CHAPTER

6 Glaciers and ice sheets

Glacial ice moving across the surface of the land has created some spectacular landscapes and landforms. Currently, 10 per cent of Earth's land area is under glacial ice. During the last ice age, glacial ice covered 32 per cent of Earth's surface, drastically reshaping and changing the land beneath.

Historically, such transformations were slow. Today, the extent and rate of glacier and ice sheet retreat has increased due to climate change. Understanding glaciers and ice sheets means understanding that they are open systems interacting with other global systems.

This chapter investigates the power of glacial ice to transform the land surface. Though mainly found in remote places, these frozen landscapes are greatly impacted by human interruptions of natural systems. The alarming rate at which glaciers and ice sheets are melting poses significant consequences for the immediate environment. At scale, large glacial ice losses will have a global impact.

> **'Where the glacier meets the sky, the land ceases to be earthly, and Earth becomes one with the heavens; no sorrow lives there anymore, and therefore joy is not necessary; beauty alone reigns there, beyond all demands.'**
>
> **Halldór Laxness, Icelandic poet**

6.0.1 Ice falls off a glacier into the sea in Alaska, USA.

Chapter glossary

ablation the process of a glacier or ice sheet losing more ice mass than it accumulates

benthic invertebrates organisms without a backbone that live in the sediment at the bottom of a water body

calving the process of chunks of ice breaking away from a glacier to become icebergs

cirque a deep, rounded hollow with steep sides found in a mountain valley head that has been eroded by a glacier

cryoconite dark dust or airborne sediment composed of dust, pulverised rock particles from volcanic eruptions, soot from fires and particulates from diesel engines and coal-fired power stations

cryospheric relating to the cryosphere, the parts of Earth's surface where water is frozen in solid form, including glaciers, ice sheets, ice caps, sea ice, lake ice, river ice, snow cover, and frozen ground

glacial abrasion where the glacial ice and the rocks it carries grind and scrape against a valley's sides or the bedrock underneath

glacial accumulation the zone of a glacier in which the amount of snow deposited exceeds the ice lost

glacial lake a body of water filling a void or depression previously occupied by glacial ice, within a cirque or dammed by the terminal moraine of a retreating glacier

glacial lake outburst flood a catastrophic discharge of water where all the water from a glacial lake rushes down a mountain when the terminal moraine holding it back is breached

glacial plucking where the moving ice of a glacier lifts out and removes angular blocks of rock, which are then embedded in the ice and move with it

glacial trough a long, U-shaped valley that was carved out by a valley glacier that has since disappeared; a trough tends to have high, steep, straight sides and a flat valley floor

heavy fuel oil the residual fuel oil remaining after crude oil has been stripped of its more valuable components in the oil refining process

moraine a deposit of soil or rock carried and left by a glacier

moulin a vertical shaft or hole worn in a glacier by meltwater falling through a crack in the ice

mountain glacier glaciers that originate in high alpine areas and form in cirques; also called alpine or cirque glaciers

peak water the tipping point of glacier melt supply when run-off in glacier-fed rivers reaches its maximum due to accelerated melting; after peak water, water flow will diminish as glacial storage has been depleted

permafrost a subsurface layer of soil that remains frozen throughout the year, mostly found in polar regions

retreat when a glacier or ice sheet reduces in size because ice melts or ablates more quickly than it accumulates

terminal moraine a rubbly heap of debris dropped at the snout or lowest end of a glacier

tidewater glacier valley glaciers that flow far enough to reach out into the sea

valley glacier glaciers that originate in the snowfields of high mountain ranges and flow through steep walled valleys

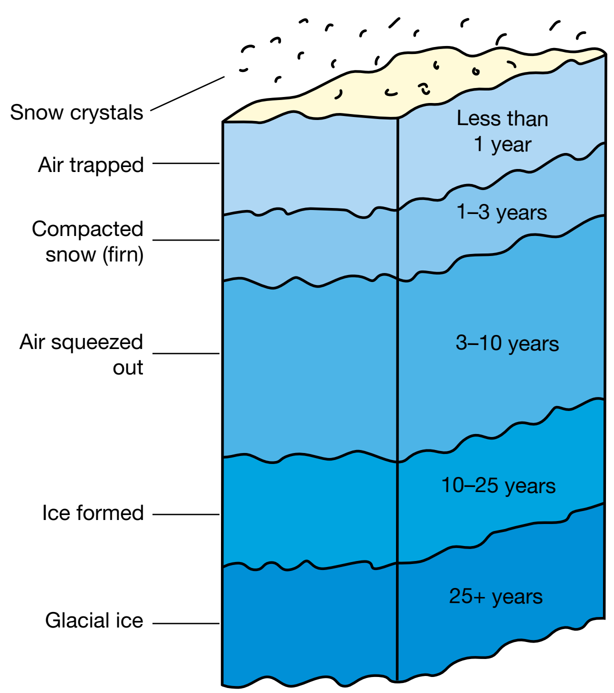
UNIT 6.1

The power of glacial ice

A glacier is a system of flowing ice that moves under the force of gravity. It originates on land through the **accumulation** and recrystallisation of snow. Glacial ice is a potent agent of erosion and drastically alters the land it covers. Glaciers carry immense weight, scouring soil and rock material in their path and transporting debris, depositing it far from its original site.

The source of glacial ice: The snowfields

Glaciers form in the world's coldest areas in high altitudes or high latitudes, where more snow accumulates each year than melts. Newly fallen snowflakes are light and loose, but as the snow accumulates it compacts and has fewer air spaces. Eventually, under the weight of more than 24 metres of snow, compaction leads to glacial ice forming (see Figure 6.1.1).



6.1.1 The transformation of snow crystals into glacial ice

Over time, the ice mass builds until it is thick enough to flow under its own weight, pulled by gravity. The weight of accumulated ice deforms ice crystals, making them slippery. Most glaciers creep just 25 centimetres daily, but in Antarctica, some move less than a metre a year. A few surge at speed, including Greenland's Jakobshavn Glacier, generally considered the fastest glacier in the world, able to cover up to 45 metres per day.

Types of glaciers

The principal types of glaciers are **mountain glaciers**, **valley glaciers**, **tidewater glaciers** and ice sheets (or ice caps and icefields).

Mountain glaciers

Mountain glaciers develop in high mountainous regions, often flowing out of icefields and spanning several peaks or entire mountain ranges (see Figure 6.1.2). They form in small bowls with steep sides called **cirques**. They are also known as cirque glaciers. They terminate before they reach the sea. The largest mountain glaciers are found in Arctic Canada, Alaska, the Andes and the Himalayas.

6.1.2 The Gorner Glacier, Zermatt, Switzerland

Valley glaciers

Valley glaciers originate in the snowfields of high mountain ranges. They are typically long and narrow, occupying previously formed valleys. Such glaciers carry the ice to lower elevations where warmer temperatures melt it. They terminate on land. Their distinctive landform features are visible in Figure 6.1.3. Mountain and valley glaciers are **retreating** at faster rates as a result of global warming.

Tidewater glaciers

Tidewater glaciers are valley glaciers that flow far enough to reach into the sea (see Figure 6.1.4). Tidewater glaciers are responsible for **calving** icebergs. Due to variations in precipitation, they undergo periods of advance and retreat. The general trend now is retreat, due to rising global temperatures.

Ice sheets

Ice sheets form in the polar regions where prevailing temperatures are low enough for ice to accumulate. Over thousands of years, layers of snow build up, forming a mound of ice that thickens

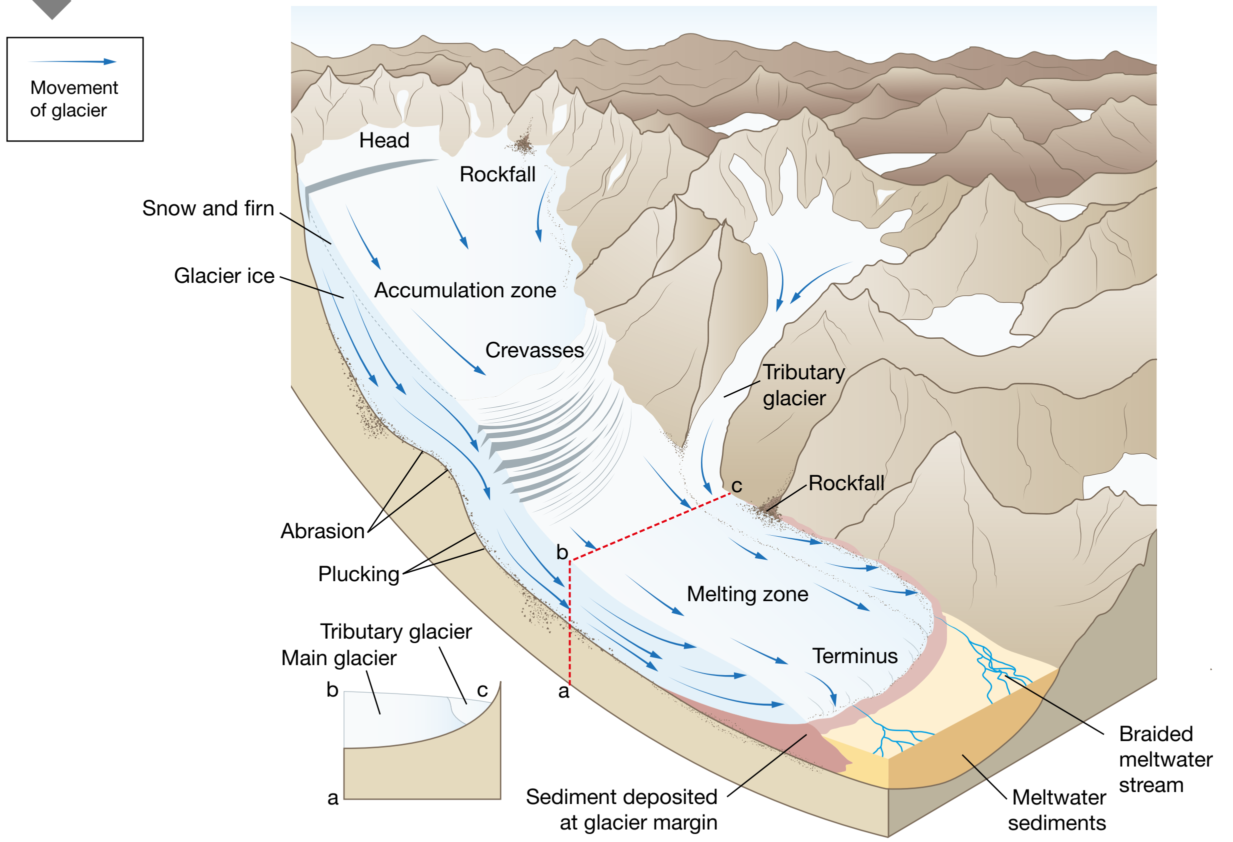
6.1.3 Yosemite National Park, California, USA, has glacial valley features from melted glaciers.

6.1.4 Three glaciers flowing into Prince William Sound, Alaska, USA.

to thousands of metres deep. Under such immense weight, ice deforms and then flows outwards in all directions from a central accumulation zone. These continent-sized ice sheets overwhelm the land, even causing Earth's crust to subside under them. During the Pleistocene ice ages, ice sheets estimated to be one to two kilometres thick covered much of the Northern Hemisphere. They exerted approximately 1000 tonnes of pressure on each square metre of the crust underneath causing it to sag under the weight.

Glacial landforms

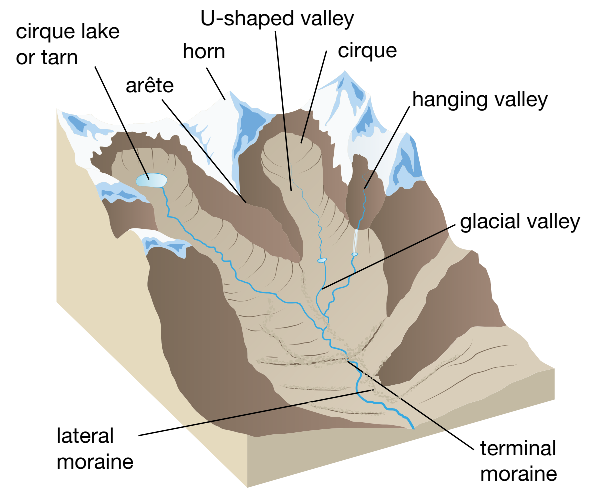
The landform features associated with mountain, valley and tidewater glaciers are illustrated in Figures 6.1.5 and 6.1.6.



