Chapter 19 Climate Change

Learning Objectives

After reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Summarize the properties of greenhouse gases and their role in controlling the climate.
- Explain the difference between climate forcing and climate feedbacks.
- Describe the mechanisms of climate forcing related to solar evolution, continental drift, continental collisions, volcanism, Earth and Sun orbital variations, and changing ocean currents.
- Describe the significance of albedo to climate and how the melting of ice or snow and deforestation affect albedo.
- Explain the roles of the melting of permafrost, breakdown of methane hydrates, and temperature-related solubility of CO_2 as positive feedbacks.
- Describe some of the ways that our extraction and use of fossil fuels contribute to climate change.
- Explain how food production contributes to climate change.
- List some of the steps that we can take as individuals to limit our personal contribution to climate change.
- Describe the role of climate change in sea-level rise, and why we are already committed to more than a metre of additional sea-level rise.
- Explain the link between climate change and the distribution of diseases and pests.

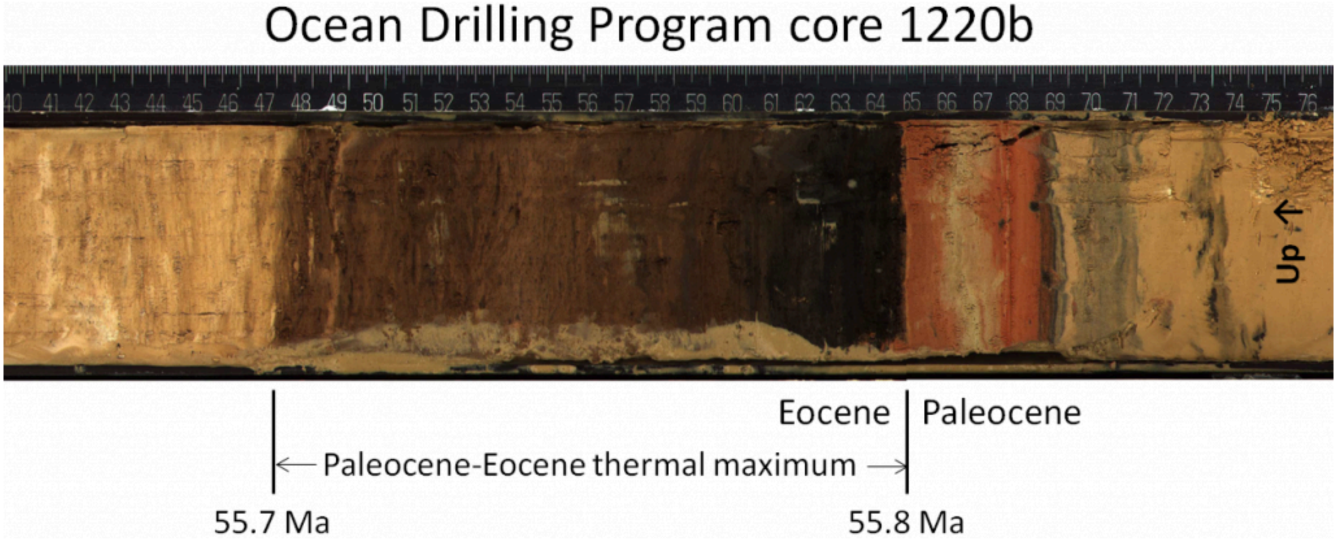


Figure 19.0.1 Core from Ocean Drilling Program hole 1220b (southeast of Hawaii) showing the boundary between the Paleocene and the Eocene (at 55.8 Ma). Marine life was decimated during the 100,000 years of the Paleocene-Eocene thermal maximum, and the dark part of the core represents the absence of carbonate sediment from planktonic organisms. The scale is in centimetres.

If one thing has been constant about Earth's climate over geological time, it is its constant change. In the geological record, we can see this in the evidence of glaciations in the distant past (see section 16.1 in Chapter 16), and we can also detect periods of extreme warmth by looking at the isotope composition of sea-floor sediments, such as those in the core shown in Figure 19.0.1. Not only has the climate changed frequently, the temperature fluctuations have been very significant. Today's mean global temperature is about 15°C. During Snowball Earth times, the global mean was as cold as −50°C, while at various times during the Paleozoic and Mesozoic and during the Paleocene-Eocene thermal maximum, it was close to +30°C.

But in spite of these dramatic climate changes, Earth has been habitable from very early in its history—as soon as liquid water was present—right through to the present day. That continuous habitability is perhaps a little more surprising than you might think, as we'll see below.

A significant part of this chapter is about the natural processes of climate change and how they work. It's critically important to be aware of those natural climate change processes if we want to understand anthropogenic climate change. First, this awareness helps us to understand why our activities are causing the present-day climate to change, and second, it allows us to distinguish between natural and anthropogenic processes in the climate record of the past 250 years.

Media Attributions

- Figure 19.0.1: "199-1220B-20X-2" © Ocean Drilling Program. Adapted by Steven Earle. Used with permission.

19.1 What Makes the Climate Change?

There are two parts to climate change, the first one is known as **climate forcing**, which is when conditions change to give the climate a little nudge in one direction or the other. The second part of climate change, and the one that typically does most of the work, is what we call a **feedback**. When a climate forcing changes the climate a little, a whole series of environmental changes take place, many of which either exaggerate the initial change (**positive feedbacks**), or suppress the change (**negative feedbacks**).

An example of a climate-forcing mechanism is the increase in the amount of carbon dioxide (CO_2) in the atmosphere that results from our use of fossil fuels. CO_2 traps heat in the atmosphere and leads to climate warming. Warming changes vegetation patterns; contributes to the melting of snow, ice, and **permafrost**; causes sea level to rise; reduces the solubility of CO_2 in sea water; and has a number of other minor effects. Most of these changes contribute to more warming. Melting of permafrost, for example, is a strong positive feedback because frozen soil contains trapped organic matter that is converted to CO_2 and methane (CH_4) when the soil thaws. Both these gases accumulate in the atmosphere and add to the warming effect. On the other hand, if warming causes more vegetation growth, that vegetation should absorb CO_2, thus reducing the warming effect, which would be a negative feedback. Under our current conditions—a planet that still has lots of glacial ice and permafrost—most of the feedbacks that result from a warming climate are positive feedbacks and so the climate changes that we cause get naturally amplified by natural processes.

What is a greenhouse gas?

Throughout this chapter we'll be talking about the role of **greenhouse gases** (GHGs) in controlling the climate, so it's important to understand what greenhouse gases are and how they work. As you know, the dominant gases of the atmosphere are nitrogen (as N_2) and oxygen (as O_2). These gas molecules have only two atoms each and are not GHGs. Some of the other important gases of the atmosphere are water vapour (H_2O), carbon dioxide (CO_2), and methane (CH_4). All of these have more than two atoms, and they are GHGs.

All molecules vibrate at various frequencies and in various ways, and some of those vibrations take place at frequencies within the range of the infrared (IR) radiation that is emitted by Earth's surface. Gases with two atoms, such as O_2, can only vibrate by stretching (back and forth), and those vibrations are much faster than the IR radiation (Figure 19.1.1). Gases with three or more atoms (such as CO_2) vibrate by stretching as well, but they can also vibrate in other ways, such as by bending. Those vibrations are slower and match IR radiation frequencies.

When IR radiation interacts with CO_2 or with one of the other GHGs, the molecular vibrations are enhanced because there is a match between the wavelength of the IR light and the vibrational frequency of the molecule. This makes the molecule vibrate more vigorously, heating the surrounding air in the process. These molecules also emit IR radiation in all directions, some of which reaches Earth's surface. The heating caused by the more vigorous vibrations of GHGs is the **greenhouse effect**.

