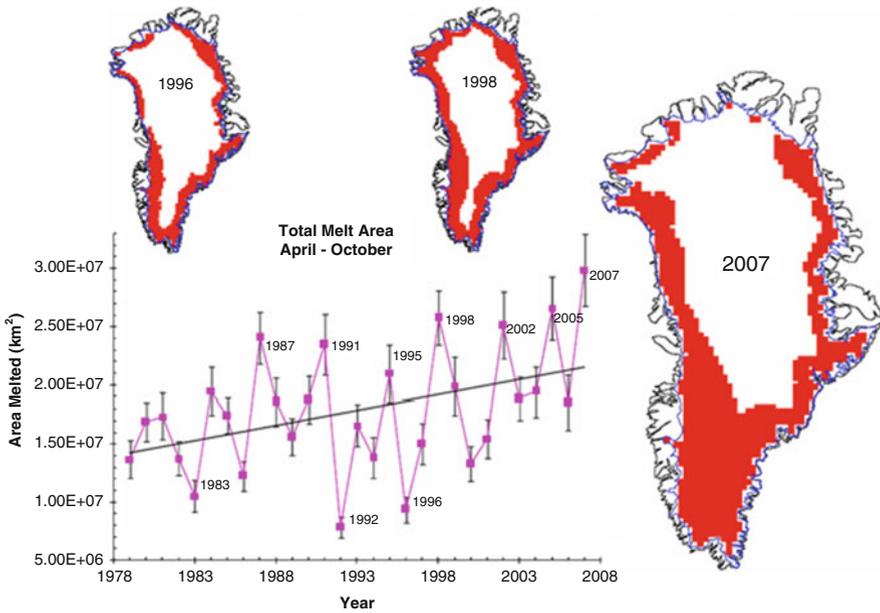
Fig. 14.1 A record melt extent was recorded in 2007. Meanwhile, the 28 year record of melt extent shows a statistically significant increasing trend (From http://cires.colorado.edu/science/groups/steffen/greenland/melt2005/index.html. *Source*: Steffen and Huff 2008, Steffen Research Group Web Page, NOAA/CIRES, Public Domain)

it becomes obvious that the ice sheet is made of individual glaciers that have had a history of being completely covered by glacial ice. Reference to the Greenland "ice sheet" is still valid.

The Greenland ice sheet is a vast body of ice covering 1,710,000 km² (660,235 square miles), roughly 80% of the surface of Greenland. It is the second largest ice body in the world, after the Antarctic Ice Sheet. The ice sheet in Greenland is almost 2,400 km (1,500 miles) long in a north-south direction, and its greatest width is 1,100 km (680 miles) at latitude 77°N, near its northern margin. The mean altitude (or elevation) of the ice is 2,135 m. The thickness is generally more than 2 km (1.24 miles) and over 3 km (1.86 miles) at its thickest point. It is not the only ice mass of Greenland. Isolated glaciers and small ice caps cover between 76,000 and 100,000 km² (29,344 and 38,610 square miles) around the periphery. Some scientists believe that global warming may be about to push the ice sheet over a threshold (or tipping point) where the entire ice sheet will melt in less than 100 years.

If the entire 2,850,000 cubic km (683,751 cubic miles) of ice were to melt, it would lead to a global sea level rise of 7.2 m (23.6 ft). This would inundate most coastal cities on Earth and remove several small island countries from the face of Earth, since island nations such as Tuvalu and Maldives have a maximum altitude
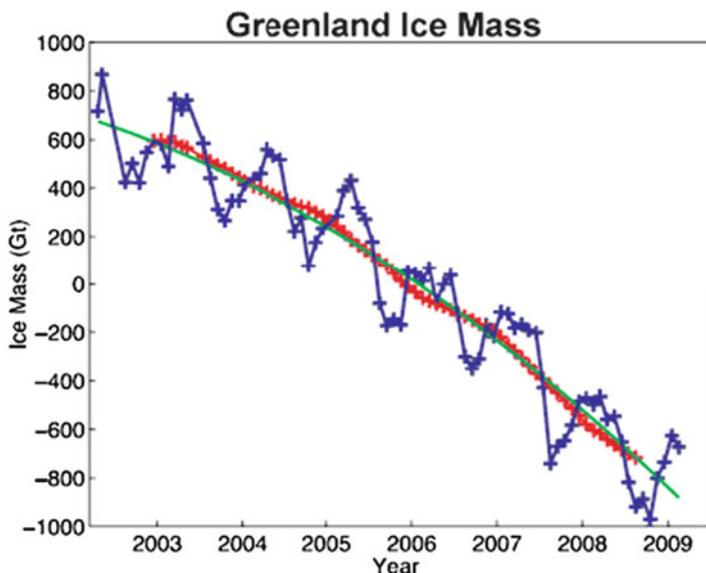
Fig. 14.2 Time series of ice mass changes for the Greenland ice sheet estimated from GRACE monthly mass solutions for the period from April 2002 to February 2009. Unfiltered data are *blue crosses*. Data filtered for the seasonal dependence using a 13-month window are shown as *red crosses*. The best-fitting quadratic trend is shown (*green line*) (From SkepticalScience.com, viewed 4/11/2012)

below or barely just above this number. For example, the highest point in the Maldives is just 7 ft above mean sea level (MSL) and the residents are already beginning to move to a mainland location.

Glaciers in west Greenland are melting 100 times faster at their end points beneath the ocean than they are at their surfaces, according to a NASA and a university study published online February 14, 2010 in *Nature Geoscience*. The results suggest this undersea melting caused by warmer ocean waters is playing an important, if not dominant, role in the current evolution of Greenland's glaciers, a factor that had previously been overlooked and not reported in the IPCC AR4 2007 report.

In fact, Greenland's glaciers are being melted by warmer ocean water at their terminus that is accelerating glacier movement from land to sea. In some of Greenland's glaciers the rate of movement toward the sea has been increased over 100% from 1 year to the next. The total ice loss from the Greenland subcontinent is shown in Fig. 14.2. The rate of this ice loss is accelerating.

In recent years, scientists have observed a widespread acceleration in the movement of Greenland's glaciers, associated with thinning of their lower reaches as they reach the sea. In the past decade, surface melting of glaciers around Greenland due to warm air temperatures has increased in both magnitude and area, while snowfall has increased just slightly. The result is a tripling in the amount of ice

mass lost in Greenland between 1996 and 2007. Of this loss, between 50 and 60% is attributable to a speedup in the flow of outlet glaciers, with the remainder due to increased surface melting. As the glaciers flow into the sea, they melt or calve and float off into the open sea as icebergs, which cause a more rapid movement of land ice toward the sea.

The glaciers also melt along their submerged faces, where they come into contact with warm ocean waters. A warmer ocean erodes a glacier's submerged, grounded ice and causes its grounding line (the point at which a tidewater glacier floats free of its bed) to retreat. Little is known about these rates of undersea melting and how they may influence the glaciers. Indications are that the Greenland ice is disappearing more rapidly than predicted by the IPCC or any other recent study.

The melting of glaciers beneath the ocean surface causes deep, warm, salty water to be drawn up toward the glacier's face, where it mixes turbulently with the glacier's cold, fresh water. The water then rises along the glacier face, melting its ice along the way, then reaches the ocean surface and flows away from the glacier in a plume. An ocean temperature of 3°C (37.4°F) can melt glacial ice at a rate of several meters per day, or hundreds of meters over the course of a summer; and this glacial ice is not completely replenished during the following winters.
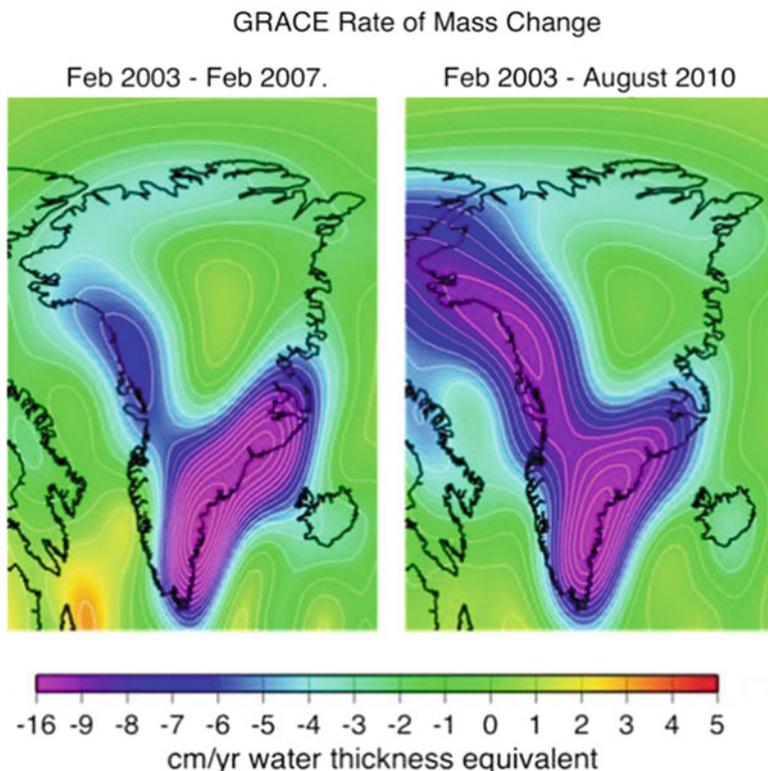
Figure 14.3 shows the recession of the Greenland glaciers as the rate of mass change. The recession (and thinning) is proceeding up the west coast as indicated by the loss of ice mass along the coast.