6.1.5 Landforms of an active valley glacier

Did you know?

The oldest glacier in Antarctica may be 1 million years old, while the oldest glacier in Greenland is thought to be 100 000 years old.



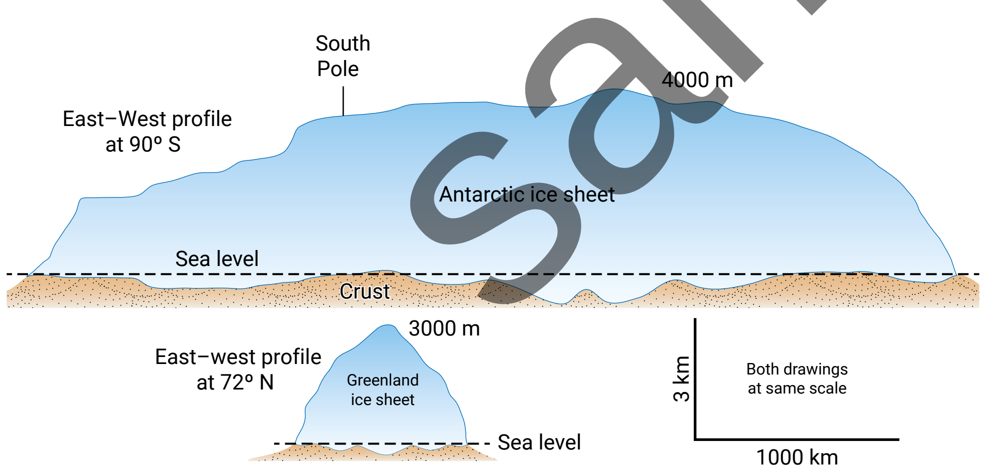
6.1.6 Distinctive landforms left by a valley glacier

Antarctic and Greenland ice sheets

Today, Earth has just two major ice sheets, one on Antarctica and one on Greenland (see Figure 6.1.7). The Antarctic ice sheet is the largest single mass of ice on Earth, covering 98 per cent of the continent. As illustrated in Figures 6.1.8 and 6.1.9, much of the ice sheet is over three kilometres thick and its extreme weight has depressed large parts of the continent's surface, leaving it below sea level. There are mountains near the edges of the continent, where the highest ranges and peaks emerge above the icy surface. These mountains funnel glacial ice towards the sea. The Greenland ice sheet covers 80 per cent of the island. It is more than three kilometres thick in its centre, where the ice is at its thickest, but then thins towards its edges.

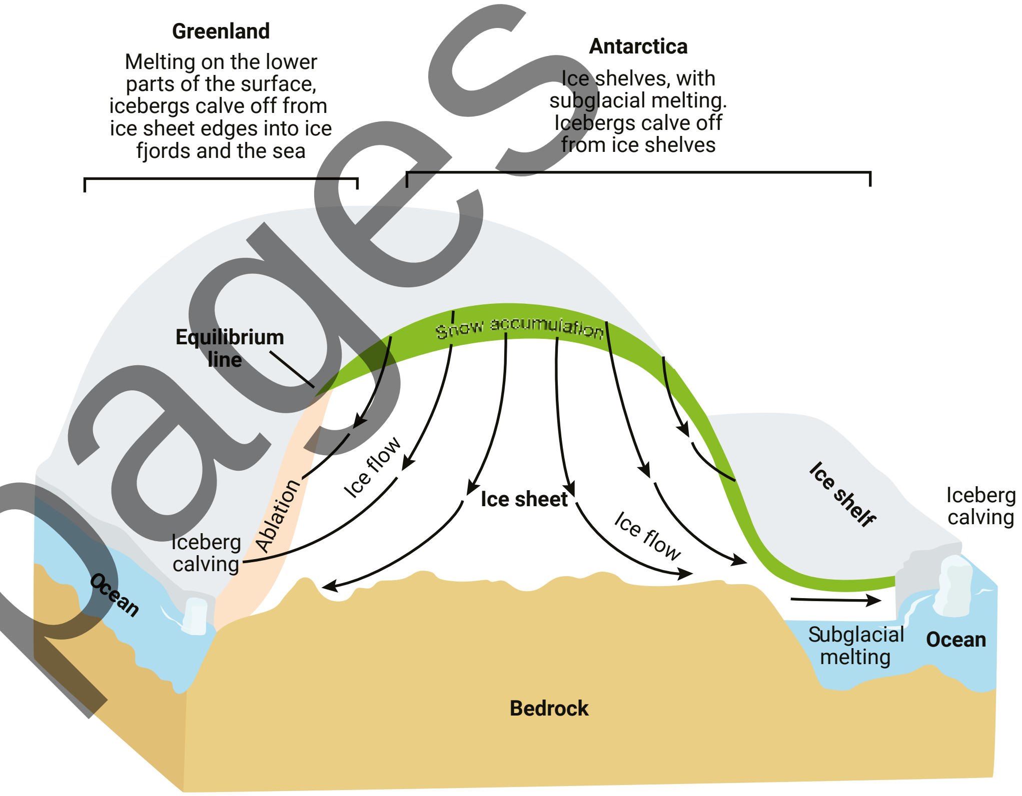
Features	Greenland	Antarctica (east & west ice sheet)
Area	1.71 million km^2	12.37 million km^2
Volume of ice	4 million km^3	25.71 million km^3
Ice cover	approximately 80%	98%
Percentage of global ice	10%	90% of global ice
Average ice thickness	1.6 km average	2.16 km average
Maximum thickness	3200 m	4776 m
Snow accumulation rate		303 mm per year in the west and 118 mm in the east

6.1.7 Features of the Greenland and Antarctic ice sheets



6.1.8 Cross-sections of Antarctica and Greenland, highlighting their vastly different sizes

Ice sheets take on a dome-like shape at the centre and flow outwards. The ice is at its thickest in the centre. The ice is pushed outwards, at a rate of only a few centimetres a year, until it reaches the ocean, where ice speeds can reach hundreds of metres or even several kilometres a year along fast-flowing outlet glaciers. For both Antarctica and Greenland, much of their ice flow terminates in the surrounding ocean. As glaciers flow into water, calving is common as ice chunks break off the end of the glacier and float away as icebergs. Antarctica is surrounded by ice shelves where permanent floating ice extends out over the ocean (see Figure 6.1.9).



6.1.9 Ice flow on the Greenland and Antarctic ice sheets

Ice shelves receive ice in several ways: the flow of ice from the ice sheet, surface accumulation (snowfall) and the freezing of marine ice to their undersides. Ice shelves lose ice by melting from below (from relatively warm ocean currents), melting above (from warm air temperatures) and from calving icebergs. These are normal parts of their **ablation**. Ice shelves can be up to 2000 metres thick, with a cliff edge up to 100 metres high.

Activities

Acquiring and processing geographical information

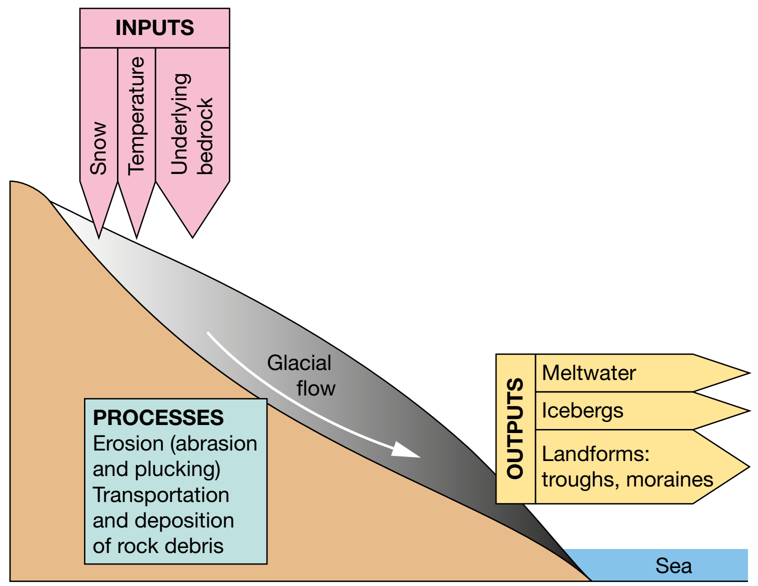
1 Distinguish between mountain, valley and tidewater glaciers.
2 Identify the parts of the world where glaciers form.
3 Explain how freshly fallen snow becomes glacial ice.
4 Explain what enables glacial ice to flow.
5 Demonstrate the differing speeds at which glaciers move, with reference to examples.
6 Explain how an ice sheet deforms the land underneath it.
7 Contrast the direction of flow between a valley glacier and an ice sheet.
8 Explain how an ice shelf gains and loses ice.
9 Describe an iceberg and identify where they originate in both the Northern and Southern Hemispheres.

Applying and communicating geographical understanding

10 Study Figures 6.1.2, 6.1.3, 6.1.5 and 6.1.6. Explain how a valley glacier transforms the mountain landscape. Identify and describe the main landform features created by the erosive power of the glacier.
11 Study Figures 6.1.7, 6.1.8 and 6.1.9. Write a brief report comparing the Antarctic and Greenland ice sheets.

Glaciers and ice sheets as open systems

Glaciers and ice sheets are open systems and have similarities with other systems like rivers, where flows occur due to gravitational forces. They have a series of linked inputs, transfers, stores and outputs, through which both energy and material are cycled (see Figure 6.2.1). The stores in this system are the atmosphere where the snow comes from, the glacial ice and the underlying bedrock. The ice moves over it and geomorphological processes—erosion, transportation and deposition—transfer the debris with the moving ice. Meltwater is a system output. So too are the distinctive landforms, such as **moraines**, **glacial troughs**, outwash plains and icebergs.



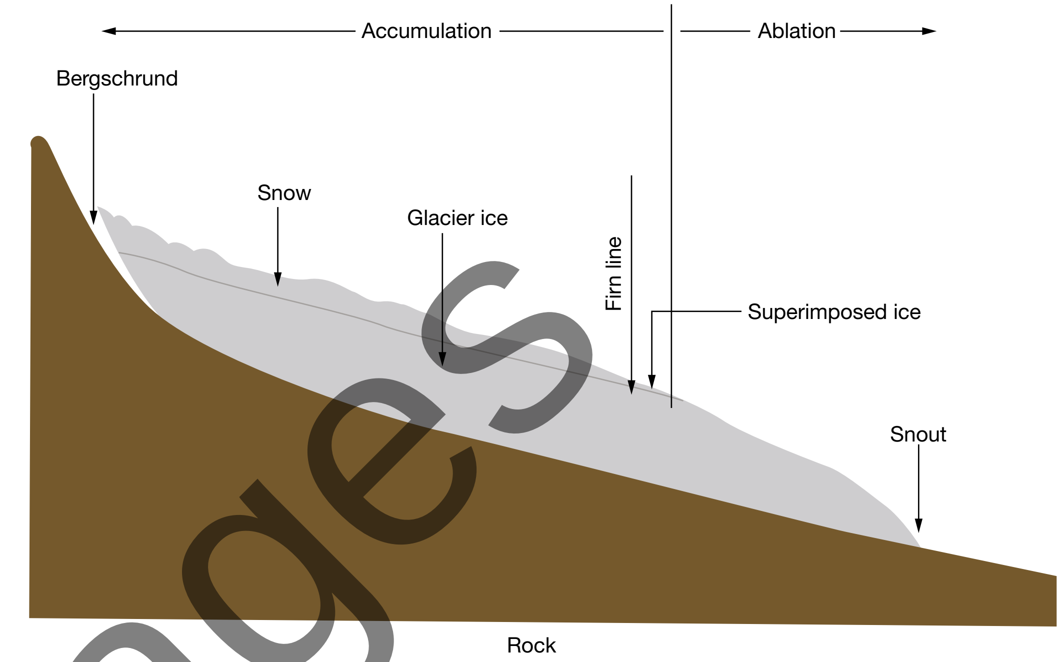
6.2.1 A glacier operating as an open system

Like other natural systems, glaciers respond to changes in inputs. They alter the rates of ice flow and determine outputs. When an increase in temperature causes an increase in melting that exceeds the input of new ice, a glacier loses mass until it reaches a new balance between accumulation and ablation. Lower temperatures and higher snowfall have the opposite effect, causing a glacier to gain mass. This relationship between total accumulation and total ablation at a point in time is called mass balance. Averaging this over a year determines a glacier's annual net balance. This determines whether it is positive or negative, indicating if a glacier's size has increased or decreased. Most glacial systems have had a negative balance since at least the 1970s.

