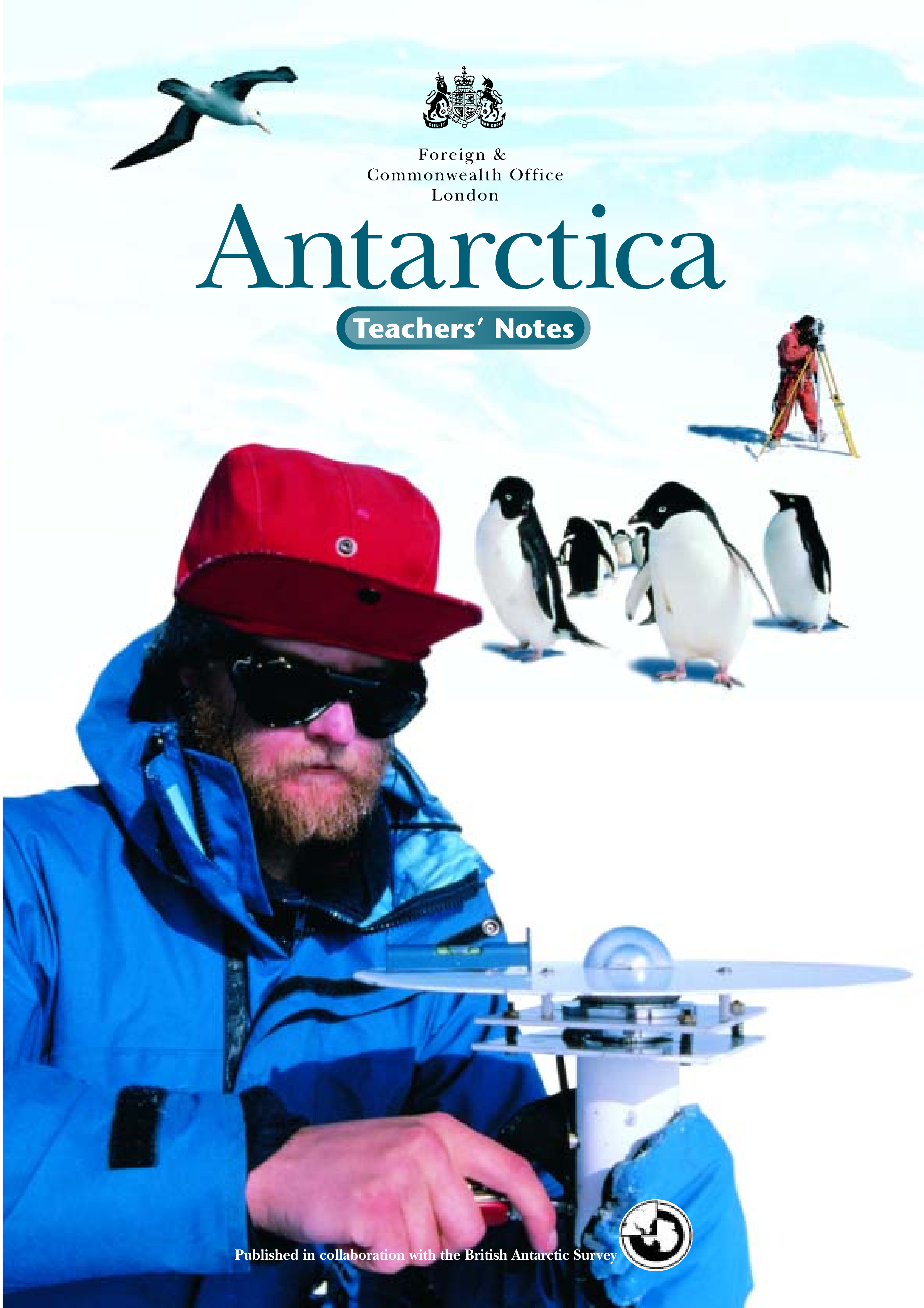
Foreign &
Commonwealth Office
London

Antarctica

Teachers' Notes



Published in collaboration with the British Antarctic Survey

Antarctica

Contents

Introduction

BAS

Antarctica is a fascinating and beautiful place. It is the world's last great wilderness and has a profound effect on the world's climate and ocean systems. Antarctica is therefore a unique natural laboratory for the study of global processes, such as climate change and ozone depletion. The study of Antarctica is becoming increasingly popular with UK secondary schools and colleges. However, there is little educational material available.

The Antarctic Schools Pack is intended for students in the 16–18 age range studying at secondary schools, sixth-form colleges and colleges of further education in the UK. The aim of the pack is to provide students with expert, new and relevant information about Antarctica, and to set this information out in an accessible and exciting way.

The pack is designed to be interdisciplinary and to be used as part of A-level and Scottish Higher studies. It will be of interest to students studying geography, biology, environmental science, physics, chemistry, geology, government and politics, leisure and tourism, and general studies. However, it is likely that the pack will be of the greatest use to A-level geography students studying Antarctica as a wilderness region.

The pack has been devised and written by scientists at the British Antarctic Survey, with the help of an educational consultant, and experts at the Scott Polar Research Institute and the Foreign & Commonwealth Office.

Each of the 15 topics comprises a double-sided worksheet and three double-sided pages of resources. The worksheet provides an introduction to the topic and a series of tasks that can be undertaken by students on their own, in small groups, or as a class. The resources provide a wide variety of materials, including scientific data, photographs, satellite images, maps, diagrams and written summaries of particular issues. Most of the resources use materials which are unavailable elsewhere and have been specially prepared by the British Antarctic Survey for the pack. The worksheet tasks and resources have been designed to cater for a wide range of student abilities. Some are easy, others difficult.

The pack is designed to be flexible. One option is for teachers to select a topic and ask students to complete all the tasks in the worksheet. In this way the pack can be used for independent study. As all the resources are designed to stand on their own, an alternative option is for teachers to select specific tasks and resources and then incorporate them into their existing teaching schemes.

To assist teachers in lesson planning, these Teachers' Notes have been produced to accompany the pack. The notes provide guidance on the key skills and ideas introduced by each topic, summary background information, and answers to the tasks set in the worksheets.

The Antarctic Schools Pack is provided copyright-free for educational use by schools and colleges. Wherever possible, worksheets and resources have been designed for multiple photo-copying.

It is hoped that the Antarctic Schools Pack will enable students to learn about and appreciate this unique and wonderful continent designated as a natural reserve devoted to peace and science.

If you or your students have any comments about the Antarctic Schools Pack or would like further information please write to the Information Officer, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 OET.

The nature of Antarctica

Worksheet 1

Key ideas

- Perceptions of Antarctica
- Size, height and remoteness of Antarctica
- Introduction to physical characteristics and climate
- The Southern Ocean and sea ice
- Climate change
- Ownership and governance of Antarctica
- Human activities in Antarctica

Key skills

- Map and satellite image interpretation and measurement
- Data gathering and analysis
- Note taking
- Summarising text, data and images

Few students have a realistic concept of Antarctica. This worksheet introduces them to the continent, and explores their perceptions and knowledge. Antarctica is the largest wilderness on Earth. The continent covers over 14 million km^2, but less than 0.5% of the land is ice-free. The Southern Ocean encircles Antarctica and forms around 10% of the world's ocean area. In winter, over half of the Southern Ocean freezes over forming pack ice covering 20 million km^2 of the sea. Human activities in Antarctica are regulated by the Antarctic Treaty, which came into force in 1961. This unique international agreement ensures that Antarctica is used for peaceful purposes only and the environment is protected. The Treaty puts aside territorial claims. Scientific research is the major activity undertaken in Antarctica, although in summer, fishing and tourism also take place. Eighteen countries operate permanent year-round research stations on the continent and nearby islands. About 5000 scientists and support staff work at these stations during the summer (UK winter), falling to around 1100 in winter. About 10,000 tourists a year visit Antarctica. There are no native peoples in Antarctica.

Model answers to tasks

Task 1 Antarctica lies at the bottom of the world, with the geographical South Pole lying near the centre of the continent. It is the fifth largest continent in the world. It is completely surrounded by the Southern Ocean.

Task 2 Antarctica is approximately circular in shape. The average diameter of this circle is 4500 km, giving a radius of 2250 km. The area of this circle is:

$\pi r^2 = 3.14 \times 2250^2 = 15.89$ million km^2

This figure compares favourably with the widely published area of nearly 14 million km^2.

Assuming Antarctica to be a circle, then its circumference is:

$2\pi r = 2 \times 3.14 \times 2250 = 14{,}130$ km

Mapping experts at the British Antarctic Survey (BAS) have worked out that the length of coastline is approximately 36,750 km, considerably more than the rough calculation. This is because the coastline is irregular and is not a perfect circle. For example, there are two large embayments – the Weddell Sea and the Ross Sea – and also the narrow Antarctic Peninsula projects out towards South America.

Task 3 In this unusual map projection, lines of longitude emerge from the South Pole. There are 12 of them, 30° apart. The vertical (upwards) longitude is the Greenwich Meridian (0°W or 0°E) and the vertical (downwards) longitude is 180°W (180°E). Thus from the South Pole to South America you go northwards along longitude 60°W; from the South Pole to Australia you go northwards along a line of longitude between 120° and 150°E; and to Africa northwards along a longitude close to 30°E.

South America is the closest continent to Antarctica (965 km away from the tip of the Antarctic Peninsula).

Part of the UK (Northern Ireland, Wales, Western Scotland and Western England) lies mid-way up the very left margin of the map. The right and left margins of the map should follow the Greenwich Meridian, so the eastern part of the UK should be visible on the very right margin. However, the right margin has been cut to fit the map on the page and the UK is not visible.

Task 4 Two of the cities furthest apart in Europe are Lisbon (Portugal) and Moscow (Russia). They are 3913 km apart. The flight time between them on a jet airliner is approximately 5 hours.

About 0.5% of Antarctica is not covered by ice.

The highest point on the Antarctic continent is Vinson Massif (4897 m).

The average elevation of the continent is 2300 m.

Task 5 From the answer in Task 2, the area of Antarctica is approximately 15.89 million km^2. The ice sheet has an average thickness of 2450 m. The volume of this cylinder is given by:

$\pi r^2 h = 3.14 \times 2250^2 \times 2450 = 38.94$ million km^3

This figure compares with a widely published estimate of 30 million km^3. The difference between the calculations is because the given average thickness of the ice of 2450 m is for the average height of the grounded ice sheet in Antarctica. This figure excludes ice shelves, which float on the sea surface. The average height of the Antarctic ice sheet, including ice shelves, is 2160 m. If the area of Antarctica is nearly 14 million km^2 and the average height is 2160 m then the volume is about 30.24 million km^3.

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The immense weight of the ice sheet has depressed the land surface beneath by as much as 800 m, so that if the load were removed the land surface would eventually rise, despite the rise in sea level caused by the melting of the ice. The rebound of the land would be a very slow process taking thousands of years. For example, the UK land mass is still slowly rising after the end of the last ice age in Europe over 10,000 years ago.

Antarctica can be divided into two distinct geographical regions: West Antarctica and East Antarctica. East Antarctica forms about two-thirds of the area of the continent and contains around 89% of the ice sheet. West Antarctica is much smaller and lower, although it contains the Vinson Massif (4897 m). The cross-section through the continent drawn in Resource N3 shows that most of the land buried by the ice sheet is below sea level. The physical feature that separates East Antarctica from West Antarctica is the Transantarctic Mountains – one of the world's great mountain chains.

Task 6 For much of the Southern Ocean the Antarctic Polar Front lies between latitudes 50°S and 60°S, although it is more southerly than this at around longitudes 75°W and 180°W. The average latitude is around 55°S.

The predominant wind and current flow around latitude 55°S is towards the east. This tends to keep the Antarctic Polar Front at a constant latitude. However, strong cold winds and currents from the Weddell Sea to the east of the Antarctic Peninsula force cold water northwards and eastwards between longitudes 0°W and 20°W which ensures that the Falkland Islands and South Georgia – two island groups on the same latitude – have very different climates. South Georgia is much colder. By around 70° W the Antarctic Polar Front has curved back to 62°S because the distribution of the continental landmasses bends the ocean circulation southwards.

When Antarctic water meets subtropical water at the Antarctic Polar Front the denser, colder Antarctic surface water sinks beneath the lighter warmer subtropical water. The Antarctic water rapidly reaches a depth of 400 m and then descends more slowly to reach a depth of 1000 m by latitude 45°S.

Task 7 The maximum extent of the sea ice from the coast of Antarctica is about 1200 km.

Sea ice forms when the air temperature is below freezing and the sea temperature is at freezing point. Conversely, the sea ice melts when the air and sea water temperatures are above freezing. The maximum extent occurs in September, at the end of winter, just as melting starts. At this time on average 20 million km^2 of the Southern Ocean is covered in ice. This area is nearly 1.5 times the area of the Antarctic continent. The least sea ice occurs in February at the end of summer just as the sea starts to freeze.