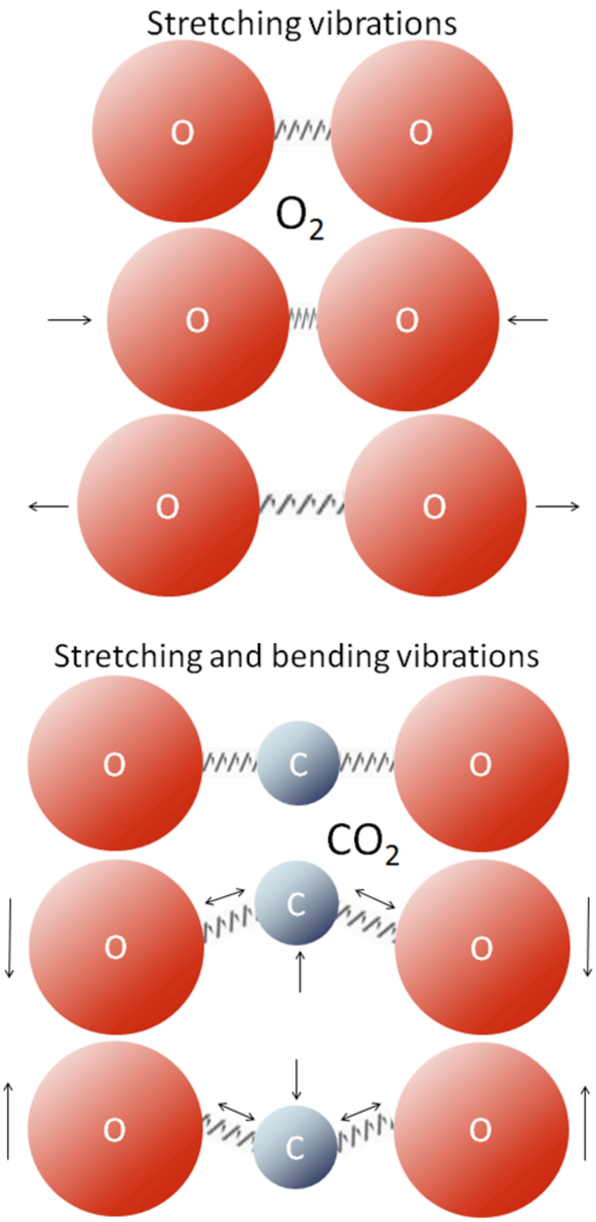


Figure 19.1.1 Stretching versus bending vibrations in atmospheric gases

Natural Climate Forcing

Natural climate forcing has been going on throughout geological time. A wide range of processes has been operating at widely different time scales, from a few years to billions of years.

The longest-term natural forcing variation is related to the evolution of the Sun. Like most other stars of a similar mass, our Sun is evolving. For the past 4.57 billion years, its rate of nuclear fusion has been increasing, and it is now emitting about 40% more energy (as light) than it did at the beginning of geological time (Figure 19.1.2). A difference of 40% is big, so it's a little surprising that the temperature on Earth has remained at a reasonable and habitable temperature for all of this time. The mechanism for that relative climate stability has been the evolution of our atmosphere from one that was dominated by CO_2, and also had significant levels of CH_4—both GHGs—to one with only a few hundred parts per million of CO_2 and just under 1 part per million of CH_4. Those changes to our atmosphere have been no accident; over geological time, life and its metabolic processes have evolved and changed the atmosphere to conditions that remained cool enough to be habitable. A scientific explanation for how this could happen is known as the **Gaia hypothesis**.

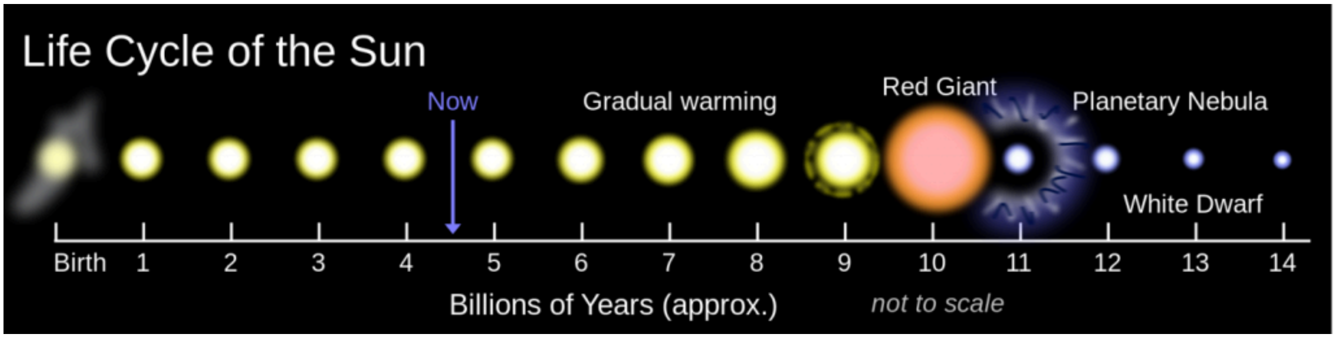


Figure 19.1.2 The life cycle of our Sun and of other similar stars. [Image Description]

The Gaia hypothesis

The Gaia hypothesis, developed by British scientist and environmentalist James Lovelock in the 1960s, is the theory that organisms evolve in ways that contribute to ensuring that their environment remains habitable. It does not include any sort of coordination of effort among organisms or any consciousness of a need to make changes. Gaia is not a superorganism. A way of understanding Gaia is through Lovelock's simple Daisyworld model. A planet with a warming star is populated only by two types of daisies, white ones and black ones (Figure 19.1.3). The black ones contribute to warming because they absorb solar energy, while the white ones reflect light and contribute to cooling. As the star's luminosity gradually increases, the white daisies have better outcomes because their reflectivity cools their local environment, while the black daisies, suffering from the heat, do not reproduce as well. Over time white daisies gradually dominate the population, but eventually the star becomes so bright that even white daisies cannot compensate, and all of the daisies perish. Obviously Earth is not Daisyworld, but similar processes—such as the evolution of photosynthetic bacteria that consume CO_2—have taken place that influence the atmosphere and moderate the climate.

Figure 19.1.3 You can read more about Lovelock, Gaia, and Daisyworld by searching the Internet using any one of those terms.

Plate tectonic processes contribute to climate forcing in several different ways, and on time scales ranging from tens of millions to hundreds of millions of years. One mechanism is related to continental position. For example, we know that Gondwana (South America + Africa + Antarctica + Australia) was positioned over the South Pole between about 450 and 250 Ma, during which time there were two major glaciations (Andean-Saharan and Karoo) affecting the South polar regions (Figure 16.1.1) and cooling the rest of the planet at the same time. Another mechanism is related to continental collisions. As described in Chapter 16, the collision between India and Asia, which started at around 50 Ma, resulted in massive tectonic uplift. The consequent accelerated weathering of this rugged terrain consumed CO_2 from the atmosphere and contributed to gradual cooling over the remainder of the Cenozoic. Also, as described in Chapter 16, the opening of the Drake Passage — due to plate-tectonic separation of South America from Antarctica — led to the development of the Antarctic Circumpolar Current, which isolated Antarctica from the warmer water in the rest of the ocean and thus contributed to Antarctic glaciation starting at around 35 Ma.

As we discussed in Chapter 4, volcanic eruptions don't just involve lava flows and exploding rock fragments; various particulates and gases are also released, the important ones being sulphur dioxide and CO_2. Sulphur dioxide is an aerosol that reflects incoming solar radiation and has a net cooling effect that is short lived (a few years in most cases, as the particulates settle out of the atmosphere within a couple of years), and doesn't typically contribute to longer-term climate change. Volcanic CO_2 emissions can contribute to climate warming but only if a greater-than-average level of volcanism is sustained over a long time (at least tens of thousands of years). It is widely believed that the catastrophic end-Permian extinction (at 250 Ma) resulted from warming initiated by the eruption of the massive Siberian Traps over a period of at least a million years.

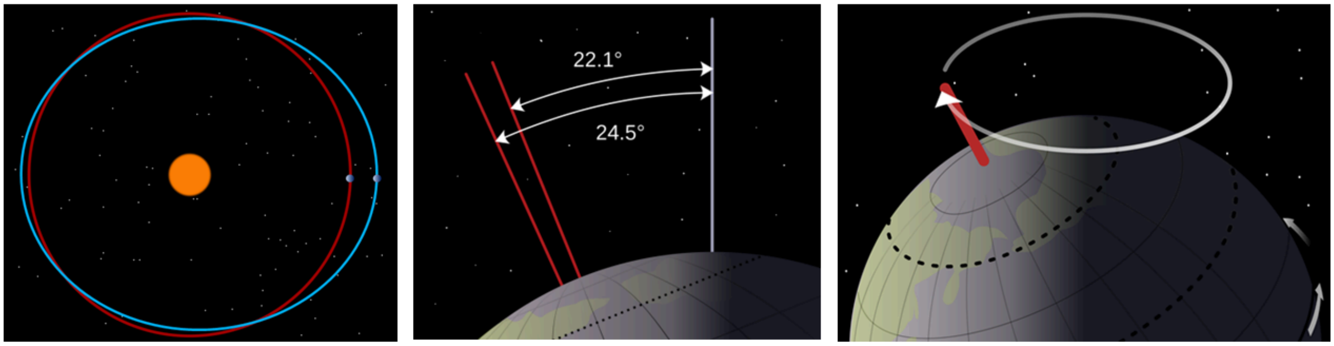
Exercise 19.1 Climate change at the K-Pg boundary

The large extraterrestrial impact at the end of the Cretaceous (Cretaceous-Paleogene or K-Pg boundary, a.k.a. K-T boundary) is thought to have produced a massive amount of dust, which may have remained in the atmosphere for several years, and also a great deal of CO_2. What do you think would have been the short-term and longer-term climate-forcing implications of these two factors?

See Appendix 3 for Exercise 19.1 answers.