Ice in the glacial system

Ice is the most significant input into a glacial system. Snow enters as precipitation and is compressed into ice. It builds up in the accumulation zone from where it is transferred downslope in a valley glacier or outward toward the margins of an ice sheet. Ice leaves the system in the ablation zone. Here, it calves and floats away as icebergs, melts or evaporates. The balance between the rate a glacier or ice sheet accumulates ice and the rate at which ice ablates determines the system's size. Temperature is the controlling factor.

The surface of a glacier or ice sheet reflects its operation as a system. The snowline generally shows the boundary between the accumulation and ablation zones. The surface appears smooth and white above the snowline, as fresh snow covers any irregularities caused by melting. Below the snowline, the surface is broken by crevasses, as gaps are left where snow melts or evaporates (see Figures 6.2.2 and 6.2.3).



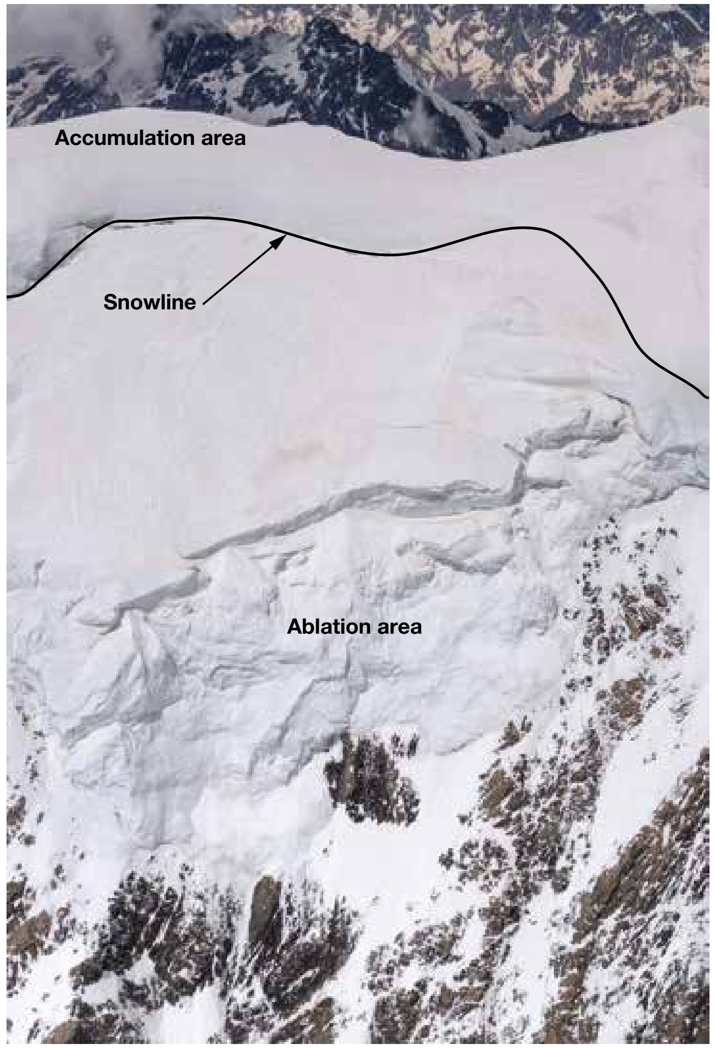
6.2.2 The accumulation and ablation zones on a glacier

Rocks and sediment in the glacial system

Rock is another important input into the system. Rocks embedded into the base of glaciers and ice sheets act as powerful agents of erosion, with the transported rock material being deposited near the margins of ablation zones. The main processes are **glacial plucking** and **abrasion**. Plucking is where the ice lifts out and removes angular blocks of rock, which move with the ice to then grind and scrape the valley sides or bedrock underneath, in a process known as abrasion.

Unlike rivers, which sort and smooth the rocks and sediment they carry, glaciers carry large rocks and small fragments side by side. Being embedded in the solid ice they remain angular and are deposited when the ice melts and the glacier retreats. This builds up a heap of debris, known as a **terminal moraine,** at the glacier's snout. Meltwater forms streams that exit the snout, carrying finer sediment to the outwash plains. Many of the largest rivers in the world, including the Ganges, the Yangtze and the Indus, have their sources in elevated, glaciated areas.

The meltwater that emptied from the continental Pleistocene ice sheets (2.58 million to 11 700 years ago) created extensive outwash plains that covered hundreds of square kilometres. Sand and gravel were dropped closest to the margins of the ice sheets, with the finer clay and silt carried the furthest. These finer sediments were pulverised rock particles generated by the grinding of the bedrock under the power and weight of the ice sheets. Due to their rich mineral content, they contributed to the fertility of the US Midwest's deep soils, where some of the world's most productive agricultural land is found. Glacial rock flour is the finest sediment produced. Being very light, it remains suspended in lake water for a long time. Sunlight reflecting



6.2.3 The surface of a glacier is different above and below the snowline.

6.2.4 The distinctive colour of Peyto Lake, Canada is evidence of its glacial origin.

off these particles gives the lakes a distinctive turquoise green (see Figure 6.2.4).

Part of an assemblage of open systems

The state of the atmosphere and temperature (which is largely a product of latitude and altitude) determines the input of snow and regulates the amount of energy entering the system. Temperature drives the growth or retreat of a glacier or ice sheet, thereby establishing the size and velocity of flow. It also sets the ice thickness and the rate at which it melts, the quantity and spatial extent of the distribution of deposited rock fragments and debris. This is why there is concern now about the extent and rate of glacial and ice sheet retreat related to climate change. Key to addressing the problem is understanding that glaciers and ice sheets are open systems, interacting with Earth's other systems.

Activities

Acquiring and processing geographical information

1 Identify the inputs, processes and outputs of a glacial system.
2 Describe how the mass balance of glaciers is determined.
3 Explain what determines the size of a glacial system.
4 Distinguish between the accumulation zone and the ablation zone of a glacier.
5 Contrast the ways in which glaciers and rivers transport rocks and sediment.
6 Distinguish between plucking and abrasion of a glacier as it erodes the valley sides or bedrock underneath.
7 Describe a terminal moraine and how it is formed.
8 Assess the importance of the Pleistocene ice sheets to the agricultural productivity of the Northern Hemisphere.

Applying and communicating geographical understanding

9 Study Figure 6.2.1. Draw two diagrams to show the response of the glacial system to:
  a warmer temperatures
  b cooler temperatures.
10 Study Figures 6.2.2 and 6.2.3. Demonstrate how the surface of a glacier moving downhill reflects its operation as a system.

UNIT 6.3

Land use change and glacier and ice sheet retreat

Land provides for human livelihood and wellbeing, including the supply of food, fresh water and multiple other resources. Tracing changes in land use over time demonstrates the extent to which humans have increasingly interrupted Earth's natural systems. Despite their remoteness in high latitudes or altitudes, glaciers and ice sheets are sensitive to alterations in natural systems occurring elsewhere in the world.

Changes in land use over time

While early agricultural practices interrupted natural systems, they were mostly localised. Much of the natural world, notably forests, was intact, maintaining a balance in the natural cycles. The Industrial Revolution began industrialising and urbanising agricultural societies from 1760, and land transformation began accelerating. Fossil fuel use increased dramatically, upsetting Earth's natural balance.

SPOTLIGHT

A brief history of land use

Humans have a long history of altering terrestrial ecosystems by hunting, foraging, land clearing, agriculture and other activities. For example, Aboriginal and Torres Strait Islander peoples have been modifying Australia's environment for at least 60 000 years. Around 8000 years ago, agricultural land uses spread throughout Mesopotamia and the Fertile Crescent areas of South-West Asia, followed by China, India and Europe. Intensive land use patterns developed in India, China, Africa and South America. By around 6000 years ago, agricultural expansion had spread across most continents, leading to native vegetation clearing and culling, and the domestication of herbivores. Native flora and fauna were replaced with intensive crop and livestock management practices, as human populations grew in size and density.

Hotter oceans also expand and melt ice, causing sea levels to rise. The measured sea levels of the decade 2010–2020 were the highest, based on records dating back to 1900. Scientists expect about 1 metre of sea level rise by 2100, potentially displacing 150 million people worldwide.

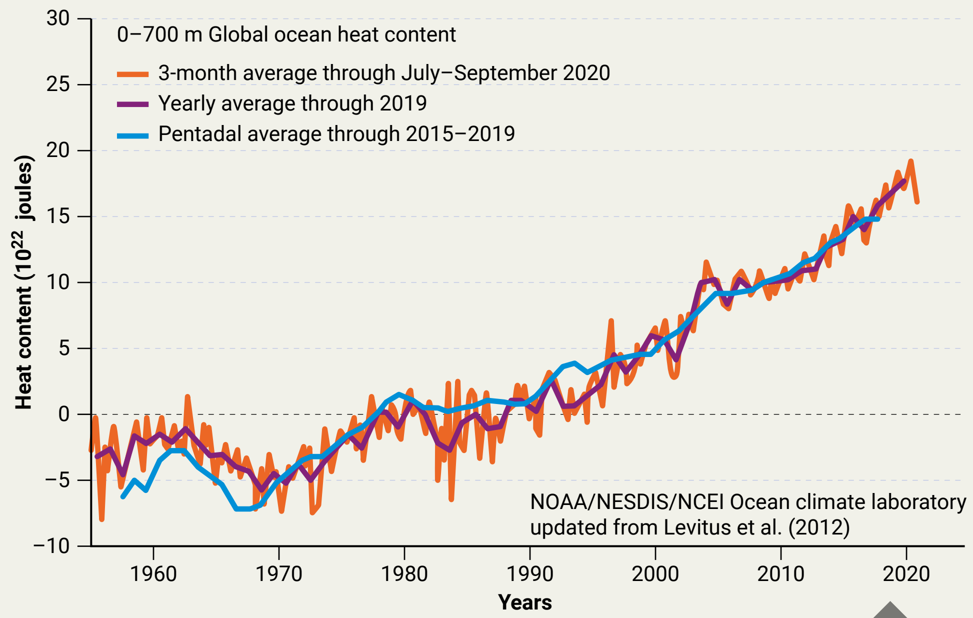
Warmer oceans melt floating ice

The ocean absorbs heat from the atmosphere and the warmer ocean water melts floating ice from below, increasing its vulnerability and speeding up iceberg calving. If warmer water reaches under the ice shelf to where the ice sheet or glacier is attached to the bedrock (known as the grounding line), it can weaken it. This makes it even less stable and it loses more ice over time (see Figures 6.3.2 and 6.3.3). As these ice shelves thin, the ice held in glaciers and ice sheets flows more rapidly into the ocean.

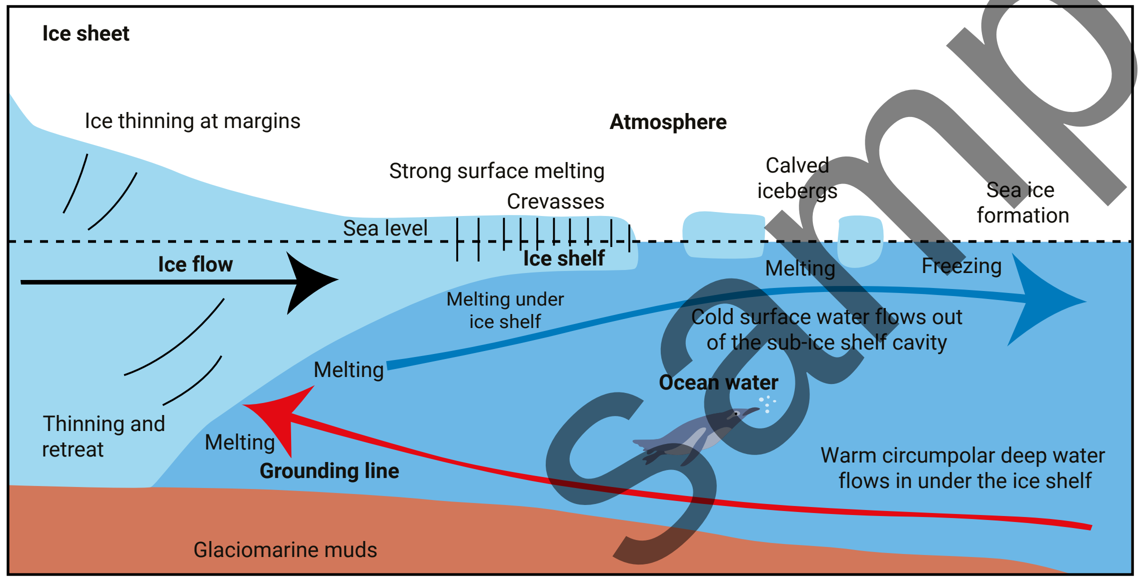
SPOTLIGHT

Ocean temperatures hit a record high

The heat in the world's oceans set a new record for the fifth consecutive year in 2022, showing irrefutable and accelerating heating of the planet. The world's oceans are the clearest measure of the climate emergency because they absorb more than 90 per cent of the heat trapped by the greenhouse gases emitted by fossil fuel burning, forest destruction and other human activities (see Figure 6.3.1). The amount of heat being added to the oceans is equivalent to every person on the planet running 100 microwave ovens all day and all night.