Task 8 Sea ice floats on the sea. Therefore when sea ice melts sea level is unaffected. Students can try an experiment with a large container of water with some ice in it. They should mark the position of the water level and see if it changes when the ice has melted. They will find that the water level remains unchanged.

Sea ice cover, and snow on top of it, cuts down the light entering the water of the Southern Ocean. Thus few phytoplankton – minute floating plants – are found beneath the ice. However, with the melting of the sea ice in spring, freshwater is produced and allows a burst of phytoplankton growth. Dense algal blooms can develop in inshore areas. This burst of spring plant growth provides the food for a huge web of other organisms living in the Southern Ocean ecosystem.

Sea ice prohibits access to much of Antarctica by ship, except for a few months in summer. Scientific research vessels and tour ships only visit the continent between November and March, and fishing activities are usually restricted to regions clear of sea ice.

Task 9 See the left hand diagram in Resource N4. There is no sunlight at the South Pole in June and there is 24 hours of darkness. In contrast, there is continual sunlight at the South Pole in December and there is 24 hours of sunlight. The reason for this is the tilt of the Earth's axis relative to its orbit around the Sun. The South Pole receives some or no sunlight depending on whether it is tilted toward (daylight – December) or away from (no daylight – June) the Sun.

Task 10 See the right hand diagram in Resource N4. There are two reasons why less solar radiation per square metre reaches the South Pole than the tropics:

- The tilt of the Earth on its axis means that the same amount of solar radiation is spread over a wider ground area in the Antarctic compared to the tropics.
- The atmosphere in Antarctica absorbs and scatters more solar radiation than in the tropics because of the longer path taken by the Sun's rays through the atmosphere.

The Antarctic ice sheet and sea ice reflect away about 85% of the solar radiation back into the atmosphere, whereas in a tropical rain forest only around 12% is reflected.


BAS

Parhelia or mock suns are formed by the refraction of light by aerial ice crystals

The Arctic is not as cold as the high, continental Antarctic. Antarctica is a continent surrounded by ocean and the Arctic is an ocean surrounded by continents. The Arctic Ocean is kept comparatively warm by inward flowing currents and insulated by sea ice. In the Southern Ocean the eastward flowing Antarctic Circumpolar Current encircles Antarctica and ensures that there is little mixing with warmer waters in the oceans to the north. Also, the belt of westerly winds over the Southern Ocean prevents mixing of the atmosphere and reduces energy transfer from the tropics to Antarctica. Surface air temperatures in Antarctica are therefore roughly 10–30°C colder than at comparable northern latitudes.

Task 11 Compared with the other Antarctic research stations listed in Resource C1, the climate at the South Pole is extremely cold and dry, but less windy than the coast. At the South Pole latitude, altitude and distance from the sea all help to control the climate. The Pole is at 90°S so it is dark for six months of the year (April – August). It is at an altitude of 2800 m above sea level on the continental plateau. Differences between summer and

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winter temperatures at the South Pole are much greater (annual temperature range of 32°C) than at the coastal station Signy (annual temperature range of 10°C) where the sea helps to moderate temperature change. However, the South Pole is not the coldest place in Antarctica. The Russian station at Vostok in the centre of Antarctica is colder because it is higher (3488 m) and is a greater distance from the sea. Vostok holds the record for the world's lowest recorded temperature (-89.2°C).

The South Pole receives less than 70 mm water-equivalent of snow precipitation each year. This means that if you melted all the snow that fell each year it would be equivalent to a rainfall of 70 mm. The central part of East Antarctica has an annual precipitation of less than 50 mm water-equivalent of snow. This large plateau area is effectively one of the world's great deserts, as one definition of a desert is a region which receives less than 50 mm of rainfall per year. Coastal areas in Antarctica, however, can receive much higher levels of precipitation both as snow and rain. At Signy the annual precipitation is 405 mm.

Areas of the world which have equivalent precipitation to the East Antarctic plateau are the Sahara, Gobi, Arabian and Namibian Deserts, parts of central Australia and inland Chile and Argentina.

Task 12 The map shows the land in Britain less than 5 m above sea level. These areas would be flooded if the sea level rose by 5 m, and if the sea defences proved to be inadequate.

Vulnerable to flooding are the Fens, the Essex marshes, the lower reaches of the Thames, parts of East Anglia, around the Solent and other parts of the south coast, the Somerset Levels, the Severn and Humber estuaries, and fringes of Wales and the Lancashire coast up to the Solway Firth – Blackpool would become an island.

The impact on society would be greatest in low lying urban areas where sea level rise would threaten housing, offices and industry. Coastal cities and ports would be at particular risk and would need to be protected. Agriculture would also be affected and large areas of highly productive land, such as the Fens, could be lost. Sea level rise would also cause the loss of important coastal habitats for wildlife, such as saltmarshes and mudflats.

Task 13 There are seven nations which claim territory in Antarctica: Australia, Argentina, Chile, France, New Zealand, Norway and the UK. Reasons for the claims include:

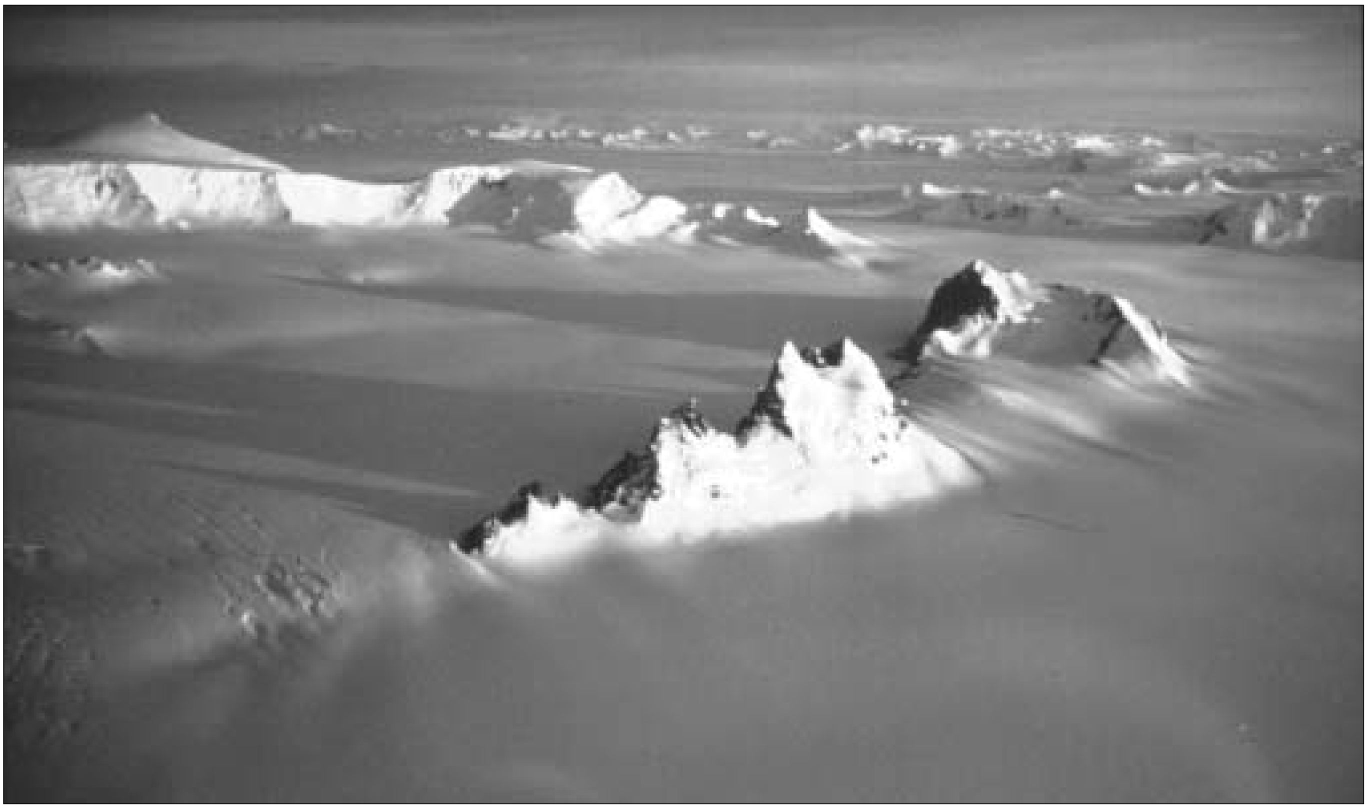
- Discovery of the territory by nationals of a claimant country.
- Geographical proximity to Antarctica by a claimant country.
- Desire to control the exploitation of natural resources within a territory by a claimant country (e.g. whales and the whaling industry in the early 1900s).

The claims of Argentina, Chile and the UK overlap.

The major powers who have not made claims are the United States and Russia. The United States operates Amundsen-Scott South Pole station and has a stake in all the claims. The only country which has close geographical proximity to Antarctica and not to have made a claim is South Africa.

The Antarctic Treaty (1961) sets aside the seven territorial claims. Today 'ownership' of Antarctica belongs to the 27 countries which are currently undertaking significant research in Antarctica and thus have consultative (voting) status under the Antarctic Treaty. These nations decide what regulations should be in place to control activities in Antarctica.

Task 14 The overall population density of Antarctica in winter is 0.00008 people per km^2. Europe has a population density of approximately 65 people per km^2. The UK is one of the most densely populated countries of the world and has a population density of approximately 240 people per km^2. Antarctica still remains virtually unpopulated.



BAS

Nunataks project through the Antarctic ice sheet

Discovery of Antarctica

Worksheet 2

Key ideas
- Perceptions of Antarctica from early history
- Early voyages of discovery (1770–1894)
- The 'heroic age' (1895–1915)
- Antarctic whaling
- The history of the British Antarctic Survey
- Discoveries and challenges in the 21st century

Key skills
- Map interpretation
- Preparation of summary tables
- Summarising text as bullet points
- Board game design
- Flow diagram construction

This worksheet describes the discovery of Antarctica. It is important that students know about the explorers who first visited Antarctica as their discoveries often resulted in subsequent territorial claims by their home nations. The earliest sighting of the continent was by the Russian Bellingshausen, in January 1820, less than 200 years ago. Many early discoveries were made by sealers and whalers who ruthlessly exploited the huge stocks of seals and whales which they found in the Southern Ocean. The British explorers, Scott and Shackleton, made major contributions to the geographical exploration of Antarctica in the early 1900s, but it was the Norwegian explorer Amundsen who was the first to reach the South Pole on 14 December 1911. Much still remains to be discovered in Antarctica. In 1996, Russian and British scientists found a huge lake covering 10,000 km^2, deep under the ice near the Russian Vostok station in the centre of the continent.

Model answers to tasks

Task 1 The map of the world drawn in 1570 shows Antarctica to be much larger than it is known to be today.

In 1570, no human being had ever seen Antarctica. As the name 'Terra Australis Nondum Cognita' (The Unknown South Land) suggests, nothing was known about the continent – the map was therefore based on a combination of hearsay dating back to ancient Greece and the map compiler's imagination. In the fourth century BC, the Greek philosopher Aristotle suggested the existence of a large land mass around the South Pole to 'balance' the land known in the northern hemisphere.

Task 2 The voyages between 1770–1830 which came closest to the Antarctic continent were led by:

Davis (United States), Palmer (United States), Biscoe (Britain), Bransfield (Britain) and Bellingshausen (Russia).

The voyages were dominated by expeditions sailing from the United States and Great Britain, which were the main nations involved in the highly lucrative sealing industry. The expedition led by Bellingshausen was a voyage of discovery undertaken by the Russian Navy. It circumnavigated the Southern Ocean in the search for new sea routes.

