Environment: understanding atmospheric and ocean flows

Contents

Introduction

The scientific theory of plate tectonics suggests that at least some of the Arctic lands were once tropical. Since then the continents have moved and ice has changed the landscape. This free course, *Environment: understanding atmospheric and ocean flows*, will concentrate on evidence from the last 800 000 years using information collected from ice cores from Greenland and Antarctica to discuss current and possible future climate.

The cores show that there have been nine periods in the recent past when large areas of the Earth were covered by ice. During the last 10 000 years – called the Holocene, which encompasses the entire development of human civilisation – there has been an unusually stable climate compared with the rest of the record.

The Arctic, like any region, has always undergone climate change but there is evidence, for example in the decreasing sea ice cover, which suggests that the changes are happening faster. In this course you will consider evidence from the ice cores which suggests that flows of chemicals and energy dominate natural systems and cause these changes. You will consider flows of water, heat and even pollution around the planet and look at how, through positive feedback processes, the flows that are affecting the Arctic are already changing the whole planet. There will be further changes, with an impact on us all.

The Arctic is often considered a victim of climate change – and it certainly is – but this course hopes to show that the Arctic acts as a planetary barometer. To discover the evidence that the Earth is dominated by flows you will start by looking at the most famous Arctic animal of all – the polar bear.

This OpenLearn course is an adapted extract from the Open University course U116 *Environment: journeys through a changing world*.

Learning Outcomes

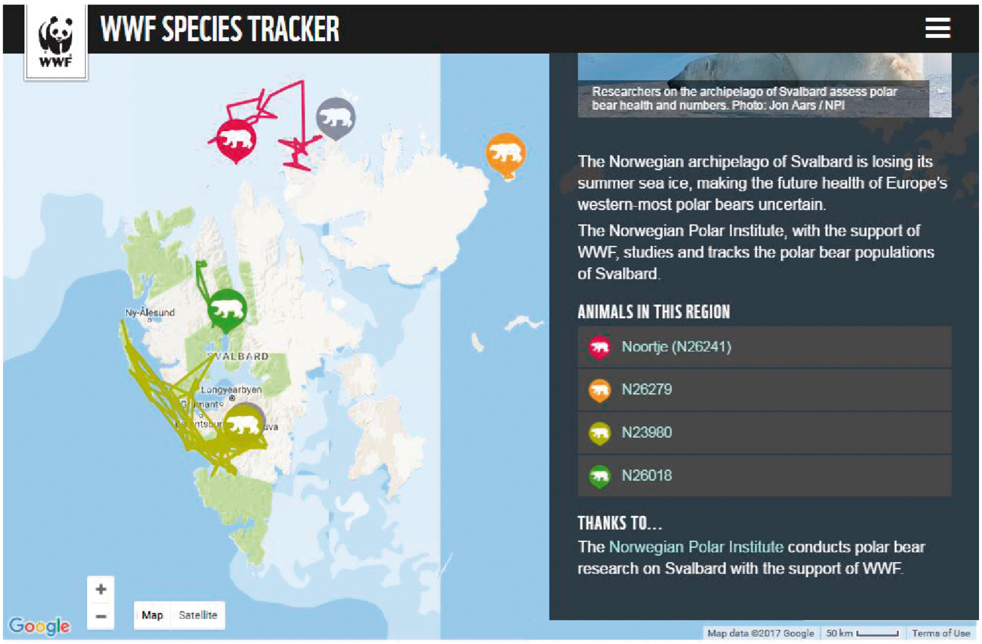
After studying this course, you should be able to:

- appreciate how chemical processes in the rest of the world affect the Arctic environment and the species inhabiting it
- recognise the physical processes that determine atmosphere and oceanic flows in the Arctic
- appreciate the scientific research process and the use of scientific evidence
- recognise the role and limitations of scientific data in attempting to predict global climatic change
- understand the concept of feedback loops.

1 An environmental icon

The polar bear has become an international climate change icon. But how much is known about this bear, its habitat and its life? By way of introduction, you will start with the name of this bear. To a British person it is the polar bear, to a German it is an *Eisbär* (ice bear), and to a French person it is an *ours blanc* (white bear). In these three examples the bear is referred to as polar, white, or ice – eminently sensible. However, the Latin name for this bear is *Ursus maritimus*, which means 'bear of the sea'. The reason for this is given by the writer Barry Lopez:

> The polar bear is a creature of arctic edges: he hunts the ice margins, the surface of the water, and the continental shore. ... He dives to the ocean floor for mussels and kelp, and soundlessly breaks the water's glassy surface on his return to study a sleeping seal. Twenty miles from shore he treads water amid schooling fish. In winter, while the grizzly hibernates, the polar bear is out on the sea ice, hunting. In summer his tracks turn up a hundred miles inland, where he has feasted on crowberries and blueberries.
>
> (Lopez, 2001, p. 77)



(a)

Figure 1 A snapshot of the travels of some polar bears around Svalbard

Figure 1 shows the movements of several satellite-tracked females around Svalbard, which is a group of islands about halfway between mainland Norway and the North Pole. A polar bear typically travels several thousand kilometres per year in search of its main prey species – the seal. The state of the seas and ice of the region will therefore directly affect the bears

It turns, however, that polar bears are also impacted by effects from much further afield as you will look at next.

1.1 Polar bears and pollutants

Attaching a satellite-tracking device to polar bears is not easy, and they have to be drugged (Figure 2). This gives an opportunity for them to be weighed, measured and tagged, and have various samples such as hair, fat and teeth removed for later chemical analysis.

(b)

Figure 2 Scientists examine a drugged polar bear

The amount of body fat on a bear indicates whether it has been eating well or is starving. But a chemical analysis of this body fat gives a surprise: polar bears have measurable amounts of a family of chemicals called polybrominated diphenyl ethers (PBDEs) in their fat. The same family has also been measured in Arctic ringed seals and other Arctic wildlife (Figure 3).

PBDEs are a group of synthetic chemicals developed over the 20th century as fire retardants. Fabrics and furniture are impregnated with them, with the sole aim of slowing the rate at which they burn, and for which they have been very successful. However, once created, PBDEs are very difficult to destroy and will not break down into their elements over time. For this reason they are considered a persistent organic pollutant (POP).

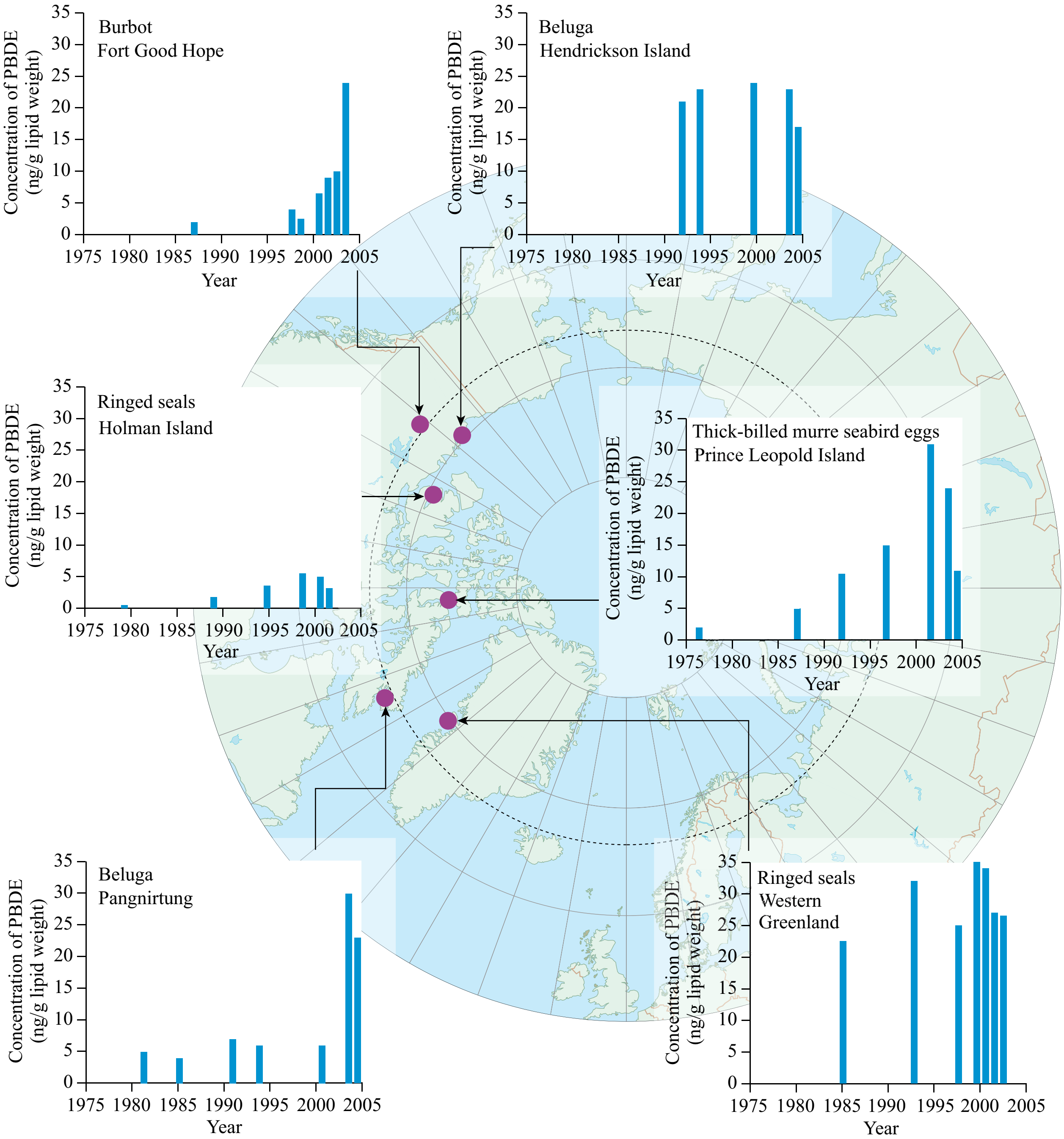


Figure 3 Measurements of PBDE concentration in wildlife at different Arctic sites (Arctic Monitoring and Assessment Programme (AMAP), 2009)

In the late 1970s and early 1980s, scientists began to detect POPs in the tissues of fish and shellfish close to populated areas. Concentrations were then detected in human breast milk, and the levels were shown to be increasing with time – perhaps through direct exposure to PBDEs or through bioaccumulation (see Section 1.2). The scale in Figure 3 is given in nanograms per gram. So in every gram of the sample of beluga fat from Pangnirtung in 2004 there are about 30 nanograms of PBDE. This is 0.000 000 03 grams of PBDE in every gram of sample, or 0.03 parts per million (ppm). This may seem an extremely small amount, but PBDEs are potentially very toxic to liver and thyroid function, and have been shown to hinder development of nerve tissue in mammals. For this reason, the European Union banned several of them in 2004 and then more in 2008.

The migration of PBDEs into humans and shellfish can be explained by proximity to where they were used. While it is relatively simple to see how PBDEs can get into subjects close to their source, the PBDEs that end up in some of the wildlife in the Arctic have to be physically transported there. You will look at how pollutants are transported to the Arctic by flows around the Earth later in this course, but before you do, the following section looks at how pollutants can accumulate in the environment.

1.2 Pollutants and bioaccumulation

The term 'pollutant' is a very wide-ranging term. When the introduction or action of something into any environment causes harm, it is considered a pollutant. This could be a harmful chemical such as smoke from a chimney, or it could be a more subtle and transient effect such as floodlights at an evening football match preventing stargazing.

There are many examples of how society has responded to pollution, such as the removal of lead in petrol, which affected human health, or the banning of chlorofluorocarbons (CFCs), which damaged the ozone layer. In both of these cases (i.e. lead and CFCs), when the pollution source was removed, the levels of them in the environment reduced and consequently so have the effects – albeit with a time delay.

By definition, persistent pollutants such as PBDEs do not break down, so continued introduction of even minute levels into an environment leads to accumulation and perhaps magnification of potential harm. For example, at a landfill site the PBDE level is likely to increase with time. Animals around that landfill may ingest PBDEs directly, but this bioaccumulation (intake and concentration of the chemical in their tissues) may be so small that it does not cause problems to any particular animal. However, a predator such as a cat might eat dozens of rats that live around the landfill, so it would receive the combined dose that each of these rats had within it. If this dose were subsequently absorbed by the cat, then the resulting accumulated level could be significantly more harmful. This concentration of pollutants at higher levels in the food chain is called biomagnification, and the result is that higher predators can be poisoned and suffer harm while animals at lower levels in the food chain are apparently unaffected.

1.3 Summary of Section 1

In examining the European name of the polar bear there is an apparent contradiction between its common and scientific names. This is because the polar bear is at home in the natural environments of land, sea and ice. In their search for food, bears can travel huge distances. Chemical analysis of the fat in the bears and their main prey species, the ringed seal, shows that they contain PBDEs – manufactured persistent organic pollutants that do not occur naturally.

In Section 2 you will look at how different flows around the Earth can transport pollutants.

2 The atmospheric and ocean flows

PBDEs end up in the Arctic through their physical transport by the winds, the ocean and the rivers of the world. All three mechanisms are important, but the most rapid carrier is the wind.

The basic principle of global atmospheric circulation is simple: warm air rises and cold air sinks. The warming effect of the Sun is much greater at the equator than at higher latitudes, so the air is much warmer and rises. At high latitudes the air cools and sinks. This drives a horizontal wind. To help picture this, imagine a room with a radiator on one wall, and at the other end of the room an open fridge (Figure 4).

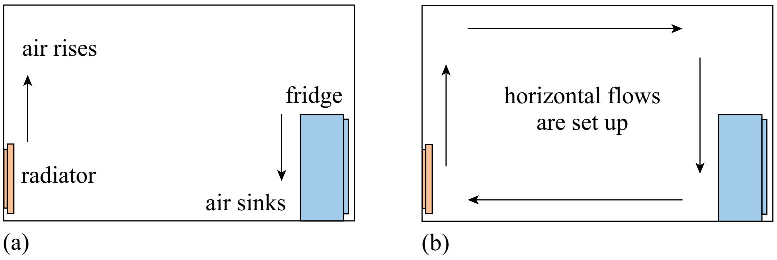


Figure 4 (a) A room with a radiator on one wall and an open fridge on the other will cause air to rise and sink at opposite ends; (b) horizontal winds are set up to replace this ascending and descending air

The radiator heats up the air around it, and the air rises in what is called a convection current all the way to the ceiling and starts to spread. At the other end, the fridge is doing the opposite and cooling the air, which sinks and spreads across the floor. To replace the air that has risen, the air beneath the radiator is pulled upwards and then heated and rises, while the opposite is happening at the other end of the room.

At the most basic level, on Earth the same process is happening, with warm air rising from lower latitudes and sinking at higher, colder latitudes. High-level winds therefore tend to blow from the hotter regions to the colder ones. This general pattern is modified by the rotation of the Earth, which deflects the wind flow away from the apparently direct path.

These wind flows are further complicated by the distribution of continents and their mountain ranges across the globe. Winds are modified as they move around and over mountain ranges. They are also affected as they travel over land and sea surfaces, where the air is warmed to different extents. This is because of two additional processes: land and sea surfaces reflect different amounts of solar energy falling on them, and materials such as rocks and water need different amounts of heat to warm them up. You will look at the impact of these processes next.

2.1 Albedo

When solar energy reaches the Earth’s surface, a proportion of it is reflected straight back out into space, and only the fraction which is not reflected heats the terrain. Different materials have a different albedo and so reflect a different amount of solar energy. If you put your hand on a black car on a warm sunny day, and then on a white car, you will notice that the black car feels warmer. This is because it reflects less energy so it heats up more. The black car has a lower albedo than the white car. Table 1 shows the albedos of some typical surfaces. For example, the surface of the ocean has an albedo of 3%, which means that 100% – 3% = 97%, or almost all of the incoming energy from the Sun, actually heats the water. Fresh snow, on the other hand, reflects away most solar energy, a property that has important consequences for the climate of the Arctic.

Table 1 The albedos of typical features on Earth

Surface	Albedo
Ocean surface	3%
Conifer forest in summer	9%
Grassy fields	25%
Sea ice	40%
Desert sand	40%
Fresh snow	80–90%

Activity 1 The importance of albedo

Allow about 5 minutes

If the Sun's energy falls on a desert and also sea ice on a frozen sea, what proportion of the energy is available to heat up each material? If snow then falls to cover the sea ice, what will be the amount of energy available to heat up the ice?

Provide your answer...

Answer

If the Sun's energy falls on a desert and a frozen sea, the amount of energy available to heat up the material will be the same, because Table 1 shows that the two substances have the same albedo: 40%. In both cases, the amount of energy available to heat up the material is

$$\text{amount of energy} = 100\% - 40\% = 60\%$$

So 60% of the incoming energy will be available to heat up the material.

If snow falls on the sea ice, then its albedo will increase from 40% to 80–90%, so the amount of energy available to heat up the ice is

$$\text{amount of energy} = 100\% - 90\% = 10\%$$

Only 10% of the incoming energy is now available to heat up the ice, and almost all of the incident energy is reflected away. Clearly, albedo is extremely important for the polar regions.