6.3.1 Oceans are getting warmer due to global heating.



6.3.2 Warm water flowing under the ice shelf melts it at the grounding line, making it more unstable, which then speeds up ice flow.

Dust and soot lower snow and ice albedo

Land uses in places well away from glaciers and ice sheets are also having an impact on melting. From the snow-capped peaks of New Zealand to Himalayan glaciers and Greenland's ice sheets, layers of dust and soot darken the surface of glaciers and ice sheets.

6.3.3 The Ross Ice Shelf, the largest Antarctic ice shelf

Windborne dust, soot and pollution that settle on the surface of glaciers and ice sheets discolour them and lower their albedo. Snow and ice have a high albedo as the white colour of the surface is highly reflective, bouncing incoming radiation back into space. Pristine white snow reflects incoming solar radiation back into the atmosphere. This has always been a natural defence against melting. However, as humans have changed land cover, intensified agriculture and become increasingly urbanised and industrialised, soot and dust have become mobilised and are found settling on the surface of remote ice sheets and glaciers. When snow becomes blanketed by darker-coloured particles of dust and soot, this coating absorbs more sunlight, which melts the snow faster. This then exposes the ice below the snow to the Sun earlier in the season, triggering earlier snowmelt in spring.

Dust-related melting in Greenland could add at least 2 centimetres more to the globally averaged sea-level rise by 2100 than current estimates suggest.

Dust

Dirt darkens snow surfaces as windstorms pick up and carry dust for thousands of kilometres before settling. In 2019, dust stained the Southern Alps of New Zealand orange-brown after drought-loosened iron oxide-rich soil particles were blown 2000 kilometres across the Tasman Sea by north-westerly winds (see Figure 6.3.4). Dust from the Sahara impacts the albedo of the European Alps (see Figure 6.3.5) and dust from the arid lands of the western and southwestern USA impacts the snowpack of North America. Dust from north-western China impacts Himalayan glaciers.

Dust is not only generated by poor agricultural practices and drought; mining also causes problems. In Chile, there are 24 114 glaciers and some of the largest ice sheets outside the polar regions. They are at risk from mining-generated dust. Because of this, environmentalists are pushing for more protective measures against mining dust to be put in place.

Did you know?

Pure snow generally has a visible albedo of 0.95. It reflects more than 95% of the visible light that hits it. Soot reflects less than 10% of incoming light (albedo 0.1). Tiny particles of car tyres and brakes are blown from densely populated areas of the Northern Hemisphere onto the Arctic, reducing its albedo.

6.3.4 Dusty glaciers in New Zealand, November 2019

6.3.5 Saharan dust heading towards the Italian Alps

6.3.6 Surface water entering a moulin on the Ferpècle Glacier in the Swiss Alps.

6.3.7 A large moulin on Langjökull Glacier, Iceland

Soot

Soot is a black powdery substance, consisting mainly of particulate carbon, and is known as black carbon. Because it is darker than dust, it absorbs more sunlight and so is much more potent at warming and melting ice than dust. As well as settling on the surface of glacial ice, soot particles can also form the nuclei of snow crystals. Then, with their additional heat, they are responsible for changing a feathery and highly reflective white snow crystal into a darker more compact grain which then absorbs more heat (see Figures 6.3.6 and 6.3.7).

Historically, increased levels of soot being carried in the atmosphere began with the Industrial Revolution. It is an unwanted by-product of the incomplete burning of fossil fuels. Research has confirmed that the reason the Little Ice Age (1300–1870) ended in Europe was the coating of soot deposited on the Alps by the Industrial Revolution.

Soot is also produced by the incomplete burning of organic matter. Forest fires and wood-burning stoves are common sources of soot (see Figure 6.3.8). As development has pushed the agricultural frontier in the Amazon Basin, smoke plumes have billowed from extensive forest fires and travelled with the wind to darken the Andes' glacial snow with soot.

The use of biomass fuels such as wood, crop waste and dried animal dung in open fires and cooking stoves also results in high levels of airborne particulate matter. Many people living in poorer regions of China, India and Tibet depend on such fuels as their major energy source. The impact is evident in the Tibetan Plateau of the Himalayas, as soot darkens snow and ice in the region.

Did you know?

Over a period of 20 years, each molecule of black carbon traps 3200 times more heat than CO_2.

6.3.8 A traditional cooking stove in northern India releases soot into the atmosphere.

● SPOTLIGHT

Historic coal soot in the Himalayas

New research published by the Proceedings of the National Academy of Sciences has found that soot dating back to the beginning of the Industrial Revolution made its way across Europe to settle on the top of the Himalayas, over 10 000 kilometres away. Soot has been found in an ice core extracted from the Dasuopu glacier, at an elevation of over 7900 metres, on Shishapangma mountain (see Figure 6.3.9).

The research began in 1997 when scientists travelled to Dasuopu to drill ice cores from the glacier. The ice cores have provided a trove of data, including snowfall records, atmospheric circulation and other environmental changes over time.

Geographers studying an ice core they believe formed between 1499 and 1992, found higher-than-natural levels of several toxic metals, including cadmium, chromium, nickel and zinc, from around 1780. All these metal trace elements are by-products of burning coal, and were probably transported by winter winds, which travel around the globe from west to east.

6.3.9 By-products of coal were found in an ice core from Shishapangma in the Himalayas.

Activities

Acquiring and processing geographical information

1 Identify the greatest dislocation to Earth's natural balances and when it started.

2 Explain how warmer atmospheric and ocean temperatures are accelerating the melting of the ice sheets of Antarctica and Greenland.

3 Describe how the main windborne pollutants from human activities are being carried to and settling on remote ice sheets and glaciers.

4 Define soot and explain why it is more potent than other pollutants in melting glacial ice.

Applying and communicating geographical understanding

5 Study Figure 6.3.1. Using data from this graph, answer the following questions.
   a Identify the year when oceans first started getting warmer.
   b Compare the rate of warming between last century and this century.

UNIT 6.4

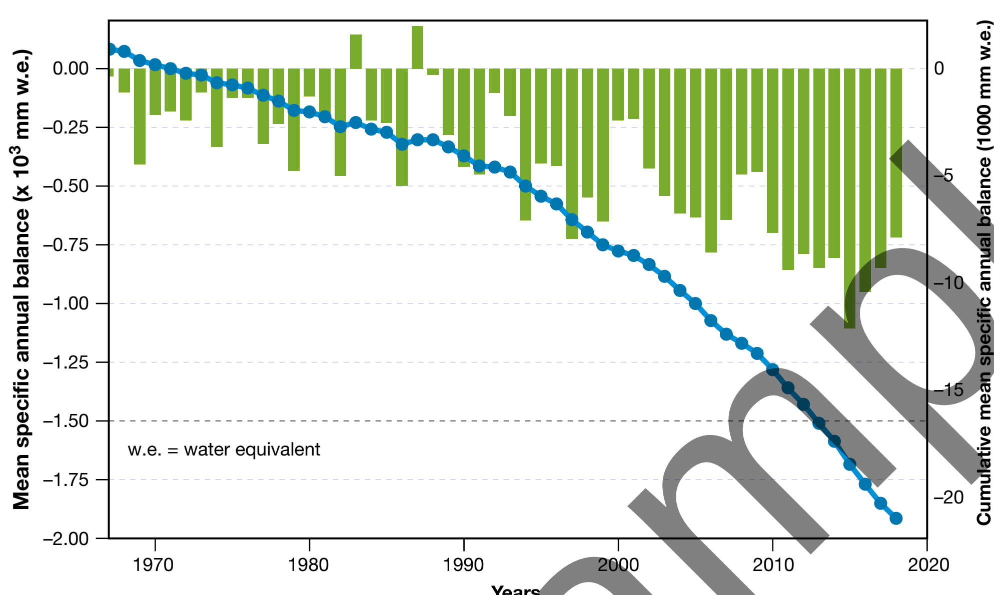
The extent and rate of glacial retreat

Glacial ice is especially sensitive to climate change. The edges of ice caps are shrinking and glaciers are retreating. When there is warmer air over a glacier or ice cap, the ice on the surface melts, which directly reduces the mass of the glacier. Once meltwater penetrates cracks on the surface of the ice, it can lead to further melting and accelerate ice flow. As these cracks open, they allow more water to drain down to the bed and spread out across its base lubricating it.

Evidence of glaciers and ice caps melting

In the past decade, Earth scientists have documented record-high average annual surface temperatures and have been observing changes in the distribution of ice. Since the early 1900s, with few exceptions, glaciers around the world have been rapidly melting and retreating at unprecedented rates. Glaciers are melting, calving into the sea and retreating on land, and ice caps are shrinking. During the last century, several glaciers, ice caps and ice shelves disappeared altogether, with many more shrinking so quickly that they may vanish within a matter of decades.

The World Glacier Monitoring Service (WGMS) has tracked changes in more than 100 glaciers worldwide. There are 37 that have records dating back 30 years and are accepted as climate-reference glaciers. Figures 6.4.1 and 6.4.2 reflect how these reference glaciers have been losing their mass balance over recent decades as melting occurs. The total mass loss over time appears to be accelerating as the downward curve steepens.



Source: American Meteorological Society 100, Si-S306

6.4.1 Mass balance of the WGMS 37 reference glaciers 1950–2022

Decade	Loss per year in metres
1980s	–0.228
1990s	–0.443
2000s	–0.676
2010s	–0.921