A recent international study finds that ice losses from Greenland's ice sheet, which have been increasing over the past decade in its southern region, are now spreading rapidly up its northwest coast (right side of Fig. 14.3).

The Greenland ice sheet is known to be a dynamic and unstable region with thousands of icebergs calving each year. In July 2008, a 27 km^2 iceberg broke free from the Petermann glacier with an approximate mass of 1–2 gigatonnes. Research by GISS and academic scientists indicates the ice-loss acceleration began moving up the northwest coast of Greenland staring in late 2005. The scientists drew their conclusions by comparing data from NASA's Gravity and Recovery Climate Experiment satellite system, or GRACE, with continuous GPS measurements made from long-term sites on bedrock at the edges of the ice sheet.

The data from the GPS and GRACE provided the researchers with monthly averages of crustal uplift caused by ice-mass loss (isostatic rebound). The team of scientists, which includes researchers from Denmark's Technical Institute's National Space Institute in Copenhagen and the University of Colorado at Boulder, combined the uplift measured by GRACE over United Kingdom-sized chunks of Greenland, while the GPS receivers monitored crustal uplift on scales of just tenths of a mile.

These changes on the Greenland ice sheet are happening fast, and Greenland is definitely losing more ice mass than scientists had anticipated. This trend is also seen in Antarctica, a sign that warming temperatures are having an unprecedented

GRACE Rate of Mass Change

Feb 2003 - Feb 2007.   Feb 2003 - August 2010

-16 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5
cm/yr water thickness equivalent

Fig. 14.3 Greenland ice cap with ice thickness contoured. The ice summit has a thickness of 3,207 m. The contour interval is 500 m. In 2010, Greenland temperatures were the hottest on record. It also experienced record setting ice loss by melting. This ice loss is reflected in the data from GRACE satellites which measure the change in gravity around the Greenland ice sheet (NASA, Public Domain)

effect on ice in Earth's colder regions. Recently acquired evidence indicates that the great ice sheets of the world are disappearing more rapidly than previously thought and the IPCC is in the process of revising its 2007 estimates in light of these new data for its AR5 report due in 2014.

The Greenland ice is often held in place by shallow ocean bottoms or continental shelves. Farther away from land, ocean currents play a greater role in moving and shaping ice. The East Greenland Current (see Fig. 12.5 and Table 12.2) flows southward from the Arctic along the island's eastern coast, carrying sea ice with it. Ice carried by this current occurs in large, thick pieces, and the ice in this swath along the Greenland coast almost certainly originated elsewhere.

Just as the relentless movement of water in rivers and streams can smooth the jagged edges of rocks over time, ocean currents can smooth ice fragments into round shapes.
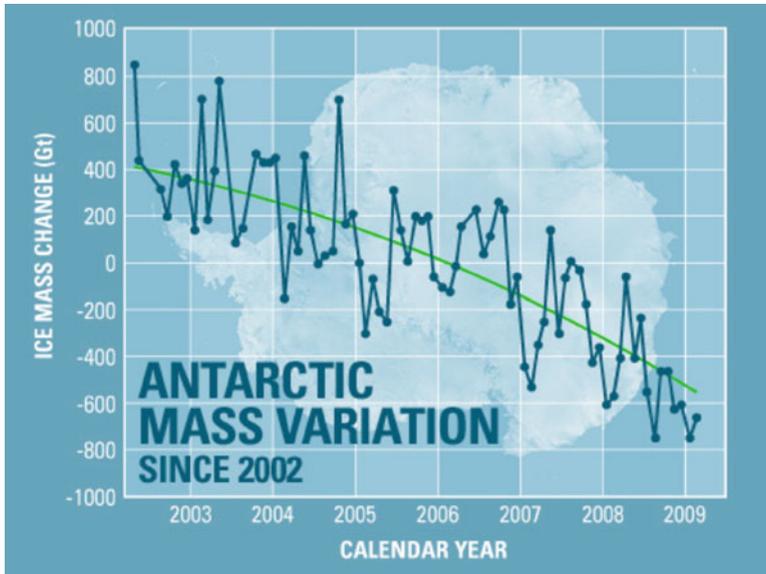
Fig. 14.4 Ice loss in Antarctica from 2002 through 2009 (From NASA, Public Domain)

Even farther out to sea than the large fragments of multiyear ice are much smaller pieces of ice, so small that they are at the mercy of even small surface currents. Collectively these tiny ice fragments form delicate swirls of ice.

If all the Greenland ice disappears, sea level will rise 26.3 ft according to an estimate by the United States Geological Survey. Tidal waters will also rise that much, tidal effects will move inland, and many of the world's cities will be inundated and millions of people will be displaced. This will cause untold turmoil among not only those displaced, but also among people where those displaced will go to find new places to settle and use resources. The rise in sea level is one of the most serious aspects of global warming.

14.3   Antarctica

The largest ice sheet (continental glacier) in the modern world is that of the southernmost continent, Antarctica and it is also loosing ice (Figs. 14.4, 14.5 and 14.6).

Antarctica is a desert and receives only 4–8 in. or less of precipitation annually. It is known to be windy but winds decrease toward the center of the continent. The coldest part of Antarctica is the eastern part, mainly because it is higher in elevation than in the west. Global warming is affecting the western part of the continent more than the eastern part and giant portions of ice shelves are now breaking off the western part.

While some areas of East Antarctica have been cooling in recent decades, the longer 50-year trend depicts that, on average, temperatures are rising across the
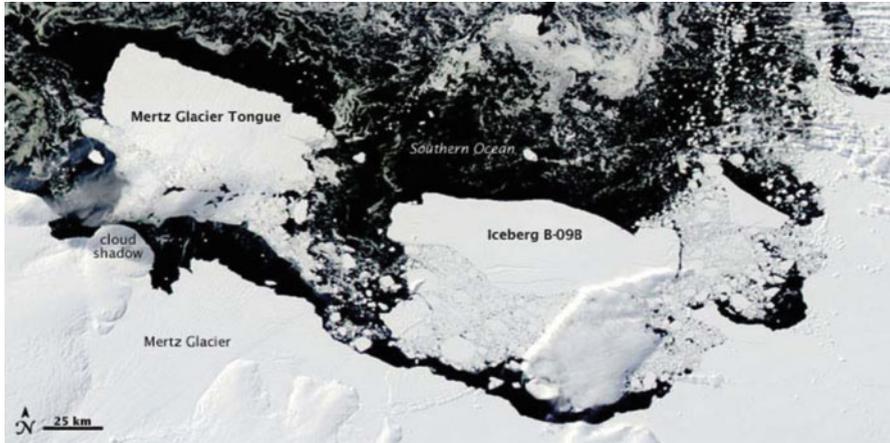
Fig. 14.5 East Antarctica ice breakup. Two massive icebergs drifted along the coast of East Antarctica in early March 2010. In mid-February 2010, the Rhode Island-sized Iceberg B-09B collided with the protruding Mertz Glacier Tongue along the George V Coast. The Mertz Glacier was already in the process of calving an iceberg when the arrival of the B-09B accelerated the process, leaving two icebergs the size of small states off this part of Antarctica's coast. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite captured this true-color image of Iceberg B-09B and the newly created iceberg off the Mertz Glacier. Between each iceberg and the coast floats a mélange of smaller pieces of ice. Farther out to sea, delicate white swirls indicate a relatively thin layer of sea ice. Occasional clouds floating overhead cast shadows on the ice surfaces below (From http://carbon-based-ghg.blogspot.com/2011/02/east-antarctic-ice-sheet-may-not-be-as.html; NASA, Public Domain)

continent. If the West Antarctic ice sheet completely melted, global sea level would rise by 5–6 m (16–20 ft).

Both Greenland and Antarctic ice sheets have been extensively drilled and cored in the last few decades and the deepest cores are still being described (in December 2012). A Vostok station drilling team in 2011 drilled into the ice almost 4,000 m and came within a few meters of drilling into a large subglacial lake, Lake Vostok (Fig. 14.7). They had to stop drilling prior to February 6, 2011 due to the end of the summer season (in the Southern Hemisphere). The last plane left Antarctica on February 6 with the core hole only 20 m above the lake. The lake has not been exposed to Earth's atmosphere for about 15–20 million years. The current plan is to continue the drilling and sample the lake water during the next drilling season taking every precaution not to contaminate the lake. Just how this is to be done has not been made public as of December 2012. On February 5, 2012 a Russian team was reported to have completed the drilling and sampled Lake Vostok. The analysis of the sampling has not been made public as of December 2012. Later reports from the Russian team state that they did not obtain samples from Lake Vostok and the lake will be sampled when they return for the next field season, probably in 2013.