Figure 19.1.4

Earth's orbit around the Sun is nearly circular, but like all physical systems, it has natural oscillations. First, the shape of the orbit changes on a regular time scale — close to 100,000 years — from being close to circular to being very slightly elliptical. But the circularity of the orbit is not what matters; it is the fact that as the orbit becomes more elliptical, the position of the Sun within that ellipse becomes less central or more eccentric (Figure 19.1.5a). **Eccentricity** is important because when it is high, the Earth-Sun distance varies more from season to season than it does when eccentricity is low.



(a) The 100,000 year cycle of eccentricity of the Sun within the Earth's orbit. The blue orbit is more elliptical than the red one, and the Sun is offset from the centre of the ellipse

(b) The 41,000 year cycle of the angle of tilt (obliquity) of the Earth's axis (red lines) compared to a line perpendicular to the plane of the Earth's orbit (light blue line).

(c) the 20,000 year cycle of precession of the Earth's rotational axis

Figure 19.1.5 The cycles of Earth's orbit and rotation. [Image Description]

Second, Earth rotates around an axis through the North and South Poles, and that axis is at an angle to the plane of Earth's orbit around the Sun (Figure 19.1.5b). The angle of tilt (also known as **obliquity**) varies on a time scale of 41,000 years. When the angle is at its maximum (24.5°), Earth's seasonal differences are accentuated. When the angle is at its minimum (22.1°), seasonal differences are minimized. The current hypothesis is that glaciation is favoured at low seasonal differences as summers would be cooler and snow would be less likely to melt and more likely to accumulate from year to year.

Third, the direction in which Earth's rotational axis points also varies, on a time scale of about 20,000 years (Figure 19.1.5c). This variation, known as **precession**, means that although the North Pole is presently pointing to the star Polaris (the pole star), in 10,000 years it will point to the star Vega.

The importance of eccentricity, tilt, and precession to Earth's climate cycles (now known as **Milankovitch Cycles**) was first pointed out by Yugoslavian engineer and mathematician Milutin Milankovitch in the early 1900s. Milankovitch recognized that although the variations in the orbital cycles did not affect the total amount of **insolation** (light energy from the Sun) that Earth received, it did affect where on Earth that energy was strongest. Glaciations are most sensitive to the insolation received at latitudes of around 65°, and with the current configuration of continents, it would have to be 65° north (because there is almost no land at 65° south).

The most important aspects are whether the northern hemisphere is pointing toward the Sun at its closest or farthest approach, and how eccentric the Sun's position is in Earth's orbit. Two opposing situations are illustrated in Figure 19.1.6. In the upper panel, the northern hemisphere is at it farthest distance from the Sun during summer, which means cooler summers. In the lower panel, the northern hemisphere is at its closest distance to the Sun during summer, which means hotter summers. Cool summers—as opposed to cold winters—are the key factor in the accumulation of glacial ice, so the upper scenario in Figure 19.1.6 is the one that promotes glaciation. This factor is greatest when eccentricity is high.

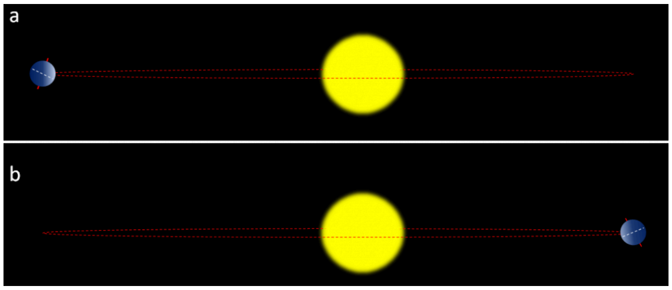


Figure 19.1.6 The effect of precession on insolation in the northern hemisphere summers. In (a) the northern hemisphere summer takes place at greatest Earth-Sun distance, so summers are cooler. In (b) (10,000 years or one-half precession cycle later) the opposite is the case, so summers are hotter. The red dashed line represents Earth's path around the Sun.

Data for tilt, eccentricity, and precession over the past 400,000 years have been used to determine the insolation levels at 65° north, as shown in Figure 19.1.7. Also shown in Figure 19.1.7 are Antarctic ice-core temperatures from the same time period. The correlation between the two is clear, and it shows up in the Antarctic record because when insolation changes lead to growth of glaciers in the northern hemisphere, southern-hemisphere temperatures are also affected.

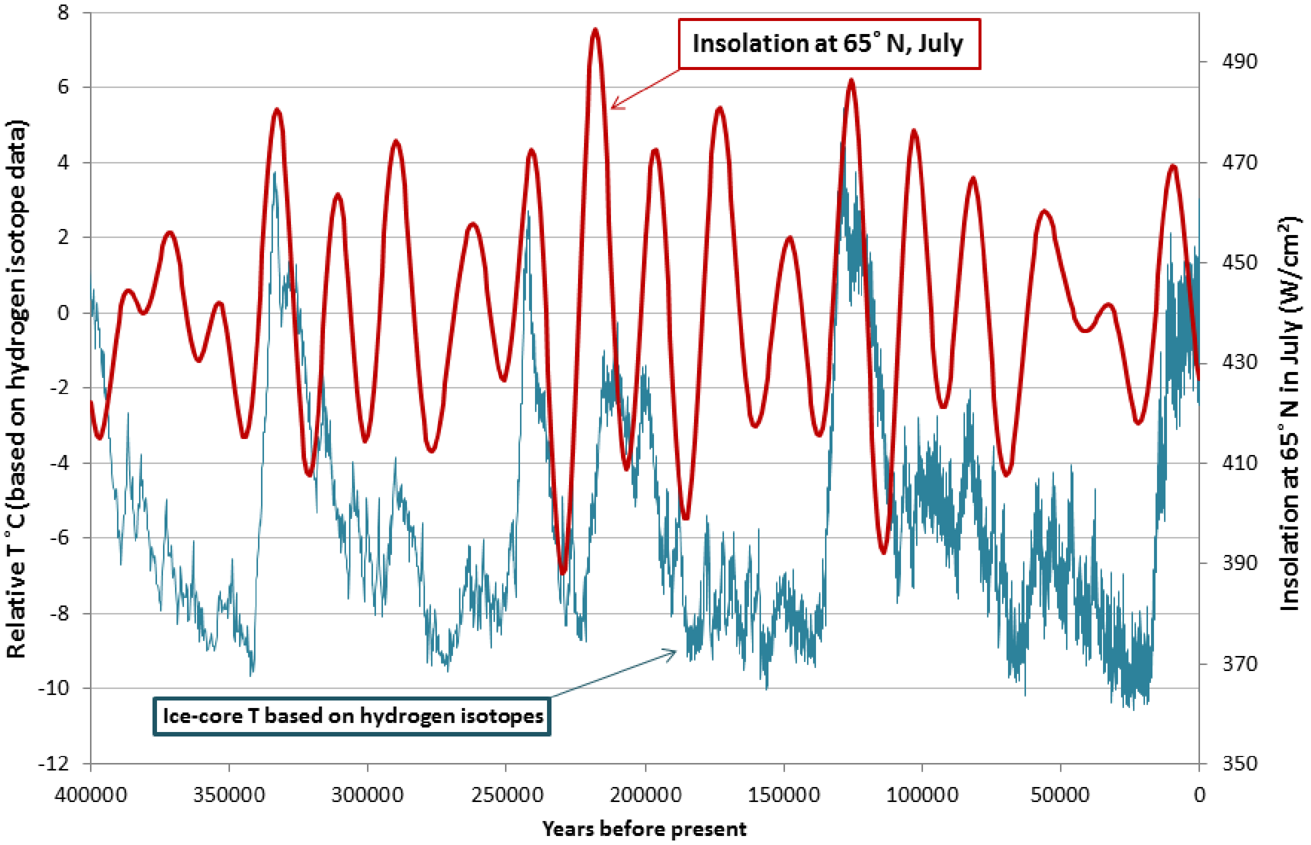


Figure 19.1.7 Insolation at 65° N in July compared with Antarctic ice-core temperatures.

Ocean currents are important to climate, and currents also have a tendency to oscillate. Glacial ice cores show clear evidence of changes in the Gulf Stream (and other parts of the thermohaline circulation system) that affected global climate on a time scale of about 1,500 years during the last glaciation. The east-west changes in sea-surface temperature and surface pressure in the equatorial Pacific Ocean—known as the El Niño Southern Oscillation or ENSO—varies on a much shorter time scale of between two and seven years. These variations tend to garner the attention of the public because they have significant climate implications in many parts of the world. The past 65 years of ENSO index values are shown in Figure 19.1.8. The strongest **El Niños** in recent decades were in 1983 and 1998, and those were both very warm years from a global perspective. During a strong El Niño, the equatorial Pacific sea-surface temperatures are warmer than normal and heat the atmosphere above the ocean, which leads to warmer-than-average global temperatures.