Task 3 **Most southerly latitude reached by major early explorers**

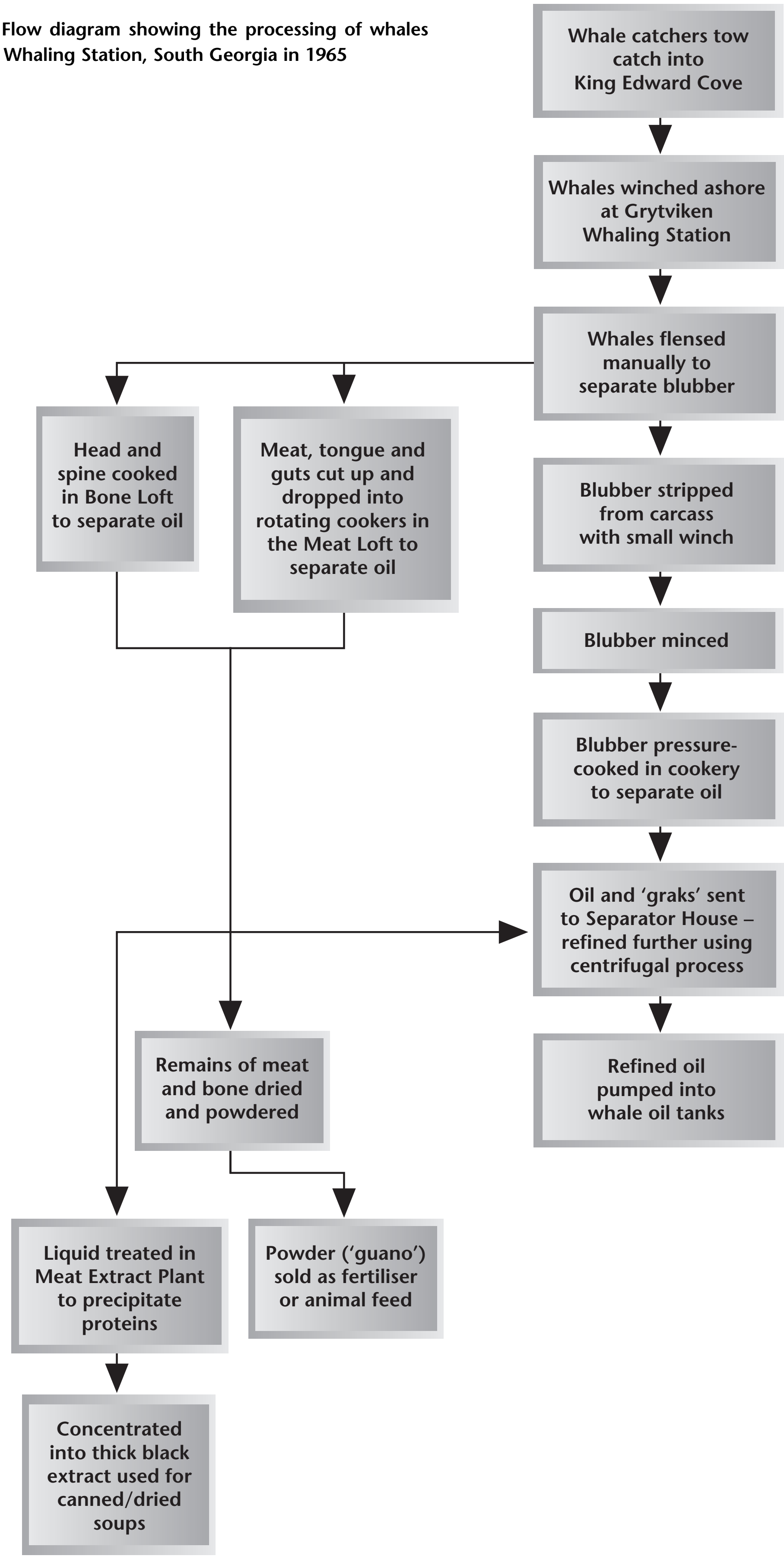
Expedition	Date	Expedition ships	Most southerly latitude reached (descending order)
Borchgrevink	1898–1900	*Southern Cross*	78°50'S
Ross	1839–43	*Erebus* and *Terror*	78°17'S
Bellingshausen	1819–21	*Vostok* and *Mirnyi*	69°53'S
Dumont d'Urville	1837–40	*Astrolabe* and *Zeelée*	66°S

Factors enabling expeditions to get closer to the South Pole included:
- Increased support from Governments, who were motivated by national interests, scientific discovery and commercial profit.
- Enhanced knowledge of Antarctic sea and ice conditions based on the experience of previous expeditions.
- Better design and construction of new ships specially adapted to Antarctic conditions.
- Increased international interest in the exploration of Antarctica after its promotion by the International Geographical Congress in 1895.

Task 4 Reasons why Amundsen was the first to attain the South Pole:
- Amundsen's camp on the Ross Ice Shelf at the Bay of Whales was about 100 km closer to the South Pole than Scott's base camp at Cape Evans on Ross Island.
- Amundsen's successful means of transport to the Pole was dog sledge. As supplies were consumed, the sledges became lighter, and spare dogs were used to feed other dogs. Scott's party painstakingly man-hauled sledges for most of the journey, as dogs, ponies and motorised sledges proved inadequate. Man-hauling was much slower than dog sledge.
- Amundsen left supply depots and markers along his route to mark the return journey. Scott set out using a relay system to lay depots increasingly further south, which, although effective, was much slower.
- Amundsen's sole objective was to reach the South Pole. Scott's expedition was primarily a scientific expedition – during the slow trek to the Pole, maps, sketches, biological and geological collections were made.
- Scott's expedition ended in tragedy due to a combination of severe weather, insufficient food and fuel, and the onset of scurvy caused by the lack of vitamin C in their sledging rations. In addition, morale on the return journey was very low because they had been beaten by Amundsen's party to the Pole.

Task 5 As the board games designed by students are likely to be very different, there is no model answer to the task set. However, key features should include reference to weather and climate, topography, methods of transport, food and fuel, clothing, shelter, equipment, and health.

Task 6 **Flow diagram showing the processing of whales at Grytviken Whaling Station, South Georgia in 1965**



BAS

Living and working in Antarctica

Key ideas
- Supporting human life in Antarctica
- Living on research stations and in the field
- Logistical support
- Food and clothing
- Physical and mental health
- Health risks
- Teamwork and morale
- Gender issues
- Environmental impacts

Key skills
- Table and matrix construction
- Map and text interpretation
- Data comparison and interpretation
- Role play
- Working in groups
- Summarising text as bullet points

Antarctica has no native human population. Students should appreciate that all the essential items people need to survive have to be imported into the continent from outside. These include food, fuel, shelter and clothing. The people who live and work on the continent are nearly all scientists and their support staff. Scientists make up only 30–40% of the population. This is because a wide range of support staff are required to keep research stations, vessels and field projects running. For example, the British Antarctic Survey (BAS) employs 185 scientists out of a total staff of 425, and has one of the highest scientist-to-support staff ratios of any Antarctic operator. Women were excluded from the early expeditions to Antarctica. Now, however, women make a vital contribution and live and work on all the BAS research stations. This worksheet explains how people survive in the harsh environment of Antarctica using case study material from the BAS.

Model answers to tasks

Task 1 **Problems of living and working in Antarctica**

Environmental characteristics	Problems for living and working	Solutions to problems	Costs
Long periods of darkness in winter	Lack of daylight hours for outside tasks in the winter season	Working long hours in the summer season	Lack of sleep and exhaustion in the summer
Low temperatures	Risk of hypothermia and frostbite	Special warm clothing, good food, shelter, heating	High financial support costs. Long supply chain
Remoteness	Isolation for people	Improved communications (e.g. satellite telephone, fax, e-mail)	High financial cost. Limited availability of satellites
High winds	Frequent blizzards. Risk of windchill	Buildings and tents designed to cope with high wind speeds. Careful planning	Poor weather frequently restricts operations
Very low rainfall (dry cold desert)	Lack of freshwater for drinking and other purposes	Snow melting. Desalination of sea water	Water production is energy intensive. High financial costs. Desalination is complex

BAS

Freezing breath forms ice on clothes and beards

The problems identified are due to:

The harsh environment (climate) – lack of daylight hours
– risk of hypothermia/frostbite/windchill
– frequent blizzards

Lack of local resources – freshwater (also food and fuel)

Remoteness – isolation of people

The figure on the far right of Resource LW1 shows the human tolerance of climatic ranges. Within the green 'comfort zone' the body feels comfortable at heights of less than 300 m, with normal indoor clothing, and performing sedentary or light work. Below the 'comfort zone' radiant heat is needed to keep the body warm.

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This means that for humans to live comfortably in Antarctica, considerable resources need to be spent on the insulation and heating of buildings.

Task 2 **Climatic differences between Rothera and Signy**

	Rothera	Signy	Comment
Latitude	67.5°S	60.7°S	Signy is further north than Rothera
Annual mean temperature	-5.2°C	-3.5°C	Rothera is colder than Signy
Annual mean windspeed	21.3 km/hr	14.2 km/hr	Rothera is windier than Signy

Signy has a milder, warmer climate compared to Rothera. As Rothera is colder it is surrounded by sea ice for a much longer period each year than Signy. At Signy sea ice may not form at all in some years. Signy is therefore more accessible by ship.

Task 3 The main accommodation platform at Halley comprises three sections with rooms split according to function. The sections are: services/technical support, living and sleeping.

- Services/technical support – this comprises the generators and workshops. The generators are at the end of the building, beside the open platform, for ease of maintenance and engine removal.
- Living area – this includes the dining room, lounge and bar, kitchen, food store, library and gym.
- Sleeping quarters – there are 20 bedrooms each with a bunk bed, as well as toilets and showers. There are no baths to save space and water. The bedrooms are kept quiet by siting them as far away as practical from the generators and living area.

High risk fire areas are the generators, kitchen and workshops. This is another reason why the bunkrooms are located at the end of the building as far as possible from these areas. Smoking is not allowed in any of the rooms on the platform.

A hospital is provided at Halley as it would be very difficult to evacuate a sick or injured patient in winter because of the station's very remote location and extreme environment. A doctor is employed at the station year-round to ensure that ill or injured staff are properly cared for. In summer, a patient can be evacuated, but this may still take several days to arrange by air.

Emergency rations and supplies, as well as back-up generators, are stored away from the main accommodation platform either on another platform or as part of raised depots on the snow surface. They are kept a safe distance away in case of fire destroying the main platform.

In winter, the station complement at Halley is 17, comprising eight scientists, one doctor and eight support staff. The jobs of the support staff are: generator mechanic, vehicle mechanic, steel erector/builder, cook, electrician, plumber, mountaineering expert, and communications technician.

Task 4 Camping in Antarctica is totally different from that on an organised campsite in the UK. The main differences are:

- Remoteness – scientific parties may operate from camps which are hundreds of kilometres away from the nearest research station. Such parties would usually be supported by aircraft bringing in resupplies.
- Duration of camp – parties may be out camping for up to four months without a break. Depending on the research being undertaken, some parties will operate from static camps but most will work at a number of sites using snowmobiles or aircraft for transport.
- Composition of party – in BAS, field parties usually comprise a two-person team of scientist and mountaineering guide. The job of the guide is to ensure the safety of the party when travelling over dangerous terrain.
- Specialised camping equipment – BAS field parties use large cotton (ventile) pyramid tents. These are capable of withstanding very high winds and low temperatures. The tents can be pitched very quickly in poor weather. They are not fitted with a groundsheet so they can be put up over a casualty, and a party can also dig a snow-hole easily should the tent be in danger of blowing away. A ground mat, inflatable airbed and sheepskin rug are used for insulation when camping on snow and ice. Cooking and melting of snow for water is done on pressurised paraffin stoves.

Extra precautions which need to be taken when camping in Antarctica are:

- Specialised pre-deployment field training (e.g. crevasse rescue, first aid).
- Use of high-frequency radio equipment to maintain daily contact with the home research station.
- Taking an extensive range of mountain rescue equipment, extra supplies and medical kit in case of emergencies.

Task 5 **Comparisons between RRS *James Clark Ross* and RRS *Discovery***

	RRS *James Clark Ross*	RRS *Discovery*
Date launched	1990	1901
Hull type	Steel	Wood
Dimensions	Length – 99.04 m Breadth – 18.85 m Draught – 6.30 m	Length – 52.43 m Breadth – 10.36 m Draught – 4.88 m
Engine speed	Passage speed 12 knots	Passage speed 6 knots
Cargo capacity	1500 m^3 general cargo	390 m^3 general stores
Scientific area	Laboratories 400 m^2	Laboratories 18 m^2
Accommodation	Officers – 11 Crew – 15 Staff on passage – 50	Officers – 12 (some were civilian scientists) Crew – 35
Purpose	Scientific research vessel and cargo carrier	Scientific exploration vessel

Note: Information on RRS *Discovery* is not provided in the worksheets and resources, but is given here for comparative purposes.

Task 6 The energy value of Scott's 1912 rations were higher than present day BAS rations (4593 kilo calories per person per day compared to 4014 kilo calories per person per day). This is because Scott's party were manhauling heavy loaded sledges and would have expended far greater energy than a BAS field party travelling by snowmobile. Scott's rations were not as diverse or as well balanced as those now used by BAS and relied heavily on pemmican (dried beef, fat and cereal). There was also a serious lack of vitamins and minerals in Scott's rations. Improvements in food technology have resulted in a much greater variety of dried and tinned foods now being available which makes modern sledging rations far more palatable and much less monotonous. New technology has also made rations lighter and quicker to prepare.

A vegan does not eat meat, fish or dairy products or drink milk. He or she would have to substitute these items in the BAS rations by

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using a variety of dried vegetables, rice and pasta and vitamin supplements.


BAS

A two-man BAS field party eat inside their pyramid tent

Task 7 Multi-layered clothing will inhibit dexterity when working on machinery and possibly obstruct vision. In addition, care must be taken that clothing does not get entangled with machinery whilst it is running (e.g. toggles on coats getting caught up in engines).