Next you will look at what is meant by specific heat capacity and its effects.

2.2 Specific heat capacity

When energy reaches the surface of an object, the amount the object heats up is determined by its specific heat capacity. This is a measure of how much energy it takes to raise the temperature of 1 kg of a particular substance by 1 °C. A lower specific heat capacity means that it takes less energy to heat up something, and vice versa. Although the term may be unfamiliar, the concept most likely is not.

Activity 2 The effect of specific heat capacity

Allow about 5 minutes

On a very hot sunny day on a table outside in the sunshine there is a glass containing 1 kg of water (i.e. 1 litre), a 1 kg piece of cork and a 1 kg piece of iron. Ignore the effects of albedo and assume that all three items absorb the same amount of energy from the Sun. Which will be the hottest after 1 hour, and which the coolest? (Ignore all sources of heat except that received directly from the Sun.)

Provide your answer...

Discussion

You probably recognised that the 1 kg of iron would be the hottest. It does not take very much heat energy to change the temperature of the iron because it has a low specific heat capacity. The other two items are harder to place, but the cork will be cooler than the iron, and the water, which has the highest specific heat capacity, will be the coolest item on the table.

Water has an extremely high specific heat capacity and it takes a vast amount of energy to heat it. This is why virtually all car engines use water in their cooling systems.

Taking into account the combined effects of albedo and specific heat capacity, even two adjacent areas such as a beach and the sea lapping on it will heat up by different amounts on a sunny day.

Areas with lower heat capacities and lower albedos heat up more. This heat is transferred to the air above, so in these areas it will rise at a faster rate, whilst in cooler areas the air sinks. The rising and sinking air drives horizontal winds much as in Figure 4, although on a planetary scale.

Sea ice cover is also constantly moving. It is pushed by the winds and ocean currents, and drifts in the pattern shown in Figure 5.

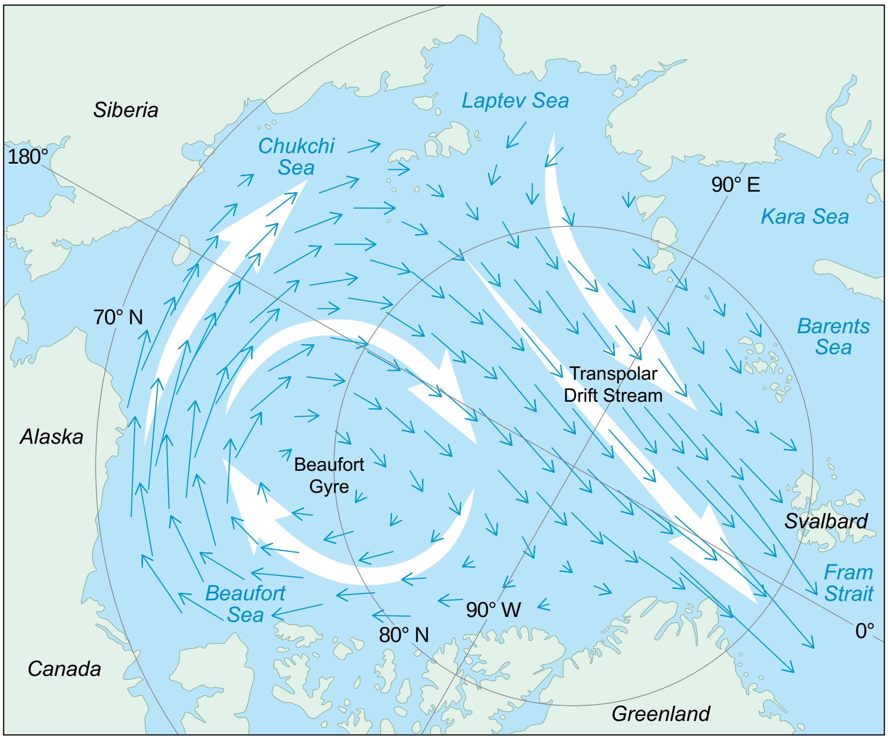


Figure 5 The mean ice drift across the Arctic Ocean. The ice is trapped in two major circulation features, the Beaufort Gyre and the Transpolar Drift Stream. White arrows show the general movement of the ocean currents; blue arrows show the general drift of the sea ice.

2.3 Russian tree trunks in the Arctic

In Northern latitudes, the treeline is often used as a means to define the Arctic region. The 'treeline' is a physical boundary of altitude or latitude beyond which trees cannot thrive because of a combination of light availability and temperature that would prevent tree growth.

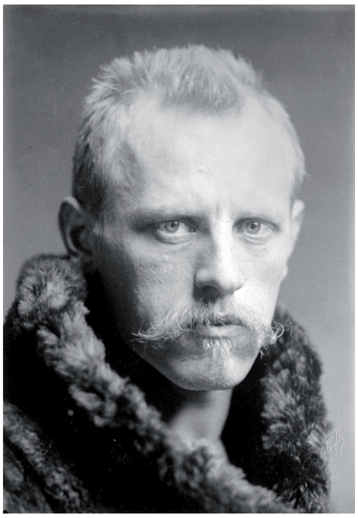
Although the Arctic is north of the treeline, it is not unusual to find tree trunks in the Arctic regions. Figure 6 shows a Svalbard beach strewn with tree trunks.

Figure 6 A photograph of a typical scene on a Svalbard beach (Norway)

How do the tree trunks get there? They are mostly Siberian fir trees (*Abies sibirica*), natives of the great forests of northern Russia. Tree trunks are carried out to sea in summer by rivers such as the Lena, Ob and Yenisei. Then they are frozen into sea ice and travel in two ocean currents called the Transpolar Drift Stream and the Beaufort Gyre. Eventually they reach the shores of Svalbard and Greenland. Dating of these tree trunks using carbon dating shows that some are several thousand years old.

2.3.1 Nansen and the voyage of the *Fram*

Wood on the shores of Svalbard and East Greenland caused confusion to the first explorers. But when wreckage from a ship called the *Jeanette* was found on the coast of East Greenland in the late 19th century, the best environmental scientist of the age, the Norwegian Fridtjof Nansen (Figure 7(a)), had a eureka moment. Nansen knew that the *Jeanette* had sunk off Alaska on the other side of the Arctic Ocean and deduced that the wreckage must have been carried across the frozen sea by the sea ice. He decided to try to use the ice drift to reach the North Pole and study the Arctic environment on the journey. He had the ship *Fram* (Norwegian for ‘forward’) built (Figure 7(b)). The ship had a round hull so that it would not get crushed like the *Jeanette*, and Nansen left Norway in 1893 for the Arctic and the North Pole. It was over three years before he and his colleagues returned.



(a)

(b)

Figure 7 (a) Fridtjof Nansen (1861–1930); (b) his ship the *Fram* frozen into the Arctic Ocean and being carried along with the moving ice in the Transpolar Drift Stream

Nansen and his crew followed the Russian coast (i.e. against the ocean currents), and the *Fram* froze into the sea ice off Siberia. As they drifted northwards, Nansen realised that the *Fram* was going to miss the pole so he and Hjalmar Johansen left the ship to make for the pole on foot. This was incredible. They knew the ship was drifting and they must have been certain that they would never find her again. The *Fram* survived the Arctic drift and reached Svalbard in the summer of 1896. Nansen and Johansen turned back just north of 86° N, having reached the highest latitude then attained. After an epic journey across the sea ice they endured the winter of 1895 on the island of Franz Josef Land and then caught a ship back to Norway, arriving only a few days before the *Fram* in August 1896 (see Figure 8).

The sea channel between the Svalbard archipelago and Greenland was named the Fram Strait in honour of the famous polar research ship.

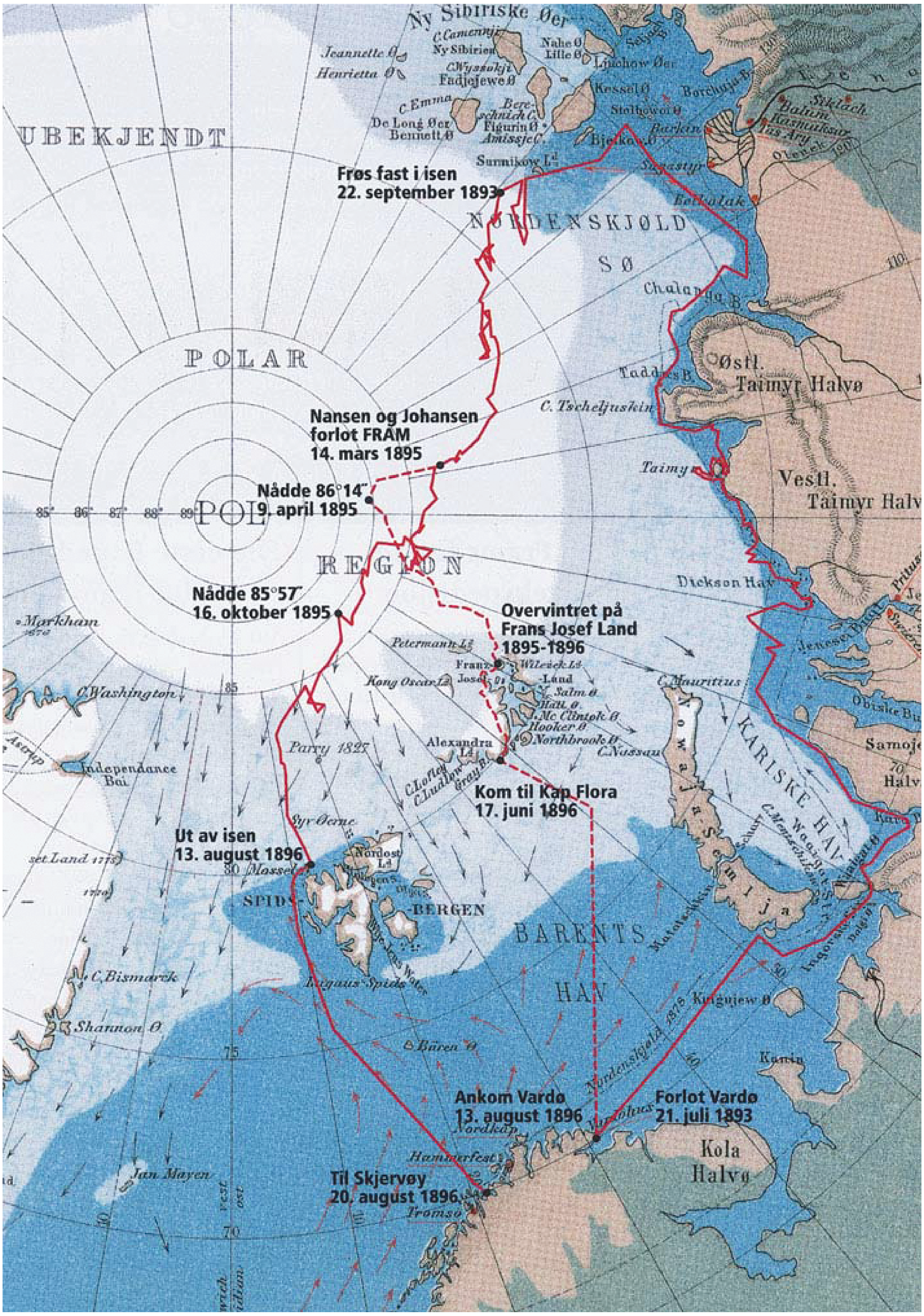


Figure 8 The voyage of the *Fram* (solid line) and route of Nansen and Johansen (dashed line) during their expedition of 1893–6

2.4 Pollutant pathways to the Arctic

Winds, ocean currents and flow from rivers can all carry pollutants from their source to the Arctic. On a stereographic plot, the routes of wind-borne contaminants from the warmer, populated areas of Earth to the cooler Arctic are clear (Figure 9). These winds can transport contaminants to the poles, where they are removed from the atmosphere most likely through snowfall and are then absorbed by animals, perhaps through direct contact.

The North Atlantic Current shown in Figure 9 flows directly past the waters off Western Europe, likely to be a major source of PBDEs. For top predators such as polar bears, there is also likely to be biomagnification from the high levels of PBDEs in their prey, the seals.

Figure 9 Transportation pathways for persistent organic pollutants (POPs) to the Arctic. Note the curving path of the wind currents caused by the rotation of the Earth. (adapted from Macdonald et al., 2005)

Overall, the toxicity of POPs to the polar wildlife is not completely clear, but the fact that they are manufactured only in populated regions and yet can be detected in Arctic wildlife is striking. POPs give a graphic demonstration that a region once thought of as remote is clearly physically connected to the rest of the planet.

The poet Nick Drake responded to his experience of the Arctic by writing a series of poems. His ‘one poem in many voices’ *The Farewell Glacier* sought to give a voice to people, places and other animals and things related to the region.

Listen to Nick reading two extracts from *The Farewell Glacier*, related to themes of the first two sections of this course. The first is about Wally Herbert (1934–2007), the British polar explorer, writer and artist. In 1968–9, Herbert led the British Trans-Arctic Expedition to walk 4000 miles from Alaska to Svalbard, making him the first man confirmed to have walked to the North Pole.

Video content is not available in this format.
Video 1 Nick Drake's Wally Herbert video

Now listen to Nick read his poem on pollutants and how they make their way to the Arctic.

Video content is not available in this format.
Video 2 Nick Drake's Mercury video

2.5 Summary of Section 2

Differences between the albedo and specific heat capacity of terrains mean that they heat up at different rates. Air in contact with the warm terrain rises in convection currents, and horizontal winds are set up across the whole planet. The winds can transport pollutants such as PBDEs to the Arctic, where they are deposited in snowfall and as a result can be detected in Arctic wildlife. Ocean currents and rivers can also transport pollution into the Arctic.

3 The ice time machine

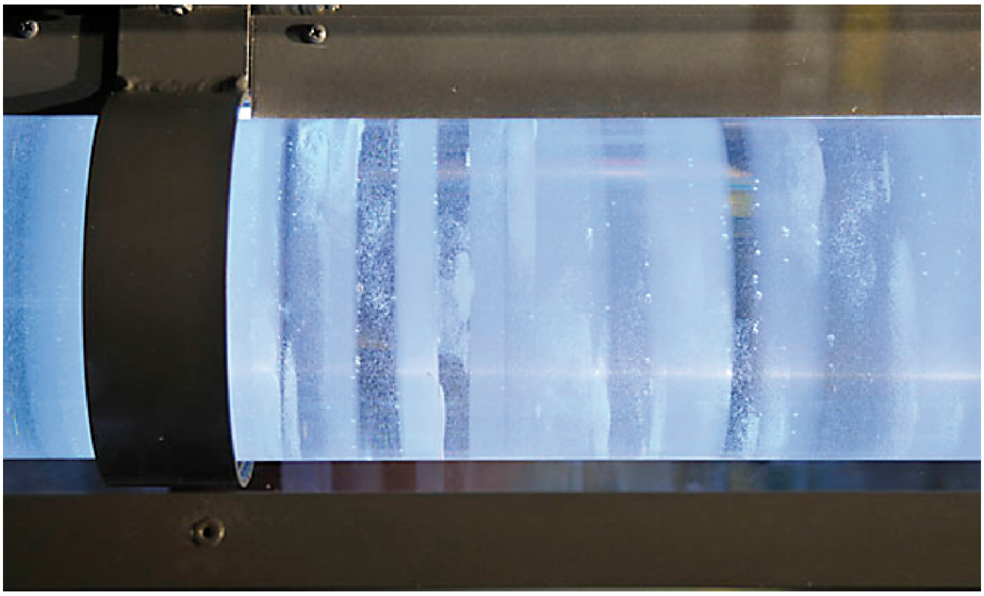
Snowfall differs depending on whether it falls in summer (when snow is comparatively warm and moist) or winter (when snow is cold and dry). These differences mean that when snow turns into ice, on the surfaces of glaciers and ice sheets, it is possible to see distinct annual layers. The layers are in a sense similar to tree rings: thick annual layers mean high snowfall, and thin annual layers mean low snowfall.

The accumulation of snowfall on the Greenland and Antarctic ice sheets – and most importantly what is trapped within the crystals as it turns to ice – can provide a record of the past. Digging down into the ice cap is equivalent to going back in time through the snowfall of previous years and you have to dig down a long way (equivalent perhaps to 300 years of snowfall) before reaching the ice.

To make the digging back in time easier, a drilling rig that extracts ice cores about 13 cm in diameter is used to get to very deep levels (Figure 10(a)). Once extracted, the annual layers in the cores are clear (Figure 10(b)).

(a)

Figure 10 (a) The NEEM (North Greenland Eemian Ice Drilling, where Eemian is the name of the last interglacial period) ice camp on the summit of the Greenland ice cap being dragged nearly 500 km to a new location to become EastGRIP (East Greenland Ice-core Project).



(b)

Figure 10(b) Annual layers in a model of a Greenland ice core. Light bands represent summer and dark bands represent winter.