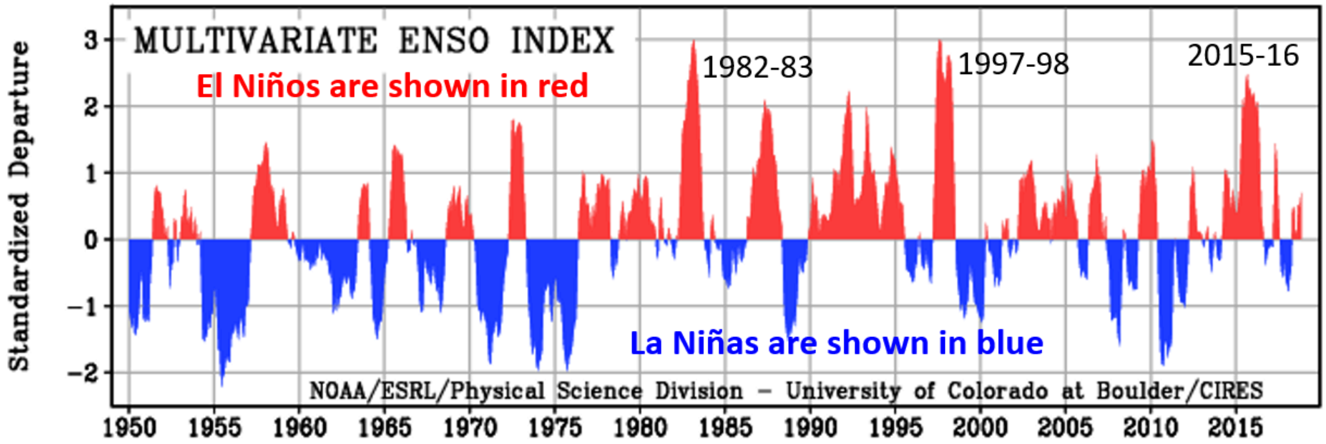


Figure 19.1.8 Variations in the ENSO index from 1950 to early-2019.

Climate Feedbacks

As already stated, **climate feedbacks** are critically important in amplifying weak climate forcings into full-blown climate changes. When Milankovitch published his theory in 1924, it was widely ignored, partly because it was evident to climate scientists that the forcing produced by the orbital variations was not strong enough to drive the significant climate changes of the glacial cycles. Those scientists did not recognize the power of positive feedbacks. It wasn't until 1973, 15 years after Milankovitch's death, that sufficiently high-resolution data were available to show that the Pleistocene glaciations were indeed driven by the orbital cycles, and it became evident that the orbital cycles were just the forcing that initiated a range of feedback mechanisms that made the climate change.

Since Earth still has a very large volume of ice — mostly in the continental ice sheets of Antarctica and Greenland, but also in alpine glaciers and permafrost — melting is one of the key feedback mechanisms. Melting of ice and snow leads to several different types of feedbacks, an important one being a change in **albedo**. Albedo is a measure of the reflectivity of a surface. Earth's various surfaces have widely differing albedos, expressed as the percentage of light that reflects off a given material. This is important because most solar energy that hits a very reflective surface is not absorbed and therefore does little to warm Earth. Water in the oceans or on a lake is one of the darkest surfaces, reflecting less than 10% of the incident light, while clouds and snow or ice are among the brightest surfaces, reflecting 70% to 90% of the incident light (Figure 19.1.9).

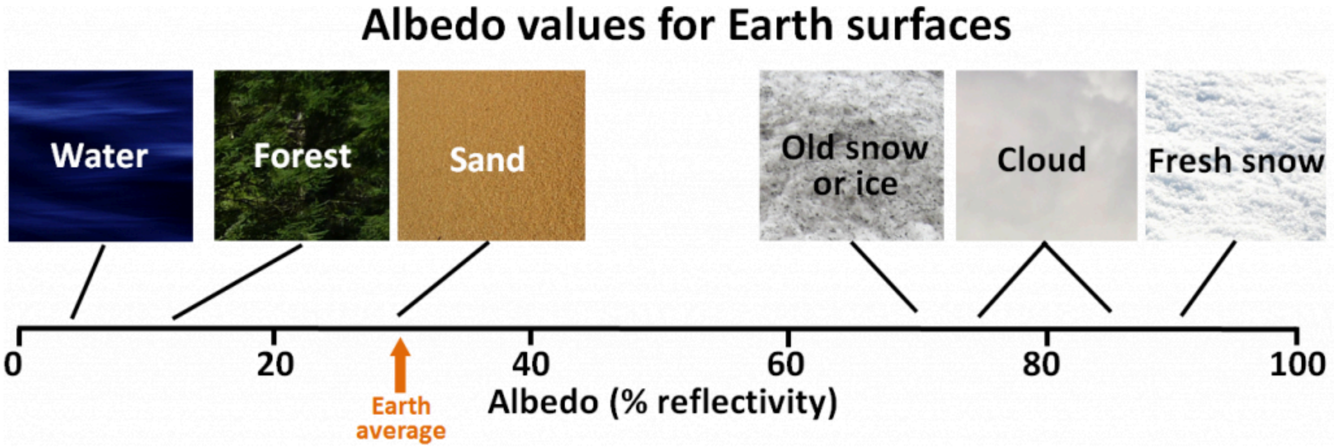


Figure 19.1.9 Typical albedo values for Earth surfaces. *[Image Description]*

Exercise 19.2 Albedo implications of forest harvesting

When a forest is harvested, there are significant changes to the rate of biological uptake of CO_2, but there is also a change in albedo. Using Figure 19.1.9, and assuming that a clear-cut has an albedo similar to sand, what is the albedo-only implication of clear-cutting for climate change? Be aware that this implication applies only to the albedo change caused by clear-cutting. Clear-cutting reduces the capacity of the area to absorb CO_2, and also has numerous negative ecological and geological implications.

See Appendix 3 for Exercise 19.2 answers.

Figure 19.1.10

When sea ice melts, as it has done in the Arctic Ocean at a disturbing rate over the past decade, the albedo of the area affected changes dramatically, from around 80% down to less than 10%. This is a positive feedback because much more solar energy is absorbed by the water than by the pre-existing ice, and the temperature increase is amplified. The same applies to ice and snow on land, but the difference in albedo is not as great.

When ice and snow on land melt, sea level rises. (Sea level is also rising because the oceans are warming and that increases their volume.) A higher sea level means a larger proportion of the planet is covered with water, and since water has a lower albedo than land, more heat is absorbed and the temperature goes up a little more. Since the last glaciation, sea-level rise has been about 125 m; a huge area that used to be land is now flooded by heat-absorbent seawater. During the current period of anthropogenic climate change, sea level has risen only about 20 cm, and although that doesn't make a big change to albedo, sea-level rise is accelerating.

Figure 19.1.11 A degrading permafrost site on the north coast of Alaska.

Most of northern Canada has a layer of permafrost that ranges from a few centimetres to hundreds of metres in thickness; the same applies in Alaska, Russia, and Scandinavia. Permafrost is a mixture of soil and ice (Figure 19.1.11), and it also contains a significant amount of trapped organic carbon that is released as CO_2 and CH_4 when the permafrost breaks down. Because the amount of carbon stored in permafrost is in the same order of magnitude as the amount released by burning fossil fuels, this is a feedback mechanism that has the potential to equal or surpass the forcing that has unleashed it.

In some polar regions, including northern Canada, permafrost includes methane hydrate (see section 18.3), a highly concentrated form of CH_4 trapped in solid form. Breakdown of permafrost releases this CH_4. Even larger reserves of methane hydrate exist on the sea floor, and while it would take significant warming of ocean water down to a depth of hundreds of metres, this too is likely to happen in the future if we don't limit our impact on the climate. There is strong isotopic evidence that the Paleocene-Eocene thermal maximum (see Figure 19.0.1) was caused, at least in part, by a massive release of sea-floor methane hydrate.

There is about 45 times as much carbon in the ocean (as dissolved bicarbonate ions, HCO_3^-) as there is in the atmosphere (as CO_2), and there is a steady exchange of carbon between the two reservoirs. But the solubility of CO_2 in water decreases as the temperature goes up. In other words, the warmer it gets, the more of that oceanic bicarbonate gets transferred to the atmosphere as CO_2. That makes CO_2 solubility another positive feedback mechanism.

Vegetation growth responds positively to both increased temperatures and elevated CO_2 levels, and so in general, it represents a negative feedback to climate change because the more the vegetation grows, the more CO_2 is taken from the atmosphere. But it's not quite that simple because when trees grow bigger and more vigorously, forests become darker (they have lower albedo) so they absorb more heat. Furthermore, climate warming isn't necessarily good for vegetation growth; some areas have become too hot, too dry, or even too wet to support the plant community that was growing there, and it might take centuries for something to replace it successfully.

All of these positive (and negative) feedbacks work both ways. For example, during climate cooling, growth of glaciers leads to higher albedos, and formation of permafrost results in storage of carbon that would otherwise have returned quickly to the atmosphere.