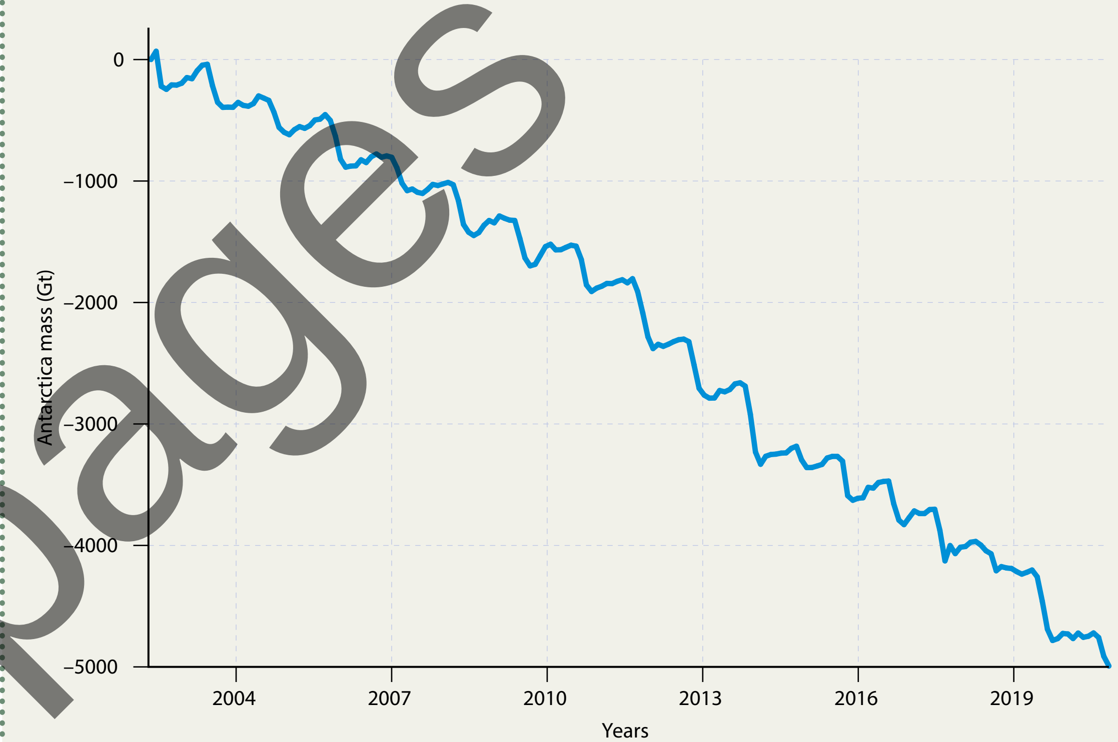
Source: NOAA

6.4.2 Glacier loss from the 1980s to 2010s

SPOTLIGHT

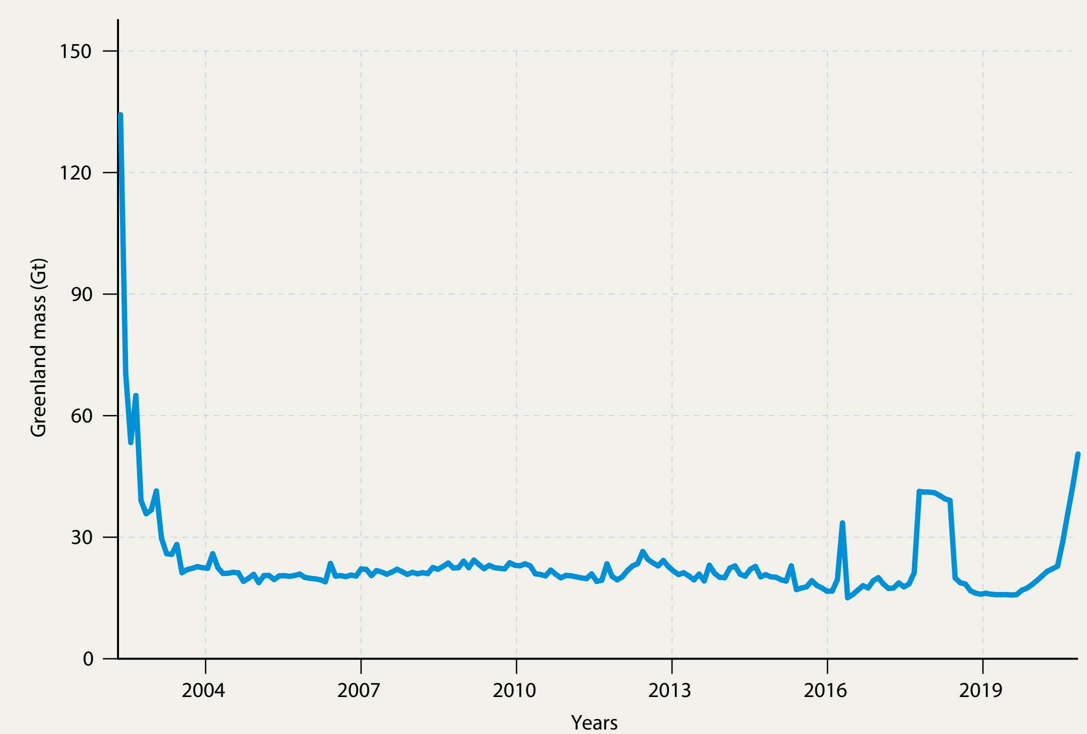
Measuring changes in Earth's gravitational pull

As NASA Gravity Recovery and Climate Experiment (GRACE) twin satellites orbit Earth, they continuously measure the slightest changes in Earth's gravitational pull. Changes in the distribution of water are the most significant cause of gravity changes, so scientists can measure the weight of water and track its shift from ice caps and glaciers to the oceans. See Figures 6.4.3 and 6.4.4.



Source: NASA

6.4.3 Antarctica mass variation since 2002. GRACE ice mass measurements of the Antarctic ice sheet



Source: NASA

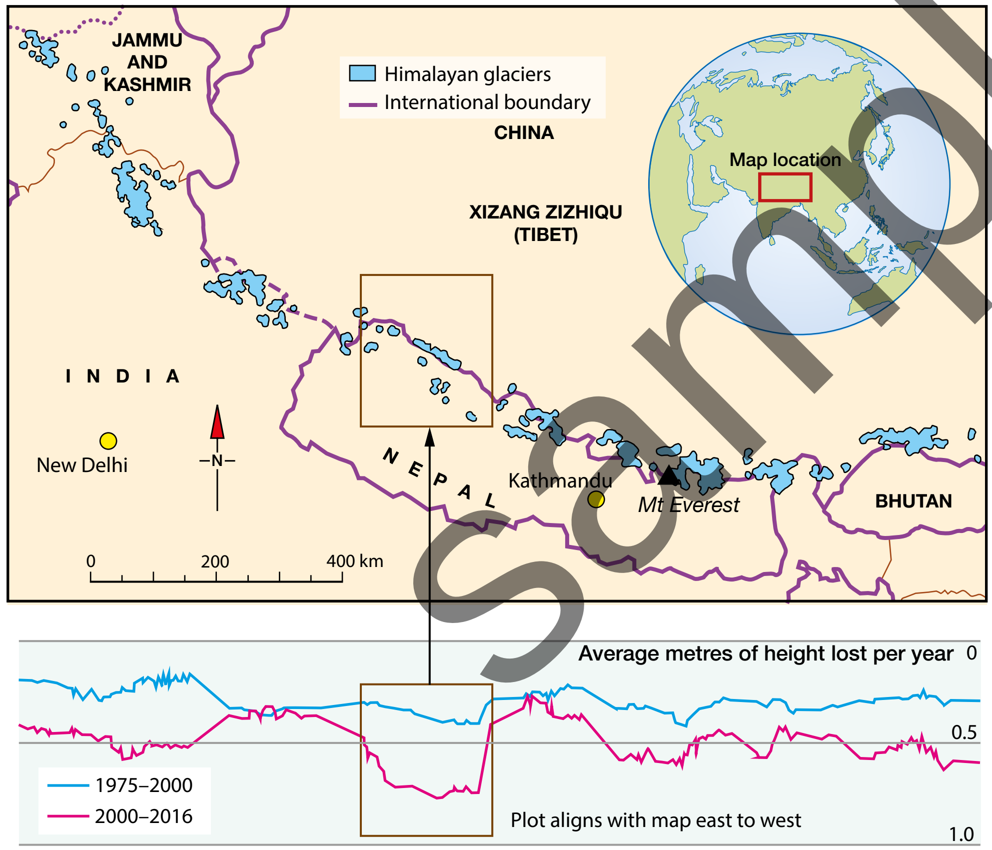
6.4.4 Greenland mass variation since 2002. GRACE ice mass measurements of the Greenland ice sheet

Alpine summits and glaciers losing ice cover

Since 1970, several hundred glaciers across the world have been losing 0.5–1.3 metres of thickness each year; this is at least twice the average loss for the twentieth century. It is predicted that by 2100, alpine summits may have lost 90 per cent of the ice that covered them in the 1920s. Figures 6.4.5 to 6.4.7 highlight just some of the loss.

European Alps	Glaciers lost half their volume between 1850 and 1975. Since 1970, 40% of their remaining glacial ice has melted. The Argentière Glacier on Mont Blanc has receded 1150 m since 1850.
Himalayas	All the estimated 15 000 glaciers will be 35–75% smaller by volume by 2035. The glacial melting has doubled since 2000, with more than a quarter of all ice lost over the last 40 years (see Figure 6.4.5). Most in the eastern and central Himalayas may all but disappear.
Tien Shan (Central Asia)	Glaciers have lost over a quarter of their mass since 1970. Since the 1960s they have been losing 60 km² annually, shrinking the size of glaciers by almost 3000 km².
Rocky Mountains (Canada & USA)	Glaciers are melting along the Rocky Mountains and many have already disappeared. All glaciers in Montana's Glacier National Park, USA, for example, have retreated, some by as much 85% (see Figure 6.4.6).
Alaska	99% of Alaska's 2000 glaciers are retreating. The Grand Plateau Glacier is visibly narrowing and thinning, and has pulled away from its valley walls.
Africa	Mt Kilimanjaro's once ice-capped summit has been partly exposed for the first time in 10 000 years. More that 80% of the mountain's glacial ice has melted since 1912.

6.4.5 Extent of ice loss on the world's major glaciated mountains.



6.4.6 Eight billion tonnes of ice are lost every year from the Himalayas. Not replaced by snow, the lower-level glaciers are shrinking 5 m annually.

6.4.7 The Grinnell Glacier in Glacier National Park in Montana's Rocky Mountains has retreated to the mostly shaded, upper confines of its basin.

SPOTLIGHT

The Andes Meltdown

The glaciers in the Andes Mountains, South America, are rapidly shrinking due to warming temperatures. A staggering 98 per cent of glaciers have shrunk and some mountain glaciers have retreated 9 kilometres over the last century. Many sit in low altitudes in the southern Andes, which makes them vulnerable to rising air temperatures. The Patagonian icefields at the southern end account for 83 per cent of all ice loss in South America (see Figure 6.4.8).

Tropical glaciers in the Peruvian Andes are thinning and losing mass, shrinking at their fastest rate in the past 300 years. They have lost almost half their surface area since the 1970s.

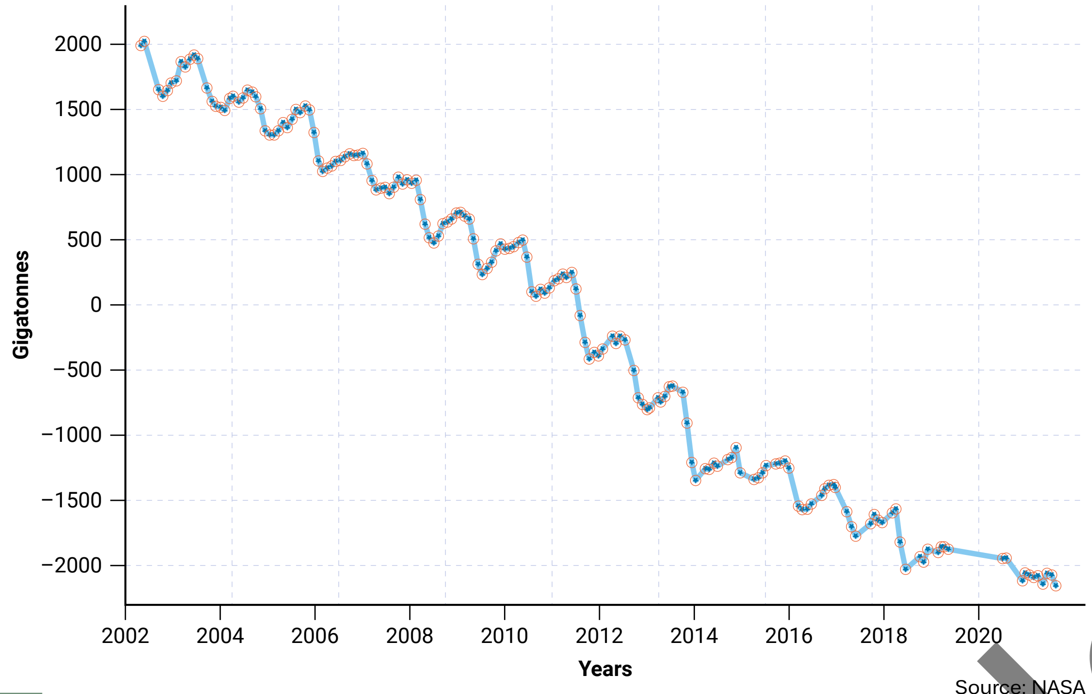
Over 70 per cent of the world's tropical glaciers are found in Peru in high mountain ranges around the Equator, many concentrated in the Cordillera Blanca, or White Range. They are acutely sensitive to rising temperatures. Small icy regions in Columbia, Venezuela and Bolivia are also rapidly melting. Glaciers in the western Andes of Bolivia have lost more than two-thirds of their mass since the 1980s. Those at lower altitudes are the most vulnerable, losing 1.35 metres of glacial ice annually, double the rate of high-altitude glaciers. Usually under 40 metres deep, they will probably disappear within decades.

6.4.8 Olivares Alpha Glacier, Chile, has lost 66% of its mass since 1953.

Shrinking of polar ice sheets

Satellite surveys show that polar ice sheets are melting six times faster than in the 1990s, when Greenland and Antarctica combined lost 81 billion tonnes of ice a year. The loss increased to 475 billion tonnes in the 2010s. From 1992 to 2017, the combined ice loss from both sheets was 6.4 trillion tonnes, with 60 per cent from Greenland.