The British Antarctic Survey (BAS) is world renowned for its polar research, including analysis of ice cores. Video 3 visits the BAS research laboratories in Cambridge, UK where Liz Thomas, head of ice core research at BAS, explains how ice cores can provide a time capsule of past snow falls that record what past atmosphere and climates were like.

Video content is not available in this format.
Video 3 British Antarctic Survey (BAS) and its polar research

The next section shows you how ice cores are extracted and illustrates how data from ice core analyses can be used to help develop our understanding of past atmospheric conditions.

3.1 Ice cores and the atmosphere

Analysis of ice cores collected in the Polar Regions can also tell us about how the climate has changed. Watch Video 4 which shows how scientists extract cores from the ice sheets and then saw them up for analysis in a laboratory.

Video content is not available in this format.
Video 4 Ice core drilling

In addition to looking at snowfall, the use of different chemical and physical techniques to analyse ice cores can tell you about dust and pollen in the atmosphere, past volcanic activity, and even the industrial production of civilisations long past. For example, Figure 11 shows the concentrations of lead in the ice of different ages, and compares it with the recorded production of lead starting with the discovery of 'cupellation' (separating precious metals like silver from base metals like lead).

Notice that the vertical axis of the lead production graph in Figure 11(a) is a logarithmic scale. Each successive tick mark up the axis has a value ten times bigger than the previous one. For example, 100 is equal to 1, 10^2 is equal to 100, and the tick mark between them is 10^1 (i.e. 10). A logarithmic axis enables changes over a large range to be compressed onto a small scale.

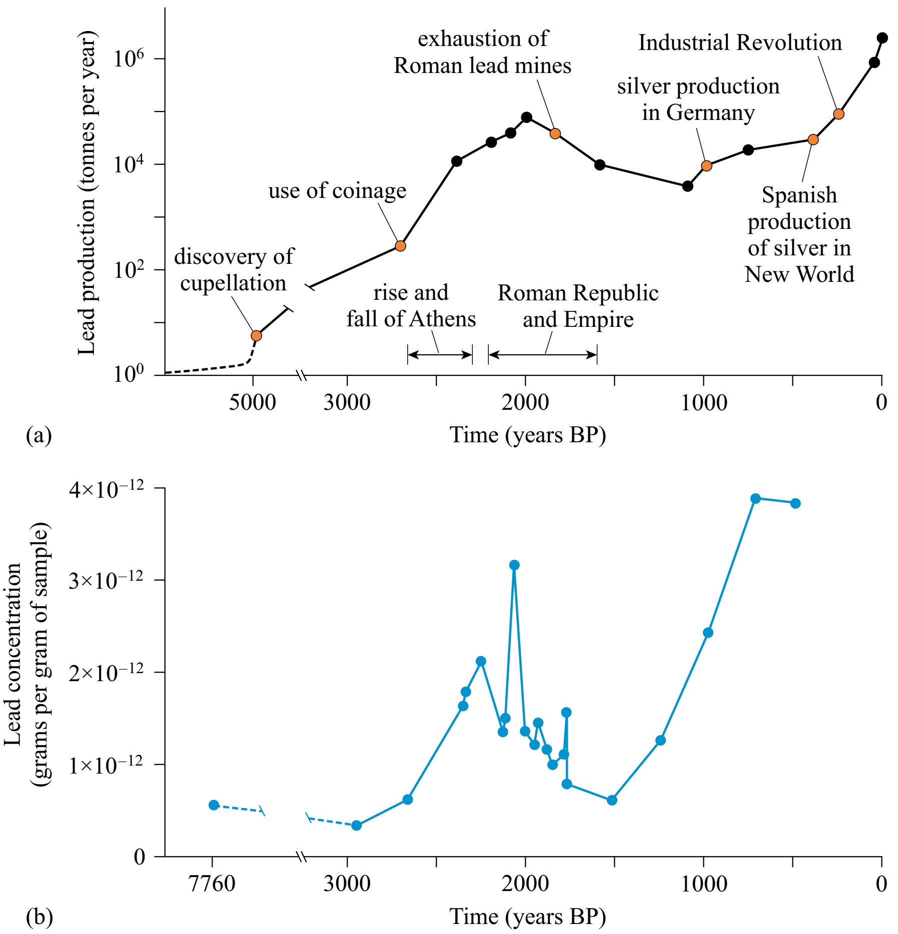


Figure 11 (a) Global lead production; (b) the concentration of lead in a Greenland ice core (years before present or 'BP') (adapted from Hong et al., 1994)

3.1.1 Powers of ten and scientific notation

In this study note you will look at how to write small and large numbers using scientific notation.

Study note: Powers of ten and scientific notation

Figure 11(a) shows the production of lead in tonnes (also known as metric tons) on a scale using different powers of ten (10^0, 10^2, etc.). When you see numbers written down, it is quite easy to read and understand them when they have few digits; for example, 0.01, 0.5, 4, 15 or 132. But when numbers have a lot of digits, for example, a small number such as 0.0000067, or a very large number such as 1 700 000 000, they are less easy to read, and consequently it is harder to understand what they are telling you. For example, if you are asked to say '75 kg' you would probably respond immediately with 'seventy-five kilograms'. But if you were asked to say the mass 330000000 tonnes, you would probably have to start counting the zeros.

To make large and small numbers easier to comprehend, there are two options. One is to use the prefixes for words illustrated in Table 2 below. The other is to use numbers as in the final column of Table 2 which is labelled 'Power of ten', where the power is the number of tens that are multiplied together. For example, 10^2, which you would say as 'ten to the power of 2', means that two tens are multiplied together (i.e. 10×10). So

$10^2 = 100$.

Similarly, ten to the power of three (i.e. 10 × 10 × 10) is

$10^3 = 1000$.

And so on. Clearly, 10^7 is easier to understand than 10 000 000. Note that 10^1 implies just one ten, that is, $10^1 = 10$, so you do not add the power 1 in this case. When dealing with powers of 10 you could also just say that the power is the number of zeros after the 1, so 10^0 is just the number 1.

That covers numbers greater than 1, but what about numbers less than 1 such as 0.1? In powers of ten this would be written as 1 divided by 10, so

$$\frac{1}{10} = 0.1$$

and this is written as 10^{-1}. Similarly, 10^{-4} is 1 divided by 10 four times:

$$10^{-4} = \frac{1}{10 \times 10 \times 10 \times 10} = 0.0001$$

So how would you write the number 150 using powers of 10? The number 150 is 1.5 × 10 × 10, so would be written 1.5×10^2. This form of writing numbers is known as scientific notation. A number written in scientific notation always looks like this: (number between 1 and 10) × $10^{\text{some power}}$.

This superscript notation can also be used to show powers of units. For example:

Square kilometres (for area):

$$\mathrm{km}^2 = \mathrm{kilometres} \times \mathrm{kilometres}$$

Metres per second (for speed):

$$\mathrm{ms}^{-1} = \frac{\mathrm{metres}}{\mathrm{second}}$$

Square kilometres per year (e.g. for a change in area through time):

$$\mathrm{km}^2\,\mathrm{yr}^{-1} = \frac{\mathrm{kilometres} \times \mathrm{kilometres}}{\mathrm{year}}$$

Table 2 Examples of different ways of writing large and small numbers

Prefix	Prefix name	Meaning	Number or fraction	Decimal	Power of ten
G	giga	billion or thousand million	1 000 000 000	1 000 000 000	10^9
M	mega	million	1 000 000	1 000 000	10^6
k	kilo	thousand	1000	1000	10^3
		one	1	1	10^0
m	milli	thousandth	1/1000	0.001	10^{-3}
μ	micro	millionth	1/1 000 000	0.000 001	10^{-6}
n	nano	billionth	1/1 000 000 000	0.000 000 001	10^{-9}

Sounds, seismic waves and starlight all have something in common: they are measured in powers of ten. Each can vary by so much that logarithmic scales are needed to describe the whole range. For example, a sound level of 110 decibels (dB) is 10 times louder than one of 100 dB. An earthquake of magnitude 8.0 has seismic waves that are 10 times larger than in an earthquake of magnitude 7.0. The brightness ('apparent magnitude') of stars is also measured on a kind of logarithmic scale.

Activity 3 Powers of ten

Allow about 10 minutes

Around 66 million years ago an asteroid or comet around 10 km wide hit the Earth, creating the 180 km wide Chicxulub crater in Mexico and causing a mass extinction including that of the dinosaurs. The impact has been estimated as causing a magnitude 13 earthquake. In recent times, the fifth largest earthquake ever measured (at the time of writing) was the 2011 Japanese Tōhoku earthquake, which had a magnitude of 9.

How many times larger would the seismic waves have been for the impact earthquake than the Tōhoku earthquake?

Answer

$$\text{Difference in magnitudes} = 13 - 9 = 4$$

$$\text{Ratio of seismic wave size} = 10^4 = 10 \times 10 \times 10 \times 10 = 10\ 000 \text{ times larger}$$

3.1.2 Interpreting a graph

Graphs can both reveal and conceal information. Read the study note below on how to interpret a graph, then complete Activity 4.

Study note: Interpreting a graph

It is important that you look closely at the axes of a graph to make sure that you understand what is being plotted, and on what scale. Some graphs just show the general trend; others may show individual points, with or without connecting lines. Where connecting lines are drawn, as in Figure 11(b), the effect may be to lead your eyes to think that an isolated point is more important than it really is. The visual impact of a graph is both a strength and a weakness!

Activity 4 Taking readings from a graph

Allow about 10 minutes

From the graph in Figure 11(a), what was the maximum global lead production in tonnes per year before the Industrial Revolution? When did this occur, and what was the lead concentration in the Greenland ice core at this time?

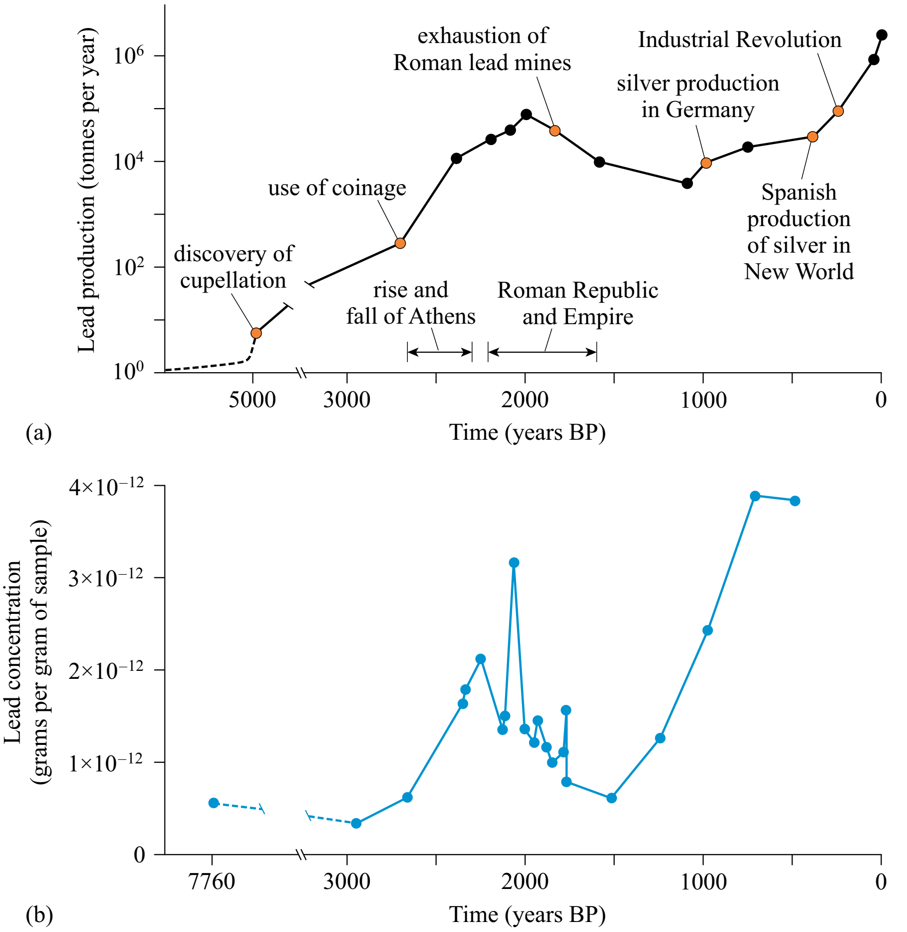


Figure 11 (repeated) (a) Global lead production; (b) the concentration of lead in a Greenland ice core (years before present or 'BP') (adapted from Hong et al., 1994)

Answer

The peak in global lead production before the Industrial Revolution was approximately 2000 years before the present (BP). At this point, the global lead production was about 10^5 tonnes per year. The concentration of lead in the Greenland ice core at this time was approximately 3×10^{-12} grams of lead per gram of ice.

Extracting lead from its ores, and to a lesser extent working the lead into pipes etc. (the word 'plumbing' derives directly from the Latin for lead, *plumbum*, as does its chemical symbol, Pb) results in a discharge of lead-rich dust to the atmosphere. Given the pattern of wind movements shown in Figure 9, it is therefore not surprising that lead should appear in the precipitation over the Arctic for the corresponding period.

3.2 The past temperature of the planet

Measuring the concentration of lead in the ice is called a direct measurement: the ice sample is melted and the water produced contains a very small but readily measured quantity of lead dust. A very accurate set of scales is needed to measure it, but it is a directly measured quantity.

There are also many indirect measurements that can be made using proxies. The concept for using proxies is both simple and brilliant: one measured property allows inference about other states of the system (Box 1).

Box 1 Proxies and correlation

The word proxy is used in various settings to mean a stand-in: representing someone or something else. One example is a proxy vote, where one person agrees to represent the voting intention of another person in the voting booth. In science, the word ‘proxy’ is used when scientists measure one, two or even several direct quantities and use these values to infer some other quantity they wish to know. This is an indirect method of measurement. It is possible for measurements of one quantity to represent another quantity when there is a relationship between the two. You can say that the quantity is a proxy, and that the measurements of the quantity are proxy data.

Take the following as an example:

> I measure my waistline, my weight and my height every week for a year, there will be a data set consisting of three variables measured 52 times over the course of a year. They are called variables because they are varying quantities; in this case, they vary with time. Typical results might be like those shown in Figure 12.
>
> Because I have stopped growing, my height does not change throughout the year so, as in the top panel of Figure 12, the graph is a flat line. However, both my waistline and weight do vary. With my body shape, when my weight goes up it all goes onto my waistline, so the graph of my waistline and the graph of my weight vary in the same way. As my waistline gets bigger, I get heavier. The opposite also applies – when my weight goes down, my waistline reduces. Because my waistline and weight seem to vary together, you say the two variables are correlated. In this case, they are positively correlated because when my waistline gets bigger, so does my weight. If, for some strange reason, as my waistline got bigger my weight decreased (not a likely scenario!), then the two variables would be said to be negatively correlated.

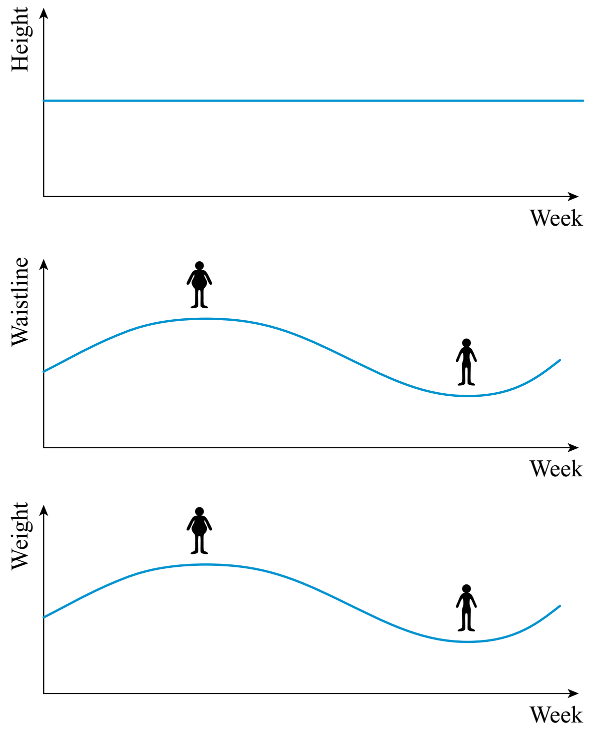


Figure 12 Schematic measurements of height, waistline and weight for the author throughout a year

Because my waistline is correlated to my weight, there is a mathematical relationship between the two variables. So, for example, it might be that when my waistline increased by 2 cm, I was 1 kg heavier. If I just gave you the data for my waistline over a year, and my starting weight, you could derive values for my weight over the whole year. This makes my waistline a proxy for my weight. If I then told you that I tended to eat more over Christmas and exercised a lot in the summer, then you could think it reasonable to add dates to the graphs in Figure 12. My weight and waistline would then be a proxy for the time of year as well.

It is important to understand that correlated variables do not tell you anything about the cause of the observation – they only tell you that the items vary in a particular way. In the example above, clearly the expansion of waistline is not the cause of weight changing – it is the result of it. A more extreme example of this is that the number of people in the British armed forces has decreased since the First World War, and at the same time global atmospheric temperatures have risen. While these two variables are negatively correlated, there is no physical mechanism for one influencing or controlling the other.