Task 8 List of psychological characteristics needed to winter in Antarctica:
- Self-sufficiency
- Enthusiasm
- Tolerance
- Cooperation ('team player')
- Self-discipline
- Good sense of humour

Characteristics to avoid:
- Intolerance
- Low motivation
- Non-cooperation ('solitary player')

Task 9 Trauma injuries and dental problems together form over 50% of the illness and injuries experienced by BAS staff. Trauma injuries are common because of the hostile environment in which people in the Antarctic work (e.g. freezing temperatures, strong winds and long periods of darkness, and travelling over dangerous crevassed areas and sea ice). Dental problems are common because the proportion of sugar in people's diet is greater than that in the UK. Also at very low temperatures dental fillings can contract and fall out!

Task 10 The danger of hypothermia increases as temperature decreases and wind speed increases. The windchill index drawn in Resource LW1 shows , for example, that a temperature of -10°C is effectively felt as -36°C if there is a wind speed of 35 miles per hour (5 metres per second).

The risks of hypothermia can be reduced by using several layers of clothing which trap warm air between them, with a windproof fabric used as an outer layer.

The condition of hypothermia may not be obvious to someone working in the field because the early signs affect the individual's judgement and behaviour. This can be overcome by 'buddy' checking by colleagues.

Task 11 Teams working in Antarctica go through a number of stages of group dynamics. Awareness of these stages assists Base Commanders and station staff in handling the stresses and strains of living in confined quarters for long periods of time with the same group of people. To explore this idea further it is useful to get students to discuss the group dynamics of their class and to determine what makes a good team.

Task 12 The BAS is an equal opportunities employer. This means that neither men nor women are given an advantage or disadvantage when living and working in Antarctica. Job selection is made on the basis of appointing the best person for the post, not on the person's gender. Women and men winter on all the BAS research stations.

Task 13 According to Greenpeace, the major station environmental impacts are:
- Alteration of rock and soil formations and loss of ice-free areas.
- Destruction of local flora (e.g. moss banks).
- Disturbance of seals and breeding birds.
- Pollution from wastes (e.g. sewage) and fuels, and noise pollution from station activities.
- Loss of specially protected areas.
- Modification of shorelines at coastal sites.
- Smothering of benthic communities by wastes.

Station environmental impacts need to be put in context. Antarctica is a huge continent. There are currently only 25 permanent research stations active on the continent and nearby islands. There are relatively few places in Antarctica suitable for stations or wildlife, and this means that station impacts can be concentrated in important wildlife locations. Whilst all stations have some form of environmental impact, and in some cases local damage can be significant, the scale of the impact on the continent as a whole is very limited. Much more worrying is the massive scale of other human impacts, such as the spring time ozone hole over Antarctica which now covers an area of 26 million km^2.

Station environmental impacts could be prevented or minimised by:
- Restricting the number of stations and/or reducing their size.
- Prohibiting the construction of stations in protected areas.
- Stopping the building of roads between stations.
- Removing all waste and abandoned bases.
- Preventing fuel spills and cleaning them up when they occur.
- Treating sewage discharges.
- Undertaking Environmental Impact Assessments (EIAs) for new developments, including international scrutiny of the proposal as part of the process.


BAS

Blowing snow makes Antarctic travel difficult and increases the risk of hypothermia

Science in Antarctica

Worksheet 4

Key ideas

- The major contribution by Britain to Antarctic exploration and research
- The Discovery Investigations (1925–32)
- International Geophysical Year (IGY) (1957/58)
- The modern age of Antarctic science (1958–today)
- The Scientific Committee on Antarctic Research (SCAR)
- Antarctic research in the UK
- The British Antarctic Survey
- Factors affecting the development of science programmes
- Future science

Key skills

- Classification of drawings
- Summarising text
- Working in groups
- Making a group report
- Role play
- Essay writing

This worksheet explains key episodes in the history of science in Antarctica, and how Antarctic research is currently organised in the UK. Britain has made a major contribution to Antarctic exploration since the earliest days of discovery of the continent over 200 years ago and British scientists continue to play an eminent role in Antarctic research. The British Antarctic Survey (BAS) based in Cambridge is one of the world's best Antarctic research institutes. Also in Cambridge is the Scott Polar Research Institute (SPRI) which has the largest polar library in the world. The coordination of the international research effort in Antarctica is carried out by the Scientific Committee on Antarctic Research (SCAR). Its small secretariat is located in the UK at SPRI. This worksheet examines the factors which affect the development of scientific research programmes. Students are asked to prioritise Antarctic research projects in BAS. Finally, the directions that Antarctic research might take in the future are discussed. This is likely to involve multinational, multi-disciplinary research teams trying to answer 'big questions' of global importance, such as the effects of climate change on the Antarctic ice sheets.

Model answers to tasks

Task 1 **Classification of vessel space on RRS *Discovery* and RRS *James Clark Ross***

	RRS *Discovery*	RRS *James Clark Ross*
Equipment for scientific investigations	Deep-water hydrological machine Lucas sounding machine Deck laboratory	Seismic compressors Gravity meter room Transducer space Laboratories and control rooms Meteorological platform Local area network Computer office Echo sounders Data preparation room
Support for scientific investigations	Sounding platform Pedestal for small Harpoon gun Whaler Norwegian pram Dinghy	Aft and midships gantries Trawl post Hydraulic boom Scientific cranes Scientific power pack room Scientific hold Scientific freezers Trawl winch room Inflatable boats with outboard engines Cargo tender Library Conference room Workboat Explosives store Cool specimen room
Navigation and powering the ship	Lucas sounding machine Chart house Standard compass Chart table Steering compass Steam and hand steering gear Main bunker Main boiler	Engine room – diesel electric engine Stern thruster Bow thruster Integrated bridge system Stabilisation system Main standard magnetic compass Wheelhouse Electronic dynamic positioning system

continued ▶

Task 1 continued

	RRS *Discovery*	RRS *James Clark Ross*
Navigation and powering the ship	Engine room casing and skylight Engine room Sail locker Propeller well Rudder well	Electronic charting and plotting Echo sounders and logs Weather satellite receiver Underway instrumentation and control room
Living accommodation	Stores Galley and kitchen Galley companion Crew space companion Quarters of crew and petty officer Deck cabin Wardroom entrance Bathroom Wardroom companion Freshwater tank Wardroom skylight Wardroom Officers' toilet Galley skylight Skylight to kitchen Skylight to crew space	16 Cabins with toilets and showers Scientists/officers' lounge Chief scientist's suite Scientists/officers' dining room Coffee lounge Duty mess Galley and kitchen Laundry/drying room Toilets Baggage locker Gym Sauna
Safety and security	Anchor davit Searchlight Chain locker Winch house and winch Lifeboat Lamp locker	Lifeboats Emergency satellite beacons Searchlights Hospital and doctor's cabin
Communications	Flag locker Wireless accumulator box Engine-room telegraph Voice tube to engine room	Satellite communications HF and VHF radio Radio room
Other purposes	Deck lights and ventilators Capstan Pedestal for small Harpoon gun Windlass Armoury	Traction winch room Ship's stores crane Main cargo crane Midships gantry Aft crane Gilson winches Darkroom Electronic workshop

Task 2 The International Geophysical Year (IGY) of 1957/58 was highly successful and demonstrated how scientific research in the Antarctic could benefit from international cooperation. IGY led the way for the Antarctic Treaty, which came into force in 1961. Specifically, the Antarctic Treaty:

- Ensures freedom of scientific investigation and cooperation in Antarctica (Article II).
- Requires the free exchange of plans for scientific programmes and scientific data and results, and encourages scientists to be exchanged between programmes when practicable (Article III).
- Obliges the Treaty nations to discuss ways to improve international scientific cooperation at Antarctic Treaty Consultative Meetings (ATCMs) (Article IX).
- Allows only those countries showing substantial research activity in Antarctica to have Consultative (voting) status at ATCMs (Article IX).

Subsequent agreements made by the Treaty nations have all acknowledged and reinforced the importance of scientific research in Antarctica. For example, the Environmental Protocol to the Antarctic Treaty, which entered into force in 1998, designates Antarctica as a 'natural reserve devoted to peace and science'. Specifically, one of the main environmental principles of the Protocol is to give priority to scientific research over other activities in Antarctica, and to preserve Antarctica as a region for carrying out scientific research.

Tasks 3&4 The BAS has recently adopted a new approach to developing its science programme. An internal competition was held to draw out the best ideas from all staff and to focus resources on the most important science areas – the 'big questions'. The competition encouraged the development of new, innovative projects, while maintaining the BAS commitment to critical long-term monitoring activities (e.g. the ozone hole). Selected projects were then developed as full research proposals and put out for external, international peer review by independent expert scientists. Only projects which were rated as outstanding were finally accepted. This new approach has produced an integrated Antarctic research programme which will make a significant contribution to answering questions of global significance in the biological, physical and geological sciences.

Students may wish to adopt one of the successful BAS projects as their own, or they may want to put forward their own ideas.

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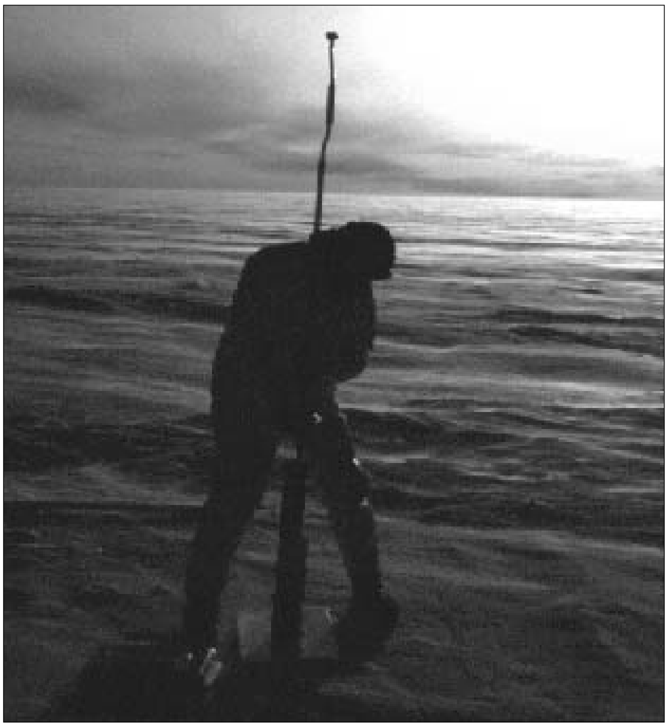
BAS

A glaciologist extracts surface ice core from the Antarctic ice sheet

The following are five of the new BAS projects:
- Signals in Antarctica of past global change
  This interdisciplinary programme will use a variety of methods to study, over a wide range of time scales, how natural climate variability has influenced the climate of Antarctica in the past. Core data from lake, ice and marine sediments will be used to examine the spatial and temporal variations in climate.
- Global interactions of the Antarctic ice sheet
  This programme seeks to understand key processes in the Antarctic ice sheet and how they influence the global system. The programme will study the West Antarctic Ice Sheet, the surrounding ice shelves and interactions with the Southern Ocean, the influence of the ice-seabed interface and the importance of vulcanism.
- Antarctica in the dynamic global plate system
  Antarctica and the once surrounding Gondwana continents provide a rock and marine offshore record that is important in deciphering key geodynamic processes related to the making and breaking of supercontinents and the interaction of tectonic plates through time. The programme will address three questions:
  – What drives the episodic break-up of supercontinents?
  – How do intra continental fold belts form?
  – What are the links between the distribution of the continents and climate change?
- Life at the edge – stresses and thresholds
  This programme will study key species to understand how they survive in a range of extreme habitats. Extremes may be from cold, lack of sunlight because of ice cover, UV radiation and other stresses.
- Management of Marine Ecosystems
  This programme will develop a new model of an integrated ecosystem to provide advice on how to manage exploitation of the marine living resources in the Southern Ocean.

Research into key strategic questions of global significance which are of direct value to society include studies of climate change, changes to the Antarctic ice sheet, and the management of the Southern Ocean ecosystem.

Task 5 Students may not know what sustainable development means. The definition produced by the World Commission on Environment and Development in 1987 is now widely used. It states that sustainable development is: 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs'.

Scientific research plays a major role in providing impartial advice to assist decision-makers in the formulation of sustainable development strategies.