Image Descriptions

Figure 19.1.2 image description: Our sun is roughly 4.5 billion years old. Over the next 5 billion years, it will continue getting warmer until it becomes a red giant. Six billion years from now, it will become a planetary nebula and then a white dwarf. [Return to Figure 19.1.2]

Figure 19.1.5 image description:

1. The eccentricity of the Sun within the Earth's orbit goes through a 100,000 year cycle. The Earth's orbit around the sun can be very circular, but when it becomes more oval-shaped, the Sun is offset from the centre of the ellipse. This means that sometimes the Earth will be farther from the sun than normal and sometimes it will be closer to the sun than normal.

2. The angle of tilt (or obliquity) or the Earth's axis goes through a 41,000 year cycle. When comparing the North Pole to a line perpendicular to the plane of the earth's orbit, the obliquity can range from 22.1° to 24.5°.
3. The Earth's axial precession operates on a 20,000 year cycle.

[Return to Figure 19.1.5]

Figure 19.1.9 image description: The albedo of Earth's surfaces: Water=around 5%; Forest=10% to 15%; Sand=30%; Old snow and ice=70%; Cloud=75% to 85%. Fresh snow=90%. Earth's average albedo is 30%. [Return to Figure 19.1.9]

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- Figure 19.1.3: © Steven Earle. CC BY.
- Figure 19.1.4: "Coast Impact" by Don Davis, NASA. Public domain.
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- Figure 19.1.5B: "Earth obliquity range" by NASA. Public domain.
- Figure 19.1.5C: "Earth Precession" by NASA. Public domain.
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- Figure 19.1.8: "Multivariate ENSO Index (MEI)" by NOAA. Adapted by Steven Earle. Public domain.
- Figure 19.1.9: © Steven Earle. CC BY.
- Figure 19.1.10: "Clearcutting-Oregon" © Calibas. CC BY-SA**.**
- Figure 19.1.11: "Collapsed permafrost block of coastal tundra on Alaska's Arctic Coast" by the USGS. Public domain.

19.2 Anthropogenic Climate Change

When we talk about anthropogenic climate change, we are generally thinking of the industrial era, which really got going when we started using fossil fuels (coal to begin with) to drive machinery and trains. That was around the middle of the 18th century. The issue with fossil fuels is that they involve burning carbon that was naturally stored in the crust over hundreds of millions of years as part of Earth's process of counteracting the warming Sun.

Some climate scientists argue that anthropogenic climate change actually goes back much further than the industrial era, and that humans began to impact the climate by clearing land to grow grains in Europe and the Middle East around 8,000 years BCE and by creating wetlands to grow rice in Asia around 5,000 years BCE. Clearing forests for crops is a type of climate-forcing because the CO_2 storage capacity of the crops is generally lower than that of the trees they replace, and creating wetlands is a type of climate forcing because the anaerobic bacterial decay of organic matter within wetlands produces CH_4.

In fact, whether anthropogenic climate change started with the agricultural revolution or the industrial revolution is not important, because the really significant climate changes didn't start until the early part of the 20th century, and although our activities are a major part of the problem, our increasing numbers are a big issue as well. Figure 19.2.1 shows the growth of the world population from around 5 million, when we first started growing crops, to about 18 million when wetland rice cultivation began, to over 800 million at the start of the industrial revolution, to over 7,700 million in 2019. A big part of the incredible growth in our population is related to the availability of the cheap and abundant energy embodied in fossil fuels, which we use for transportation, heating and cooling, industry, and food production. It will be hard to support a population of this size without fossil fuels, but we have to find a way to do it.

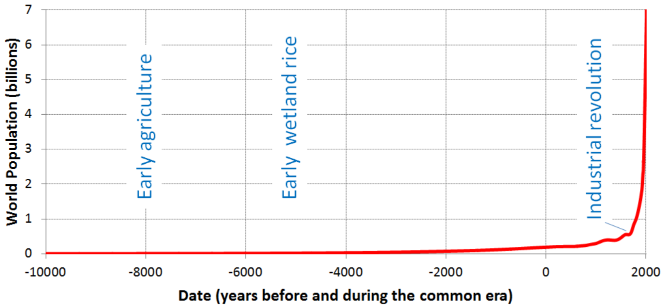

Figure 19.2.1 World population growth over the past 12,000 years.

A rapidly rising population, the escalating level of industrialization and mechanization of our lives, and an increasing dependence on fossil fuels for transportation and energy generation have driven the anthropogenic climate change of the past century. The trend of mean global temperatures since 1880 is shown in Figure 19.2.2. For approximately the past 55 years, the temperature has increased at a relatively steady and disturbingly rapid rate, especially compared to past changes. The average temperature now is approximately 1.0°C higher than before industrialization, and two-thirds of this warming has occurred since 1975. One of the driving factors of the recent increase in the rate of climate change has been the migration of North Americans from city centres to the suburbs, and the resulting need for virtually every household to own at least one car, when previously they were able to get around on foot or public transit.

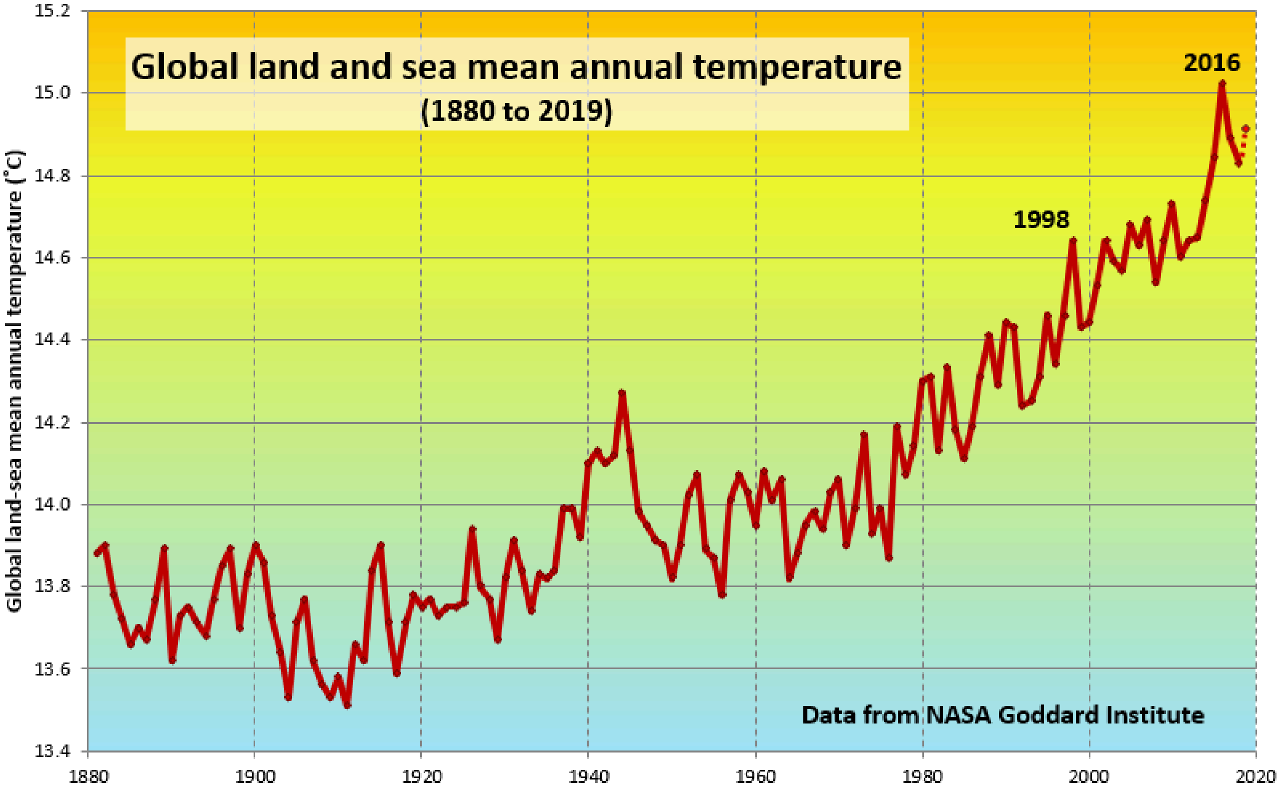

Figure 19.2.2 Global mean annual temperatures for the period from 1880 to 2019. The value for 2019 is projected, based on only 6 months of data. 1998 and 2016 were strong El Niño years.

The **Intergovernmental Panel on Climate Change** (IPCC)—established by the United Nations in 1988—is responsible for reviewing the scientific literature on climate change and issuing periodic reports on several topics, including the scientific basis for understanding climate change, our vulnerability to observed and predicted climate changes, and what we can do to limit climate change and minimize its impacts. Figure 19.2.3, which is based on data from the fifth assessment report of the IPCC, issued in 2014, shows the relative contributions of various long-lasting anthropogenic GHGs to current climate forcing, based on the changes from levels that existed in 1750.