So, just because two things are correlated it does not necessarily mean that one causes the other, although in the case of the lead data there is an obvious causal link. What is perhaps not so obvious is that you cannot be sure just by looking at a graph whether two variables are correlated.

To be sure that the observations do show correlation, scientists use formal statistical tests. The details of these are beyond the scope of this course, but they are essential in scientific investigation. In principle, statistical tests use mathematics to tell the likelihood that the results you see occur just by chance. If the mathematics suggest that the results are indeed just chance, you cannot draw any conclusions from them. If, however, the likelihood of it being just a chance relationship is very small, then you can assume that there really is some robust relationship between the two.

To use one item as a proxy for others, you therefore need first to be sure that there really is a correlation, according to accepted scientific standards. Observing a correlation should also lead you to look for a plausible mechanism whereby one item affects the other. In the example of temperature and service personnel given above, such a mechanism is almost totally implausible. Even if the correlation were statistically acceptable, its implausibility would lead a scientist to reject it as being due to chance.

Activity 5 Proxy variables

Allow about 10 minutes

Do the data in Figure 11 suggest that lead production and the concentration of lead in ice cores are correlated, so that one could be used as a proxy for the other?

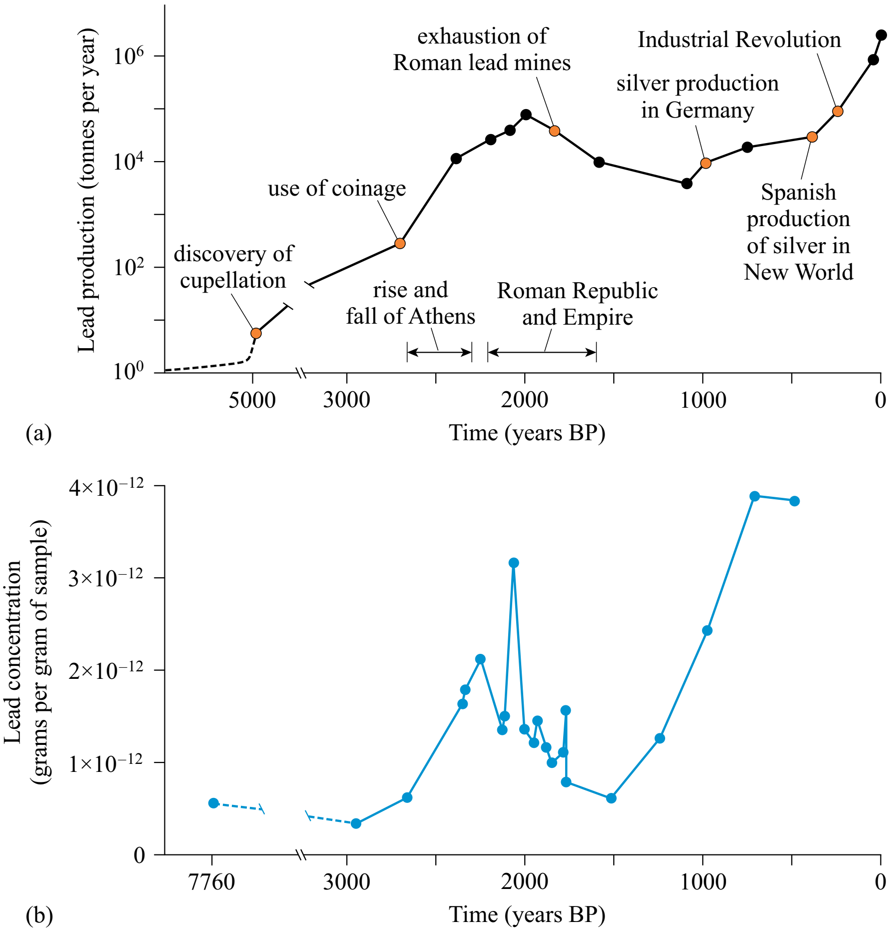


Figure 11 (repeated) (a) Global lead production; (b) the concentration of lead in a Greenland ice core (years before present or 'BP') (adapted from Hong et al., 1994)

Answer

Yes, they do appear to be correlated as the values rise and fall together. There is also a direct physical link between the two items, so it might be acceptable to use one as a proxy for the other.

The example in Activity 5 shows that some measurements can be direct or a proxy, depending on the question of interest. If you wish to know about lead dust concentrations in Greenland ice in the past, you can measure them directly from the lead dust trapped in ice cores. If you wish to know about global lead production in the past, you can try to use measurements of lead concentrations in Greenland ice cores as proxy data, as long as you can estimate the relationship between the two.

3.3 Proxy data and past climates

The process of analysis and checking for plausible mechanisms using proxy data has revolutionised the study of past climates. This is because many parts of the environment respond to climate: they change if the climate becomes warmer, or wetter, and so on. Wherever these changes are preserved, they serve as a record of the past climates.

For example, the thickness of annual layers in an ice core is a simple proxy for moisture in the atmosphere at the time snow fell. This is because more snow forms and falls when the air is more moist. A thicker layer means more snow fell, so the atmosphere must have been wetter to form and hold the increased snow before it fell. A thinner annual snow layer would imply the opposite.

Another type of proxy data from ice cores is the chemical composition of the water itself. Past Antarctic temperatures can be deduced from ice cores. Past temperature records have been constructed entirely from the relative amounts of oxygen-16 and oxygen-18 *isotopes* (see Study note: the central part of an atom). Water molecules in the ice have a proportion of all three isotopes of oxygen in them, and it has been shown that the relative amounts of the different isotopes vary depending on the temperature of the oceans at the time the snow fell. So scientists can measure the amount of oxygen-16 compared with the amount of oxygen-18 in an annual layer of an ice core to derive the temperature at that time. The ratio of the oxygen isotopes is a proxy for the temperature of the planet.

You now know that proxy data measured in ice cores include:

- the concentration of lead, as a proxy for global lead production
- the thickness of annual layers, as a proxy for atmospheric moisture
- the ratio of oxygen isotopes, as a proxy for temperature.

There are also many other types of proxy than those found in ice cores. For example, the types of pollen found in ancient lake and ocean sediments are a proxy for the temperature and rainfall in the area at the time the plants grew.

The great advantage of proxies is that they form a historical record of the planet, surviving from the past and giving information about things that cannot be observed directly. An important disadvantage is that proxy data are less accurate than direct measurements. This is because as well as measuring the proxy variable, scientists need to know the relationship between this and the variable of interest, which is an extra source of error.

The following video sees poet Nick Drake read another of his poems from *The Farewell Glacier*. This one is about ice cores and how they can give a picture of the past. Nick is filmed reading in the ice core laboratory at the British Antarctic Survey, which is kept at a temperature of around minus 20°C.

Video content is not available in this format.

Video 5 The ice core

3.3.1 The central part of an atom

In this study note you will look at the central part of the atom, the nucleus, and isotopes which were discussed in the previous section.

Study note: The central part of an atom

The central part of an atom, which makes up most of its mass, is called the *nucleus*; this is surrounded by an 'electron cloud', which largely determines how the atom reacts with other atoms or molecules. The nucleus of an atom is made up of building blocks called *protons* and *neutrons*. The number of protons determines what element the atom actually is. An atom with one proton is hydrogen, and an atom with eight protons is oxygen.

However, the number of neutrons in the nucleus of an atom can vary. Oxygen exists in its natural state with eight protons and either eight, nine or ten neutrons. Atoms with the same number of protons but different numbers of neutrons are called isotopes. The most abundant oxygen isotope, with eight protons and eight neutrons, is called oxygen-16 (8 protons + 8 neutrons), the oxygen isotope which has eight protons and nine neutrons is oxygen-17 (8 protons + 9 neutrons), and the oxygen isotope which has eight protons and ten neutrons is called oxygen-18 (8 protons + 10 neutrons).

3.4 Ice core going back 800 000 years

Throughout this course so far the focus has been on the Arctic, but because some data from the ice cores tell us about conditions over the entire planet (such as Figure 11), you will now look at data from another core, this time from Antarctica. The Antarctica ice cores go back much further in time than any Greenland ones. The particular core you will look at now is called the EPICA (European Project for Ice Coring in Antarctica) – Dome C core.

Dome C is currently the longest ice core and has snow layers going back almost 800 000 years throughout the Quaternary, and includes the period when *Homo sapiens* evolved. In fact, the EPICA core can be used to reconstruct Antarctic temperatures more than half a million years before *Homo sapiens* ever walked the Earth (Figure 13).

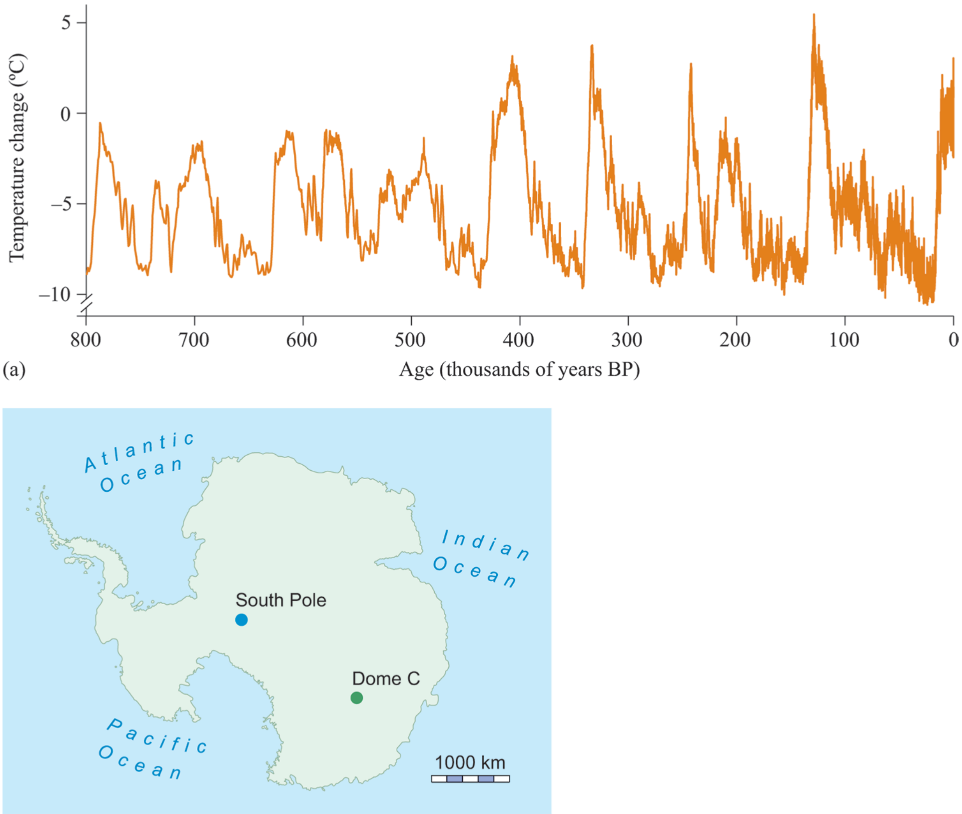


Figure 13 (a) Antarctic temperature changes from the EPICA ice core from 800 000 years before present (BP) up to 1911. The vertical temperature scale has 0 °C for the mean temperature over the past 1000 years, and goes from −10 °C to +5 °C relative to this (Jouzel et al., 2007). (b) Map showing location of Dome C in Antarctica.

Figure 13(a) shows that Antarctic temperatures have varied considerably, but there also appear to be regular cyclical patterns. At the low points, the temperature shown by the core was as much as 10 °C colder than today: colder periods happen about every 100 000 years, with warmer periods between. Four times in the last 450 000 years, the intervening warm periods have been warmer than today (up to 5 °C warmer around 130 000 years ago). During the nine cold periods shown in Figure 13(a), the snow that fell in winter did not melt in the following summer heat, and the ice sheets grew.

3.5 Interglacial periods and sea levels

The EPICA ice core is a record of temperature variations in Antarctica, but what was happening in the rest of the world? Temperatures in other areas varied in a similar pattern of cycles. Other proxy data, such as from sediments found at the bottom of the oceans and lake beds, and the dating of rocks and analysis of ice cores from high-altitude mountain glaciers, show that during the cold periods a large proportion of the northern hemisphere was covered by an ice sheet that was, in places, several kilometres thick. Glaciers advanced, eroding valleys and mountains, and northern hemisphere wildlife moved south to more temperate regions. At the lowest temperatures the ice sheets covered about 10% of the entire planet – up to 30% of all the land. This meant sea levels were very much lower than today, so the area of exposed land was larger. Figure 14 shows how different the ice sheets and coastlines were.

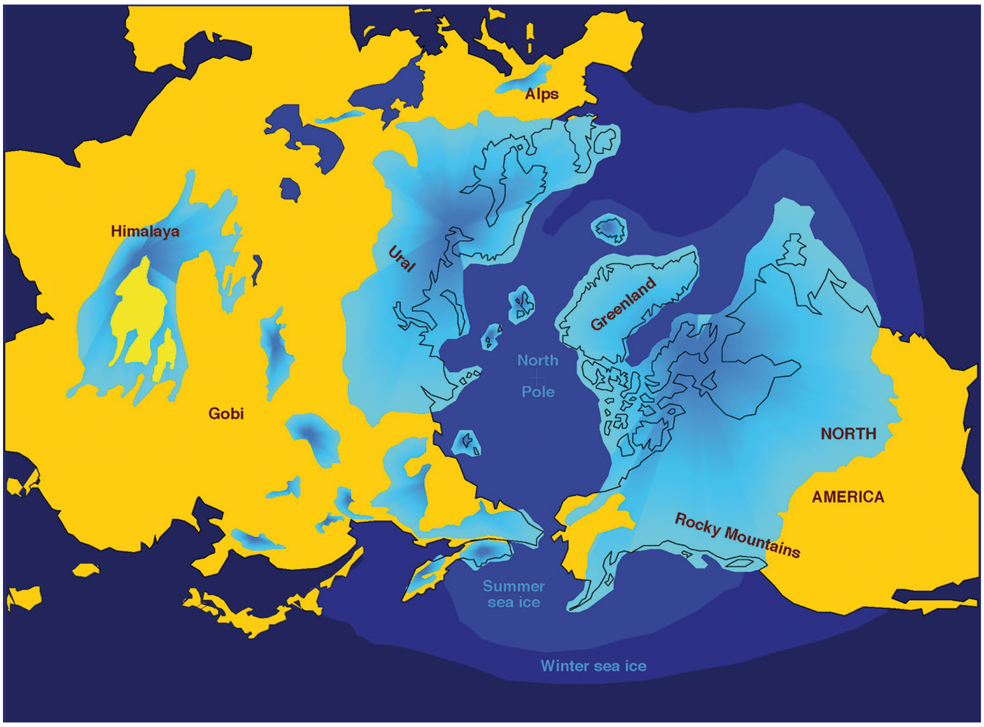


Figure 14 The maximum extent of the ice sheets of the northern hemisphere during the 800 000 years of EPICA ice core data. Oceans are coloured dark blue and continents yellow. Ice is shown as lighter shades of blue.

The sea froze as far south as the northern Spanish coast, and almost all of Britain was buried beneath the ice. These periods are called the ice ages. A vast quantity of water was locked in these ice sheets, so sea level was as much as 120 m lower than today, and there was dry land between Britain and the rest of Europe. During times between these cold periods, the ice sheets melted and the water from land ice meant that sea levels rose. These are called interglacials.

Note that it is only the melting of land ice that changes sea levels: melting sea ice does not change the sea level. Recall that ice is less dense than water, so it floats. As sea ice melts, it forms a smaller volume of water than the volume of ice. In fact, the volume of water formed is exactly the same as the volume of ice that was below the water surface when it was floating, so no change in sea level occurs (Figure 15). Of course, when ice on the land melts and flows into the seas, this does raise sea levels.

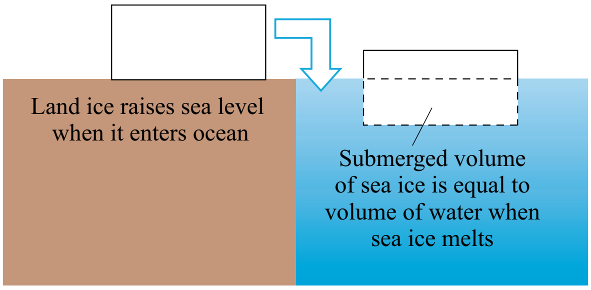


Figure 15 Floating ice does not increase sea level when it melts, because the volume underwater is the same as the volume of water when the whole piece of floating ice melts. Ice on the land does increase sea level when it melts, because it adds new volume to the ocean.

What would happen to the size of the Arctic, as has been defined in this course, during an ice age?