Key points that students should include in their essays are explanations of:
- What are global priorities?
  Issues which are of great importance to the whole of humanity, such as climate change. Such global problems may compromise the needs of future generations.
- Why study global priorities in Antarctica?
  Antarctica is an excellent location for research because it is an unique and unparalleled 'natural laboratory'. It is a sensitive indicator region, where early detection of global change can be picked up. It gives us an accurate picture of past rates of change (e.g. temperature records from ice cores), which can be used to predict future trends. Antarctica is also an integral component of the world's climate and ocean systems. What happens in Antarctica will have impacts worldwide.
- How might funding affect the direction of Antarctic science?
  Antarctic research is expensive (e.g. infrastructure, transportation of people, equipment and supplies) and must therefore have clearly defined goals and priorities. Increasingly, the governments who pay for Antarctic research want answers to 'big questions' addressing global priorities. Also, sources of funding are shifting, with more financial input coming from industry (e.g. insurance companies wanting scientific information to improve the assessment of risk of sea level rise).
- Is sustainable development changing the way Antarctic science is carried out?
  In Antarctica, we are seeing a shift in how science is undertaken, with fewer people going to the continent. The widespread use of remote sensing systems, particularly satellite sensors, means that researchers can carry out much of their work from their desks at home. The Environmental Protocol also requires national Antarctic programmes to reduce the human 'footprint' of their operations. Antarctic science itself is becoming more sustainable.

  Sustainable development research is also required to support the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) which controls fishing in the Southern Ocean. Research is needed to help manage and develop fisheries in a sustainable way, and to create a knowledge base for future exploitation.

Students should realise that although most Antarctic science now examines global priorities, there is still much fundamental basic research being undertaken. Such research can lead to unexpected and important new discoveries, particularly if carried out over a long period of time. For example, in 1998 BAS scientists reported that 'the sky was falling in'. They used 40 years of Antarctic radio sounding data to show that the Earth's upper atmosphere (the ionosphere) had fallen by 8 km. This result is consistent with cooling of the upper atmosphere as a result of increasing concentrations of greenhouse gases, and could be an early indicator of global climate change. Thus, fundamental basic research can make important contributions to the study of global priorities.

The Antarctic Treaty System

Key ideas
- Territorial claims
- The International Geophysical Year (IGY) (1957/58)
- The Antarctic Treaty
- Development of the Antarctic Treaty System
- The Environmental Protocol
- Evaluation of the Antarctic Treaty System

Key skills
- Summarising text
- Map interpretation and analysis
- Text interpretation and analysis
- Working in pairs
- Role play
- Working in groups

Activities in Antarctica are regulated by the Antarctic Treaty (1961) and its associated agreements. The Treaty ensures that the continent is used for peaceful purposes, bans military activities and nuclear weapons testing, and sets territorial claims to one side. This worksheet examines the history of the claims and the problems they created, explains the Treaty and its associated agreements and evaluates the successes and failures of the Antarctic Treaty System over the past 40 years. Forty-three countries have now signed the Treaty, 27 of which carry out scientific research on the continent and therefore have voting status at Treaty meetings. It is important that students have a good understanding of the Antarctic Treaty System. It is a unique international agreement and serves as a global example of how nations can work together to preserve peace, encourage science and protect the environment.

Model answers to tasks

Task 1 The countries involved in major Antarctic expeditions or voyages up until the mid 20th century were:

1772–75 **Britain,** Cook
Voyage of discovery. Sailed further south than anyone before. Discovered South Georgia and the South Sandwich Islands.

1819–20 **Britain,** Smith
Mercantile voyage. Visited and surveyed the South Shetland Islands. Landed on King George Island and took possession for King George III.

1819–20 **Britain,** Bransfield
Voyage of discovery. Visited South Shetland Islands. Discovered north-western coast of Antarctic Peninsula, calling it Trinity Peninsula.

1819–21 **Russia**, Bellingshausen
Russian Navy expedition. Circumnavigation of Antarctica. First sighting of the Antarctic continent in 1820.

1820–21 **USA,** Palmer
Sealing expedition. Visited South Shetland Islands and the Antarctic Peninsula.

1820–21 **USA,** Davis
Sealing expedition. Visited South Shetland Islands. Possibly made the first landing on the Antarctic mainland – Hughes Bay area, Antarctic Peninsula, 7 February 1821.

1822–24 **Britain,** Weddell
Sealing and exploratory expedition. Independently charted South Shetland Islands and South Georgia. Discovered the Weddell Sea and sailed as far south as 74°25’S.

1830–32 **Britain,** John Biscoe
Voyage of discovery. Circumnavigated Antarctica. Discovered Enderby Land. Discovered and annexed land for King William IV calling it Graham Land – southern part of the Antarctic Peninsula.

1837–40 **France,** Dumont d’Urville
French naval expedition. Circumnavigated the earth. Discovered Terre Adélie. Claimed Terre Adélie for France.

1838–42 **USA,** Wilkes
American scientific and exploratory expeditions. Six vessels involved in a circumnavigation of the Antarctic continent.

1839–43 **Britain,** Ross
Royal Navy expedition. Circumnavigated Antarctica. Discovered Ross Island and Ross Ice Shelf. Claimed Victoria Land for Queen Victoria.

1897–99 **Belgium,** De Gerlache
Scientific and discovery expedition. Visited South Shetland Islands. Discovered and mapped Gerlache Strait. First scientific exploration vessel to winter in Antarctica.

1898–1900 **Britain,** Borchgrevink
Scientific and exploratory expedition. First party to winter on Antarctica (10 men) at Cape Adare, Ross Island. First sledging trip using dogs.

1901–04 and 1910–13 **Britain,** Scott
Scientific and exploratory expeditions. During both expeditions attempts were made to reach the South Pole. On the second expedition the South Pole was attained, but Scott and four others died on the return journey.

1903–05 and 1908–19 **France,** Charcot
Scientific expeditions. Both expeditions involved significant surveys of the west coast of the Antarctic Peninsula and discoveries of islands.

1907–09 and 1914–16 **Britain,** Shackleton
Scientific and exploratory expeditions. The second expedition was to make an attempt to cross the Antarctic continent, but failed when the expedition vessel *Endurance* was trapped and crushed by ice in the Weddell Sea and was finally abandoned on 27 October 1915.

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1910–12 **Norway,** Amundsen
Discovery and endeavour. Amundsen and four others were the first to reach the South Pole on 14 December 1911. They all returned safely.

1928–30, 1933–35, 1939–41 and 1946–47, **USA,** Byrd
Discovery and scientific expeditions. The first expedition to use aeroplanes for exploration and surveying. Marie Byrd Land discovered and claimed for the US in 1929. Territorial claims also made during the 1946–47 expedition when a flight over the South Pole was made. The US Government never enforced these claims.

1929–31 **Britain – Australia – New Zealand,** Mawson
Science and discovery expedition. Surveyed the coastline of East Antarctica from Cape Adare to Enderby Island.

1934–37 **Britain,** Rymill
Major surveying programme of the Antarctic Peninsula and offshore islands.

1925–39 **Britain,** Discovery Expeditions
Major marine and oceanography research programmes funded by income from the Southern Ocean whaling industry.

1943–44 **Britain**, Operation Tabarin
Top secret, Royal Navy wartime operation. Two permanent meteorological stations established at Port Lockroy and Deception Island. Some science conducted during winter 1944. The precursor to the Falkland Islands Dependencies Survey, now the British Antarctic Survey.

The above list includes all those expeditions shown in Worksheet 2 on the Discovery of Antarctica. It is not necessarily representative of all countries involved in Antarctic expeditions up until the mid 20th century. Nevertheless, Britain and the USA undertook the vast majority of Antarctic voyages during the early to mid 1800s, primarily as a result of their support for the sealing industry. In the latter part of the 1800s and early 1900s, a number of other countries began to undertake expeditions, notably Australia, France, New Zealand and Norway. During the first half of the 20th century the number of countries engaged in Antarctic activities increased significantly, culminating in the International Geophysical Year of 1957/58.

As a general trend the very early expeditions of exploration and discovery of the late 1700s grew into a significant number of private sealing (and whaling) expeditions during the 1800s. In the latter part of the 1800s and early 1900s science played a more prominent role in Antarctic expeditions, although geographical exploration, claiming territory, and national prestige were also important components. In the 1930s and 1940s, many expeditions were funded by national governments, and political and strategic motives were important factors. These early expeditions were dominated by the major sea-faring nations of the time, including Britain, USA, France and Norway. Today scientific research is the main objective of most government-supported Antarctic expeditions, although most private expeditions go to Antarctica for reasons of adventure.

Task 2 There are seven nations which claim territory in Antarctica: Australia, Argentina, Chile, France, New Zealand, Norway and the UK. See Resource ATS 1.

The reasons for the seven claims are:
Australia: Australia played a significant role in Antarctic discovery. As a result of Sir Douglas Mawson's expeditions in 1929–31, a British Order in Council of 7 February 1933 established Australian Antarctic Territory. Note also the geographical proximity between Australia and her territorial claim.

Argentina: Argentine Antarctic Territory announced 15 February 1943, in response to disputed claims made by Britain and Chile. Argentina regards the Antarctic Peninsula region as a geographical extension of her own country.

Chile: Chilean claim made on 6 November 1940. Like Argentina, Chile regards the Antarctic Peninsula as a geographical extension of her own country.

France: Presidential decree of 27 March 1924 established Terre Adélie. This was as a result of the territorial claim made by Dumont d'Urville on 22 January 1840.

New Zealand: New Zealand played a significant role in Antarctic discovery. A British Order in Council established the Ross Dependency on 27 March 1923. Note the geographical proximity of New Zealand to the Ross Dependency.

Norway: Dronning Maud Land was annexed by Royal Proclamation on 14 January 1939 as a result of whaling expeditions to the region in 1930–31. The Norwegian claim was prompted by a German expedition which overflew the region in 1939 and scattered spear-like markers carrying the swastika over the ice.

United Kingdom: British Royal Letters Patent of 21 July 1908 consolidated the numerous earlier British territorial claims, dating from 1775 onwards, as the Falkland Islands Dependencies. The claim was made to control the lucrative and strategically important whaling industry which was starting up in the South Orkney Islands and the South Shetland Islands. British Antarctic Territory was established by a British Order in Council on 26 February 1962.

Major powers which do not have claims are the United States of America and Russia, although both nations have reserved their right to make a claim should they so wish. A territorial claim to Marie Byrd Land was made by Admiral Richard Byrd on behalf of the US in 1929. However, the US Government has never advanced this. During the 1940s and 1950s territorial claims to Antarctica created international tension. A claim from either of the two superpowers would have added significantly to this problem.

The success of the International Geophysical Year of 1957/58 persuaded the US not to make a claim and instead to call for the internationalisation of Antarctica. This initiative eventually led to the agreement of the Antarctic Treaty on 1 December 1959.

The claims of Argentina, Chile and the UK overlap. The UK claim to the Antarctic Peninsula is based on significant exploration and discovery in the 1800s and 1900s. However, both Argentina and Chile consider the Antarctic Peninsula to be a geographical extension of their countries, and have made their own respective claims. Britain made several unsuccessful attempts to resolve these disputes, through the International Court of Justice, during the 1950s. As a result, the three nations carry out a variety of activities in Antarctica designed to reinforce their territorial claim. For example, both Argentina and Chile have established small permanent settlements in the region, which include banking and postal facilities. Chile encourages the birth of Chilean nationals in Antarctica. The UK has established several administrative functions at British research stations in Antarctica. For example, all of the British stations have Post Offices, which are run by the base staff, and British Base Commanders are also Magistrates.

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Neither the Chilean nor the Norwegian claims have a northern limit. The Norwegian claim also has no southern limit.

The unclaimed sector of Antarctica is in Marie Byrd Land. There are several reasons why this sector has remained unclaimed:

- It is a particularly inhospitable part of the continent.
- Few stations have ever been established in the region and it still remains one of the least visited parts of the continent.
- It was not an important region during the sealing and whaling era.
- It has no geographical proximity to any other country, being adjacent to the Southern Pacific Ocean.
- A territorial claim to the region for the US was made by Admiral Richard Byrd during his expedition in 1929. This has never been enforced by the US Government, but may have deterred other potential claims to the region.
- The Antarctic Treaty entered into force before any further claims could be made on the region and it prevents any more being made.

Task 3 The measures in the Treaty which show that it was signed at the height of the Cold War are Articles I and V. Article I prohibits military activities in Antarctica and Article V prohibits nuclear explosions and the disposal of radioactive waste. Also Articles II, III and VII are indicative of the international politics of the time, as they respectively require freedom of scientific investigation and information exchange and free access for the international inspection of all stations, ships and aircraft.

Article VI of the Treaty states that it covers the area south of 60°S, including the ice shelves. It does not cover the high seas and the deep-sea bed around the Antarctic continent. The major implications of these omissions are in respect of the exploitation of marine resources (e.g. sealing, fishing and offshore oil and gas production). This has required the Treaty nations to negotiate additional international agreements in order to conserve Antarctic seals, marine living resources and mineral resources, although the latter agreement has never entered into force.

The key criteria for nations to participate in Antarctic Treaty Consultative Meetings is given in Article IX which limits attendance to those countries undertaking substantial research activity in Antarctica. In the past, this was taken to mean that a country had to establish a scientific station or despatch regular scientific expeditions. This is a major expense which many poor countries cannot afford. Also, many less developed countries do not have the scientists available to run an Antarctic research programme. Recently, attempts have been made by some countries to overcome this problem by joining the research programmes of other nations.