The illustration below (Fig. 14.9) contains the analysis from a core taken by the European Project for Ice Coring in Antarctica (EPICA) which covers the past 650,000 years of Earth history. The first 200,000 years or so of the record show peaks and val-
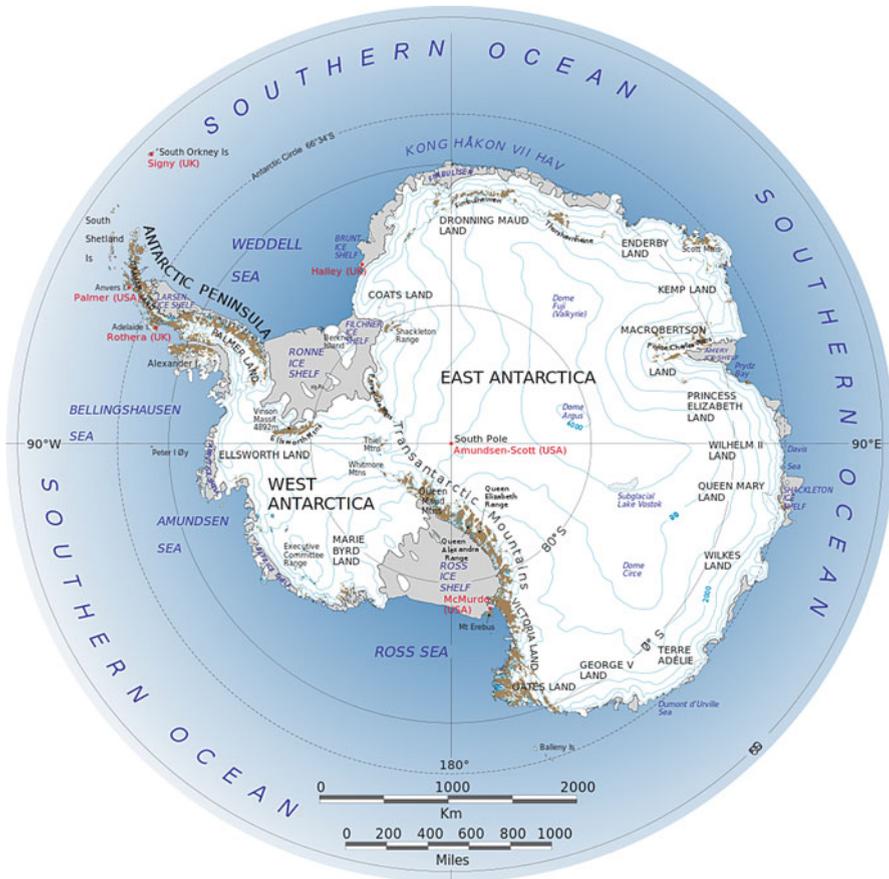
Fig. 14.6 Transantarctic Mountains, West Antarctica, East Antarctica. Antarctica is surrounded by the Southern Ocean and is the coldest place on Earth. The coldest temperature ever recorded was at the Russian Vostok station, −89.2°C (−128.6°F)

leys that are different from those from 430,000 years to the present. There has not been a good explanation as yet proposed for these differences. There is somewhat of a 100,000-year cyclicity pattern to the glaciations (as represented by the decreases in CO_2 and CH_4 concentrations) but this is the weakest of the Milankovitch cycles. Paleoclimatologists think that perhaps the initial episode of glaciation was the result of a Milankovitch cycle, but that CO_2 has controlled the other episodes in the cycle.

Temperature and carbon dioxide are shown to be related in some way, but such a relationship does not prove a cause and effect. Analysis of data from both EPICA and Vostok cores shows a lag of approximately 800 (or perhaps only 200) years of carbon dioxide behind temperature. This does not mean that this is *prima facie* evidence that temperature causes CO_2 to increase or that CO_2 is the cause of temperatures to rise. However, scientists know that the World Ocean absorbs the majority of Earth's carbon dioxide (a sink) and that a warming ocean will release carbon dioxide (a source) at a certain warming temperature. Therefore, it is not surprising
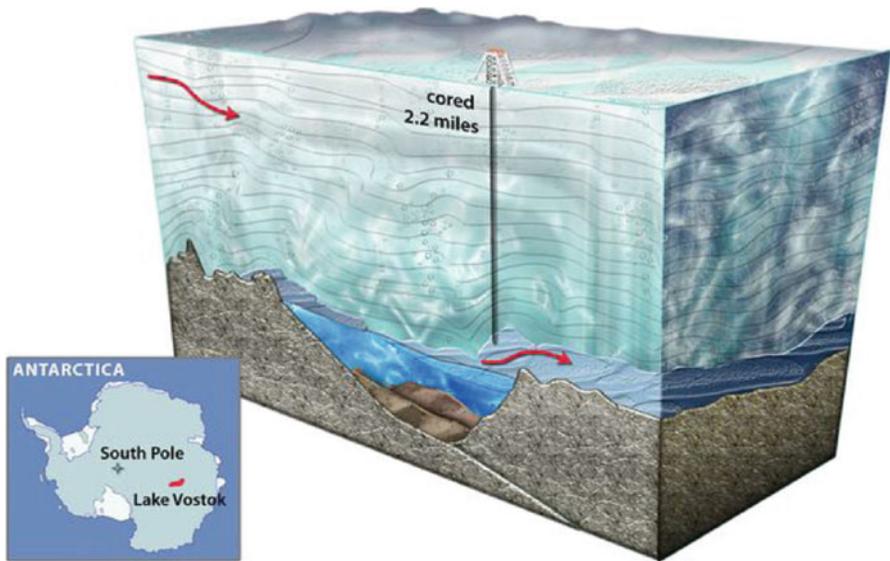
Fig. 14.7 Map of Antarctica and cross-section through the glacial ice to Lake Vostok (Illustration from the U.S. National Science Foundation, Public Domain)

that thousands of years ago a warming ocean gave up some of its carbon dioxide and "amplified" or led to a further increase in warming. This is another example of a positive feedback loop.

The illustration below (Fig. 14.8) shows carbon dioxide levels, temperature (°C), methane, solar variation at 65°N latitude, and oxygen-18 changes in a core from the Russian Vostok station in Antarctica. The age of this core goes back 420,000 years before the present.

In the illustration below (Fig. 14.9) two Antarctica ice cores are compared with ice volume over the past 420,000 years.

In both Figs. 14.8 and 14.9, note the relatively rapid rise in temperature compared to the slower decline in temperature, CO_2, and CH_4. Also note the good correlations with ice volume and the other parameters.

Locations for some of the sites and the geography of Antarctica are shown on Fig. 14.6.
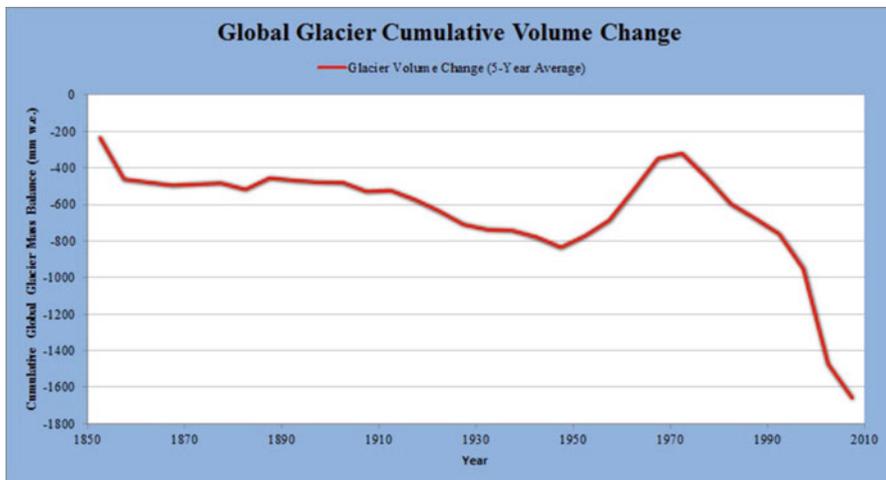
14.4   Mountain Glaciers

Mountain glaciers are found in high mountain ranges throughout the world. They are tongues of ice which occupy former stream valleys. They modify these stream valleys by eroding and depositing material. Glaciers are a powerful erosive agent and convert V-shaped stream valleys in mountainous regions into U-shaped glacial valleys. Mountain glaciers are also referred to as alpine, valley, or piedmont glaciers depending on their location relative to the topography. Alpine glaciers are found in the Alps
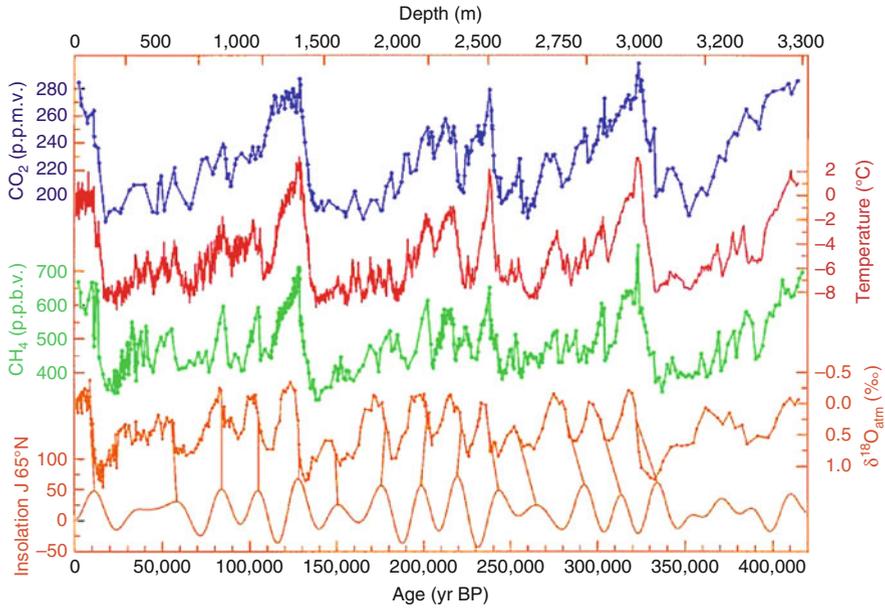
Fig. 14.8 CO_2, CH_4, insolation, $\delta^{18}O$, and temperature (°C) from Antarctica's Vostok ice core for the past 420,000 years. Current period is at *left*. From *bottom* to *top*: Solar variation at 65°N; (connected to ^{18}O); ^{18}O isotope of oxygen; Levels of methane (CH_4); Relative temperature; Levels of carbon dioxide (CO_2) (Government of the United States, Public Domain; Data obtained from the Vostok Ice Core)
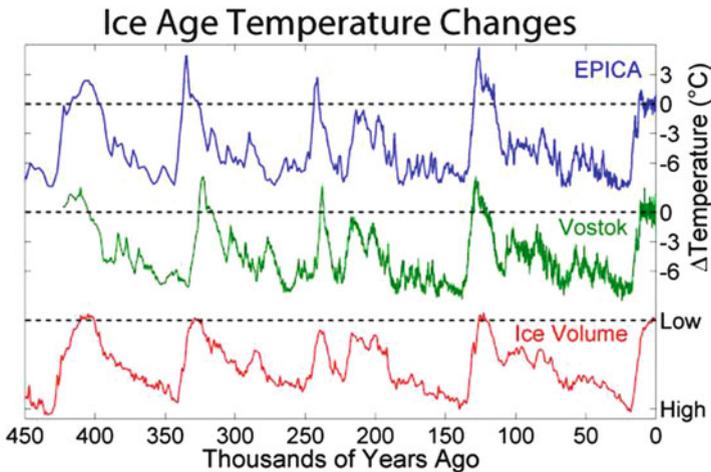
Fig. 14.9 Antarctic temperature changes and ice volume for the past 450,000 years as measured from ice cores from EPICA and Vostok