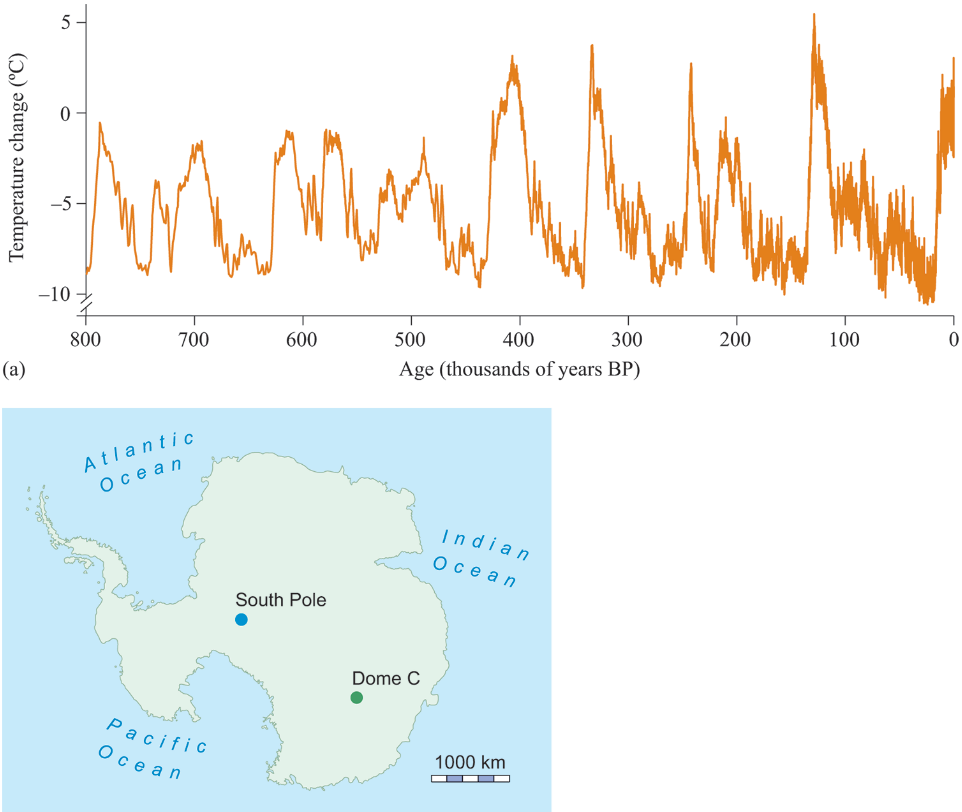
Answer

During an ice age, because the planet was colder and ice covered so much land, the treeline – our proxy for the Arctic definition – was much further south than today. This means that the area of the Arctic would have been much larger than at present.

Activity 6 Rates of change of temperature

Allow about 10 minutes

Look carefully at the Antarctic temperature record in Figure 13(a). Are there any general observations you can make about the rates of change of temperature between the relatively warm and relatively cold periods?



(b)

Figure 13 (repeated) (a) Antarctic temperature changes from the EPICA ice core from 800 000 years before present (BP) up to 1911. The vertical temperature scale has 0 °C for the mean temperature over the past 1000 years, and goes from −10 °C to +5 °C relative to this (Jouzel et al., 2007). (b) Map showing location of Dome C in Antarctica.

Answer

The record in Figure 13(a) shows that the temperatures fall relatively slowly but rise relatively quickly – particularly in the most recent 450 000 years.

Assuming (correctly) that the timing of Antarctic temperature changes is a proxy for the timing of changes in the amount of ice on the planet, the ice sheets in Figure 14 took about 100 000 years to grow, and yet they rapidly decreased in size – typically in only approximately 10 000 years. Consequently, sea levels fall slowly as the ice sheets grow, and rise relatively quickly as they decay again. The obvious question from Figure 13 is what causes these regular fluctuations in temperature and ice cover. One of the most influential is the Milankovitch cycles of the Earth's orbit. You will look at this in more detail next.

3.6 The Milankovitch model

The amount of energy that the Earth receives from the Sun depends on its distance from the Sun. You tend to assume that this is constant, but in fact, the orbit of the Earth around the Sun is an ellipse – with the Sun at one of its foci (Figure 16) – so the distance from the Earth to the Sun varies over the course of an orbit (one year). If the Sun emits a constant amount of energy, then when the Earth is closer it will receive more than when it is further away.

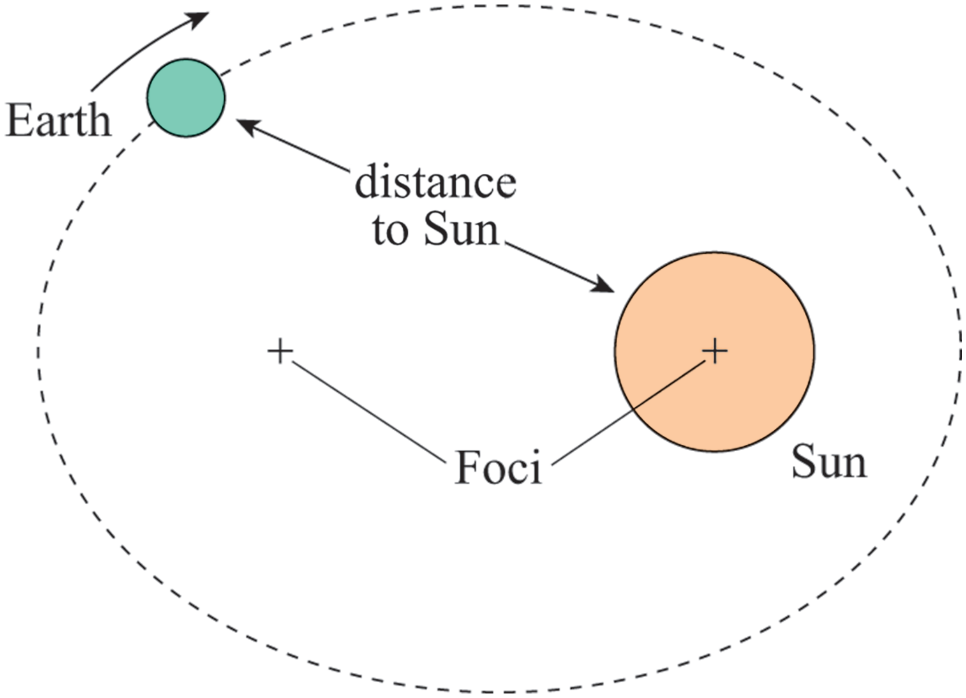


Figure 16 The orbit of the Earth around the Sun is an ellipse, so throughout a year the Earth–Sun distance, and consequently the amount of solar energy received at the surface of the Earth, varies. Note that this picture shows the elliptical shape of the orbit greatly exaggerated.

However, the shape of the ellipse also varies with time, and the Earth's axis of rotation also wobbles, like a gyroscope. The Serbian geophysicist Milutin Milankovitch realised in 1920 that the varying energy received by the Earth as a result of these two factors could be the cause of the ice ages.

Milankovitch showed that the ellipse changes shape over periods of about 100 000 years. The timing of these changes, combined with the wobble in the Earth's rotation, matched up with data he had for the times and durations of the ice ages. He showed that the incoming energy would be at a minimum when there was an ice age and at a maximum during an interglacial.

While his findings are important, modern records go back much further than the data to which Milankovitch had access, and further back in time the match is not so good. Earlier ice ages can be earlier and later than the predictions from the Milankovitch model. Clearly, there are other factors affecting the climate. You will see some of these other factors later in the course, but the differences are still not completely explained.

This story illustrates another aspect of the way that science develops. The Milankovitch model was tested against new data, and found not to be fully consistent with it. The challenge was then for scientists either to completely reject that model, or to look for other effects that could be combined with the basic model to provide a better explanation of the observations. Scientific models are always subject to revision as new data are found.

3.7 The Keeling Curve

The Keeling Curve, illustrated in Figure 17, shows the trend in rising atmospheric CO_2 concentrations since 1958 recorded at Mauna Loa in Hawaii. The story of atmospheric CO_2 in those past 60 years is a relentless rise derived from human use of hydrocarbons: in 2008, the annual mean concentration was 383 parts per million (ppm), and eight years later it reached 400 ppm.

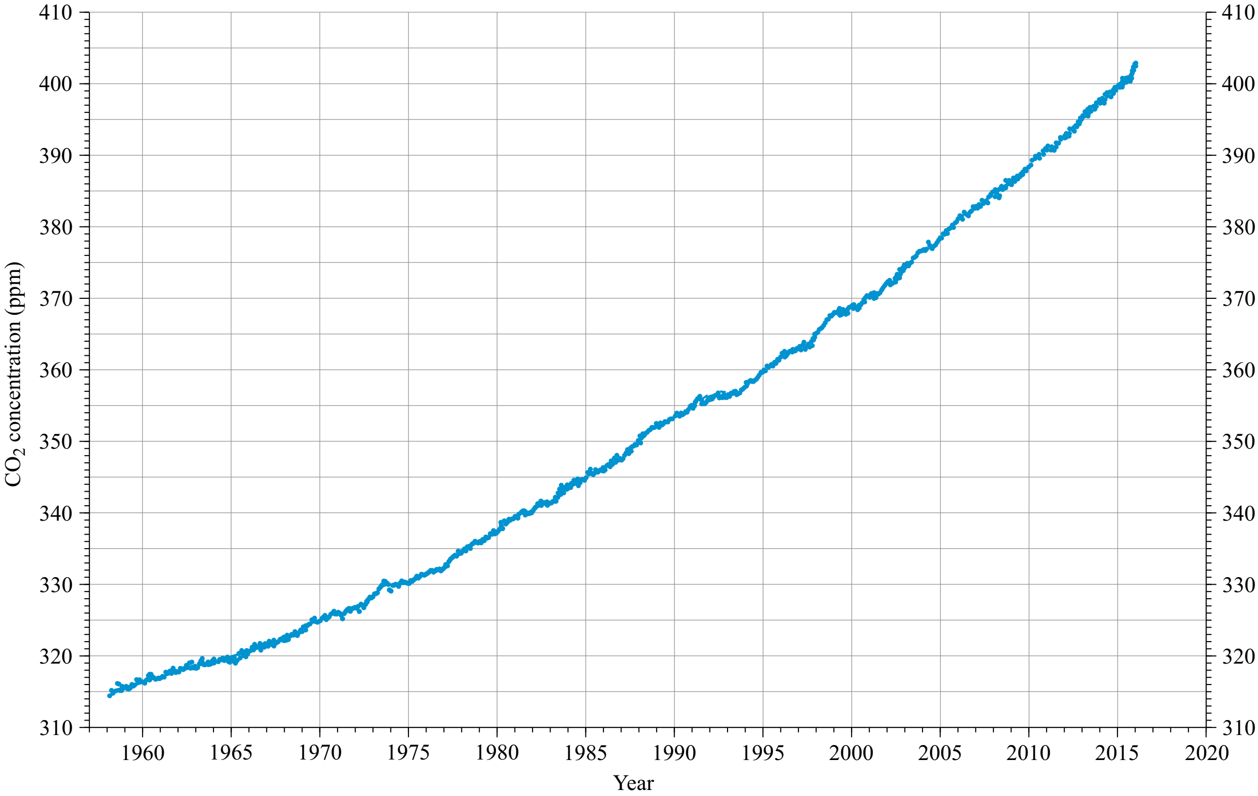


Figure 17 The Keeling curve: measurements from Mauna Loa of the monthly average carbon dioxide (CO_2) concentration in the atmosphere, seasonally adjusted (Scripps, 2016)

When Charles Keeling first collected his CO_2 data, he travelled around making the measurements at widely spaced locations – but he saw that apart from the daily and seasonal variation caused by local plant photosynthesis and respiration, the concentration was virtually the same wherever he measured it. Keeling quickly realised that this meant it was possible to measure the CO_2 in one location, such as Mauna Loa, and it would be a reference point for the whole planet.

Activity 7 How representative is the Keeling Curve?

Allow about 5 minutes

Is Keeling's contention that the Mauna Loa data are a good reference for the whole planet consistent with what you have learned about atmospheric movements?

Discussion

Recall from the discussion of the spread of pollutants by wind (and from your own experience if you live in an exposed area!) that there are constant air movements around the planet. These movements stir up the air and mix it constantly. This constant mixing means that the concentration of CO_2 is likely to be similar all over the globe. This sort of questioning as to whether methods and data are plausible is another good example of scientific method.

3.8 Ice cores and past CO_2 levels

After a few years of measurement, Keeling was the first to discover that CO_2 levels in the atmosphere were rising, rather than emissions being absorbed by the oceans. The problem, of course, with the Keeling CO_2 data is that they extend back only to 1958. However, ice core researchers realised that the air bubbles trapped when the ice was formed would contain atmospheric gas samples. As well as giving a proxy record of past temperatures, ice cores can give the exact atmospheric CO_2 concentration for the last 800 000 years.

Activity 8 Direct and proxy measurements

Allow about 5 minutes

To understand how past atmospheric concentrations of greenhouse gases have changed, are measurements of gas concentrations from an air bubble in an ice core layer a direct or a proxy measurement?

Answer

Measurements of the greenhouse gas concentrations in a trapped gas bubble are direct data, not proxy data, because they are measurements of the actual quantities you wish to know about. It is perhaps surprising that it is direct, because it is a measurement of something that happened in the past! This is possible only because the actual quantity (gas) has been preserved (as bubbles trapped in the ice).

This can be contrasted with, for example, measurements of the ratio of oxygen isotopes in the water, which are proxy data because the ultimate aim is to know the temperature of the planet. Here, only the proxy variable (isotope ratio) has been preserved (in the form of ice), not the temperature itself.

It takes a certain period of time for the bubbles to be closed off and air to be isolated. As a result, it is not possible to measure the concentrations of gases until this has happened. In the case of the Dome C core, the most recent atmospheric CO_2 concentration available is from around 100 years ago.

3.9 Global CO_2 levels and Antarctic temperatures

Figure 18 shows that over the last nine glacial cycles, the global CO_2 and Antarctic temperature appear to be positively and very closely correlated, showing the same patterns of change.

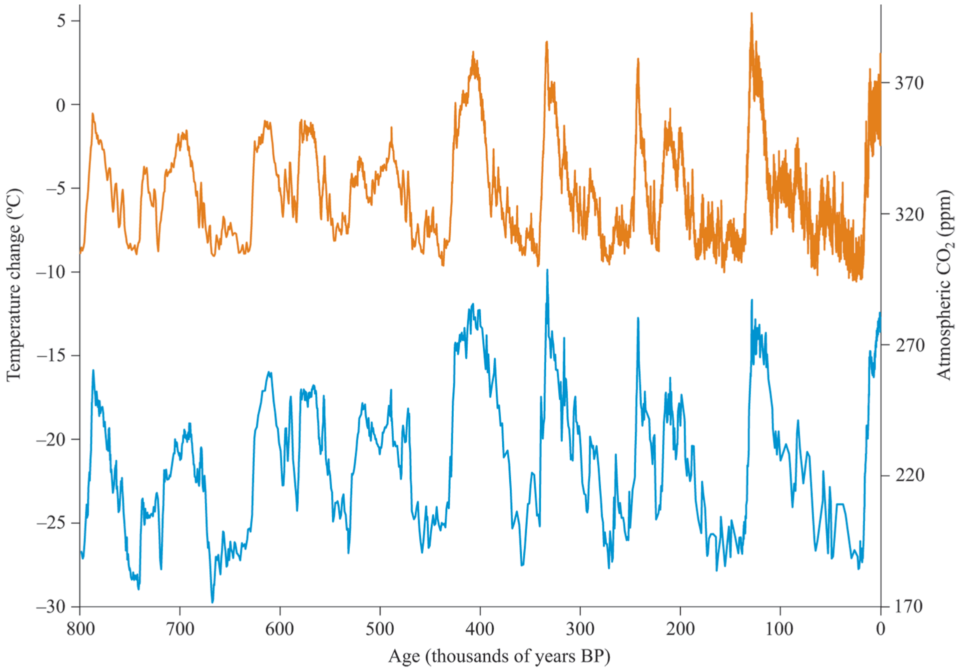


Figure 18 Past Antarctic temperature changes (top) and global atmospheric CO_2 concentrations (bottom) going back through nine ice ages, derived from the EPICA ice core (Luthi et al., 2008)

Activity 9 Temperature and CO_2 values

Allow about 10 minutes

(a) According to Figure 18, what were the typical CO_2 levels during the extreme low-temperature periods (ice ages) and at the height of the warmer interglacials?

(b) How does the value of the atmospheric CO_2 concentration for 2016 (see Figure 17) compare with that in the interglacials of the previous nine cycles of the EPICA Dome C ice core?

Answer

(a) In an ice age, when the temperature is low, the CO_2 is also low, typically 180–200 ppm. When the temperature is highest, in the interglacials, the CO_2 is also high, at about 280 ppm for the most recent four interglacials and slightly lower at 260 ppm for the earliest five interglacials.

(b) The 2015 atmospheric CO_2 concentration is around 400 ppm. This is about 120 ppm higher than in the most recent four interglacials, and about 140 ppm higher than the earliest five interglacials in the EPICA Dome C record.