The biggest anthropogenic contributor to warming is CO_2, which accounts for 56% of positive forcing. CH_4 accounts for 32%, and the halocarbon gases (mostly leaked from older air-conditioning appliances that still contain CFCs) and nitrous oxide (N_2O) (from burning fossils fuels) account for 6% each.

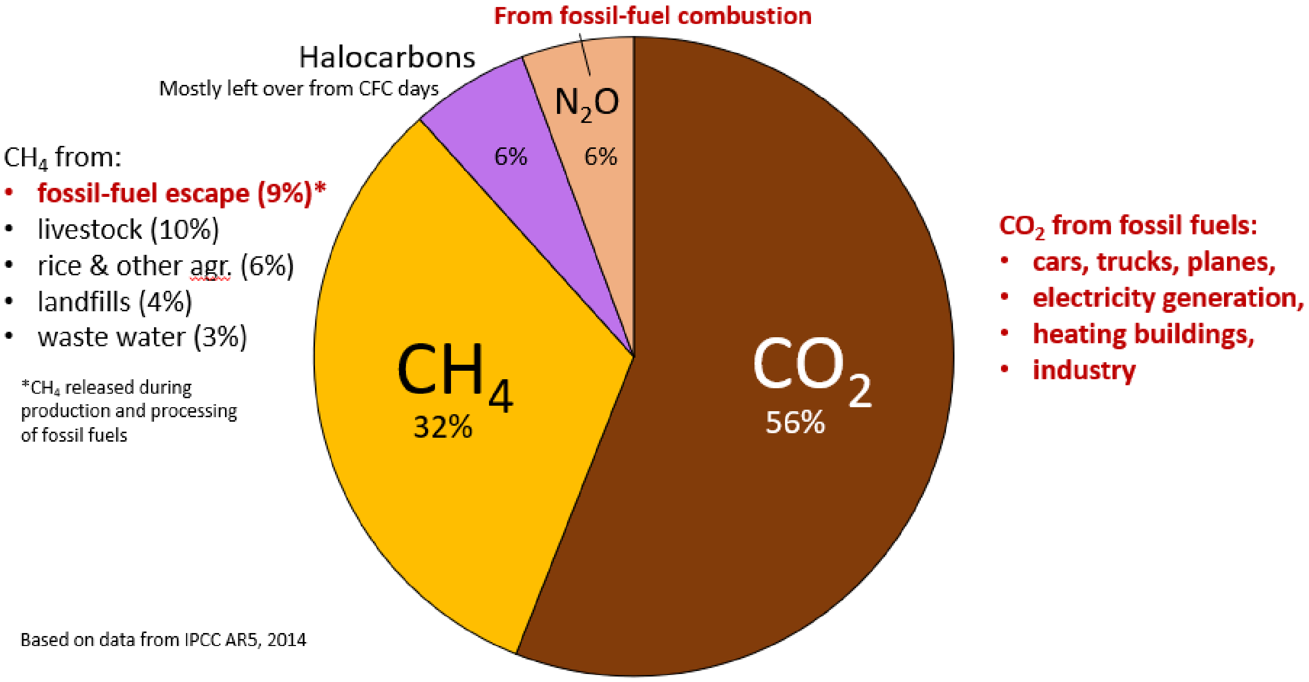

Figure 19.2.3 The relative climate-warming effects of the various greenhouse gases. (Effects listed in red are all related to fossil fuels.)

CO_2 emissions come mostly from coal- and gas-fired power stations, motorized vehicles (cars, trucks, and aircraft), and industrial operations (e.g., smelting). CH_4 emissions come from production of fossil fuels (escape from coal mining and from gas and oil production and processing), livestock farming (mostly beef), landfills, waste water, and wetland rice farming. N_2O is derived almost entirely from the combustion of fossil fuels. In summary, most (by far) of our current GHG emissions come from fossil fuel production and use.

Exercise 19.3 What are the primary sources of climate forcing?

Figure 19.2.3 shows the proportions of climate forcing related to the 4 main greenhouse gases, and also includes lists of where those gases come from. The ones that are primarily derived from our use of fossil fuels are shown in red text.

Using the numbers provided in Figure 19.2.3 determine the percentage proportions of GHGs from the 4 main sources listed in the table below. Make sure that your percentages add to 100.

Source	**Percentage**
Fossil fuel production and use	
Food production	
Solid and liquid wastes	
Halocarbons	

See Appendix 3 for Exercise 19.3 answers.

Media Attributions

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- Figure 19.2.2: © Steven Earle. CC BY. Based on data from NASA.
- Figure 19.2.3: © Steven Earle. CC BY. Based on data in IPCC AR 5, 2014.

19.3 Implications of Climate Change

Although we've all experienced the effects of climate change over the past decade it's not straightforward for climatologists to make the connection between a warming climate and specific weather events, and most are justifiably reluctant to ascribe any specific event to climate change. In this respect, the best measures of climate change are those that we can detect over several decades, such as the temperature changes shown in Figure 19.2.2, or the sea-level rise shown in Figure 19.3.1. As already stated, sea level has risen approximately 20 cm since 1750, and that rise is attributed to both warming (and therefore expanding) seawater and melting glaciers and other land-based snow and ice (melting of sea ice does not contribute directly to sea-level rise as it is already floating in the ocean).

Projections for sea-level rise to the end of this century vary widely. This is in large part because we do not know which of the possible climate change scenarios we will most closely follow, but many are in the range from 0.5 m to 2.0 m. One of the problems in predicting sea-level rise is that we do not have a strong understanding of how large ice sheets—such as Greenland and Antarctica—will respond to future warming. Another issue is that the oceans don't respond immediately to warming. For example, with the current amount of warming, we are already committed to a future sea-level rise of between 1.3 m and 1.9 m, even if we could stop climate change today. This is because it takes decades to centuries for the existing warming of the atmosphere to be transmitted to depth within the oceans and to exert its full impact on large glaciers. Most of that committed rise would take place over the next century, but some would be delayed longer. And for every decade that the current rates of climate change continue, that number increases by another 0.3 m. In other words, if we don't make changes quickly, by the end of this century we'll be locked into about 3 m of future sea-level rise.

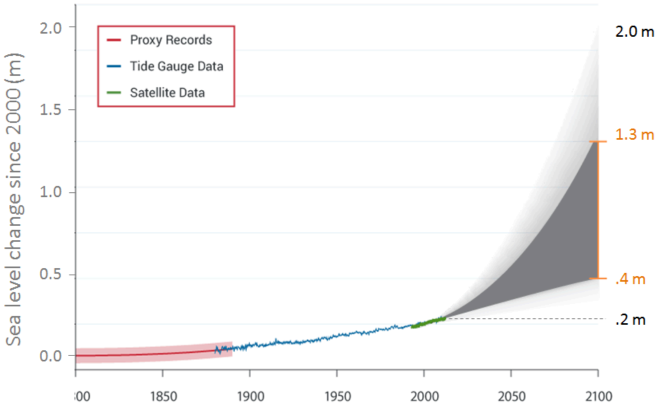


Figure 19.3.1 Projected sea-level increases to 2100, showing likely range (grey) and possible maximum.

In a 2008 report, the Organisation for Economic Co-operation and Development (OECD) estimated that by 2070 approximately 150 million people living in coastal areas could be at risk of flooding due to the combined effects of sea-level rise, increased storm intensity, and land subsidence. The assets at risk (buildings, roads, bridges, ports, etc.) are in the order of $35 trillion ($35,000,000,000,000). Countries with the greatest exposure of population to flooding are China, India, Bangladesh, Vietnam, U.S.A., Japan, and Thailand. Some of the major cities at risk include Shanghai, Guangzhou, Mumbai, Kolkata, Dhaka, Ho Chi Minh City, Tokyo, Miami, and New York.

One of the other risks for coastal populations, besides sea-level rise, is that climate warming is also associated with an increase in the intensity of tropical storms (e.g., hurricanes or typhoons), which almost always bring serious flooding from intense rain and storm surges. Some recent examples are New Orleans in 2005 with Hurricane Katrina, and New Jersey and New York in 2012 with Hurricane Sandy (Figure 19.3.2).

Tropical storms get their energy from the evaporation of warm seawater in tropical regions. In the Atlantic Ocean, this takes place between 8° and 20° N in the summer. Figure 19.3.3 shows the variations in the sea-surface temperature (SST) of the tropical Atlantic Ocean (in blue) versus the amount of power represented by Atlantic hurricanes between 1950 and 2008 (in red). Not only has the overall intensity of Atlantic hurricanes increased with the warming since 1975, but the correlation between hurricanes and sea-surface temperatures is very strong over that time period.

Because warm air is able to hold more water than cold air, the general global trend over the past century has been one of increasing precipitation (Figure 19.3.4).

Figure 19.3.2 Damage to the Casino Pier, Seaside Heights, New Jersey, from Hurricane Sandy, November 2012.