Article IV of the Treaty sets aside existing territorial claims. It neither recognises nor prejudices these claims, and it prohibits any new claims being made. The advantage to this approach is that it allows the Treaty nations to 'freeze' the existing claims and dissolves the political tensions that they create. The Treaty nations can thus concentrate on positive actions which everyone can agree. The disadvantage is that Article IV does not solve the problem but holds the issue in abeyance.

The overriding goal of the Treaty is to preserve Antarctica as a continent for peace and science. The key to doing this has been to internationalise the continent by setting aside territorial claims. The Treaty fails to address the issues of resource exploitation or environmental protection. This is because they were not considered to be important issues when the Treaty was negotiated in the late 1950s. The Treaty nations have dealt with these issues by negotiating further agreements to conserve flora and fauna, seals, and marine living resources. Most recently, the Treaty nations have acted to protect more comprehensively the Antarctic environment and have adopted the Environmental Protocol.

Task 4 The effects that the introduction of non-native species might have on Antarctic animals and plants include:

- Predation of native species (e.g. the South Georgia pipit by introduced rats).
- Destruction of natural habitat (e.g. overgrazing and trampling of lichens and other flora by reindeer introduced on South Georgia) leading to soil erosion.
- Potential introduction of disease.

Sealing has not returned to Antarctica for a number of reasons:

- The fur seal was virtually eradicated in Antarctica by the sealing industry during the late 1800s and early 1900s. The seal only began to recover in the 1970s, and has now reached, and possibly exceeded, its former population level.
- All species of seal living south of 60°S are now protected by agreements under the Antarctic Treaty System. For example, the killing of both Ross and Antarctic fur seals is prohibited by both the Convention on the Conservation of Antarctic Seals and the Environmental Protocol.
- Since the 1960s there has been a marked change in public attitude in the UK and other developed countries towards the killing of seals for their fur or other body products. Many people see sealing as cruel and unnecessary. Also, people's opinions have been swayed by the protest campaigns carried out by non-governmental environmental pressure groups, such as Greenpeace, against sealing in the Arctic.

A bull elephant seal (right) is much larger than the cow (left)

The 'ecosystem approach' as used by CCAMLR considers not only the impacts of exploitation on the target species, but also takes into account the potential impacts on the prey and predators of that species. Such a holistic approach, which considers the impacts on the Antarctic marine ecosystem as a whole, ensures that the likely effects on all links in the food chain are properly examined. Thus the catch of a particular species of fish is regulated both to conserve its stocks, and also to protect the seals and seabirds which prey on it.

Task 5 The political positions taken by Greenpeace, Australia and the UK were:

- Greenpeace – Greenpeace took the view that Antarctica should be declared a 'World Park' where mining would be prohibited from taking place, and other human activities would be strictly controlled to prevent environmental impacts. Greenpeace has

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BAS

BAS scientist carrying out a geological investigation using a hammer drill. Scientific minerals research is permitted by the Environmental Protocol

long argued that Antarctica should be protected as the world's last great wilderness.

- Australia – Initially, Australia took the view that there should be a regulatory framework to control mining in Antarctica and thus took part in the negotiations over CRAMRA. Ultimately, however, Australia changed its view and decided not to sign CRAMRA in 1989. This was as a result of a combination of factors, including: intense pressure from environmental pressure groups; the Exxon Valdez oil spill in Alaska on 24 March 1989 which demonstrated the damage pollution can do in the polar regions; the need for the ruling Labour Party to attract the 'green' vote in the 1989 Australian general election; the potential threat to Australian sovereignty in Antarctica because of the lack of preferential access by claimant states to mineral resources given in CRAMRA; and the absence of royalty payments in CRAMRA for mining on Australian Antarctic Territory.
- UK – The UK took the view that mining in Antarctica was acceptable provided a sufficiently stringent environmental protection regime was in place. The UK considered that it was very important for the Antarctic Treaty nations to agree a regime before mining began as unregulated and uncontrolled minerals activity had the potential to cause serious environmental and political problems.

Less developed countries, who are not part of the Antarctic Treaty System, have regarded it as a cosy, exclusive club of rich nations controlling a massive continent which is rich in natural resources. In the past, Malaysia has led a campaign at the United Nations that Antarctica should be part of the common heritage of mankind and that its natural resources, including minerals, should be shared amongst all the world's nations.

For CRAMRA to come into force it had to be signed and ratified by all of the Consultative Parties, including all seven of the claimant nations, which had participated in the negotiations. The decision by first Australia and then France not to sign the convention put the agreement into severe trouble. However, the Convention's final demise was provided by New Zealand who decided that it would not ratify the Convention, even though it had signed. As the ATS operates by consensus, the dissent of New Zealand was all that was required to prevent CRAMRA from entering into force.

CRAMRA took seven years to negotiate and was a well thought out agreement which contained tough measures to protect the Antarctic environment. The Convention ensured that if minerals activities did take place they would be judged against rigorous environmental standards; that agreed means would be in place for minimising and monitoring the impacts of mining; and, if necessary, for suspending or cancelling mining activities. Most importantly, no mining could take place unless all the Parties agreed that there would not be a risk to the environment. However, those who were opposed to mining in Antarctica on principle considered CRAMRA a badly flawed regime. Opponents considered that the overriding purpose of the Convention should have been to stop mining, rather than to regulate it.

Task 6 The main principles that underlie the Protocol are:

- All activities in Antarctica are to be planned and conducted so as to limit adverse impacts on the environment.
- No proposed activity can proceed unless sufficient information is available to determine that the impact of the activity on the environment is acceptable.
- The impacts of ongoing activities must be regularly and effectively monitored.
- Priority is given to scientific research.

Task 7 The purpose of this class exercise is to compare consensus against majority voting.

The key points that should emerge from the exercise are:

- It is harder to reach agreement through consensus.
- Agreement reached by consensus is likely to be weaker than that achieved by majority voting.
- Reaching consensus is likely to take much longer than making decisions by majority voting.
- Agreements reached through consensus should be better thought through and take account of everybody's views.
- Reaching consensus means that decisions will have the support of all concerned and are unlikely to be rejected and more likely to be implemented.

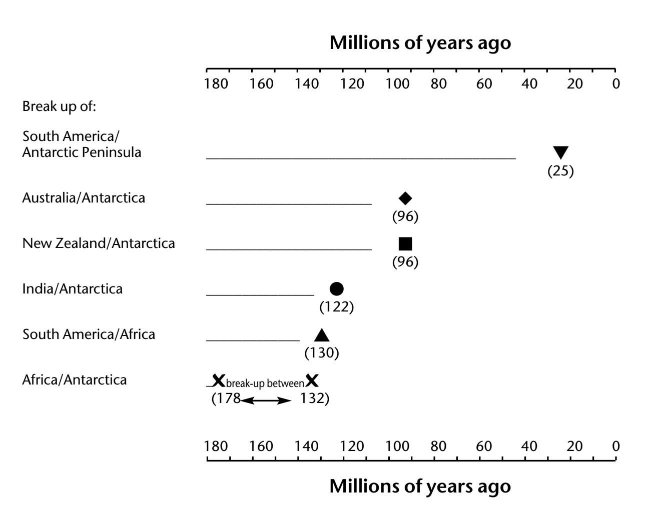
Key ideas
- The supercontinent – Gondwana
- Continental drift
- Mantle plumes
- Palaeoclimates
- Volcanoes of Antarctica
- Meteorites
- Minerals in Antarctica

Key skills
- Map interpretation
- Time line diagram construction
- System diagram construction
- Summarising text

Antarctica is extremely important to the science of geology because it formed the centre of an ancient supercontinent called Gondwana which also included South America, Africa, India, Australia and New Zealand. The study of Antarctic rocks and fossils therefore helps geologists to understand the geological histories of all the southern continents. Gondwana started to break up 180 million years ago and the separate continents drifted apart on different plates over the next 150 million years. Geologists are still uncertain exactly how the break up took place, and some suggest it was caused by abnormally hot upwellings of magma, or mantle plumes, from deep below the Earth's surface. This worksheet introduces students to the supercontinent of Gondwana and the concepts of continental drift and mantle plumes. Meteorites in Antarctica are briefly discussed. Finally, the evidence for mineral resources in Antarctica is examined. However, students should be made aware that mineral resource activities in Antarctica are prohibited under the Protocol on Environmental Protection to the Antarctic Treaty which was agreed in 1991 and which came into force in 1998.

Model answers to tasks

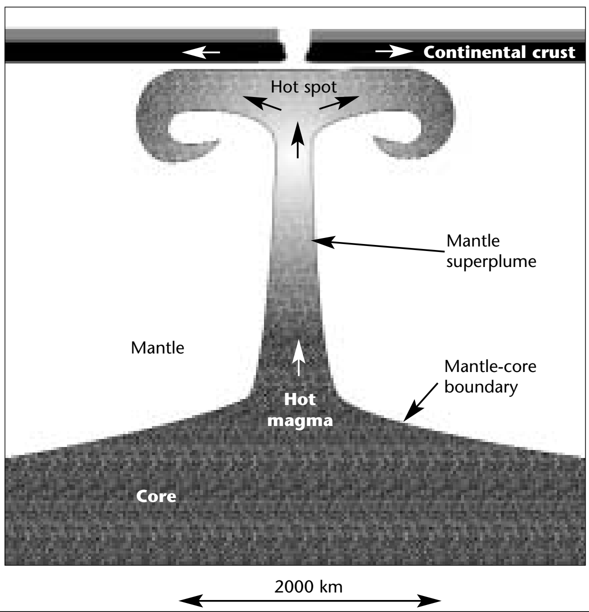
Task 1 **Time-line diagram charting the break-up of Gondwana from 180 million years ago to present**



BAS

The effects of Gondwana break-up on the climate, flora and fauna of Antarctica would have included:
- Progressively greater isolation of the Antarctic flora and fauna so that species evolved separately from those on other continents.
- Antarctica finally reached its polar position about 100 million years ago, but the climate was still relatively warm. The principal adaptation needed, particularly by the flora, would have been to the extreme seasonality of long periods in winter without sunlight.
- The last continental separation, from South America at 25 million years ago, led to the opening of the Drake Passage. This had the following effects:
  - The circumpolar current developed and completed the climatic isolation of Antarctica which began to cool;
  - Mountain glaciation developed and gradually spread to lower altitudes eventually producing the continental ice sheet and ice shelves;
  - Cooling of the ocean around Antarctica led to the formation of the circumpolar front;
  - Many species became extinct as the climate cooled and habitats were overrun by the ice sheet;
  - Other species adapted to the colder temperatures;
  - Adaptation also by terrestrial flora and fauna to extreme seasonal variations in temperature.

Task 2 **Annotated sketch diagram showing how superplumes could have caused continental break-up**



BAS

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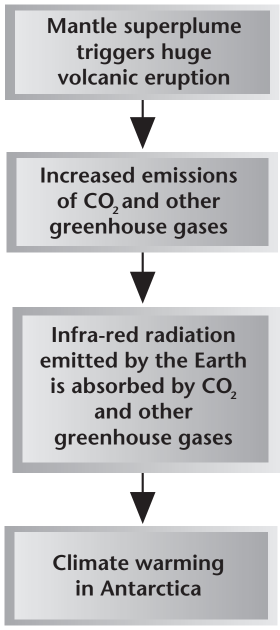
Superplumes appear to originate at the mantle-core boundary. Solid mantle rises quickly towards the surface, decompresses and melts. Lavas are then erupted out, such as the lava fields of the Deccan Plateau of western India. There are doubts among some geologists as to whether superplumes would actually have had sufficient energy to initiate the continental break-up of Gondwana. However, it is generally accepted that convection in the mantle maintains plate tectonic movement of continents.

Task 3

Simple system diagram showing past climate change in Antarctica, possibly caused by superplumes



BAS

Fossil trees found in Antarctica from the Cretaceous period (135–85 million years ago) show that the continent was much warmer than it is now. It is apparent that at this time there were vast forests comprising many types of conifers and ferns. The prolific biological activity of the forests, coupled with marine activity in the Southern Ocean, would have resulted in more CO_2 uptake and eventually helped to reduce temperatures. Antarctica also cooled after the last continental separation from South America at 25 million years ago. Once the Antarctic Circumpolar Current developed, it cut off tropical warmth and brought moisture which precipitated as snow on the cooling continent. The high Antarctic landmass kept the snow frozen and temperatures fell further eventually producing a massive ice sheet.

Task 4 Minerals including gold, silver, iron and low grade coal have been found in Antarctica. These mineral occurrences do not necessarily mean that the concentration of the mineral is sufficient that it could be worked at a profit. If a profit cannot be made then the resource is not economically viable. The concentration of an economic mineral in Antarctica would need to be significantly greater than in other areas of the world because of the great expense and tremendous difficulties of exploitation.