You now have data that you could possibly use to predict what might happen as a result of the increasing CO_2 concentration that Keeling detected. You could theoretically plot a graph of temperature against CO_2 concentration to highlight the correlation and, from this, read off the temperature for any given CO_2 concentration. Unfortunately, there is a problem with this. The current atmospheric CO_2 concentration is higher than at any time in the previous 800 000 years, so even if you had a graph of the mathematical relationship between temperature and CO_2 concentration from the earlier data, it would not include the current (and much less, any possible future increased) CO_2 concentration. You would have to extrapolate (that is, extend) the graph beyond the available set of values, and you do not know enough from this data alone to be sure that the relationship will hold outside these limits. This means that it is difficult to use information from these earlier periods to predict what may happen in the future.

It is possible to be fairly sure that Milankovitch cycles amplified by greenhouse gases are at least partly responsible for the coming and going of ice ages; it is the best theory and one to which almost all climate scientists subscribe. But as you have seen, it is not a complete explanation, and some of the earlier cycles do not conform to this theory. To make useful predictions for the near future, and hence to suggest actions to protect the environment, you need to look for some more detailed information and more accurate scientific models.

3.9.1 Scientific method

Much of science is concerned with gathering data, so a key part of scientific method involves scientists making observations or measurements about the world, and from these constructing theories about the causes of the observed phenomena. Using these theories or models, the scientist is then able to make predictions as to what might occur in a new but related situation to the ones previously observed. The scientist should then set up or seek such a situation, and test whether the observed behaviour does indeed occur. If it does, then the theory is supported. But if the observations do not accord with the theory, then the theory is either inadequate or possibly completely wrong. So a key part of scientific method is making testable predictions from the data.

The philosopher of science Karl Popper (1902–94) was a major advocate of this approach, and brought in the concept of ‘falsifiability’. In essence, this suggested that a scientific theory would be useful only if it were possible to devise an experiment to test it, whose outcome could be in accord or not with the expectations. The results of such experiments may lead to the theory being rejected, revised, or accepted as possibly true until proved otherwise. Ideally, scientists should strive their hardest to disprove a theory rather than selectively only looking for the evidence that supports it!

The story of Nansen’s expedition in the drifting ice is a spectacular example of scientific method. From the observation that trees from Siberia turned up in Svalbard, he predicted that a ship trapped in the ice would follow the same path. He then proceeded to test this theory in a very practical, but dangerous, way.

The continual attempt to test, and potentially ‘falsify’ (prove to be false), theories is regarded as the essential feature of scientific method that distinguishes it from other approaches. An artist or a journalist may want to present their interpretation of a situation, but this interpretation is often only descriptive, not predictive. Some religions and similar codes make predictions and suggestions about what could or will happen, but these are rarely testable in a way that would be considered scientific.

3.10 Summary of Section 3

The ice cores in Greenland and Antarctica currently provide a direct record of the snowfall going back around 800 000 years. As snow falls, impurities such as lead are trapped in the ice, so ice cores can give direct measurements of past atmospheric concentrations. By using isotope proxies such as oxygen-16 and oxygen-18, ice cores can be used to estimate temperature changes.

Over the time period of the ice cores, the Earth has gone through nine cyclical temperature variations, with a cold period (ice age) approximately every 100 000 years. Trapped gases within the ice cores allow a direct measurement of atmospheric CO_2 concentration, and throughout the entire Dome C record you can see that temperature and CO_2 are positively correlated.

Milankovitch cycles caused by variations in the Earth's orbit, amplified by greenhouse gases, are the best current theory for the cause of ice ages, but these do not provide a sufficiently accurate model to predict the near future course of atmospheric change.

4 The end of the last ice age: the Holocene

As noted earlier, the great ice sheets took about 100 000 years to grow and only about 10 000 years to decay. So what happened at the end of the last ice age? Figure 19 shows the EPICA ice core CO_2 concentration and Antarctic air temperature for the most recent 20 000 years, which is within the last ice age. The temperature scale shows the difference from the average temperature of the last 1000 years, so 0 °C represents no change from (fairly) recent climate.

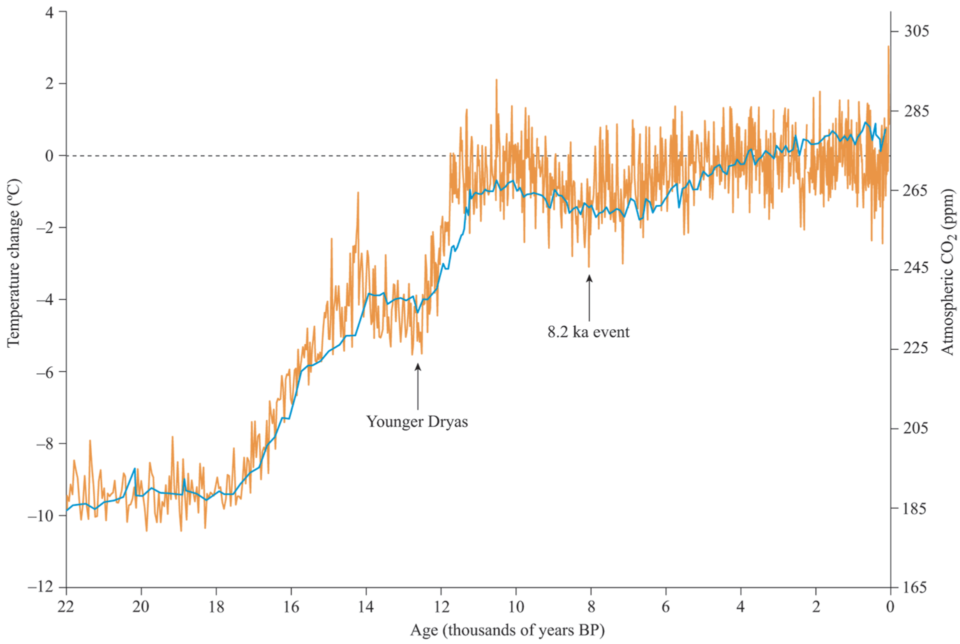


Figure 19 The global atmospheric CO_2 concentration (relatively smooth line) and Antarctic air temperature change (spiky line) from the EPICA ice core over the last 20 000 years up to 1813 (CO_2) and 1911 (temperature)

Figure 19 shows again the high correlation between the two variables: 20 000 years ago it was up to 10 °C colder in Antarctica, and global CO_2 concentration was more than 200 ppm lower than today. Over the most recent 10 000 years the temperature was within about 2 °C of current temperatures, and this climatically stable time period is called the Holocene. Figure 18 shows that such a warm, stable period has been very unusual in the last 800 000 years, yet it is only during the Holocene that agriculture and the civilisations that rely on it have developed. *Homo sapiens* has flourished in the stable climate era.

Figure 19 shows that up to approximately 14 000 years ago the planet appeared to be leaving the ice age, and Antarctic temperatures rose to within 1 °C of the 0 °C line. But then there was a very rapid cooling of 4–5 °C (and most of this in just a couple of decades), and lower temperatures resumed from 12 900 to 11 600 years before the present. This cold period affected most of the planet and is called the Younger Dryas, after a pretty Arctic alpine flowering plant called the white dryas (Figure 20). This species spread its geographical range as temperatures fell and the tundra biome expanded in area.

Figure 20 The white dryas. The Latin name of this flower is Dryas octopetala, meaning 'dryas flower with eight petals' – although it can have up to 16 petals.

Another interesting event shown in Figure 19 happened just before 8000 years ago (called the '8.2 ka event' where 'ka' is an abbreviation meaning 1000 years), when there was a definite but relatively small temperature and CO_2 decrease which was associated with drier conditions in some parts of the world. This represents the largest climatic variation that civilisation has currently had to cope with.

So what happened in the Younger Dryas and 8000 years ago to make the planet suddenly colder? The changes occurred too fast for the Milankovitch cycle to be responsible. It is now believed that the only way to cause that much cooling is by a sudden change in part of the global ocean circulation. Just as there are global patterns of air circulation, so there are also much slower, but enormous, movements of water around the oceans, driven by changes in water temperature and salinity, which you will look at next.

4.1 Wally Broecker's great ocean conveyor belt

The density of fresh water decreases as its temperature rises above 4 °C. The density of salt water in the oceans likewise depends on temperature, but also on the amount of salt within it; saltier water is more dense.

In the seas of the North Atlantic Ocean the surface waters are cooler and therefore denser than the lower layers. In places like the central Pacific Ocean the relatively dry, warm air increases evaporation and the surface waters are both warm and salty. All around the planet different regional climatic conditions create surface waters with different densities.

Because denser waters sink, over time horizontal currents are set up similar to the processes for the winds. The result is a vast, three-dimensional circulation across the entire ocean. In the 1980s, the American climate scientist Wallace Broecker suggested that the global ocean circulation could be viewed as analogous to a conveyor belt that moved heat and salt around the planet. Broecker's schematic picture (Figure 21) has become one of the iconic images of climate science.

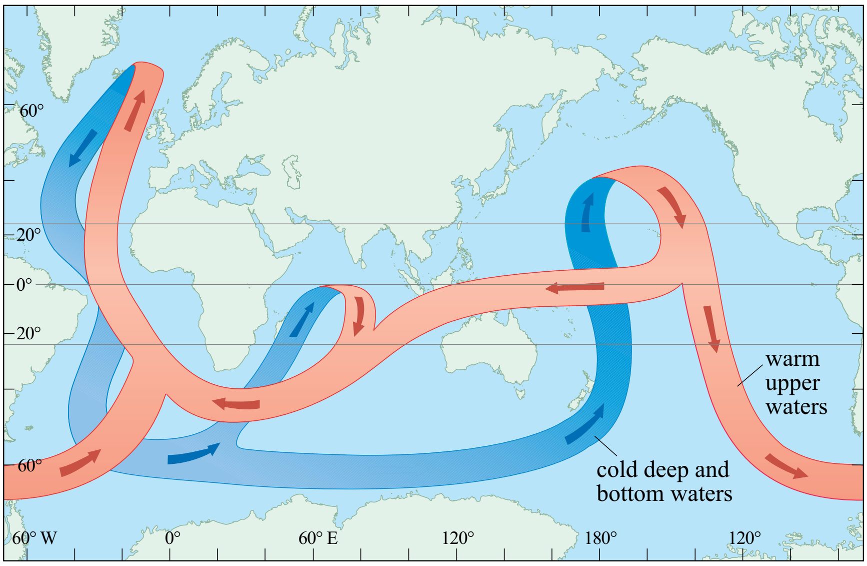


Figure 21 A schematic of the great ocean conveyor that moves both heat and salt around the planet

It is a huge simplification, but on a global scale Broecker's conveyor belt is excellent at helping to understand planetary processes such as the Younger Dryas and the 8.2 ka event.

Heat that is carried in the ocean conveyor past Britain and up the coast of Norway towards Svalbard keeps the UK climate warmer and moister than it would otherwise be and means that the ice edge is a long way north compared with similar latitudes in North America, all year round (Figure 22).

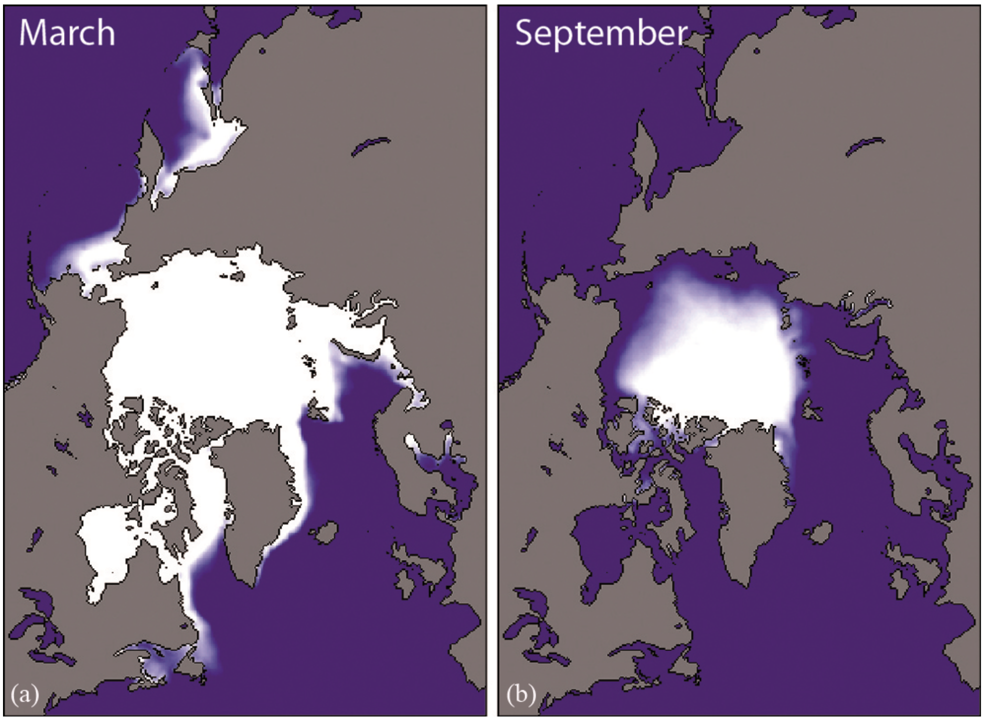


Figure 22 Average Arctic sea ice concentration at the seasonal (a) maximum and (b) minimum from 1981 to 2010

4.2 Stopping the ocean conveyor belt

One way to cool the planet, as occurred in the Younger Dryas or the 8.2 ka event, is to stop the ocean conveyor carrying the heat northwards. It is believed that this indeed happened as a result of large quantities of melt water from the North American continental ice sheets flooding into the North Atlantic and changing the surface density of the ocean. Once the conveyor was stopped, the climate was plunged into a cold period.

Although similar events seem to have occurred further back in time, the Younger Dryas and the 8.2 ka events may have been particularly significant for human civilisation. The earliest dated farming settlements are in the Mediterranean about 13 000 years ago – around the time of the Younger Dryas. It is interesting to compare the spread of these settlements across the Middle East and Europe (Figure 23) with the temperature data of Figure 19.

During the first 5000 years of human agriculture, from 13 ka BP to 8.4 ka BP, farming settlements are concentrated on the shores of the Mediterranean and Black Sea. However, after the 8.2 ka event and the collapse of the North American ice sheets, the flooding of fresh water into the Atlantic that stopped the conveyor also caused a rapid sea-level rise of around 1.4 m and large-scale flooding. After this date, the settlements rapidly spread northwards.

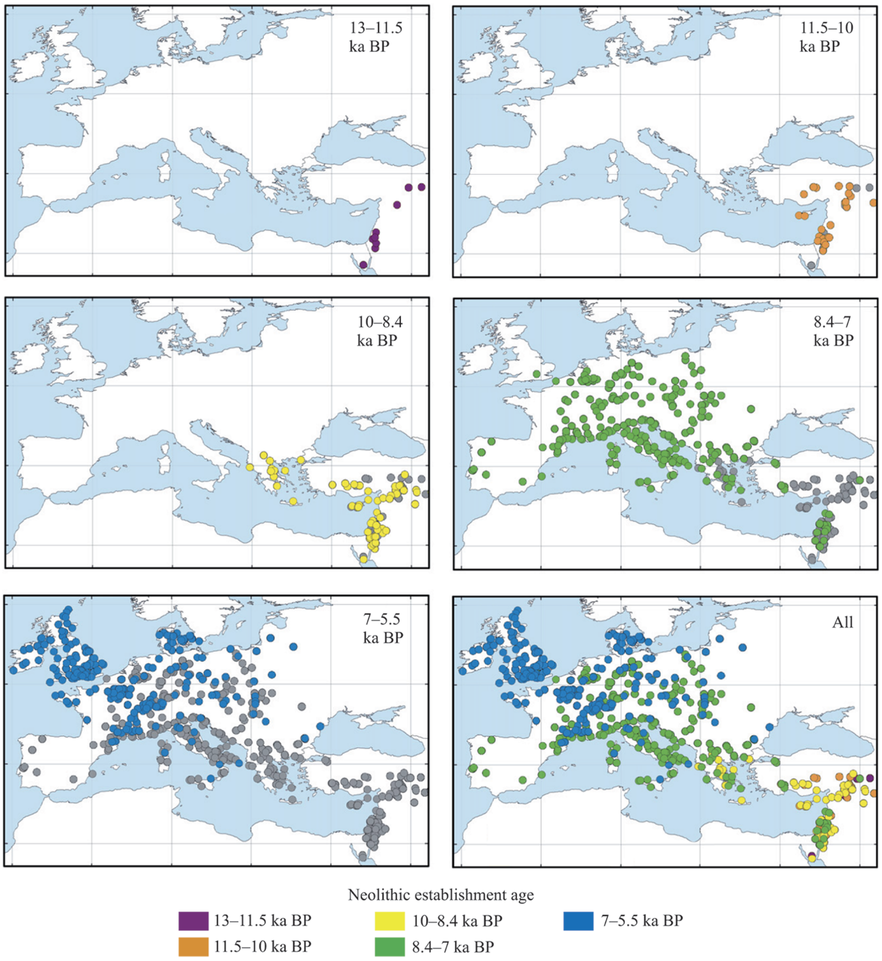


Figure 23 Locations and dates of sites of Neolithic farming settlements across the Middle East and Europe. The coloured dots indicate new sites that were established during each time period; grey dots represent pre-existing sites established during earlier time periods. The final panel shows the full time period (13–5.5 ka BP). (Turney and Brown, 2007)

The exact driving factor for this human migration is impossible to determine, but it is interesting that it seemed to begin after the 8.2 ka climate event. This is an example of the kind of climate change that society will have to cope with.