Fig. 14.10 Global glacier cumulative volume change (From Cogley 2009; NOAA, Public Domain)
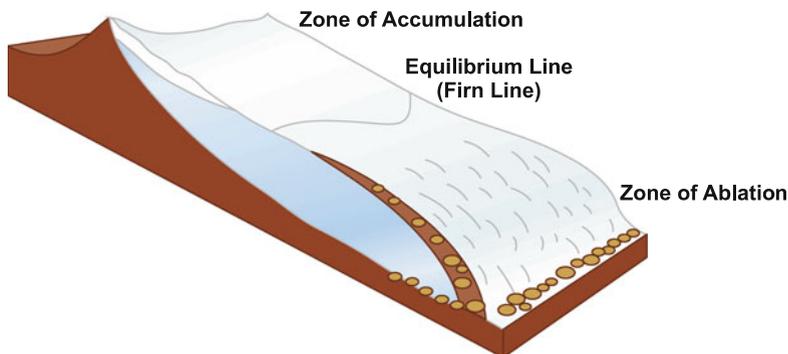
Fig. 14.11 Zones of accumulation and ablation, and the equilibrium line (Credit: John Cook)

or any high mountainous area. Valley glaciers occupy valleys and piedmont glaciers are usually formed by the coalescing of valley glaciers at the foot of a mountain.

Most mountain glaciers are receding at present. They are losing ice at a rate not previously known by mankind. Only a few glaciers are gaining ice. The great majority of glaciers throughout the world are retreating and losing ice. Some mountain glaciers are advancing but they are doing so under an unusual set of circumstances. Figure 14.10 shows the world-wide loss of glacial ice.

Glaciers are at equilibrium when the amount of feeder snowfall equals loss of ice at or near the glacier's terminus. As can be seen in the illustration (Fig. 14.11),
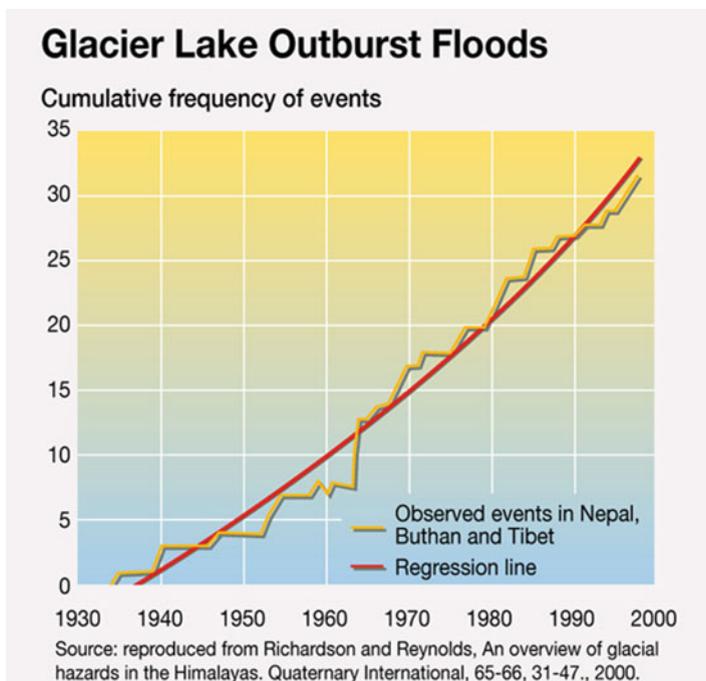
Fig. 14.12 The Bernard Glacier in Alaska's Saint Elias Mountains. The material it carries will be dropped as glacial till as the glacier recedes. Till is the general term that refers to all unsorted glacial deposits

a mountain glacier can be divided into a zone of accumulation and a zone of ablation separated by a zone of equilibrium (equilibrium line in Fig. 14.11). When annual accumulation exceeds annual ablation, the glacier advances. When annual ablation exceeds annual accumulation, the glacier retreats. When glacial ice retreats or is in equilibrium, the glacier itself continues to move downslope due to the influence of gravity and acts similar to a conveyor belt bringing rocks, soil, and ground-up rock (rock flour) to its terminus. The materials carried by the glacier and deposited as the ice recedes are called moraines and are further named according to their relationship to the glacier. Thus, there are terminal moraines which mark the glacier's terminus, medial moraines which are carried within the glacier, lateral moraines which were carried along the sides of the glacier, and end moraines which mark the various points of the terminus as the ice receded. The terminal moraine marks the end of the furthermost extent of the glacier.

Figure 14.12 shows the location of moraines carried by glaciers. Notice how the medial moraines are formed from former lateral moraines as tributary glaciers enter the main glacier.

A special case of the cryosphere is that of the Himalayan glaciers. These glaciers provide drinking, domestic, and agricultural water to over one billion people in Southeast Asia and they are rapidly losing ice. As these glaciers melt, there is an abundance of water and floods are common. Glacial lake outburst floods (GLOFs) are happening in the Andes and Asia as flood patterns and severity are changing (GLOFs for Asia are shown in Fig. 14.13).

The illustration below (Fig. 14.13) shows the cumulative frequency of glacial lake outburst events in the Himalayan region from the 1930s to the 1990s. These are

Glacier Lake Outburst Floods

Cumulative frequency of events

Observed events in Nepal, Buthan and Tibet

Regression line

Source: reproduced from Richardson and Reynolds, An overview of glacial hazards in the Himalayas. Quaternary International, 65-66, 31-47., 2000.

Fig. 14.13 Glacial Lake outbreak floods cumulative frequency in Asia (Reference from Richards and Reynolds 2000 is given above)

rapidly increasing and when the glaciers disappear, which is likely to happen before the middle of this (the twenty first century), a billion people will have to resettle or find other sources of water for drinking and agriculture.

Over half of the world's population lives in areas where the streams they depend upon originate in mountains with glaciers and snow. Global warming is an imminent threat to these people as the glaciers are rapidly receding and will almost certainly disappear before the end of this century; and many within the next 40 years. The results of climate change are being felt already in many areas as weather patterns change, rivers change their course, flooding increases in some areas, droughts increase in other areas, the number of major fires increase, agriculture is affected, drinking water is contaminated, and people must migrate to survive.

14.5 Ice Cores

Ice cores have been taken from drilling into glaciers and ice caps in many parts of the world and those from Greenland and Antarctica are especially well known.

Recent studies (2010–2012) have shown that ice also forms by meltwater from the glacial ice re-freezing at the bottom of glaciers. This does not affect data that are

obtained from above the re-freezing zone but the re-frozen ice does provide a slick surface over which glacial ice can move more rapidly down slope, often toward the ocean.

As glacial ice forms from snow which accumulates year after year, it entraps part of the environment from which it forms such as dust from volcanic eruptions and air trapped in bubbles preserved in the ice. Thus, glacial ice cores tell scientists a great deal about Earth history at the time the ice was formed, especially the volcanic eruptions and the composition of the atmosphere. Glacial air bubbles also contain stable isotopes that are used to tell scientists past atmospheric temperatures.

14.6   Stable Isotope Analysis

Oxygen and carbon stable isotopes are the two most often used for environmental and climate change applications, although others are sometimes used.

Oxygen has three natural isotopes, ^{18}O, ^{16}O, and ^{17}O. Oxygen-16 (^{16}O) is the most abundant oxygen isotope found in nature with a small amount of oxygen-18 (^{18}O) and an even smaller amount of oxygen-17 (^{17}O). The oxygen isotope numbers refer to the atomic mass of each isotope. Therefore, ^{16}O is lighter than ^{18}O and it takes less energy to convert it to the vapor state when it is the isotope found in H_2O. Oxygen-16 is the first oxygen isotope to be converted to the vapor state when H_2O evaporates leaving the remaining H_2O enriched in ^{18}O. Oxygen-18 also liberates more energy when H_2O condenses.

Air masses moving from the tropics to higher latitudes have a lower ratio of ^{18}O to ^{16}O as condensation removes the ^{18}O first and the water vapor is enriched in ^{16}O.

The ratio of ^{18}O to ^{16}O is temperature dependent in the following way: as climate warms, the organisms in the oceans that use oxygen in the secretion of their skeletons (e.g., $CaCO_3$) secrete more of ^{18}O because the lighter ^{16}O is evaporated leaving behind more ^{18}O. Therefore, the ratio of the oxygen isotopes is higher during warm periods and lower during colder or cooler periods when evaporation is less. This ratio is very useful in distinguishing glacial from interglacial periods.