The further knowledge about a mineral occurrence that is needed before its viability as a resource can be assessed include:
- The percentage of the required element (e.g. gold or another metal) in the mineral's composition.
- The percentage of the rock outcrop composed of the required mineral.
- The volume of the outcrop estimated from its area and height and/or depth.

These data would indicate the amount of the element that is present in a mineral occurrence. This is the basic geological assessment of the resource. Further data would then be needed to determine the economic viability of mining. This would include:
- The cost of extracting the mineral.
- The cost of shipping the mineral to a refinery for processing.
- The quantity of the element (e.g. metal) that could be extracted from the mineral.
- The market value of the element obtained.

With this information it would then be possible to calculate the expenditure required to exploit the mineral occurrence and the income that would derive. If the income is greater than the expenditure plus the required profit margin, then the occurrence will be an economically viable resource.

The extra knowledge needed to commercially exploit minerals in Antarctica is unlikely to be acquired in the near future as the Environmental Protocol prohibits mineral resource activities. This prohibition can be reviewed by those nations that have ratified the Protocol after 50 years, or earlier if they all agree to do so. Scientific research investigating minerals in Antarctica is permitted by the Environmental Protocol. However, such research will normally involve only identifying the presence of a mineral, estimating its possible extent, and determining its formation. Very much greater detail would be needed about a mineral occurrence before it could be exploited commercially.

The technical problems in exploiting minerals in Antarctica are immense, with the extreme climate and harsh environment making mining far more difficult and expensive than elsewhere in the world. Problems include:
- Lack of daylight in winter
- High wind speeds
- Freezing temperatures
- Remoteness
- Lack of water
- Very high logistical costs
- Ice cover and depth.

Exploiting hydrocarbons (oil and natural gas) off-shore of Antarctica on the continental shelf would be much more difficult that the North Sea and Alaska for several reasons. Among these are the fact that the average water depth over the Antarctic continental shelf is 500–1000 metres, very much greater than other continental shelves around the world. Very large icebergs (often more than 100 km^2 in area) would be a constant threat to drilling rigs and production platforms. Sea ice would limit tanker access to production wells and also threaten drilling rigs and production platforms. It is likely that none of these problems is insurmountable, but the technology is not currently available.

In the reconstruction of Gondwana, the Falkland Islands lie between South Africa and Antarctica. It would be reasonable to conjecture that if oil is discovered on the Falkland Plateau then it may also be present on other parts of the continental shelf of Gondwana that were formally adjacent. This would mean that the continental shelf of Antarctica might also contain major deposits of oil and gas. The prospect of major oil and gas reserves in Antarctica might encourage some Treaty nations to seek a review of the prohibition on minerals resource activity agreed under the Environmental Protocol.

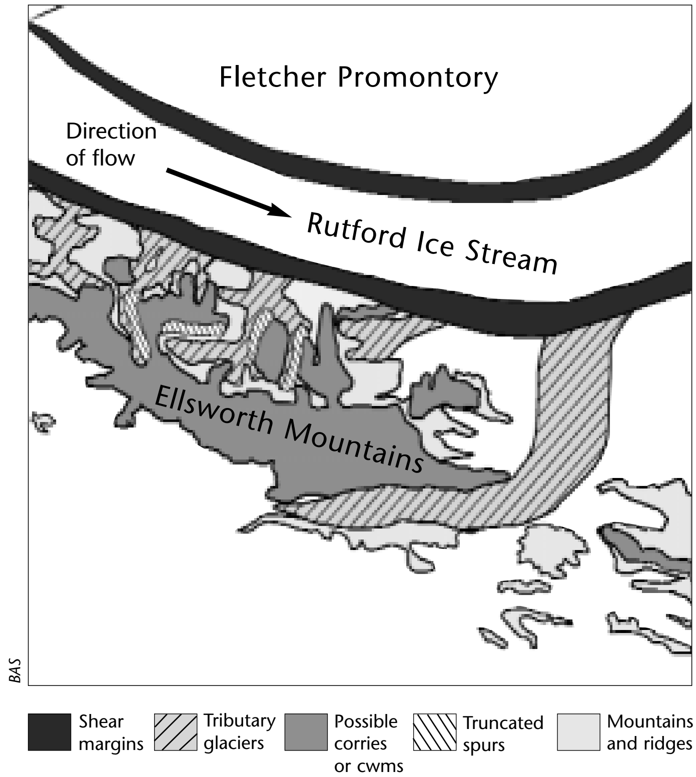
Key ideas
- Ice sheets in Antarctica
- Ice streams
- Ice shelves
- Sea ice
- Effects of climate change on ice sheets
- Ocean circulation and ice sheets

Key skills
- Satellite image interpretation
- Diagram construction and annotation
- Map construction and interpretation
- Sketch map preparation
- Summarising text
- Essay writing

Antarctica is a continent of snow and ice. Students may not be aware that over 99% of the continent is covered by massive ice sheets, in places up to 4700 m thick. Huge floating ice shelves fringe much of the continent, with the Ross and the Ronne-Filchner ice shelves each being larger than the British Isles. In winter, much of the Southern Ocean is covered in sea ice, reaching an annual maximum of around 20 million km² in early October and totally encircling Antarctica. Traditional geographical textbooks have tended to focus on glacial geomorphology, but this worksheet examines how Antarctic ice sheets influence the rest of the world through climate, sea level and oceanic circulation. If the West Antarctic Ice Sheet were to collapse then world sea levels would see a major rise of about 5 m. The expert scientific consensus is that there is a low probability of a major collapse of the main ice sheet during the next 100 years. However, this low probability must be balanced against the severity of the possible worldwide impact. It is important therefore that students realise the linkages between the Antarctic ice sheet and possible future sea levels around the UK.

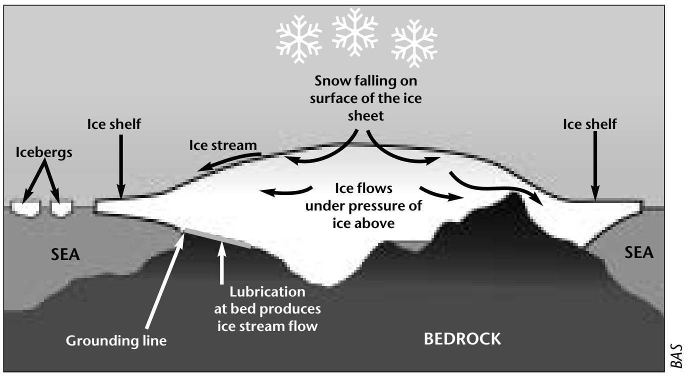
Model answers to tasks

Task 1 Satellite image interpretation of the Landsat image of the Rutford Ice Stream

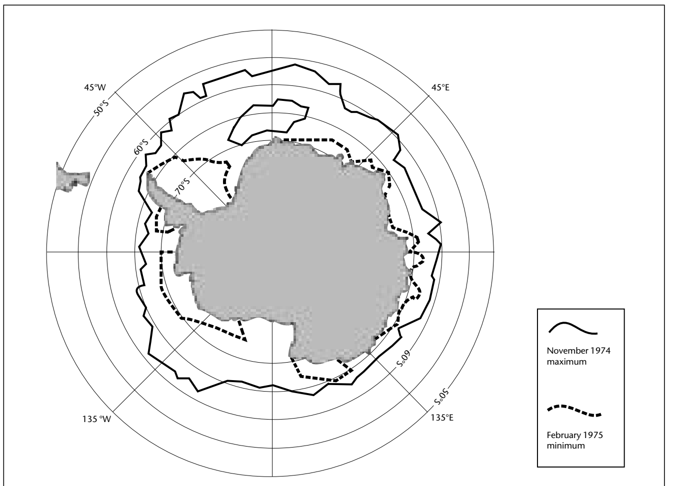


You can tell the direction of flow of the Rutford Ice Stream by the sharp deflections of the tributary glaciers as they enter the main ice stream from the Ellsworth Mountains. These deflections show that the ice stream is running from west to east (left to right) across the Landsat image.

Task 2 Cross section of ice sheet



Task 3



Sketch map of the seasonal limits of sea ice

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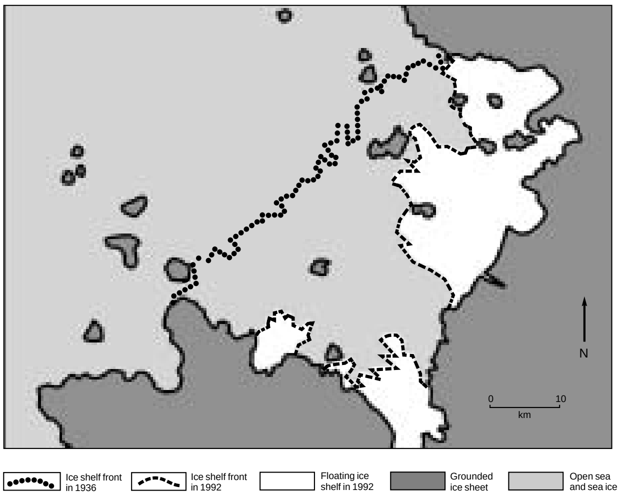
The difference in area between the sea ice extent in November 1974 and February 1975 is about 13 million km^2. This compares with an average value of 17 million km^2 based on the figures given in Resource ICE1. The polynya seen in the November 1974 image accounts for about 0.5 million km^2. The difficulty of knowing where the land-based ice ends and sea ice begins adds to the error in the calculations. Also, sea ice varies in its surface coverage and at low coverages it is difficult to determine what is sea ice and what is open water.

Task 4 The total area of ice lost from Wordie Ice Shelf between 1936 and 1992 is about 2700 km^2. Wordie Ice Shelf has broken up because temperatures in the region of the Antarctic Peninsula have increased by about 2.5°C since the 1940s. Scientists at BAS have shown that there is a climate limit for ice shelf viability related to Antarctic summer temperatures. Regional warming is moving the limit of ice shelf viability further south.



Sketch map of the retreat of Wordie Ice Shelf between1936 and 1992

BAS

Task 5 If the West Antarctic Ice Sheet were to melt it would raise global sea level by between 4 and 7 m. The impact would be catastrophic for small, low-lying island nations and for countries with big coastal populations such as Bangladesh. The UK would also be badly affected with flooding of low-lying coastal areas (see map shown in Resource N5).

Most of the base of the West Antarctic Ice Sheet rests on land below sea level and is held down, or grounded, by its own weight. However, at the edge of the ice sheet are two massive ice shelves – the Ross and Ronne-Filchner ice shelves – which float on the sea.

Some scientists believe that the Ross and Ronne-Filchner ice shelves help to protect and stabilise the West Antarctic Ice Sheet. If the ice shelves collapsed due to climate change, then there could be a surge in the ice sheet fed by fast moving ice streams draining from the interior and the ice sheet could disintegrate by rapid calving in a few hundred years. Sea level rise could reinforce melting as it would allow water to work its way under the ice sheet moving the grounding line – the boundary between floating ice and that sitting on the bedrock – inland possibly causing a runaway collapse of the ice front.

Other scientists are not convinced that the West Antarctic Ice Sheet will disintegrate rapidly and believe that melting will happen slowly over thousands of years and have little impact. Recent research has shown that the ice sheet has been steadily and slowly retreating over thousands of years. Some scientists believe that this natural retreat will continue for a further 7000 years until the ice has melted, and can only be halted by the onset of another ice age. Human induced global warming might not have any effect on the ice sheet. Indeed, climate change could actually cause the ice sheet to thicken. Global warming in the southern hemisphere will produce warmer air which can carry more moisture and this is likely to cause more snowfall in Antarctica. Thus the ice sheet in the interior of the continent could well build up.