4.3 Carbon dioxide (CO_2), methane (CH_4) and human activity

In recent decades, the understanding of the reality of climate change has moved from one of slow and gradual change over deep time to clear evidence that there have been naturally-occurring climate changes of several degrees Celsius and sea-level rises of half a metre within timescales of a decade or so (IPCC, 2013). In fact, research by Steffensen et al. (2008) on the Younger Dryas using ice core data revealed that central Greenland cooled by a staggering 2–4 °C in just 1–3 years, around ten times faster than the highest reconstructed rates of warming over the past two centuries (Box et al., 2009).

While the Younger Dryas and the 8.2 ka event were entirely natural, there is an additional human contribution to consider. But when exactly did the human contribution begin? Often the phrase ‘pre-industrial levels’ is used to mean ‘before significant anthropogenic changes started', but it is not specific. Could humans have influenced the climate before the Industrial Revolution of the 18th century?

Another very significant greenhouse gas is methane (CH_4), and 1 cubic metre of methane in the atmosphere can be over 25 times more effective at trapping heat than the same amount of CO_2. Past atmospheric methane concentrations can also be directly measured from ice cores.

Over the last quarter of a million years, CH_4 concentration and the variation of solar radiation reaching the Earth attributed to the Milankovitch cycle are positively correlated (Figure 24(a)). But this correlation dramatically breaks down in the most recent data of the Holocene.

The latest 5000 years of methane data show that the atmospheric concentration has risen dramatically out of synchrony with the solar radiation (Figure 24(b)). Three metres down in the EPICA ice core, dating to the 1820s, methane concentrations are as high as any period in the entire ice core record – approaching 800 ppb (parts per billion). Carbon dioxide has a similar break from the expected downward trend, although starting earlier, at about 8000 years ago.

If the 'normal' trend of methane and carbon dioxide was downwards, along with the Milankovitch cycle, then where have the extra gases come from?

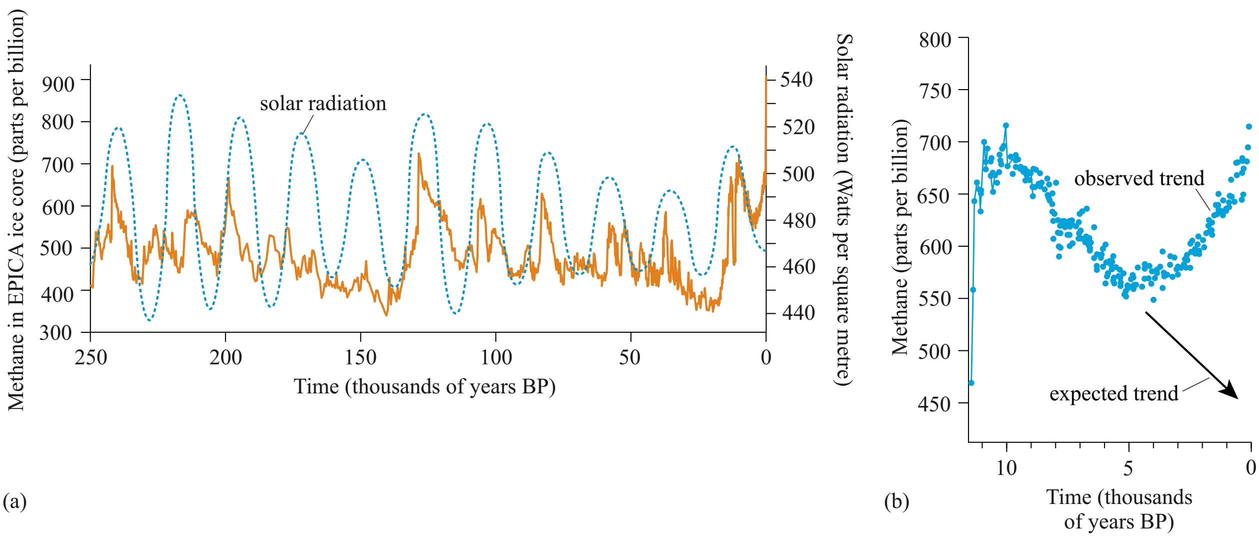


Figure 24 (a) The atmospheric concentration of methane, and changes in solar radiation reaching the Earth's surface due to the Milankovitch cycles; (b) observed and expected atmospheric methane levels over the last 11 000 years up to 1937

Carbon dioxide and methane are by-products of civilisation. You often think of these by-products as beginning with the Industrial Revolution, but their story begins far earlier. In 2003, climate scientist William Ruddiman proposed that society had been altering the levels of these gases – and therefore influencing global climate – for many thousands of years. In his own words:

> Human activities tied to farming – primarily agricultural deforestation and crop irrigation – must have added the extra CO_2 and methane to the atmosphere.
>
> (Ruddiman, 2005, p. 48)

Ruddiman suggests that these activities could have increased atmospheric concentrations by up to around 40 ppm for CO_2 and 300 ppb for methane, increasing the expected natural levels by around 15% and 70% respectively (Ruddiman et al., 2016).

The amounts of CO_2 and methane added to the atmosphere – and therefore the degree to which human activities changed the climate – during the agricultural era are still being debated, but now, of course, the human effect on these gases is clear.

As with CO_2, since the Industrial Revolution the atmospheric concentration of methane has rapidly increased and currently is over 1800 ppb. Virtually all of that rise has been from anthropogenic sources, including major food production activities such as growing rice and cattle. Not only were humans possibly affected by climate change during the Holocene, but the impact by humans on the planet had already been started thousands of years before the Egyptian Pyramids were built. How then are these changes being seen today?

Activity 10 Recent climates

Allow about 10 minutes

How does the Earth's climate over the last 10 000 years compare with that of previous times, and what does this mean for humans in the future?

Answer

Over the last 10 000 years, the Earth's climate appears to have remained in a warm, stable state for longer than was normal in the preceding climate cycles. This has probably been important for humans in that they have been able to develop agriculture and other aspects of civilisation without the major disruption that would be caused by the major rapid cooling associated with ice ages. This means that when the Earth becomes warmer in future, humans may be less well adapted to the climate.

4.4 Summary of Section 4

Since the end of the last ice age, the climate has been uncharacteristically stable compared with the previous 800 000 years of the ice core record. This stable period is called the Holocene. The change from ice age to interglacial was not smooth, and there were two rapid cooling periods: the Younger Dryas and the 8.2 ka event. These are the most significant climate changes that humans have had to endure, and both have been linked to changes in the global ocean circulation. The 8.2 ka event coincided with the start of the spread of human settlement throughout Europe. By 5000 years ago there appears to be evidence of human influence on the composition of the atmosphere.

5 The contemporary Arctic climate

There is a remarkable seasonality in the Arctic climate. For example, the flow in some of the great rivers of Russia and North America that empty into the Arctic Ocean almost stops in winter (Figure 25). During May, ice in the rivers starts to break, and in June there is a rapid flood of fresh water followed by a fall in flow until November, when it freezes.

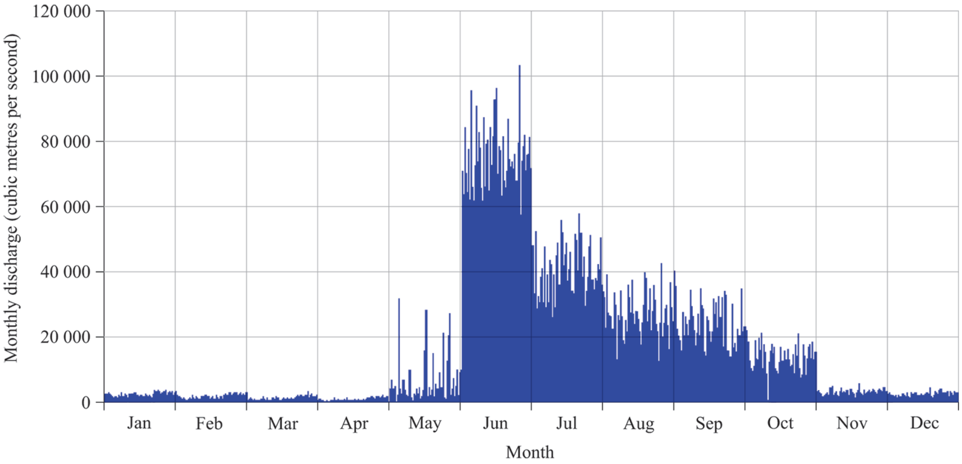


Figure 25 The monthly discharge on the Lena River (Russia). Each individual bar in the graph represents a monthly value for each year during 1935–99.

A similar huge seasonal signal is seen in the Arctic sea ice cover (Figure 22). Most people are surprised to realise that the sea ice of the frozen Arctic Ocean is only a few metres thick. Beneath this are a few kilometres of water. In winter as much as 16 million square kilometres of the ocean freezes, and as this melts in summer, only about 6 million square kilometres remains frozen. The seasonal variation of almost 10 million square kilometres is equivalent to about 45 times the area of the United Kingdom.

The contemporary Arctic climate appears to be changing. However, average global temperatures mask regional variations and the Arctic has been warming faster than the global mean (Figure 26).

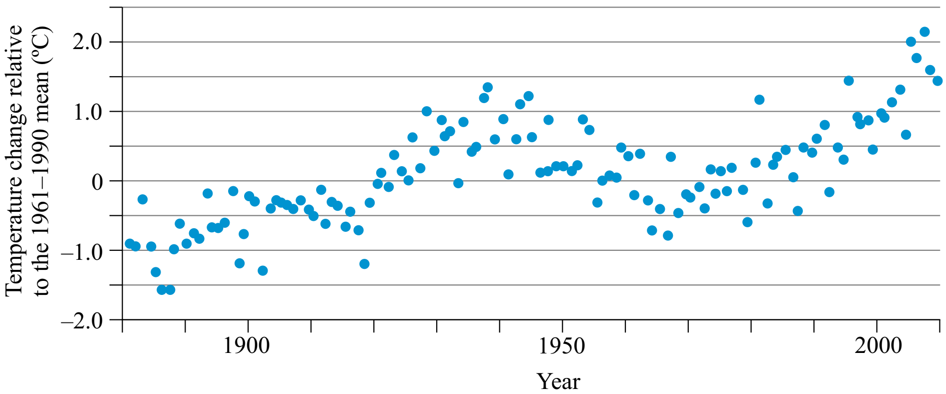


Figure 26 The annual average near surface temperature from all weather stations on land relative to the average for 1961–90 for all regions from 60° N to 90° N (AMAP, 2012)

Activity 11 Recent climate change in the Arctic

Allow about 10 minutes

Describe the changes in Arctic temperature that are shown in Figure 26.

Discussion

With the exception of a period in the 1960s and 1970s, the Arctic land temperature has been above the 1961–90 average in most years since 1920 and reached 2 °C above the 1961–90 average in the early part of the 21st century. These data came from the Arctic Monitoring and Assessment Programme. They appear to use the latitude of 60°

N as their definition of the Arctic, so Figure 26 must include meteorological stations that are not in the Arctic as it has been defined in the course, which are less likely to be affected directly by changing ice and snow cover. For this reason, Figure 26 most likely underestimates the land temperature increase.

Next you will look at the impact of land temperature increases.

5.1 Melting ice caps and sea ice extent

Figure 27 compares the surface melting on the Greenland ice cap in 1992 and 2005 as measured by satellite. For ice to form, the snow has to survive the following summer. But an increasing area of the Greenland ice cap is melting in summer, so annual snow layers are not being converted to ice in these regions.

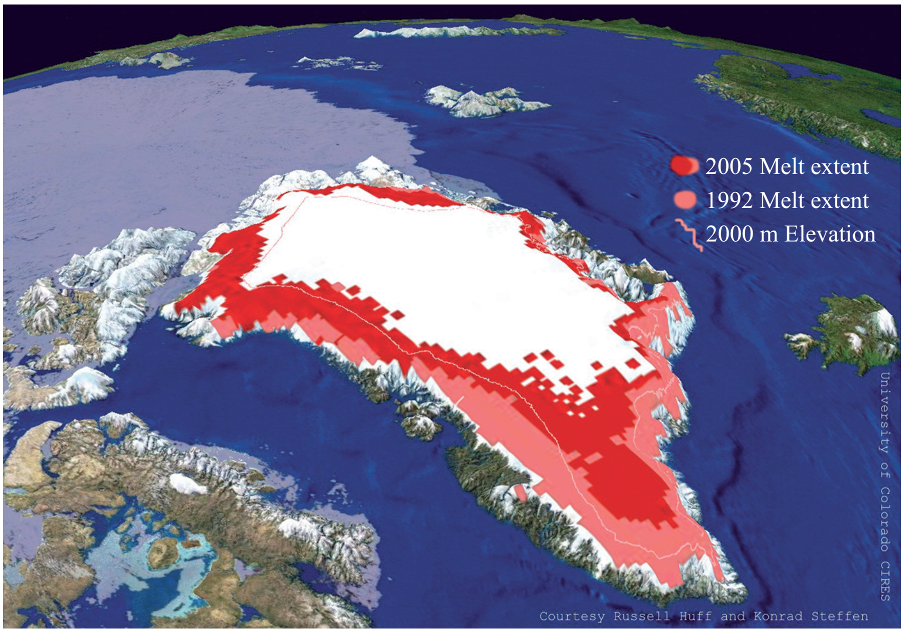


Figure 27 A comparison of the surface melt of the Greenland ice cap in 1992 and 2005

It is an extremely complex process to estimate the melt of the whole ice cap, and the current best value is that Greenland was losing around 160–270 billion tonnes of ice per year in the first decade of the 21st century. All of this melt is contributing to the predicted sea-level rise of around half a metre to a metre by 2100; a rise of a metre could affect around 150 million people worldwide (Anthoff et al., 2006).

These impacts are primarily through increased flooding, rather than widespread loss of land: note the sea level changes predicted for this century are 10–20 times smaller than those of the much longer ice age cycles. The fresh water from the Greenland ice sheet could also slow Broecker's conveyor (Section 4.1), causing other climate impacts.

For the Arctic sea ice, the signal of climate change is clear: it is getting thinner and the amount of it that survives the summer is reducing. Figure 28 shows the trend in extent of sea ice in September each year from 1979–2016 (the summer minimum, of which the median for 1981–2010 is shown as a pink line in Figure 29). The sea ice minimum is decreasing at a rate of approximately 90 000 square kilometres each year. Near the start of the observations, in 1980, the September ice area was around 7.9 million square kilometres (white area in Figure 29(a)). In 2012, the September ice area was less than half this (3.6 million square kilometres, Figure 29(b)), though in subsequent years it recovered to some extent.

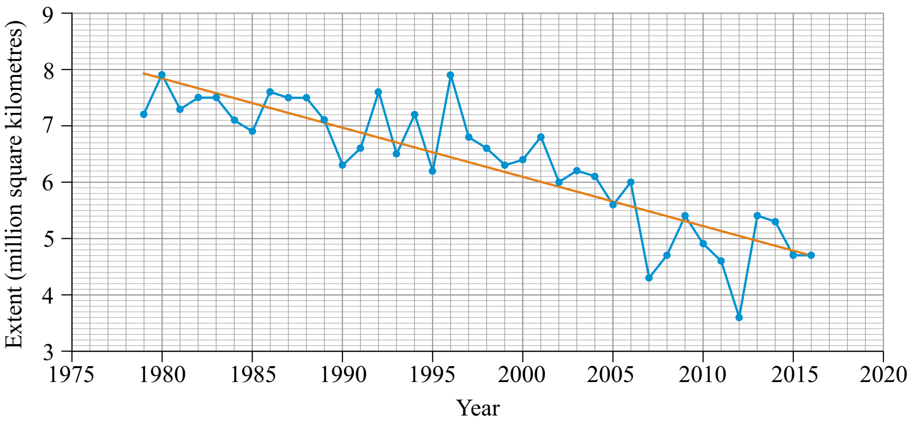


Figure 28 The minimum extent of Arctic sea ice in September of each year from 1979–2016

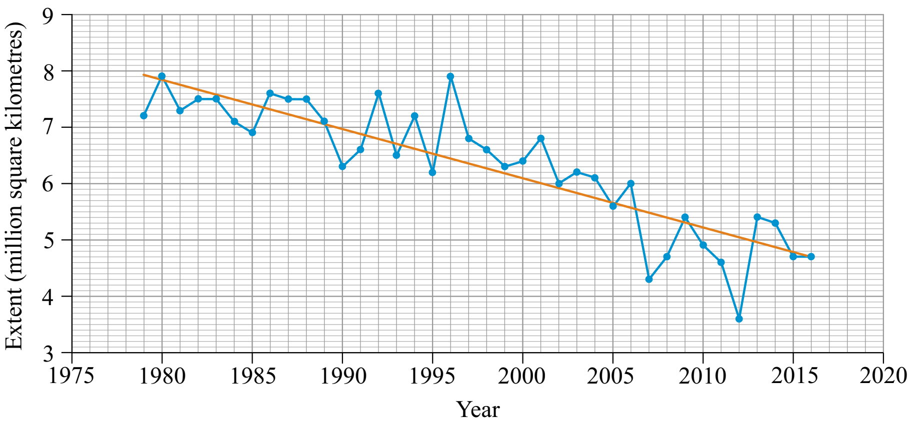


Figure 29 Arctic sea ice extent in September: (a) 1980; (b) 2012. These years have been selected to show the largest observed changes. The median September sea ice extent from 1981–2010 is shown as a pink line.