Carbon has three naturally occurring isotopes, ^{12}C, ^{13}C and ^{14}C. Carbon-12 and -13 are stable and occur in a consistent ratio of 99–1, respectively. Carbon-14 is formed in the atmosphere by cosmic radiation impacting nitrogen atoms and forms a negligible part of total carbon in the environment. It, however, is radioactive and has a half-life of 5,730 years. Radioactive carbon (or radiocarbon) is used to date materials that are 50,000 years and younger from plants and animals. When living, these organisms absorb carbon-12 and carbon-14 in a given ratio. When the organism dies, it stops absorbing carbon-14 and the carbon-14 begins to decay. By knowing the ratio of ^{12}C to ^{14}C when the organism died and determining how much ^{14}C is remaining, and knowing the half-life of ^{14}C as stated above, scientists can determine the age of the organism or its remains. After about 50,000 years there is not enough ^{14}C left to measure.

14.7   Ice Cores and Proxies

Ice cores are retrieved from glaciers and ice caps by a special coring or drilling method. If the snow and ice at the top of the glacier are soft, a hollow tube may be used to a depth where the ice becomes hard; hard ice necessitates the use of a core drill which involves a cutting tube and a drilling rig at the surface. The cutting material is at the end of a hollow tube and the drilling is done in 4- to 6-m increments. After the increment bottom or depth is reached, the tube is extracted from the borehole and the ice sample is retrieved from the tube. Collection of a long core record requires many cycles of lowering a drill/sample-tube assembly, cutting a core 4–6 m in length, raising the assembly to the surface, emptying the core barrel, and preparing a drill/sample-tube assembly for additional drilling. It is of course necessary to keep the samples well below freezing at all times after extracting the sample and adequate documentation of every step in this process is essential.

   Ice cores form a continuous record of the atmospheric conditions only at the location from which the ice is retrieved. The bubbles in the glacial ice have samples of the atmosphere in them. These samples may give indications of the global climate throughout the world or they may not. If there is a correlation with events in Antarctica and Greenland cores, then confidence of a global record is increased.

   Ice cores record volcanic eruptions as dark layers of volcanic ash. They also contain chemical signatures of fingerprint compounds from the beginning of the burning of coal.

14.7.1   Dating Ice Cores

Near the top of glacial ice, it is usually possible to identify annual layers of alternating light- and dark-colored bands. The light-colored bands represent summer and the dark-colored bands represent winter. The light- and dark-colored bands together represent 1 year.

   Deeper below the ice surface, the original snow is recrystallized and the annual layers are indistinguishable. Dating the deeper ice becomes a much more difficult problem. Methods of dating ice cores can be summarized as follows:

- Layer counting;
- Glaciological modeling;
- Orbital tuning;
- Gas synchronization;
- Tephrochronology; and
- Correlation with other dated records.

   Layer counting is used mainly in the upper few meters of glacial ice (Fig. 14.14). Other methods are necessary for ice below where annual layers are absent.

Fig. 14.14 Portion of an ice core showing annual layers (USGS, Public Domain)

Glaciological modeling takes advantage of physical constraints of accumulation and glacial flow to determining age.

Orbital tuning correlates cyclical variations with orbital variations such as the Milankovitch cycles, discussed later in this chapter. Earth's orbital parameters vary with a distinct periodicity: 100,000 and 400,000 for the eccentricity of the orbit, 41,000 for the Earth's axial tilt (obliquity) of the axis of rotation, and 23,000 and 19,000 for the precession of the vernal equinox.

Gas synchronization uses records of gases that are well mixed in the atmosphere to link ice core records. This has been used with $\delta^{18}O$ to compare the timing of deglacial changes recorded in Greenland and Antarctica. The rapid variations in atmospheric methane concentrations has allowed more accurate comparisons of the relationship between Dansgaard-Oeschger (rapid warming, gradual cooling) events in Greenland and warming events in Antarctica. This type of correlation has led to the "bipolar seesaw" hypothesis for latitudinal heat transfer in the Atlantic.

Tephrochronology uses the elemental composition and geochemical signature of volcanic ash (tephra) found in ice cores as stratigraphic markers. If the age of the volcanic eruption is known, tephra offer a means to date an ice core with radioisotopes and to correlate between ice cores in different parts of the world.

Correlation with other dated records allows researchers to establish relative chronologies between ice cores and with marine sediments.

14.7.2   *Mountain Glacier Ice Cores*

Mountain glaciers occur in the higher mountainous regions of Earth, such as the Himalayas, Andes, Rockies, Alps, Coast Ranges of the western U.S., and other high standing mountains. There are mountain glaciers on the equator in Ecuador.

Obtaining ice cores from mountain glaciers presents logistical problems as the drilling and sampling equipment have to be carried into the drilling site. In the case of coring of larger mountain glaciers it may be possible to fly it in by helicopter or small fixed-wing airplane. For these and other reasons, mountain glaciers have provided fewer cores than have the ice sheets of Greenland and Antarctica.

The illustration below (Fig. 14.15) shows the loss of mass in mountain glaciers from 1960 through 2006.

The illustration below (Fig. 14.16) is a summary of observed variation in the atmosphere from 1993 to 2003 during which ice melt contributed 0.6–0.8 mm/year rise in eustatic sea level.
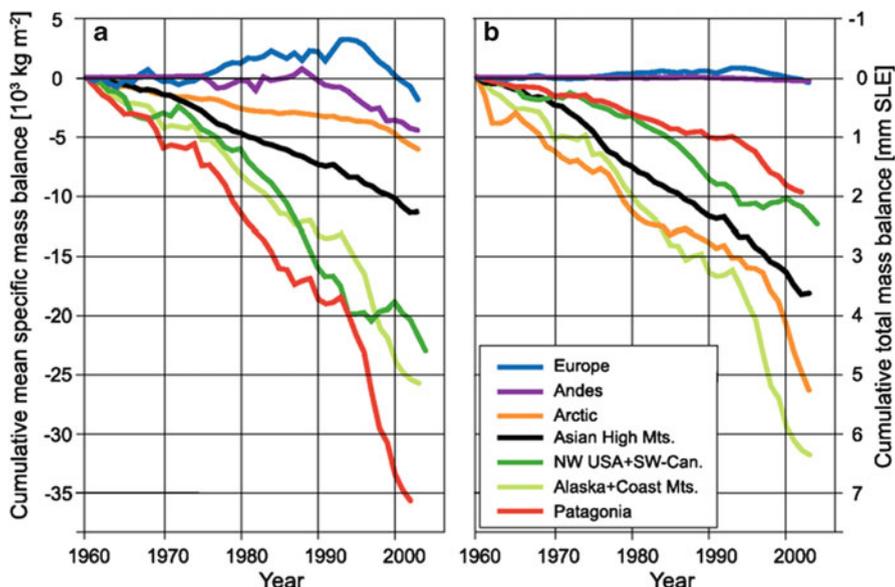
Fig. 14.15 Cumulative mean specific mass balances (**a**) and cumulative total mass balances (**b**) of glaciers and ice caps, calculated for large regions (Dyurgerov and Meier 2005). Mean specific mass balance shows the strength of climate change in the respective region. Total mass balance is the contribution from each region to sea level rise (From IPCC AR4 2007)
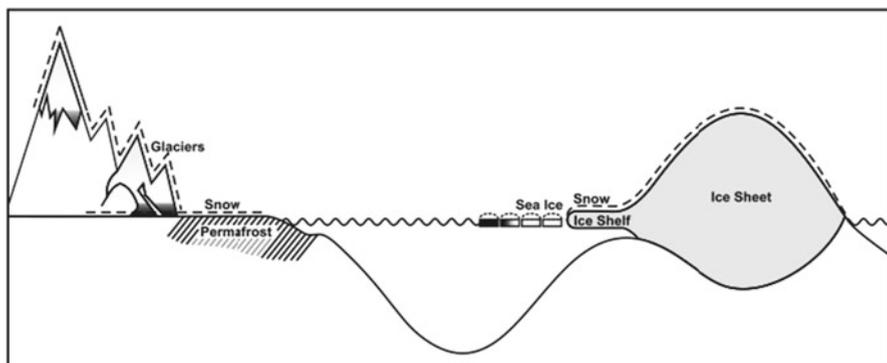
Fig. 14.16 Summary of observed variations in the cryosphere (Redrawn from IPCC AR4 2007 by John Cook)

There has been substantial retreat of arctic sea ice, especially in summer; the continued shrinking of mountain glaciers; the decrease in the extent of snow cover and seasonally frozen ground, particularly in spring; the earlier breakup of river and lake ice; and widespread thinning of Antarctic ice shelves along the Amundsen

Sea coast, indicating increased basal melting due to increased ocean heat fluxes in the cavities below the ice shelves. An additional new feature is the increasingly visible fast dynamic response of ice shelves, for example, the dramatic breakup of the Larsen B Ice Shelf in 2002, and the acceleration of tributary glaciers and ice streams, with possible consequences for the adjacent part of the ice sheets.

As ice shelves collapse, land glaciers that fed the ice shelves speed up in their way to the sea to replace the ice shelf that collapsed.