Increasing sea temperatures drive the melting Antarctic ice sheet. The ocean melts the outlet glaciers, speeding up their flow. In Greenland, ice loss has been triggered by a combination of atmospheric and sea temperature rises, exacerbated by complex feedback loops that are speeding up surface melting (see Figures 6.4.9 and 6.4.10).



6.4.9 Estimated total mass change in Greenland's ice sheet 2002–2019 from GRACE

6.4.10 The edge of Greenland's ice sheet south of Ilulissat

Did you know?

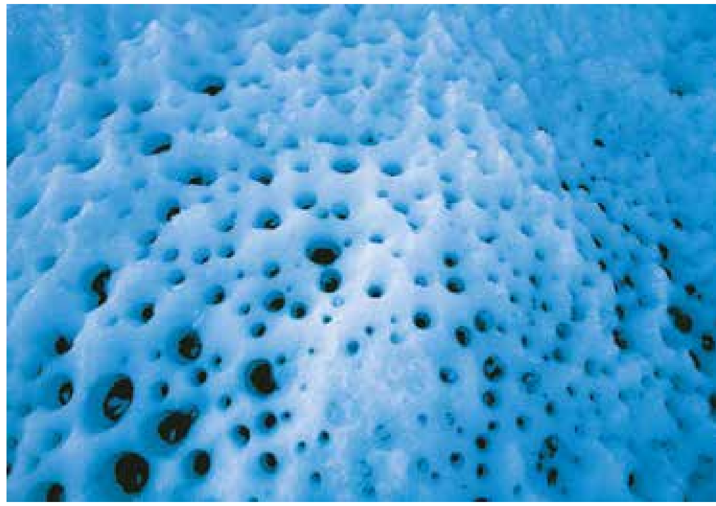
Australian scientists have used NASA satellite data to calculate the weight of the Greenland ice sheet. During the summer of 2019, the loss of ice has been calculated to be enough to cover all of Tasmania in water almost 5 metres deep.

Greenland is losing glacial ice seven times faster than in the 1990s. This could create another 7 centimetre rise in sea levels by 2100. Glacial ice is reacting to the rapid Arctic warming, with temperatures rising 0.75°C in the decade 2010–20. Most ice loss comes from surface melting where water runs off into the ocean. Melting is most apparent on the edges of the ice sheet where the glaciers carrying ice from the interior calve and crumble into the sea. The speed the ice moves towards the sea has also more than doubled. Seawater thaws the ice from below and this is thought to be a growing driver of ice loss.

Temperatures are rising across the Arctic at about twice the global average. This causes surface melting of the ice sheet, particularly its edges. Summer temperatures are now among the highest on record, often over 20°C near where the Jakobshavn Glacier enters the ocean. Across Greenland, 600 billion tonnes of ice are now lost during summer. If sustained, the melt could raise global sea levels by 2.2 millimetres a year. Recent persistent high pressure systems across the Arctic have brought warm air to northern parts of the ice sheet. This has helped to maintain clear skies leading to a lack of snowfall. If this becomes a regular summer weather pattern, future melting could double. A Danish meteorological team estimated that over 30 billion tonnes of ice melted in three days in the summer of 2019.

As warming melts the edges of the ice sheet, rock that has been crushed by it is exposed. As it dries it releases mineral dust. This blows back over the retreating ice sheet, settling on its surface, darkening it, reducing its albedo and accelerating melting. This is a significant feedback loop as melting causes even more melting. Much dust is generated elsewhere in the Arctic as there is a longer snow-free season, leaving soil exposed. Soot also blows in, which absorbs heat more effectively. Large wildfires in northern Russia and Alaska produce most of the black particulates settling on Greenland's ice sheet. Together with the dust, they form **cryoconite**, which accelerates melting.

With the surface of the ice sheet becoming increasingly wet in the warmer summers, microbes and algae thrive on the cryoconite. The algae also produce a dark pigment as a sunscreen, which further boosts the ice's absorption of solar energy. This is another feedback loop, as the absorption of heat by the dark cryoconite deepens the holes where the algae lives. This stops the water from freezing, creating a suitable environment for more to grow. **Moulins** develop and this fuels more melting (see Figure 6.4.11).



6.4.11 Cryoconite matter is made up of microscopic mineral and organic particles carried by the winds to fall on the ice.

Activities

Acquiring and processing geographical information

1. Describe what has been happening to ice sheets and glaciers since the early 1990s. Explain how this has created a feedback loop.
2. Assess the extent of ice cover from the world's major glaciated mountains this century.
3. Identify which mountain range in the world has lost the most glacial ice relative to its size and account for its vulnerability and the speed with which glaciers are melting.
4. Describe how ice cover in the Arctic and Antarctica has been lost and explain what the main drivers of melting are in both the Antarctic and Greenland.
5. Explain why the rate of melting of the Greenland ice sheet exceeds that of the Antarctic ice sheet.
6. Describe and account for the extent of melting of the Greenland ice sheet in 2019.
7. Explain how the melting of the edges of the Greenland ice sheet creates a feedback loop.
8. Explain how a combination of airborne pollutants combine to form cryoconite, which can exacerbate melting and form moulins, and how these accelerate the speed with which a glacier flows.

Applying and communicating geographical understanding

9. Study Figure 6.4.1. Using data from this graph, answer the following questions.
   a. Identify the two years in which the reference glaciers gained mass.
   b. Calculate how many years the reference glaciers lost mass, as a percentage of the time frame represented.
   c. What has happened to the rate of melting over the period shown? Validate your answer.
10. Study Figures 6.4.3 and 6.3.4. Compare the rate of change of the ice masses in Antarctica and Greenland. Account for the difference.
11. Study Figure 6.4.5. Complete the following tasks.
    a. Assess the severity and extent of ice loss on the world's major glaciated mountains.
    b. Investigate recent statistics of ice melts in these mountains to establish the current situation and whether ice loss has accelerated or abated.
12. Study Figure 6.4.6. Compare the rate of melting in the Himalayas moving from west to east.
13. Study Figure 6.4.9. Calculate the percentage change in the mass of the Greenland ice sheet from 2002 to 2019.

UNIT 6.5

The impact of glacier and ice sheet retreat

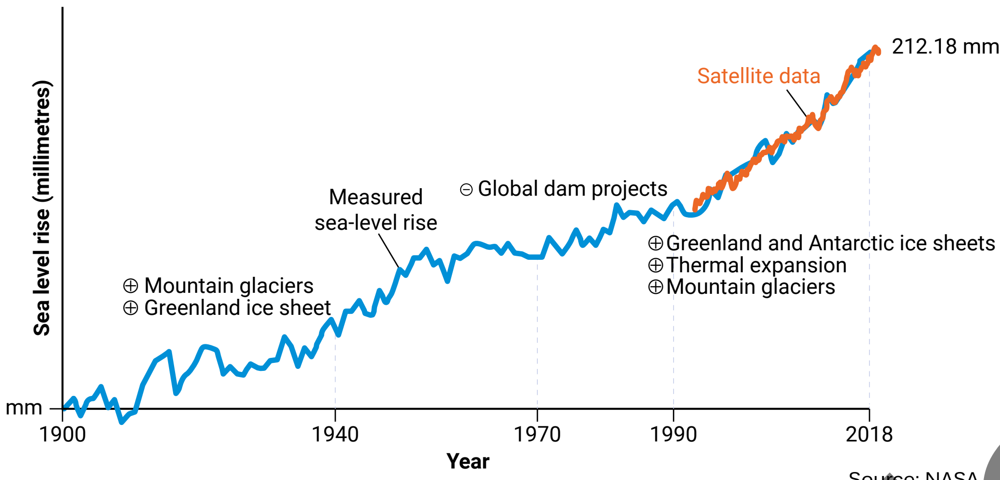
The retreat of glaciers and ice sheets can have significant and even devastating effects on the immediate environment, such is the scale of the loss of glacial ice.

Did you know?

If all the ice in Greenland melted, sea levels would rise by 7 metres.

Rising sea levels

The loss of land ice directly causes the sea level to rise, putting at risk low-lying islands and coastal communities throughout the world. Rising sea levels loom as one of the most damaging long-term impacts of the climate crisis. Figure 6.5.1 shows how the sea level has risen since 1900. The accelerated increase reflects the ice sheet mass loss from both Antarctica and Greenland. The Greenland ice sheet has become the largest contributor, currently raising the level by more than 1 millimetre each year.



6.5.1 Causes of sea level rise since 1900

Did you know?

Greenland and especially Antarctica were quite stable at the start of the 1990s. It took until the 2010s for the ice sheets to react to decades of a warming climate.

6.5.2 Invasion of a low-lying coastal area by the sea

The Intergovernmental Panel on Climate Change's (IPCC) most recent mid-range prediction for global sea level rise in 2100 is 53 centimetres. But the new analysis of satellite data suggests that if current trends continue, seas will rise by an additional 17 centimetres. It is estimated that every centimetre of sea level rise leads to coastal flooding and coastal erosion, disrupting people's lives around the planet. For example, an extra 17 centimetres would mean the number of people exposed to coastal flooding each year would rise from 360 million to 400 million (see Figure 6.5.2).

Disruption of ocean currents

Fresh water pouring off the Greenland Ice Sheet is altering the salinity of seawater and disrupting the ocean conveyor belt in the Atlantic Ocean. This global process, the Atlantic Meridional Overturning Circulation (AMOC) ensures heat and energy are distributed globally and ocean waters are continually mixed. Warm water moves northward and colder, denser, saltier water moves south, moving the current. Adding fresh water reduces the water's salinity, making it harder to drive the current southward.

If the AMOC continues to weaken it will affect the weather patterns of countries bordering the Atlantic Ocean. Europe may experience both hotter summers and colder winters, and more destructive storms could hit the US coast. Rainfall patterns in the tropics could also be altered.

Long-term decline in water resources

Nearly one-sixth of humanity lives near streams and rivers that source their water from glacial meltwater originating in the headwaters of drainage basins. Some are already finding that run-off is decreasing, while others face an uncertain future.

In response to accelerated melting, decreasing glacial mass will deliver increasing water in the basin with more run-off until the point of **peak water** is reached. Beyond that, water flow will diminish as glacial storage is depleted. The timing of reaching peak water depends on geographical location. Research indicates that it has already passed for almost half of the basins in the Alps, Andes and Rocky Mountains, where flow is now diminishing. The smaller the glacier and the closer it is to the Equator, the quicker peak water is reached. Many of the smaller tropical glaciers in the Andes have already reached peak water and may disappear altogether. Being further away from Equator, larger glaciers in Alaska are not expected to reach peak water until near the end of this century. While the Himalayas sit at a low latitude, their high altitude tempers melting and they are expected to reach peak water in the middle of the century.

Potential water crisis in the Hindu Kush

The Hindu Kush–Himalayan (HKH) region is the source of the waters flowing in the Ganges, Brahmaputra, Indus, Yangtze and Yellow rivers. This water sustains close to 2 billion people. These rivers drain the Himalayas, delivering sediment-laden water that supports intensive agriculture on the region's fertile soils. Any change in the flow of water from melting glaciers will severely impact farming, the availability of drinking water and the generation of hydro-electricity. An accelerated spring melt is expected to increase water flow out of the mountains until 2050, when peak water is reached, before river flows start to plummet. Food security in the region is threatened.

Andes water shortages

With ever-increasing climate stress, the availability of water is becoming critical, particularly in semi-arid and arid regions, where other sources of water are limited. Meltwater from glaciers in the Andes ensures that many rivers continue to flow in the dry season and during droughts. In Peru, for example, the source of the Rio Santa is in the Cordillera Blanca. The river supplies drinking water and irrigation for large-scale agriculture schemes along the dry Atacama coast. Further glacial retreat in the upper reaches of the Rio Santa is expected to reduce the flow of the river in the dry season by 30 per cent.

For many large cities in the region, glacial melt from the Andes is a critical natural resource. Santiago (population 6.8 million) in Chile, sources as much as two-thirds of its water from river systems fed by glaciers high up in the Andes. La Paz (population 2.7 million) in landlocked Bolivia, relies on glaciers in the surrounding Andean mountains for its water supply. The city has three main dams, but they have almost run dry as they can no longer rely on glacial melt water (see Figure 6.5.3). Water rationing has been introduced and a state of emergency declared.