5.1.1 Gradient of a straight-line graph

In this study note you will learn how to calculate the gradient of a straight-line graph.

Study note: Gradient of a straight-line graph

Figure 28 shows a general trend of Arctic sea ice decreasing with time, though the annual fluctuations can be quite large. To measure this trend, a 'best fit' line is constructed as shown on the graph. This is drawn so that approximately the same number of data points lie above and below the line, but where there are significant fluctuations (as here) it may not pass through many or indeed any of these original points.

The average rate of change of ice extent can be deduced by measuring the slope or gradient of this straight line on the graph. To do this, take two convenient points on the line and read off the values on each axis. These points should ideally be widely spaced (to improve accuracy) and will not necessarily correspond to original data points.

In this example, the years 1980 and 2009 have been chosen, and the corresponding values on the vertical scale for the ice extent (according to the best fit line) are 7.8 and 5.3 million square kilometres.

So the time interval is (2009 – 1980) years = 29 years.

Change of ice cover is (5.3 – 7.8) million km^2 = –2.5 million km^2.

(*Note*: the minus sign denotes a negative change, in other words a decrease.)

$$\begin{aligned}\text{Rate of change} &= \text{gradient}\\ &= 2/5\text{million km}^2/29\text{ years}\\ &= -0.09\ \text{million km}^2\text{ per year}\end{aligned}$$

This is easier to interpret if you convert millions to thousands (multiply by 1000), giving a mean rate of decrease of 90 000 km^2 per year.

This is the standard method for calculating the gradient of any straight-line graph, often summarised by the formula

gradient = rise / run

where the rise and the run are measured respectively from the change in values on the vertical and horizontal axis scales of the graph for the two chosen points.

5.2 Ice-albedo feedback loop

You have learned that the Earth's albedo refers to the proportion of solar energy that reaches the Earth's surface and is reflected straight back out into space. Section 2.1 explained how different surfaces on the Earth have a different albedo and so reflect a different amount of solar energy. Ice has a much higher albedo, and so reflects a much greater amount of solar energy, than the surface of the oceans.

Activity 12 The changing mean albedo

Allow about 10 minutes

What is likely to be the effect of these changes in ice cover on the albedo of the Arctic region?

Discussion

Recall from Table 1 that the albedo of open water is 3% and that of sea ice is 40%. So the increased thawing during summer will decrease the albedo, so that less energy will be reflected back into space, and more energy will be absorbed.

The effect on the albedo is actually more complex than suggested by Activity 12, but this ice–albedo feedback loop (Figure 30(b)) is potentially very important. Table 1 gives the average albedo of sea ice as approximately 40%. Sea ice is not uniform, and it could consist of a mixture of bare ice, ice with snow on (the snow could be either wet or dry) or even ponds of fresh water on the ice as it melts, and each one of these types has a different albedo.

As temperatures rise there will be more bare ice, melt ponds and open water, and the overall albedo will decrease. This means that less energy will be reflected, so more solar energy is absorbed by the ocean, causing further warming and ice melting. The ice–ocean system is in a positive feedback loop, and changes such as melting ice naturally lead to more melting ice.

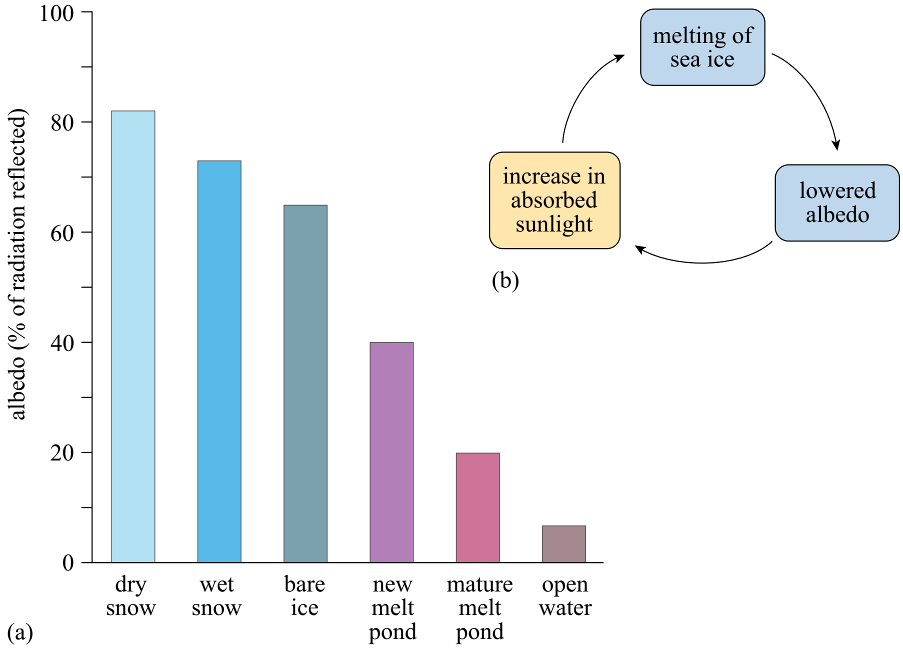


Figure 30 (a) Graph of the albedo of various ice categories and open water; (b) the ice albedo feedback look – an increase in absorbed sunlight leads to ice melting which lowers the albedo, causing more sunlight to be absorbed

5.2.1 Positive and negative feedback

'Feedback' is the term used to describe the situation where the output from a process affects the input to that process. You may have encountered the 'howl' that can occur when a microphone is placed too near a loudspeaker; the sound from the loudspeaker feeds back to the microphone, gets amplified and is fed back again so that the volume of sound keeps on increasing until the amplifier overloads. This is an example of positive feedback.

Populations of organisms can exhibit the same effect. If one generation produces more than one surviving offspring per adult, there are more organisms to produce young in the next generation, who produce more young in the next, and so on. This leads to a population explosion. Economic growth is supposed to work the same way – increased wealth this year allows us to spend and invest to produce more wealth next year, with this continuing year after year.

Of course, the sound from the loudspeaker cannot get louder and louder forever, populations of organisms don't actually go on expanding forever, and whatever economists may say, economic growth is unlikely to continue unchecked. The sound from the speaker is limited by the power available to the amplifier, and populations can be limited by their food supply. These limits can either have an effect like running into a brick wall, or be more subtle.

The subtler version is the phenomenon of negative feedback, where an increase in the output from the process causes the process itself to 'slow down', so that output returns to a lower level. A room thermostat is a classic example. If the room warms too much, the thermostat reduces the central heating output to let the room cool to the correct temperature. Populations offer another negative feedback situation. When there are more organisms present, there is likely to be less food available per individual (or the increased population may attract more predators), so that the rate of production of young decreases (or the rate of mortality increases) and the population tends to stabilise. Negative feedback is a fundamental concept in the control of machinery and electronic devices, and there are many other examples from ecosystems.

Note that the popular uses of 'positive feedback' and 'negative feedback' are praise and criticism, but the scientific meanings are not inherently 'good' or 'bad'.

5.3 Permafrost

Climate models suggest that, given the predictions of Arctic warming, the sea ice could disappear completely in summer by the middle of the 21st century. Given this and the changes you have observed in this course, you could not put the current situation any better than this:

> With sharply rising atmospheric greenhouse gas concentrations, the change to a seasonally ice-free Arctic Ocean seems inevitable. The only question is how fast we get there. The emerging view is that if we're still waiting for the rapid slide towards this ice-free state, we won't be waiting much longer.
>
> (Serreze and Stroeve, 2008, p. 143)

The extent of snow cover in the northern hemisphere is decreasing in a similar way in another positive feedback loop, but what about the frozen ground beneath the snow that is called permafrost? Most of the global permafrost is in the Arctic and high mountain areas (Figure 31), and many cities use the frozen ground as foundations for building – and even for temporary roads in winter.

Figure 31 The permafrost distribution in the northern hemisphere. The largest area of continuous permafrost is in the Arctic and high mountain areas.

It should be expected that the area of permafrost will decrease, but it is difficult to measure. Virtually all boreholes into the permafrost show that Arctic warming (Figure 26) is penetrating into the ground. While frozen, permafrost provides a solid surface – a vehicle will leave no trace. As the permafrost melts, the situation is different. The State of Alaska has strict rules for vehicle travel on permafrost to prevent environmental damage. When it is too warm, travel is not allowed. The duration of allowed permafrost travel set by the Alaska Department of Natural Resources is an interesting climate change proxy (Figure 32)!

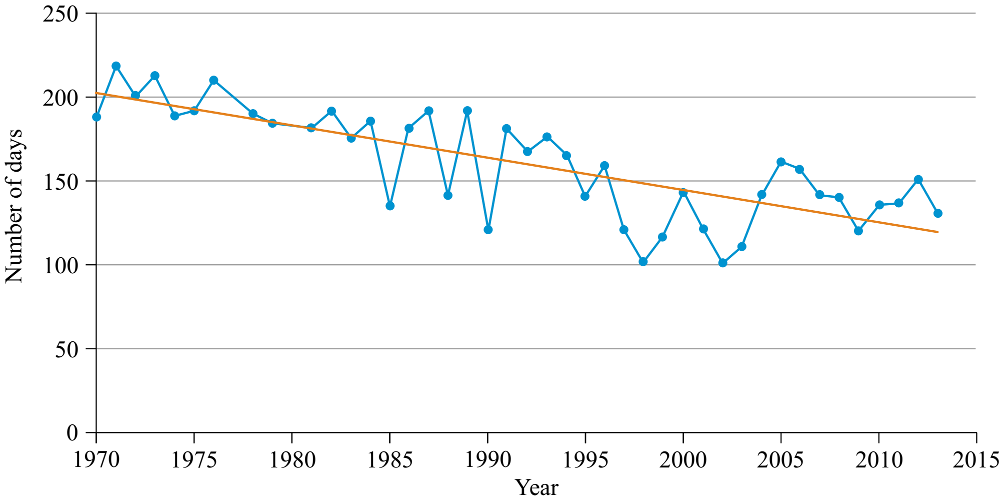


Figure 32 The annual duration of allowed winter tunda travel days set by the Alaska Department of Natural Resources, from 1970 to 2013

5.4 Permafrost and tundra travel days

The retreat of the permafrost is serious. Building foundations are collapsing, and there are 'drunken forests' as land beneath trees melts, subsides and slumps. Buildings require carefully built foundations, and the Trans-Alaska Pipeline was even designed with refrigerated pillars to prevent pipe fracture through permafrost thaw subsidence.

Activity 13 Tundra travel days

Allow about 10 minutes

Figure 31 (repeated below) shows the number of days on which travel has been allowed on the tundra (land with underlying permafrost is known as tundra). The best fit line has a value of 203 days in 1970 and 120 days in 2013. Estimate the average rate of change in the number of days over this period, to the nearest whole day per year.

Figure 31 (repeated) The permafrost distribution in the northern hemisphere. The largest area of continuous permafrost is in the Arctic and high mountain areas.

Answer

$$\begin{aligned}
\text{Rate of change in number of days} &= \frac{\text{change in number of days}}{\text{time interval}} \\
&= \frac{(120\text{–}203)\ \text{days}}{2013\text{–}1970\ \text{years}} \\
&= \frac{-83}{43} \\
&= 2\ \text{days yr}^{-1}
\end{aligned}$$

The number of days on which travel has been allowed on the tundra has decreased by an average rate of 2 days per year from 1970–2013.

There is, however, another more worrying problem as the permafrost retreats. As the ground subsides, the depressions usually form lakes because the melt water cannot flow through the frozen ground beneath. Thawing of the permafrost at the lake bottom releases organic matter that is perhaps 30 000–40 000 years old into the water. The organic matter decomposes, giving off methane – a potent global warming gas (Figure 33). The permafrost–methane feedback cycle is another positive feedback in the system.

Figure 33 Researcher Katey Walter Anthony ignites trapped methane from under the ice in a pond on the University of Alaska, Fairbanks campus

5.5 Methane trapped in ice

Another potentially significant source of methane in the Arctic is trapped in the shallow seabed of the Arctic Ocean and is called methane clathrate (Figure 34). A clathrate is a lattice that contains other molecules, and methane clathrate is ice that has methane trapped within the crystal matrix. As the ocean warms, the release of large quantities of methane into the atmosphere from clathrates would be yet another positive feedback. This has been called the ‘clathrate gun hypothesis’ and it could lead to a strong amplification of the greenhouse effect that may have happened before in deep time. It could even have been responsible for previous mass animal extinctions.

Figure 34 Burning methane released from methane clathrate

Currently, it is thought that some methane is indeed being released from clathrates due to climate change, but also that it is very unlikely that there will be a catastrophic release in the 21st century. However, it could be a substantial effect over the following hundreds to thousands of years.

Activity 14 Arctic feedbacks

Allow about 10 minutes

What is the particular importance of feedback processes in the context of climate, particularly with respect to the Arctic?

Answer

There are probably many positive and negative feedback processes associated with climate, but in the Arctic, changes in ice cover are a particularly good example of positive feedback, as is the role of methane. Reduction of ice cover changes the albedo so that more heat is absorbed, warming the water and reducing ice cover still further. As the permafrost melts, it may release methane, a powerful greenhouse gas, potentially raising global temperature and causing further melting of permafrost and release of methane. On the other hand, the possible effect of ice melt on the ocean currents could provide a form of negative feedback. If the warm current flowing north past north-west Europe were to cease, then this would produce a major cooling effect. Currently, it is thought that this would not completely compensate for the warming, at least in the 21st century, but this is an interesting open question.

It is ironic that anthropogenic climate change driving sea ice and permafrost retreat means that more oil, coal and gas fields are becoming accessible.

5.6 The Arctic and our environment

As you approach the end of this course, you will return to the same topic that you began with: *Ursus maritimus* – the sea bear. Figure 1 showed some areas used by polar bears, and computer models can predict the effects of anthropogenic climate change on these areas. The story is complex, but the message is stark and clear. The bear sea ice habitats will decrease in extent in the future. It may soon be possible to see bears in their natural habitat only in northern Greenland and the Canadian archipelago. Whether you believe this is an issue of concern depends on your values and your political opinions.

The evidence of change is too clear to ignore. You may decide that a region as remote as the Arctic is not relevant. But the positive feedbacks and global environmental flows mean that the Arctic will not only be affected by climate change but will also be a source for some of the changes that humans may have to adapt to, such as rising sea levels from the melting Greenland ice cap and amplification of global warming. It is therefore more than just a barometer of global change – it is key to shaping the environment.

To be more literary, the Jacobean poet John Donne wrote in the 17th century, before the Arctic was mapped:

> No man is an island, entire of itself; every man is a piece of the continent, a part of the main … never send to know for whom the bell tolls; it tolls for thee.
>
> (Donne, 1624)

5.7 Summary of Section 5

The Arctic climate is strongly seasonal, and many processes such as river flow virtually stop in winter. However, the region is warming and this is affecting many aspects of the local and global environment. The area of the Greenland ice cap that is melting is increasing, and the melt water is contributing to global sea-level rise. The amount of sea ice in summer is consistently decreasing due to increasing temperatures amplified by the positive ice–albedo feedback loop. A summer ice-free Arctic is almost certain, and the only question is how soon it will be. The permafrost is in all probability retreating in extent, causing problems both for humans and for the natural environment. An additional consequence is that the permafrost is releasing methane which, through a positive feedback mechanism, may further amplify the greenhouse effect.

Conclusion

This free course, *Environment: understanding atmospheric and ocean flows*, has presented evidence showing that even apparently remote regions on Earth are intimately connected through physical processes. For example, once an organic POP is transported to the poles, biological processes can take over and through bioaccumulation perhaps cause harm. But this physical connection has allowed the ice to preserve unique proxy records of the past climate of our planet.

Directly measuring the gases trapped in the ice has enabled histories of past atmospheric CO_2 and methane concentrations to be compiled, and it is now known that the current atmospheric CO_2 concentration is higher than at any time in the last million years.

It is remarkable to think that agricultural history has been established only over the last 10 000 years or so, when the ice cores show that the climate has been uncharacteristically stable. However, humans are likely to have been affecting the climate for at least half of that time, and the Arctic is now warming at a higher rate than almost all of the rest of the planet. Observations show that there are already significant regional changes that humans and animals will have to adapt to. Through feedback processes these regional changes will affect us all.

This OpenLearn course is an adapted extract from the Open University course U116 *Environment: journeys through a changing world*.

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