14.8   The "Ice Age"

The ice age most familiar is the most recent ice age or the extensive glaciation that occurred over most of the Northern Hemisphere and high mountain ranges during the past few hundreds of thousands of years. Earth has experienced several earlier "ice ages" dating back as far as 700 million years during Precambrian time and possibly even further back than that, if the "Snowball Earth" hypothesis proves to be correct. But we will concentrate on the most recent ice age because that is the one that presents us with the most evidence. It is sometimes referred to as the Pleistocene glaciation.
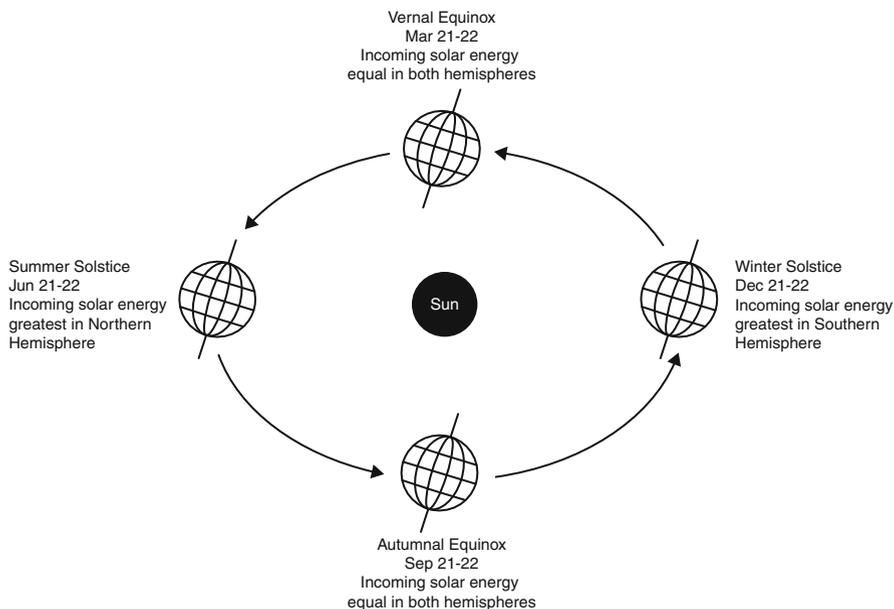
14.8.1   History

The Earth is still in an ice age as we have continental sized glaciers and ice at the poles and over Greenland and Antarctica. There are also numerous glaciers throughout the highest mountains of the planet. Glacial ice has been much more extensive in the past than it is today and most glacial ice on Earth is now receding. But what caused the ice sheets to grow in the first place? What causes ice ages?

In order for the climate to change it needs to have a forcing agent, as we have seen in earlier chapters, something that happened that caused the change. Let's look at a few things that might force the climate to change.

14.8.2   Climate Forcing by Orbital Variations

Earth's orbital variations include how it revolves around the Sun, how its rotational axis behaves, what its degree of inclination is to the Sun, and its axial precession.

Many climate change scientists think that orbital forcing started or triggered the latest, i.e., the Pleistocene, "ice age" and there is some supporting evidence for this hypothesis.

Vernal Equinox
Mar 21-22
Incoming solar energy
equal in both hemispheres

Summer Solstice
Jun 21-22
Incoming solar energy
greatest in Northern
Hemisphere

Sun

Winter Solstice
Dec 21-22
Incoming solar energy
greatest in Southern
Hemisphere

Autumnal Equinox
Sep 21-22
Incoming solar energy
equal in both hemispheres

Fig. 14.17 Earth's rotation on its axis, its revolution around the Sun, the seasons of the year, the tilt of the Earth's axis, the solstices and equinoxes (Redrawn from NASA by John Cook)

Figure 14.17 shows the position of the Earth relative to the Sun at different times of the calendar year; the vernal and autumnal equinoxes and the winter and summer solstices. Notice the differences in sunlight striking the Earth at different times during the year. During the summer solstice the Northern Hemisphere is receiving more direct sunlight and during the winter solstice the Southern Hemisphere is receiving more direct sunlight.

The Earth's axis completes one full cycle of precession approximately every 26,000 years (see Fig. 14.19). At the same time, the elliptical orbit rotates, more slowly, leading to a 21,000-year cycle between the seasons and the orbit. In addition, the angle between Earth's rotational axis and the normal to the plane of its orbit moves from 22.1° to 24.5° and back again on a 41,000-year cycle; currently, this angle is 23.44° and is decreasing.

14.8.3   Eccentricity

The Earth's eccentricity is a measure of the departure of its ellipse from being circular. An exactly circular orbit has no eccentricity but the Earth has an eccentricity of between 0.005 and 0.058 (Fig. 14.18). The shape of the Earth's orbit varies in time between being nearly circular (low eccentricity of 0.005) and being mildly

Fig. 14.18 Earth's
orbital eccentricity
(From NASA, Public
Domain)
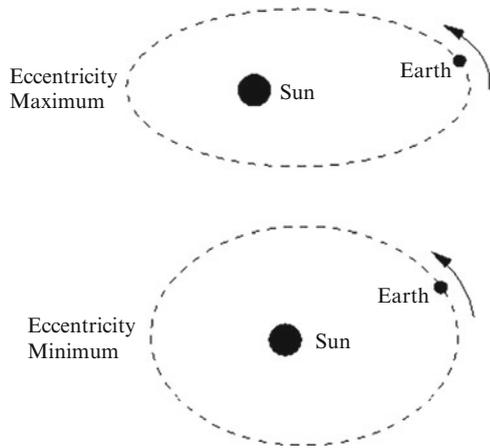
elliptical (high eccentricity of 0.058) and has a mean eccentricity of 0.028. The major component of these variations occurs on a period of 413,000 years. A number of other terms vary between components 95,000 and 125,000 years (with a "beat period" of about 400,000 years), and loosely combine into a 100,000-year cycle (variation of −0.03 to +0.02). The present eccentricity is 0.017.

If one looks at the beginning of each glacial advance during the Pleistocene, there is a periodicity of about 100,000 years, and the eccentricity may be an explanation for this periodicity. However, this is a relatively small forcing on the climate system and is thought to not be strong enough to trigger an ice age by itself.

14.8.4   Obliquity

The angle of the Earth's axial tilt (obliquity) varies with respect to the plane of the Earth's orbit (Fig. 14.19). These slow 2.4° obliquity variations are roughly periodic, taking approximately 41,000 years to shift between a tilt of 22.1° and 24.5° and back again. When the obliquity increases, the amplitude of the seasonal cycle in insolation (**IN**coming **SOL**ar radi**ATION**) increases, with summers in both hemispheres receiving more radiative flux (constant change) from the Sun, and the winters less radiative flux.

The changes in the summer and winter are not of the same magnitude. The annual mean insolation increases in high latitudes with increasing obliquity, while lower latitudes experience a reduction in insolation. Cooler summers are suspected of encouraging the start of an ice age by melting less of the previous winter's ice and snow. So it can be argued that lower obliquity favors ice ages both because of the mean insolation reduction in high latitudes as well as the additional reduction in summer insolation. However, no significant climate changes are associated with extreme axial tilts but they could be a contributing factor.

**Fig. 14.19** 22.1–24.5° range of Earth's obliquity (Credit: John Cook)
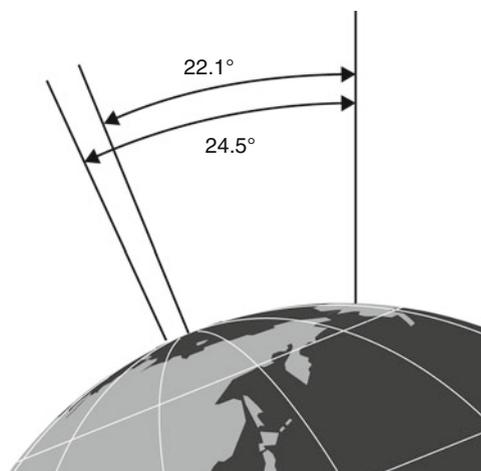
Fig. 14.20 Precessional movement of Earth's axis of rotation (Credit: John Cook)
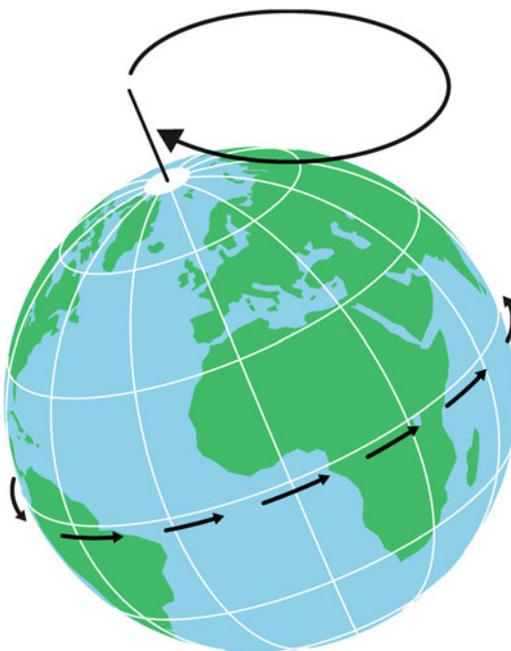
14.8.5   Precession

Precession is the change in the direction of the Earth's axis of rotation relative to a fixed point, like a star, with a period of roughly 26,000 years. This gyroscopic motion (Fig. 14.20) is due to the tidal forces exerted by the Sun, moon, and other celestial
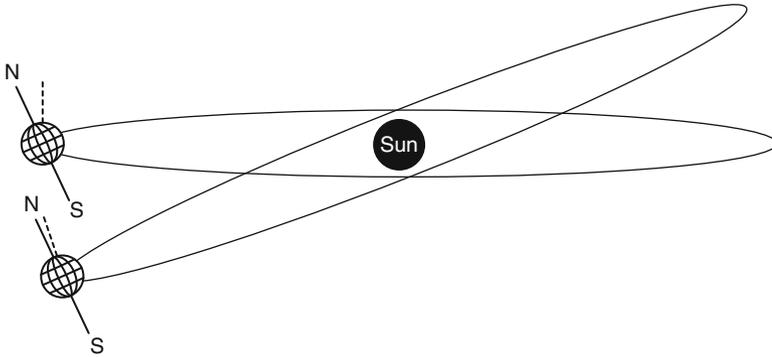
Fig. 14.21 Change in the Earth's orbital plane. Even if the spin axis always pointed in the same direction (for example, on a perfectly spherical planet) it would make a different angle with its orbital plane as the plane moved around (Credit: John Cook)

objects on the solid Earth, associated with the fact that the Earth is an oblate spheroidal shape and not a perfect sphere. The Earth bulges at the Equator and is slightly flattened at the poles making it an oblate spheroid. The Sun and Moon contribute to this shape.