6.5.3 Low water levels in Milluni Zongo reservoir near La Paz, Bolivia

Significant changes to flow regimes in glacierised catchments are expected as glacier melt diminishes. Stream and river flow will become more dependent on unpredictable rain events. There are many challenges facing those seeking water security, and similar struggles across the world could lead to conflict between neighbouring countries in the future, as water resources become scarce.

Did you know?

In Alberta, Canada, agriculture relies on meltwater from glaciers in the Canadian Rockies, which are expected to lose 90% of their current volume by 2100.

Hydro-electricity

Glacial run-off contributes significantly to the generation of hydro-electric power in many countries: 91 per cent in Iceland; 70 per cent in Austria and 25 per cent in Switzerland. The Mauvoisin Dam in Switzerland collects run-off from nine glaciers. Its power plant output is expected to increase until 2050 as run-off increases, but then fall as the glacier melt drops towards the end of the century.

Did you know?

A warming climate may see a longer growing season in Greenland and farming may return to a similar state to what it was a thousand years ago. Dairy cattle have recently been brought in and there are now locally-grown potatoes and broccoli.

Glacier tourism numbers follow retreating ice

Glacial mountain landscapes rank as some of the world's most popular tourist destinations. In 2019, more than 4 million people visited Banff National Park in Canada and 672 000 visited Glacier Bay National Park in Alaska. In New Zealand, glacier tourism contributes more than US$85 million to the economy annually.

Clearly, the loss of mountain snow and ice will mean such sites may lose their appeal. Initially, it may spur people to want to see glaciers before they are lost, but accessing some glaciers is becoming increasingly difficult. Hiking up onto New Zealand's two iconic glaciers, the Fox and Franz Josef glaciers was stopped in 2015 because it is too dangerous. The rapid melting of glaciers has left the steep sides of the glacial trough exposed and vulnerable to rockfalls. The only way onto these shrinking glaciers now is by helicopter (see Figure 6.5.4).

6.5.4 Franz Josef glacier, New Zealand, from a helicopter cockpit

Too many visitors may also degrade the glacial surface and threaten the ecological integrity of the region. In 2016, the Xinjiang government banned tourism on glaciers in the Tien Shan Range in the far northwest of China, ensuring that the glaciers be observed from a distance rather than having people step onto them.

Glacial lake outburst floods

Melting glaciers can also trigger catastrophic discharges of water where the contents of a whole **glacial lake** rushes down a mountain at once, known as **glacial lake outburst floods**. As the run-off from glaciers has increased, there has been a significant increase in the formation of glacial lakes. As glaciers retreat up a mountain they leave behind a large void or depression that was formerly occupied by glacial ice. Meltwater forms a glacial lake. On the downslope side, the water is held back by the terminal moraine of the glacier, which sits as a pile of unconsolidated, rocky rubble that had been pushed forward by the glacial snout. As melting continues, the lake increases in size. These lakes become deadly if the moraine is breached allowing the water to escape. This will happen if the loose rocks shift when ice at the core of the moraine melts. Even a small crack is quickly enlarged by surging water being pulled downslope by gravity. This leads to the glacial lake emptying without warning, sending a destructive flood wave down the valley below.

6.5.5 Creek flowing after a flood emptied the Tulsequah Glacier glacial lake, Canada

Glacial lake outburst flood waves comprise water mixed with sediment, rock debris and chunks of ice which makes them deadly, as illustrated in Figure 6.5.5. They have significant societal impacts causing a loss of life as communities are engulfed, as well as damaging land, property and infrastructure in remote regions. They have killed over 12 000 people worldwide—in South America, the European Alps, Central Asia and Iceland. They also negatively impact the ecology of systems downstream.

The number of glacial lakes in the world has increased. Research using over 250 000 Landsat images showed that between 1990 and 2018 the number and size of glacial lakes increased by more than 50 per cent from roughly 9400 to over 14 300. The water volume in the lakes also increased by about 50 per cent. Lakes at high latitudes exhibited the fastest growth. Some countries have begun mitigation strategies to reduce flooding risks by glacial lakes. In Nepal, for example, officials lowered the water level in Imja Lake, a glacial lake near Mt Everest, by more than 3.5 metres.

Loss of biodiversity

The rapid shrinking of glaciers is having cascading impacts on downstream systems. The continual melt from glaciers keeps rivers flowing during summer and drought periods when other sources are depleted. This creates a perennial riverine habitat, which is especially important in arid and semi-arid regions. The inevitable reduction in such river flow once glaciers have passed peak water will place vulnerable ecosystems at risk. The high Andean wetlands are particularly sensitive to glacial melting and are considered ecosystem sentinels for the impact of climate change. Many species depend on the slow-growing mossy pillows of cushion plants of the wetlands that are struggling to keep up with the pace of melting. Some specialist organisms are starting to disappear, including the meltwater stonefly, as its larvae depend on the cold, glacial streams.

Diverse ecological communities have evolved in the harsh environmental conditions of glacier-fed streams and rivers. Many of the aquatic species that have evolved in mountainous environments require cold temperatures to survive. **Benthic invertebrates**, or organisms that live in the sediments at the bottom of rivers, drive gross primary production. They are critical to energy flows and nutrient cycling within the ecosystem, from the lower trophic levels of algae and detritus feeders to upper trophic levels of fish, amphibians, mammals and birds. Many of these temperature-sensitive benthic organisms become extinct when water temperatures rise, disrupting the basis of the aquatic food chain. Such changes to glacier-fed stream habitat may similarly have an adverse effect on cold water fish such as trout and salmon.

Water contamination

An unexpected impact of the glaciers melting is the release of contaminants that have been locked up in the ice for a long time. Many originated as emissions from industrial activity, often thousands of kilometres away, with particulates and compounds carried by wind and settling on the ice, subsequently becoming part of it. Black carbon, mercury, pesticides and other pollutants have been historically deposited in the snowpack. The freeing of these harmful substances could significantly reduce water quality downstream.

Loss of spiritual significance

Glacial mountain peaks have spiritual significance for indigenous peoples throughout the world. Their sophisticated understanding and connection to the natural world are ingrained in their cultures. They recognise the mountains as the source of the streams and rivers on which their very existence depends. In India, the Gangotri Glacier is considered a sacred place and receives thousands of pilgrims each year.

Some indigenous peoples consider glaciers gods. In Peru, the loss of ice and snow from mountain peaks is thus associated with the god's departure and the end of the world.

Permafrost is melting

Permafrost sits beneath the surface across vast swathes of the higher latitudes in the Northern Hemisphere. It is permanently frozen ground that can be more than a kilometre thick. With Arctic temperatures increasing at more than double the global rate, ice within the permafrost is melting, causing the ground to collapse (see Figure 6.5.6).

6.5.6 The colour of melting permafrost indicates its high organic content.

Did you know?

The only bird known to nest on a glacier is the white-winged diuca finch, also known as the glacier bird, of the Andes. As glaciers retreat, it will have to move further up the mountains to find ice to build its nest on. Eventually, it may run out ice completely.

Did you know?

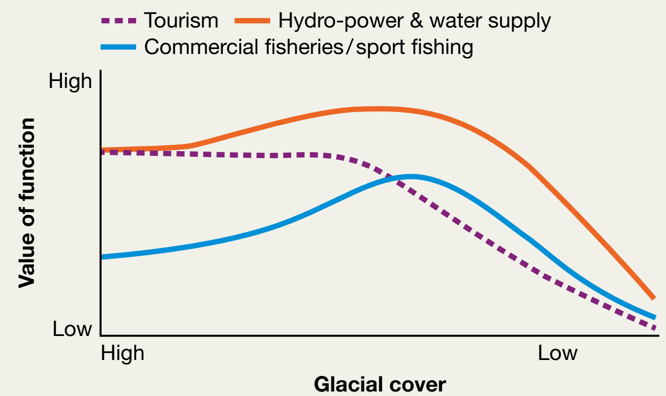
The continued thawing of the Greenland ice sheet could release radioactive waste. It was buried by the US Army in the 1950s, believing it would be buried forever.

Sinkholes and hollows pockmark the surface. Once the organic material that was held within the permafrost thaws, it decomposes and releases both carbon dioxide and methane into the atmosphere. The permafrost has long served as a 'carbon sink' and it is believed to hold twice as much carbon as the atmosphere. By releasing greenhouse gases, it is creating yet another climate change feedback loop with the potential to accelerate warming.

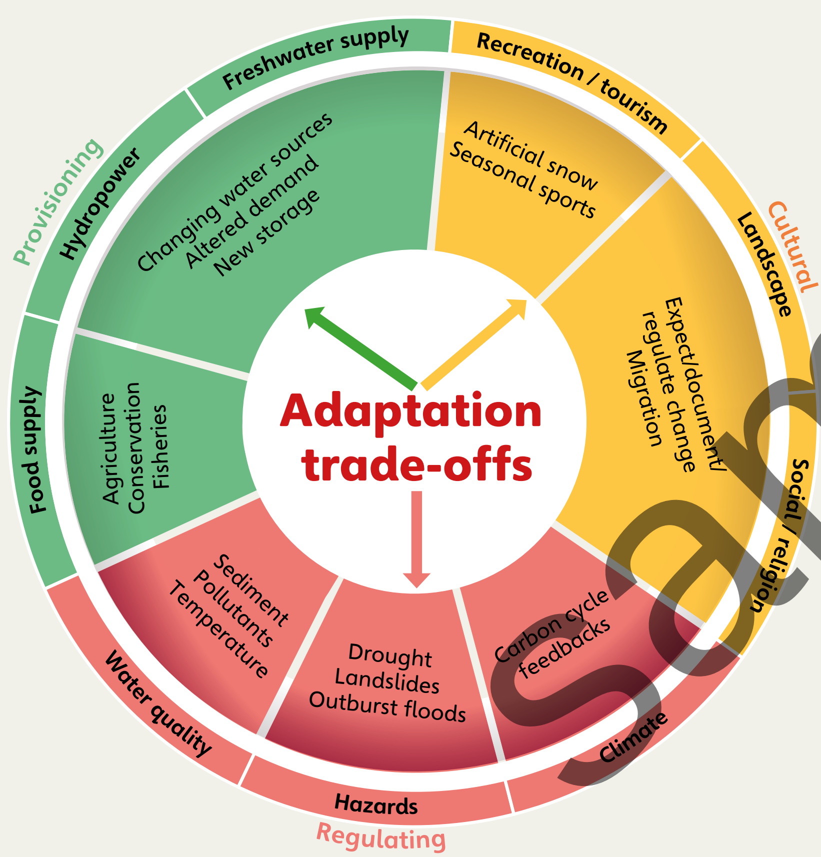
SPOTLIGHT

A framework integrating the effects on ecosystem services

The impacts of glacial and ice sheet retreat on human activities are far-reaching. As Figure 6.5.7 predicts, there may be some initial increase in the value of some activities up to when peak water is reached, but beyond the peak, they will all decrease as the glacial storage is depleted. Figure 6.5.8, by the National Academy of Sciences of the USA, highlights the complexity of adapting to this change. The outer ring highlights the broad groups of ecosystem services provided by glacier-fed watersheds. The inner ring highlights specific services potentially altered by glacier retreat and disappearance. The centre highlights the complexity of interactions among the various services, which will necessitate trade-offs as society adapts to **cryospheric** change.



6.5.7 Projected impact of decreasing glacial cover on human activities



6.5.8 The impact of glacial retreat on human activities

Activities

Acquiring and processing geographical information

1. Identify the two contributing causes of sea level rise and analyse their respective impacts.
2. Assess the impact of sea level rise on coastal communities.
3. Outline the predictions of the Intergovernmental Panel on Climate Change on global warming.
4. Explain how fresh water pouring off Greenland could disrupt ocean currents and what this would mean for global weather patterns.
5. Describe how water supplies will be impacted by the melting of glaciers and what will happen once peak water is reached. Provide illustrative examples to determine the likely impact on water resources for many communities relying on glacial meltwater.
6. Describe a glacial lake outburst flood. Explain why they are dangerous to those living downstream.
7. Explain how glacial meltwater becomes contaminated.
8. Outline the spiritual significance of glacierised mountain peaks and what the loss of their ice and snow signifies to those that have a spiritual connection with them.
9. Explain why holes are appearing in the ground above the permafrost in the Arctic and how this may trigger a feedback loop that would accelerate climate change.