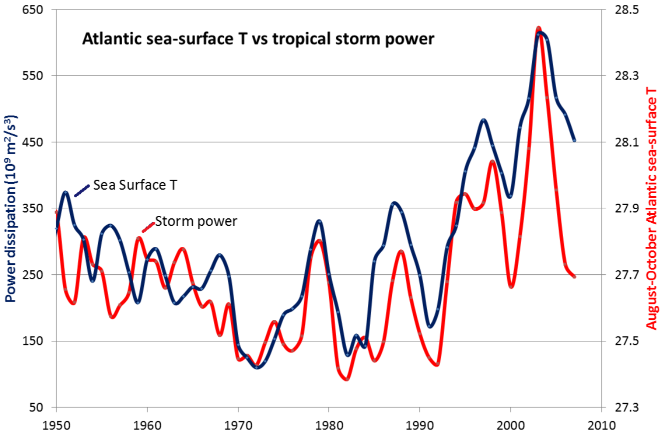


Figure 19.3.3 Relationship between Atlantic tropical storm cumulative annual intensity and Atlantic sea-surface temperatures.

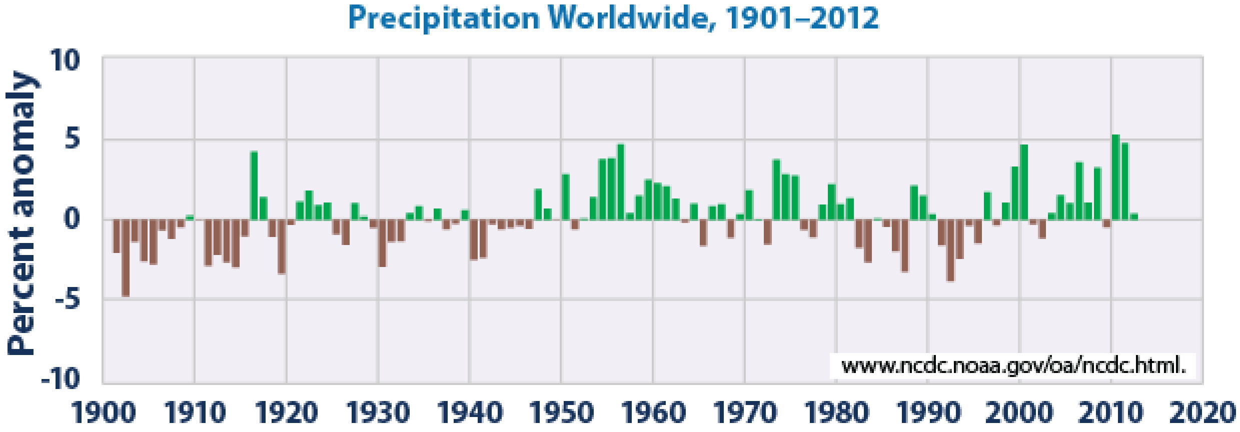


Figure 19.3.4 Global precipitation anomalies compared with the average over the period from 1901 to 2012.

A similar trend is evident for British Columbia based on weather data from 1945 to 2005 for 29 stations distributed around the province (Figure 19.3.5). Of those stations, 19 show an increase in precipitation and 10 show a decrease. While the decreases are all less than 12%, some of the increases are greater than 48%. Based on the data from these stations, it is estimated that approximately 60 mm/year more precipitation fell on British Columbia in 2005 compared with 1945. That is equivalent to about six months of the average flow of the Fraser River.

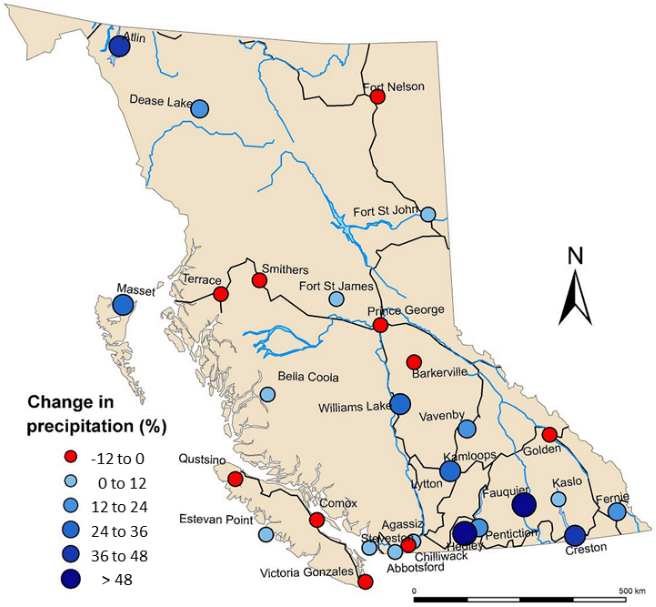


Figure 19.3.5 Change in precipitation amounts over the period 1945 to 2005 for 29 stations in British Columbia. [Image Description]

While the overall amount of precipitation (total volume of rain plus snow) increased at 19 out of 29 stations between 1945 and 2005, the amount of snowfall decreased at every single station. This is a disturbing trend for many of us, including: operators and users of winter resorts and hydroelectric dams, the Wildfire Management Branch, people who drink water from reservoirs that are replenished by snow, and people who eat food that is grown across western Canada and is irrigated with water derived from melting snow.

Exercise 19.4 Rainfall and ENSO

Figure 19.3.6 shows the monthly precipitation data for Penticton, BC from 1950 to 2005 (solid line) along with the ENSO (El Niño Southern Oscillation) index values (dotted line). High ENSO index values correspond to strong El Niño events, such as 1983 and 1998. Describe the relationship between ENSO and precipitation in B.C.'s southern interior.

It's not necessarily a consistent relationship.

See Appendix 3 for Exercise 19.4 answers.

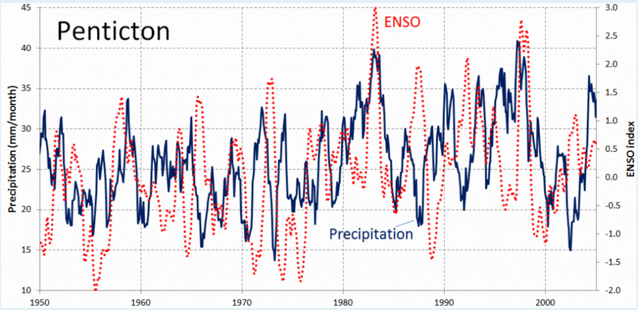


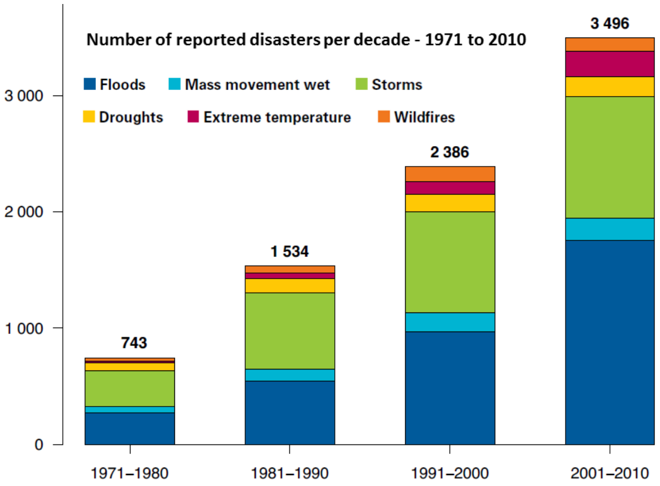
Figure 19.3.6 Monthly precipitation in Pentiction and ENSO index from 1950 to 2005.

The geographical ranges of diseases and pests, especially those caused or transmitted by insects, have been shown to extend toward temperate regions because of climate change. West Nile virus and Lyme disease are two examples that already directly affect Canadians, while dengue fever could be an issue in the future. Canadians are also indirectly affected by the increase in populations of pests such as the mountain pine beetle (Figure 19.3.7).

A summary of the impacts of climate change on natural disasters is given in Figure 19.3.8. The major types of disasters related to climate are floods and storms, but the health implications of extreme temperatures are also becoming a great concern. In the decade 1971 to 1980, extreme temperatures were the fifth most common natural disasters; by 2001 to 2010, they were the third most common.