When the axis is aligned so it points toward the Sun during perihelion (when it is closest to the Sun), one polar hemisphere will have a greater difference between the seasons while the other hemisphere will have milder seasons. The hemisphere which is in summer at perihelion will receive much of the corresponding increase in solar radiation, but that same hemisphere will be in winter at aphelion (when it is furthest from the Sun) and have a colder winter (Fig. 14.21). The other hemisphere will have a relatively warmer winter and cooler summer.

In addition, the orbital ellipse itself precesses in space, primarily as a result of interactions with Jupiter and Saturn. This orbital precession is in the same sense to the gyroscopic motion of the axis of rotation, shortening the period of the precession of the equinoxes with respect to the perihelion from 25,771.5 to ~21,636 years (Fig. 14.22).

14.9   Milankovitch Cycles and Ice Ages

Milutin Milankovitch (1879–1958) was a Serbian scientist and mathematician who was placed under house arrest during WWI when the Austro-Hungarian Empire declared war on Serbia, and had much time on his hands to do numerous calculations concerning the Earth's rotation on its axis and revolution around the Sun. He also did calculations of the amount of insolation the Earth received at various latitudes and used his calculations in his theory for the ice advances and retreats of the past 600,000 years of Earth history.

The Milankovitch or Astronomical Theory of Climate Change is an explanation for changes in climate which result from changes in the Earth's orbit around the Sun

Fig. 14.22 The Earth's axis of rotation wobbles like a top on a ~23,000 year cycle. This causes the Earth's seasons to reach their maximum at different distances from the Sun due to the elliptical shape of the Earth's orbit (From the Science Museum of the U.S. National Academy of Sciences, http://www.koshland-science-museum.org/exhibitgcc/causes08.jsp, Public Domain)

and its rotation on its axis. Milankovitch calculated the slow changes in the Earth's orbit by careful measurements of the position of the stars, and through equations using the gravitational pull of other planets and stars. He determined that the Earth "wobbles" in its orbit. The Earth's "tilt" is what causes seasons, and changes in the tilt of the Earth change the strength of the seasons. The seasons can also be accentuated or modified by the eccentricity (degree of roundness) of the orbital path around the Sun, and the precession effect, the position of the solstices in the annual orbit (see Fig. 14.23).

The figure below (Fig. 14.24) shows insolation changes at various latitudes in mid-June for the last 1 million years. The Milankovitch cycles modulate the insolation received at the top of Earth's atmosphere.

Milankovitch's theory (the Milankovitch or Astronomical Theory of Climate Change) was largely ignored for about 50 years. Then, in 1976, a study published in the journal *Science* examined deep-sea sediment cores and found that Milankovitch's theory did in fact correspond to periods of climate change. Specifically, the authors were able to extract the record of temperature change going back 450,000 years and
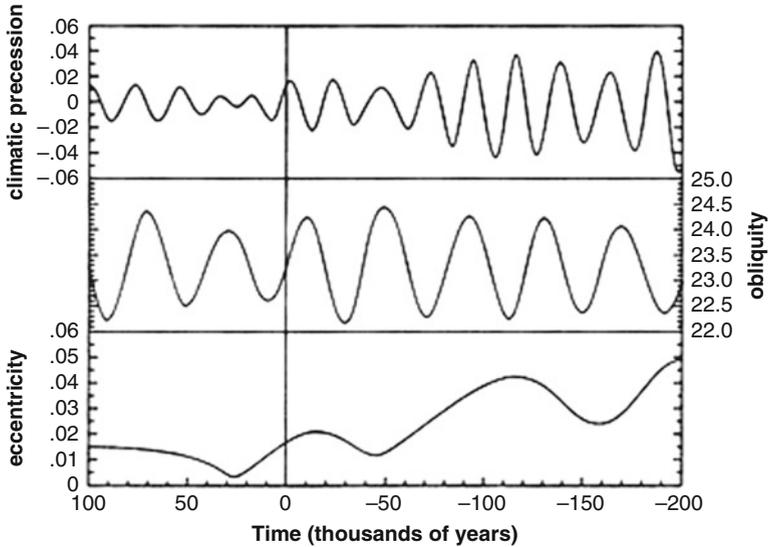
Fig. 14.23 Milankovitch calculated solar energy receipt during summer at 65°N for the past 600,000 years (also for 55° and 60°, but they are not shown in the above graph). The above graphs show calculated values for 300,000 years of orbital variation. The line labeled "0" represents today, while "−200" indicates 200,000 years in the past and "100" indicates 100,000 years from now. Milankovitch noticed that these cycles of orbital mechanics correspond to many indicators of past climate change, such as Ice Ages (From NASA, Public Domain; originally from Berger and Loutre 1991)

found that major variations in climate were closely associated with changes in the geometry (eccentricity, obliquity, and precession) of Earth's orbit. The Pleistocene ice ages had occurred when the Earth was going through different stages of orbital variation.

14.10 Solar Variations

Solar variations are climate forcings that cause climate changes on Earth. The Sun varies in the amount of energy that it provides to Earth. There are periods when there is more energy from the Sun and periods when there is less energy from the Sun. These are solar maxima and solar minima, respectively (Fig. 14.25). During a period of solar maximum, the Sun produces its maximum amount of energy and the Earth warms. During a solar minimum, the Sun produces its minimum amount of energy and the Earth should cool. The Sun has been in a period of solar minimum for the past several decades while the Earth continues to warm, so something other than the Sun must be causing global warming.
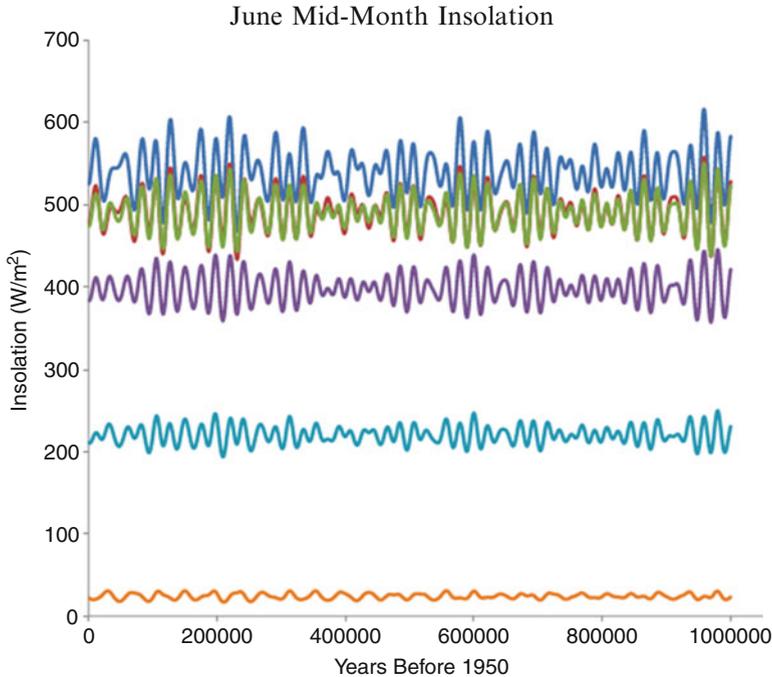
Fig. 14.24 June (daily averaged) insolation (W/m²) over the last 1,000,000 years (0 = 1950) at (*blue* = 90 N), (*red* = 60 N), (*green* = 30 N), (*purple* = Equator), (*light blue* = 30 S), (*Orange* = 60 S). Data from Berger and Loutre (1991) (From Colose, C., SkepticalScience.com. Viewed 7-22-2011)

In 1978 NASA launched the first of several satellites that measure solar energy received by the Earth at the top of the atmosphere (TOA). The illustration below (Fig. 14.25) shows the results of some of these measurements from 1978 through 2010.

What is known about the internal structure of the Sun is shown in the illustration below (Fig. 14.27). The Sun's outer visible layer is the photosphere and its temperature is about 6,000°C. The photosphere has a mottled appearance due to the turbulent eruptions of energy.

Solar energy is created deep within the core of the Sun by nuclear reactions which produce helium from hydrogen. The difference in mass is converted to energy and makes its way to the surface by convection where it is released as light and heat.