Applying and communicating geographical understanding

10. Study Figure 6.5.1 and, using data from this graph, answer the following questions.
    a. By how much did the sea level rise from 1900 to 2018?
    b. What contributed to this rise from 1900 until 1990?
    c. What contributed to this rise from 1990 until 2018?
    d. What evidence from the graph is there that the rate of rising sea levels has accelerated from the 1990s?
    e. What additional data has been available since the 1990s?
11. Study the information explaining the various impacts of glacier and ice sheet retreat. Draw up a table summarising the information provided. Use the following as a guide.

	Cause	Effect	Examples
Rising sea levels			
Disruption of ocean currents			
Long-term decline in water resources			
Declining tourism			
Glacial lake outburst floods			
Loss of biodiversity			
Contamination of water			
Loss of spiritual significance			

12. Study the box, Spotlight: A framework integrating the effects on ecosystem services, and complete the following tasks.
    a. Describe the impact of the loss of glacial cover on human activities and how this changes over time.
    b. Write a paragraph or two explaining the complexity of addressing the issues arising from glacial retreat and disappearance as society adapts to the change.
13. As a class, brainstorm the strategies that could be undertaken at a local, regional and global level to slow the rate of melting of the Greenland ice sheet.

UNIT 6.6

Sustainable management: Banning heavy fuel use in Arctic shipping

The complexity of the interconnections between the natural systems of ice sheets and glaciers has become evident, as have the feedback loops that increase the rate of warming. It is by understanding the damage that can be done by one of these feedback loops, namely the settling of black carbon particulates on glacial ice, that is spurring a campaign to ban the **heavy fuel oil** (HFO) responsible.

Why heavy fuel oil is a threat to the Arctic

HFO is the dirtiest marine fuel. It is the residual oil left after crude oil has been stripped of valuable components during refining. Being cheap it's widely used for long-haul shipping. A spill from a ship does not disperse like regular oil. It leaves a highly viscous thick, tar-like sludge that emulsifies in seawater forming a paste. This is difficult to capture and gets trapped under the ice. Sensitive marine environments are at risk as it persists in the environment far longer than other fuels.

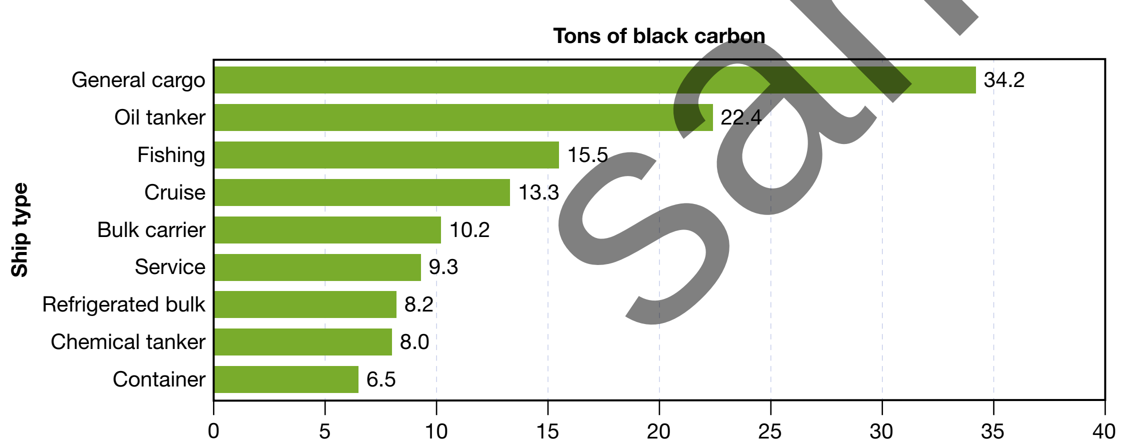
These heavy fuels burn slowly, emitting a high concentration of black carbon particles that contribute to the Arctic's more rapid warming. Reducing soot emissions is the fastest and most economical means to slow down that rate. HFO spills:

- are 50 times more toxic to fish compared to medium and light oil spills
- pose a severe risk to Arctic residents, many of the 4 million inhabitants depend on the sea for survival
- can cause hypothermia and death in seabirds and marine mammals
- produce harmful pollutants such as black carbon, sulphur and nitrogen oxides.

The growing use of heavy fuel oil in the Arctic

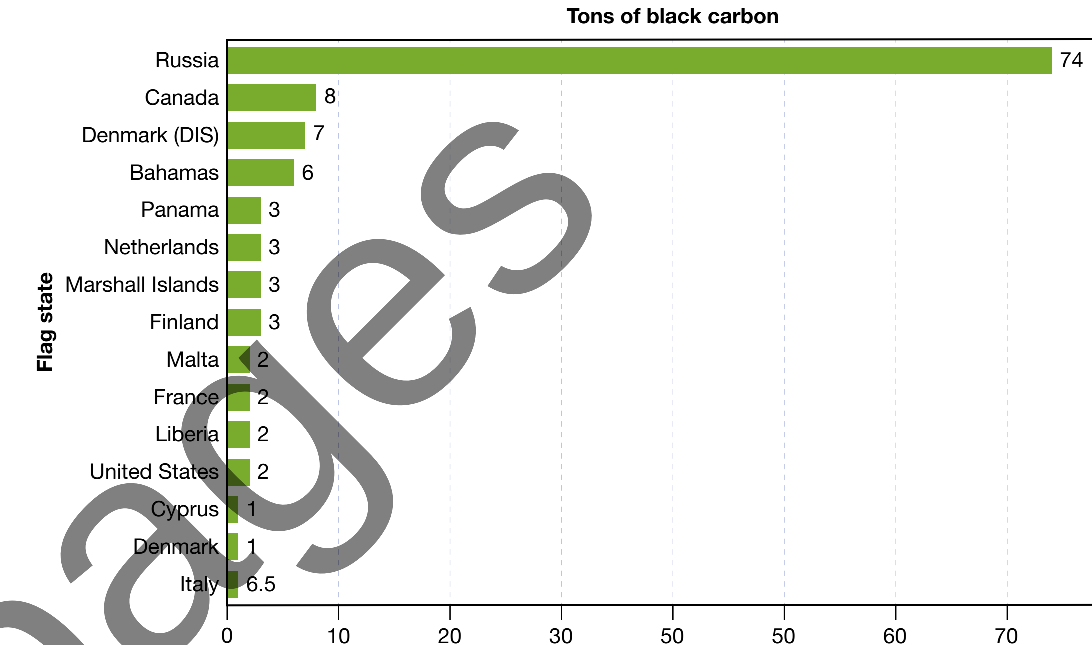
Dwindling polar ice makes traversing the Arctic Ocean easier for ships, attracting many countries and corporations to this route. HFO is the most commonly used fuel by bulk carriers, tankers and cargo vessels in the Arctic (see Figure 6.6.1). Russia is the biggest user as it needs to deliver supplies to remote coastal communities that lack road or rail connections (see Figures 6.6.2 and 6.6.3). With sea ice vanishing, Russia sees the Northern Sea Route (NSR) as a Suez Canal alternative. Shipments between Europe and Asia could possibly use the NSR as a shortcut for 10 months of the year. During the coldest months, sea ice means ships needed an icebreaker to traverse the passage.

There has already been explosive growth in shipping on the NSR, with 31.5 million tonnes of goods moved in 2019, up more than 60 per cent from 2018. In 2020,



6.6.1 Black carbon emissions by type of ship using heavy fuel oil in the Arctic Ocean, 2015

commercial shipping began in May, earlier than ever before. A Russian carrier loaded with liquefied natural gas crossed the NSR to China without an icebreaker for the first time. Even the most icy and difficult parts of the route provided safe passage. The ease of early-season navigation will expedite the growth of cargo traffic in the Arctic.



Note: Flag state is the country a ship is registered in, and not necessarily the owner's country of origin. Panama, Liberia, Marshall Islands, Bahamas and Malta register a large number of foreign vessels. DIS is the Danish International Shipping Register.

6.6.2 Black carbon emissions by ship's flag state, from ships using heavy fuel oil in the Arctic Ocean, 2015

6.6.3 A cargo ship with containers at Anadyr, Chukotka in far east Russia

Action to ban the use of heavy fuel oil in the Arctic

With the growth of shipping in the Arctic, the use of HFO will rise and with it more accelerated melting of glacial ice. Robust measures are needed to reduce the risks arising from the use and carriage of HFO. Concerns have long been held about the reliance on this dirty fuel in such a delicate and remote environment. It led to the International Maritime Organization (IMO) prohibiting its use in Antarctica in 2011. Efforts to include the Arctic region in that ban fell short. The IMO has been working for a decade to have heavy fuels banned in the Arctic. They have only secured this for some of the waters of the Norwegian archipelago of Svalbard.

Considerable pressure has been placed on the IMO by environmental non-profit organisations. At the forefront has been the Clean Arctic Alliance, which led a multi-year campaign to ban HFO in the Arctic. They gained increasing support from many of the member states of the IMO. In 2020, the IMO agreed on a draft regulation to phase out the use and carriage of HFO, recommending a ban on Arctic shipping in the circumpolar north, starting from July 2024. This is the first-ever agreement to limit greenhouse gas emissions from shipping. Although Russia was initially hesitant, it eventually supported the measure, along with the other countries bordering the Arctic Ocean. The designated boundary of the zone where the bans apply is shown in Figure 6.6.4. There were some key exceptions:

- ships engaged in search and rescue or oil spill preparedness and response
- nation-states whose coastlines border the Arctic waters can waive the ban if their ships are flying their own flag and they are operating in their sovereign waters where they have jurisdiction. This was integral to securing Russia's support as they rely heavily on domestic journeys servicing coastal communities.

6.6.4 The International Maritime Organization's Arctic boundary designation

Other operators in the Arctic move to cleaner fuels

Apart from regulatory efforts, several shipping operators, including those operating in Arctic waters, have begun to phase out HFO or have even committed to transitioning to carbon-neutral fleets over the coming decades.

Norway's Hurtigruten implemented a voluntary ban on HFO a decade ago and is now moving to even cleaner vessels. The company took ownership of the first hybrid-powered, ice-strengthened expedition cruise ship in June 2018. The vessels can operate for short stints on silent, emission-free fuel cells. Ponant, a French cruise-ship operator with frequent voyages to the Arctic, no longer uses HFO in its fleet of five cruise ships.

Maersk, the world's largest shipping operator, and first company to sail a container ship through the Arctic in September 2018, is committed to operating a carbon-neutral fleet by 2050. It has already achieved a 46 per cent reduction in emissions compared to the 2007 baseline. The company says that the next five to ten years will be crucial for developing and investing in clean fleet technology.

Activities

Acquiring and processing geographical information

1. Describe heavy fuel oil (HFO).
2. Outline the impacts that HFO can have on the Arctic environment.
3. Account for the increasing use of HFO in the Arctic.
4. Describe the work that has been undertaken by the IMO in addressing the threat of HFO.
5. Outline the draft regulation that was agreed on in 2020. Explain what exemptions were needed to gain the support of Russia and other countries bordering the Arctic Ocean.
6. Investigate the current situation regarding regulations banning the use of HFO in the Arctic.
7. Describe how other operators in the Arctic Ocean are moving towards cleaner fuels. What may be motivating them to do so?

Applying and communicating geographical understanding

8. Study Figure 6.6.1. Using data from this graph, answer the following questions.
   a. Calculate the total tons of black carbon emitted by all ships using HFO in the Arctic.
   b. Calculate the percentage of combined emissions from general cargo ships and oil tankers.
9. Study Figure 6.6.2. Using data from this graph, calculate the percentage of Russia's contribution to black carbon emitted in the Arctic. Suggest why it dominates.

APPLICATION AND CONSOLIDATION TASKS

Task 1: Class debate

Conduct a class debate on the topic 'Atmospheric carbon levels are likely to be reduced in the future and the balance in glacial systems will be restored'.

To prepare for the debate:

- write down all the arguments for and against the topic
- re-read this chapter (and undertake further research) to find data to support your argument.

Task 2: Report writing

Write a short report assessing how land use changes have interrupted the operation of glacial systems and contributed to the accelerated melting of ice sheets and glaciers; and the impacts of the melting ice sheets and glaciers.

In your report, consider the framework that integrates the effects on ecosystem services (see Figure 6.5.7).

Task 3: Create an infographic

Prepare an infographic promoting the benefits of cruise ships bringing tourists to the Arctic using cleaner fuels. Your task is to encourage tourists to select a tourism operator that only uses clean fuels and has sustainable practices.

Your infographic should include the following information:

- what HFO is
- why HFO is a problem
- what the tourism operator is doing
- what the benefits are of using cleaner fuels
- reasons to take a cruise to the Arctic.