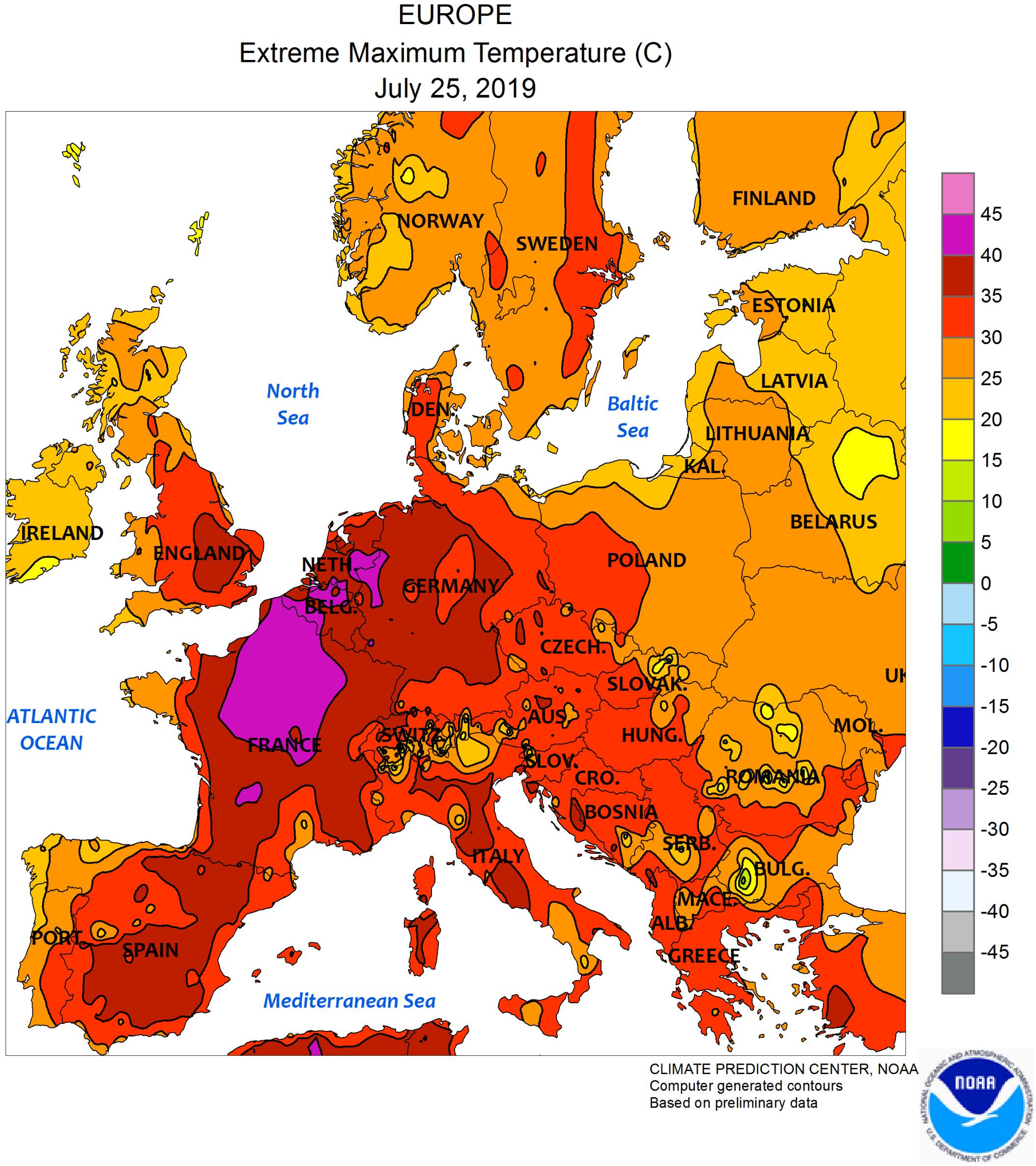
For several days in both June and July of 2019, many parts of Europe experienced massive heat waves with all-time national record temperatures set in several countries (Belgium, Finland, France, Germany, Luxembourg, Netherlands, and United Kingdom) (Figure 19.3.9). At the time of writing (August 2019) the death toll from these events is not known. A similar event in Russia in 2010 is estimated to have resulted in over 55,000 deaths.

Figure 19.3.7 Mountain pine beetle damage in Manning Park, British Columbia.



World Meteorological Association - Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes - 2014

Figure 19.3.8 Numbers of various types of disasters between 1971 and 2010. [Image Description]



CLIMATE PREDICTION CENTER, NOAA
Computer generated contours
Based on preliminary data

Figure 19.3.9 Maximum temperatures across Europe on July 25th 2019

Exercise 19.5 How can you reduce your impact on the climate?

If you look back to Figure 19.2.3 and the related text, you can easily see what aspects of our way of life are the most responsible for climate change. Think about how you could make changes to your own lifestyle to reduce your impact on the climate. It may depend on where you live, and the degree to which fossil fuels are used to generate the electricity that you use, but it’s most likely to include how, how far, how fast, and how frequently you move around.

If you hold the opinion that there isn’t much point in making changes to your lifestyle because others won’t or because your contribution is only a tiny fraction of the problem, bear in mind that all of us have the opportunity to set an example that others can follow. And remember the words of the American anthropologist Margaret Mead:

> *Never doubt that a small group of thoughtful, committed citizens can change the world. Indeed, it is the only thing that ever has.*

Image Descriptions

Figure 19.3.5 image description: The percent change in precipitation by city in British Columbia from 1945 to 2005

Negative 12% to 0%	0% to 12%	12% to 24%	24% to 36%	26% to 48%	Greater than 48%
Barkerville Chilliwack Comox Fort Nelson Golden Prince George Qustsino Smithers Terrace Victoria Gonzales	Abbotsform Agassiz Estevan Point Kaslo Steveston	Fort St. James Fort St. John Bella Coola	Fernie Penticton Vavenby	Dease Lake Kamloops Masset Williams Lake	Atlin Fauqu Hedle

[Return to Figure 19.3.5]

Figure 19.3.8 image description: From the 1970s, the number of reported disasters by decade has grown steadily. In the 1970s, 743 disasters were reported; in the 1980s, 1,534 were reported; in the 1990s, 2,386 were reported, and in the 2000s, 3,496 were reported. Together, floods and storms make up about three quarters of the reported disasters each decade, followed by mass movement wet, droughts, extreme temperature, and wildfires. [Return to Figure 19.3.8]

Media Attributions

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Based on data from Papers, Data, and Graphics Pertaining to Tropical Cyclone Trends and Variability.

- Figure 19.3.4: “Precipitation Worldwide, 1901-2013” by NASA. Public domain.
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- Figure 19.3.6: © Steven Earle. CC BY. Based on precipitation data from Environment Canada and ENSO data.
- Figure 19.3.7: “Pine Beetle in Manning Park” © Jonhall. CC BY.
- Figure 19.3.8: WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes, 2014. CC BY-NC-ND.
- Figure 19.3.9: “Heatwave in Russia” by Jesse Allen/NASA Earth Observatory. Public domain.

Summary

The main topics of this chapter can be summarized as follows:

Section	Summary
19.1 What Makes the Climate Change?	The two components of climate change are forcings and feedbacks. Natural climate forcings, which have operated throughout geological time, include solar evolution and cycles, continental drift, continental collisions and mountain building, volcanism, orbital variations, and ocean current cycles. Feedbacks include melting of ice, snow, and permafrost (changing albedo and releasing GHGs); temperature-related changes to solubility of CO_2; and vegetation growth.
19.2 Anthropogenic Climate Change	The key contributors to anthropogenic climate change are our use of fossil fuels, what we eat and how we produce it, and how much waste we produce and what we do with it.
19.3 Implications of Climate Change	The most reliable indicators of climate change are those that we can detect by looking at records going back for decades. These include temperature and other climate parameters, of course, but also sea-level rise and the incidence of major storms. Some of the implications of climate change include changes to the distribution of disease vectors and pests, and an increase in the incidence and severity of heat waves.

Questions for Review

See Appendix 2 for answers to Review Questions.

1. What property of greenhouse gases allows them to absorb infrared radiation and thus trap heat within the atmosphere?
2. Explain why the emission of CO_2 from fossil fuel use is a climate forcing, while the solubility of CO_2 in seawater is a climate feedback.
3. Explain how the positioning of Gondwana at the South Pole contributed to glaciation during the Paleozoic.
4. Most volcanic eruptions lead to short-term cooling, but long-term sustained volcanism can lead to warming. Describe the mechanisms for these two different consequences.
5. Using the orbital information on eccentricity, tilt, and precession, we could calculate variations in insolation for any latitude on Earth and for any month of the year. Why is it useful to choose the latitude of 65° as opposed to something like 30°? Why north instead of south? Why July instead of January?
6. If the major currents in the oceans were to slow down or stop, how would that affect the

distribution of heat on Earth, and what effect might that have on glaciation?

7. Explain the climate implications of the melting and breakdown of permafrost.
8. Much of the warming of the Paleocene-Eocene thermal maximum is thought to have been caused by the release of CH_4 from sea-floor methane hydrates. Describe what must have happened before this could take place.
9. Burning fossil fuels emits CO_2 to the atmosphere via reactions like this one: CH_4 + O_2 —-> CO_2 + $2H_2O$. Describe some of the other ways that our extraction, transportation, and use of fossil fuels impact the climate.
10. Explain why, even if we could stop our impact on the climate tomorrow, we would still be facing between 1 and 2 m of additional sea-level rise.
11. Use the Internet to research West Nile virus, and explain why its spread into Canada from the United States is related to climate change.