Above the photosphere is the chromosphere. Solar energy passes through the chromosphere on its way out from the Sun. Faculae and solar flares arise in the chromosphere. Faculae are the lighter areas in the illustrations (Figs. 14.26 and 14.27). Faculae are bright luminous hydrogen clouds which form above regions where sunspots are about to form. Flares are bright filaments of hot gas emerging
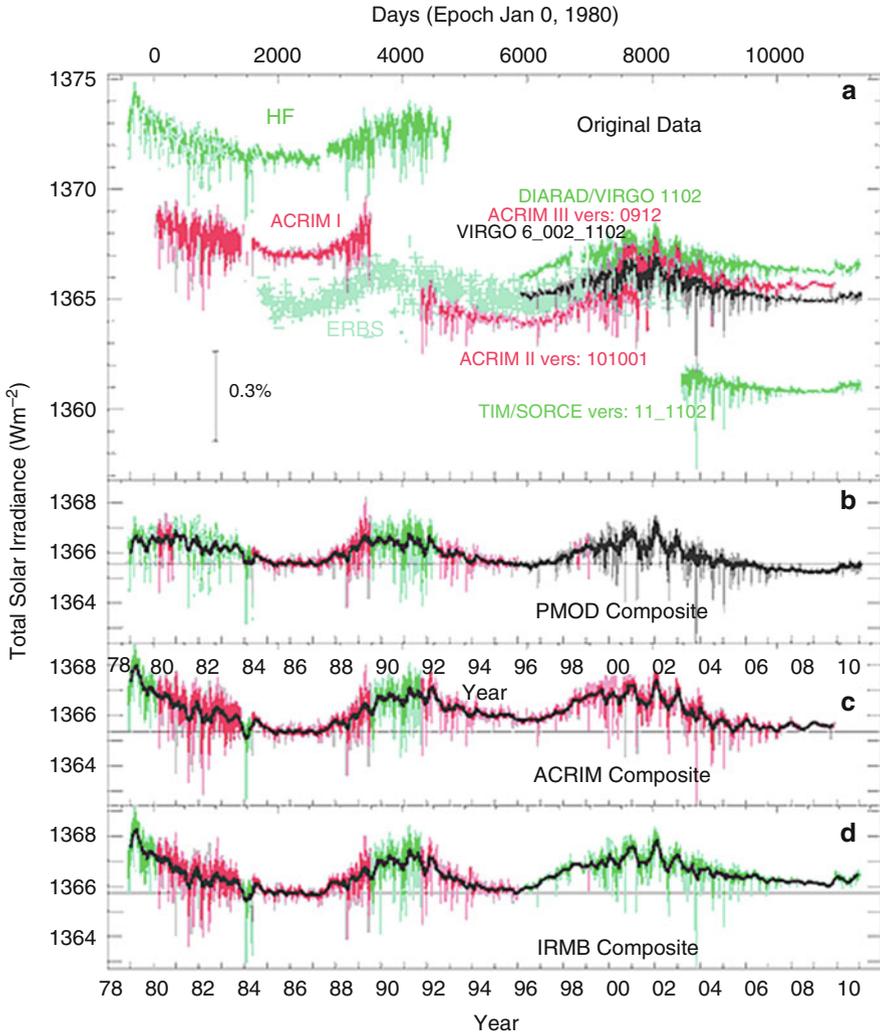
Fig. 14.25 Three solar maxima and three solar minima from 1978 to 2010. *Upper panel*: Compared are daily averaged values of the Sun's total irradiance (TSI) from radiometers on different space platforms since November 1978: HF on Nimbus7, ACRIM I on SMM, ERBE on ERBS, ACRIM II on UARS, VIRGO on SOHO, and ACRIM III on ACRIM-Sat. The data are plotted as published by the corresponding instrument teams. Note that only the results from the three ACRIMs and VIRGO radiometers have in-flight corrections for degradation. *Lower panels*: The PMOD, ACRIM and IRMB composite TSI as daily values plotted in *different colors* to indicate where the data are coming from (From http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant)

from sunspot regions. Sunspots are dark depressions on the photosphere with a typical temperature of around 4,000°C (7,000°F).

The outer part of the Sun's atmosphere is the corona. The corona can only be seen during total solar eclipses.

Fig. 14.26 An image of the
Sun showing a number of
solar flares and faculae
(NASA, Public Domain)
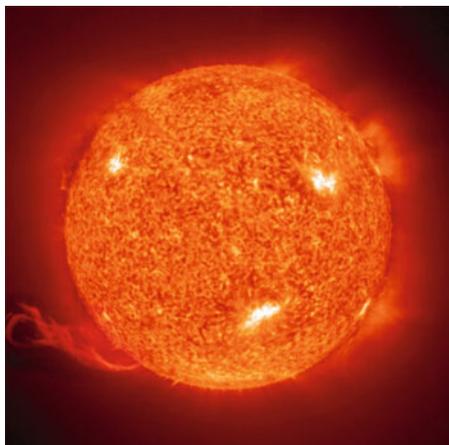
Fig. 14.27 Features of the
Sun (From http://www.
solarviews.com/eng/Sun.htm)
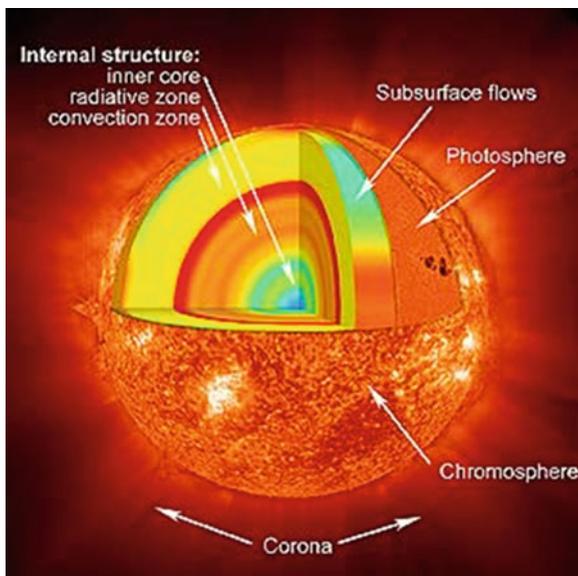
14.11   Questions Not Explained by Milankovitch Cycles

There are a number of unresolved questions that remain in the Milankovitch or
Astronomical Theory of Climate Change, even during the more familiar Pleistocene
timeframe. For instance, while changes in Earth's orbit match ice ages somewhat,
the precise way the three Milankovitch variations regulate the timing of glacial-
interglacial cycles is not well known.

For example, about 800,000 years ago a shift of the dominant periodicity from a
41,000-year to a 100,000-year signal in glacial oscillations occurred (called the

Mid-Pleistocene Transition), and while a lot of ideas exist for why this should be the case, there's no absolute answer for this shift. Explaining the 100,000-year recurrence period of ice ages is difficult because although the 100,000-year cycle dominates the ice-volume record, it is small in the insolation spectrum. Therefore, there is still a lot to be learned about the trigger(s) for an ice age.

Whatever it is that begins an ice age, it happens to the Northern Hemisphere first. If the North and South are alternatively near and far from the Sun during summer, why has glaciation been nearly globally synchronous? What connections are there between Northern insolation and Antarctic climate at the obliquity and precession timescales? What are the competitive roles between a further distance from the sun during summer and a longer summer? These questions are still not resolved. This problem also involves work at the interface of carbon cycle and ice sheet dynamics, processes that are in their infancy in terms of modeling.

It is also possible that some combination of forcing mechanisms combined at just the right instant in time that triggered the initiation of global glaciation. And it may be that other influences caused the subsequent periodicity of the glacial-interglacial episodes. We will consider some possibilities as we go along in this text.

Additional Readings

Benn, D. I., & Evans, D. J. A. (1999). *Glaciers and glaciation*. London/New York: Publisher Arnold, London 1998 (734pp) 50.00 (hardback) ISBN 0-340-65303-5 24.99 (paperback) ISBN 0-340-58431-0.

Bennett, M. R., & Glasser, N. F. (1996). *Glacial geology: Ice sheets and landforms*. New York/ Chichester: Wiley. OCLC 37536152 33359888 37536152. ISBN 0-471-96344-5.

Berger, A., & Loutre, M. F. (1991). Insolation values for the climate of the last 10 million years. *Quaternary Sciences Review, 10*(4), 297–317.

Fröhlich, C. (2000). Observations of irradiance variability. *Space Science Reviews, 94*, 15–24.

Fröhlich, C. (2003). Long-term behaviour of space radiometers. *Metrologia, 40*, 60–65.

Fröhlich, C. (2004). Solar irradiance variability, Chapter 2: Solar energy flux variations. In *Solar variability and its effect on climate* (Geophysical Monograph Series No. 141, pp. 97–110). Washington, DC: American Geophysical Union.

Fröhlich, C., & Lean, J. (1998). The Sun's total irradiance: Cycles and trends in the past two decades and associated climate change uncertainties. *Geophysical Research Letters, 25*, 4377–4380.

Fröhlich, C., & Lean, J. (2004). Solar radiative output and its variability: Evidence and mechanisms. *Astronomy and Astrophysics Review, 12*, 273–320. doi:10.1007/s00159-004-0024-1.

Paterson, W. S. B. (1994). *Physics of glaciers* (3rd ed.). Oxford/Tarrytown: Pergamon Press. OCLC 26188. ISBN 0-08-013972-8.

Pollack, H. (2009). *A world without ice*. New York: Avery. ISBN 978-1-58333-357-0.

Post, A., & LaChapelle, E. R. (2000). *Glacier ice*. Seattle: University of Washington Press. ISBN 0-295-97910-0.

Roe, G. (2006). In defense of Milankovitch. *Geophysical Research Letters, 33*(24), L24703. doi:10.1029/2006GL027817. Bibcode 2006GeoRL..3324703R.

Wunsch, C. (2004). Quantitative estimate of the Milankovitch-forced contribution to observed Quaternary climate change. *Quaternary Science Reviews, 23*(9–10), 1001–1012. doi:10.1016/j. quascirev.2004.02.014. Bibcode 2004QSRv…23.1001W.