The Intergovernmental Panel on Climate Change (IPCC) considers that the likelihood of a major sea level rise by the year 2100 due to

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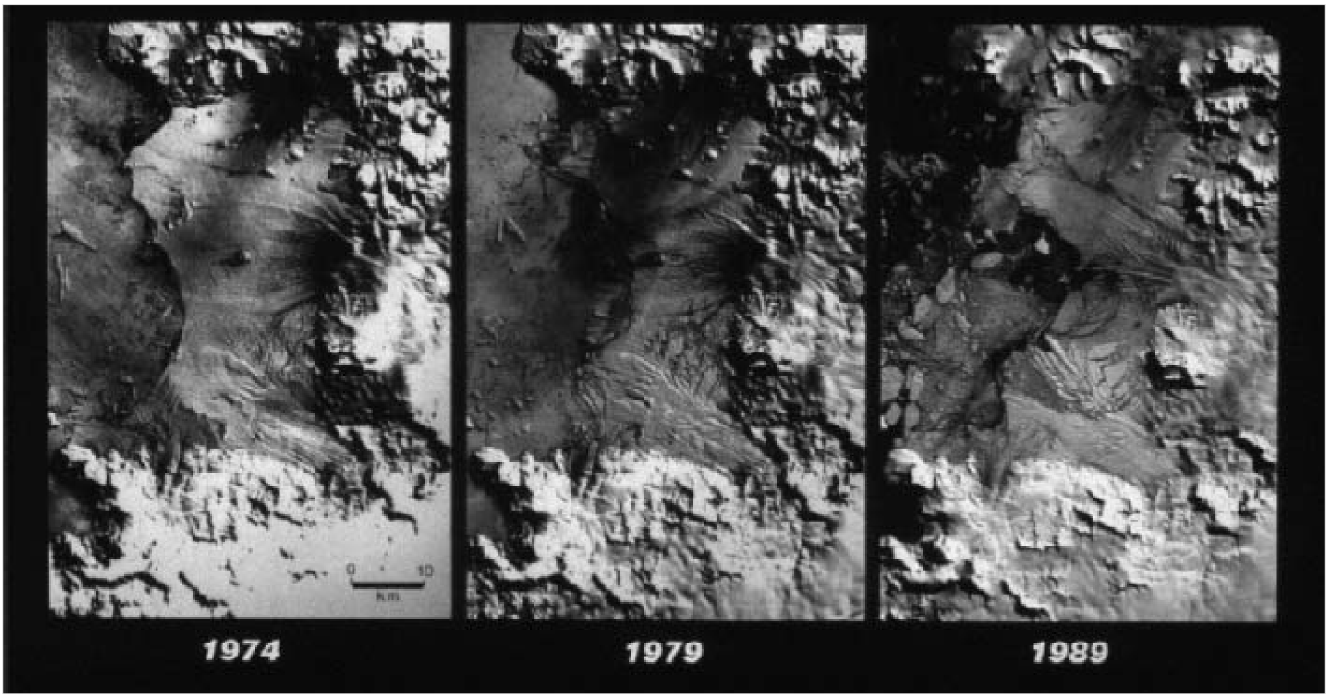
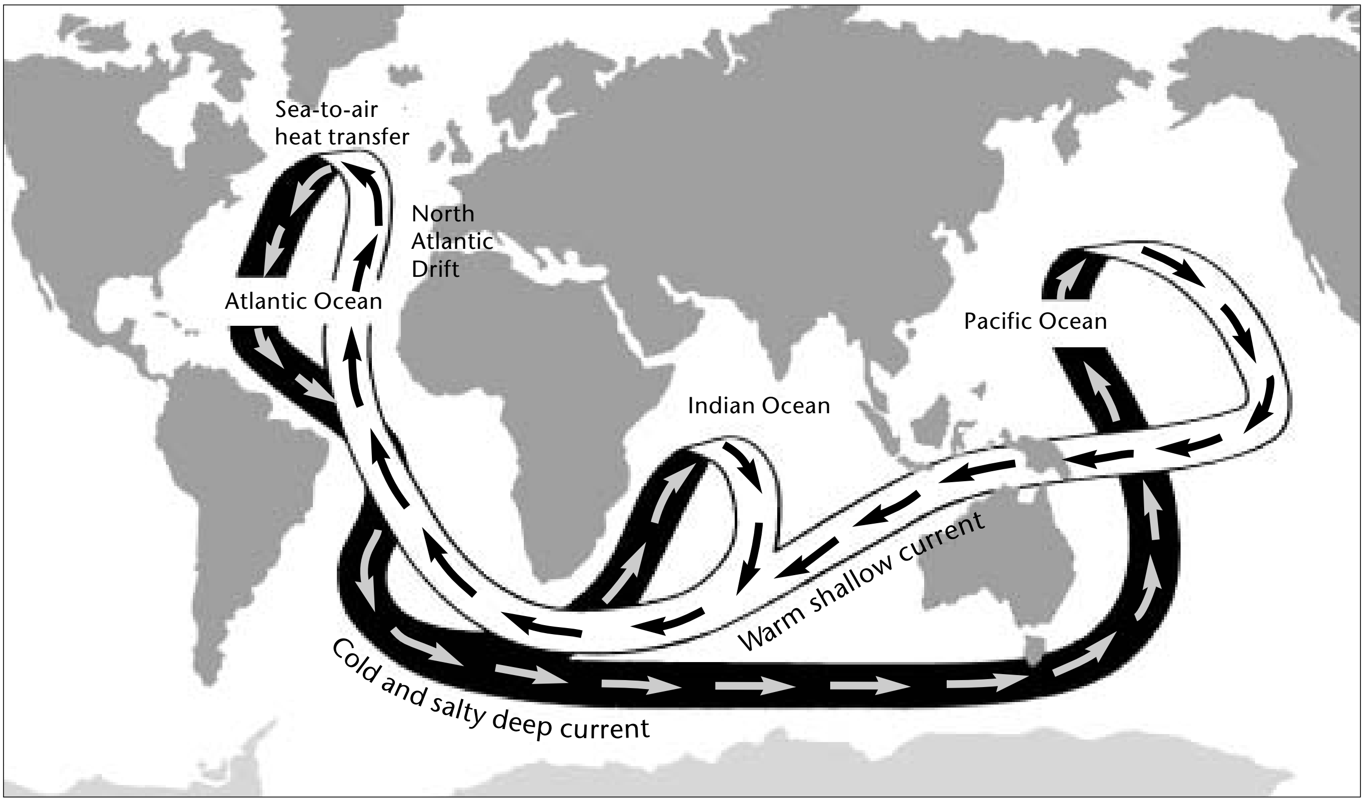


BAS/EOSAT

Landsat satellite images showing the progressive collapse of Wordie Ice Shelf from 1974 to 1989

Sketch map of the major ocean currents comprising the thermohaline circulation or ocean conveyor belt



BAS

Task 5 continued
a collapse of the West Antarctic Ice Sheet is low. However, the IPCC has also declined to take into account melting of the entire Antarctic ice sheet in its sea level rise predictions because it has been impossible for scientists to say with any degree of certainty how much melting might take place, and if melting might be compensated by the extra snowfall over the continent. The lack of certainty and the severity of the possible impact justifies the need for further extensive research into understanding the behaviour of the entire Antarctic ice sheet.

Task 6 The climate of Britain is warmed by heat from the tropics transported to our shores in a massive surface ocean current – the Gulf Stream or North Atlantic Drift. Our climate is therefore much milder than other locations at a similar northern latitude, such as the east coast of Canada.

The North Atlantic Drift forms part of a much larger oceanic heat transport system known as the 'thermohaline circulation' (THC). The THC consists of a continuous 'conveyor belt' with warm shallow currents in one direction balanced by cold and salty deep currents moving in the opposite direction (see diagram). The 'conveyor belt' is driven largely by the production of cold, dense (salty) water in the Arctic and Antarctic.

In Antarctica, cold, salty water is produced when sea ice is formed close to floating ice shelves. This water sinks because of its high density and after mixing with water melted off the base of the ice shelves, it forms Antarctic Bottom Water. The largest volume is produced in the Weddell Sea, off the Ronne-Filchner Ice Shelf. The Antarctic Bottom Water moves away northwards along the continental shelf and into the Southern Ocean from where it influences much of the world's oceans.

Changes in the production of sea ice in the polar regions could alter the amount of dense, cold water supplied to the deep ocean currents of the THC and thus affect our own climate. There is strong evidence that such changes have occurred in the past. For example, rapid cooling occurred in Britain at the end of the last Ice Age about 10,000 years ago. Scientists believe that freshwater input from the rapid melting of the North American ice sheet at that time may have 'turned off' the North Atlantic Drift causing a major reduction in temperatures of up to 10°C in north west Europe.

Some complex computer simulation models also show disruption to the North Atlantic Drift due to enhanced melting of the Greenland ice sheet caused by global warming. If this were to happen, the climate of Britain would change dramatically. In particular, winters would become much colder. Such predictions are highly speculative as the processes controlling the THC are poorly understood and very complex. However, it is clear that changes in sea ice and ice sheet melting in the polar regions could have a major influence on the future British climate.

BAS

The RRS *James Clark Ross* working in heavy sea ice. Global warming could result in less sea ice around the coast of Antarctica

The Antarctic climate

Key ideas

- Variation of Antarctic climate
- Climate change over geological time
- The use of ice cores in studying past climates
- Current climate change in Antarctica
- Global warming and greenhouse gases
- Future global temperature trends

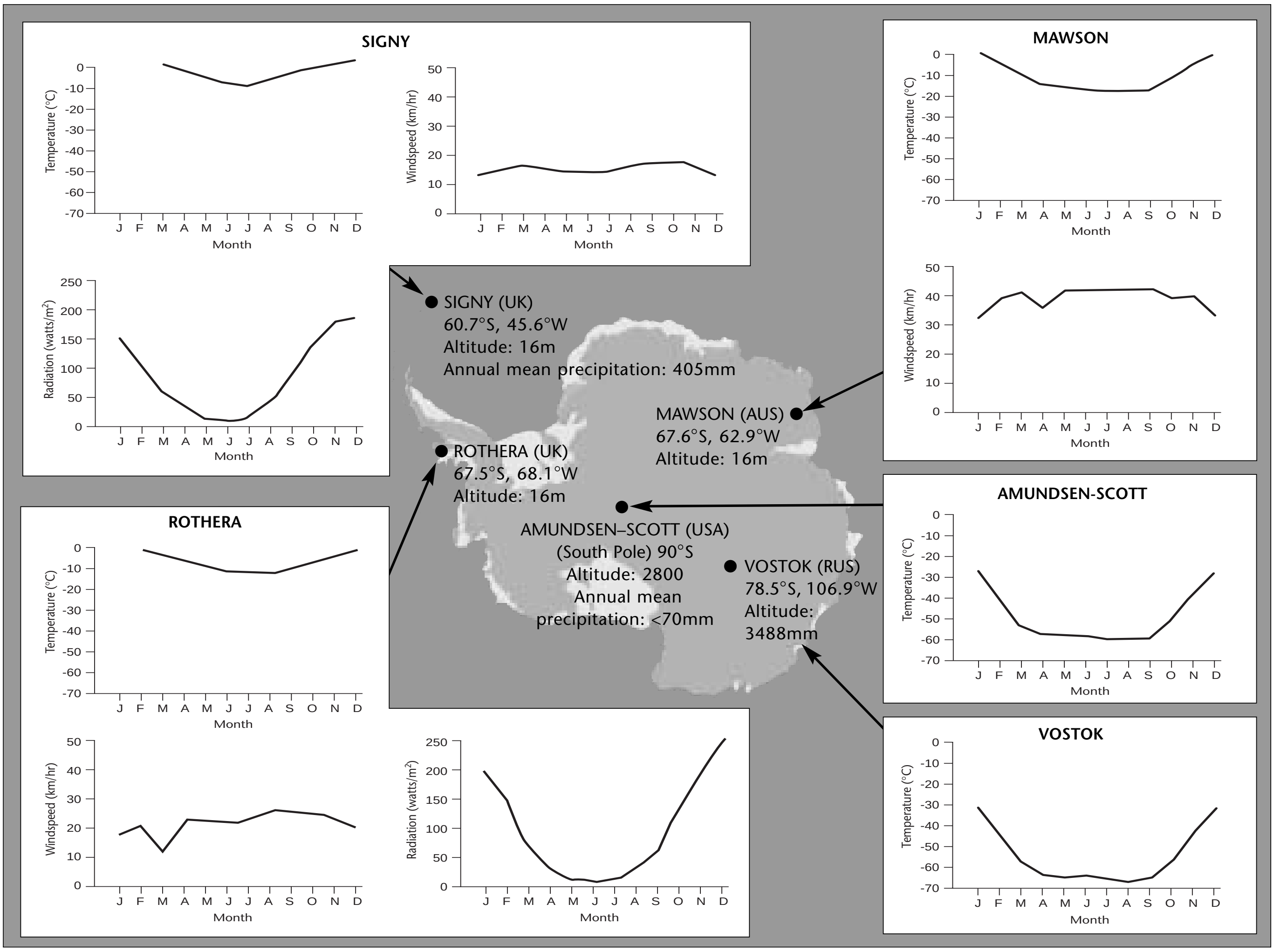
Key skills

- Analysis of climate data and graphs
- Map and graph construction and interpretation
- Summarising information using bullet points
- Statistical data analysis
- Summarising text

Antarctica is the coldest and driest continent. Surface temperatures in Antarctica depend on latitude, height and distance from the sea. Mean average winter temperatures in the high interior are well below -40°C, and on average rise to only about -25°C in summer. The low coastal areas are warmer, with means of -10 to -20°C in winter, and temperatures of around freezing in summer. Winds can be severe, particularly near the coast. Cape Denison (67°S, 142°E) on the south coast of East Antarctica is the windiest place in the world, with an average annual windspeed of 68 km/hr. The high Antarctic plateau is effectively a desert, with annual precipitation, all in the form of snow, of less than 50 mm. The climate of Antarctica varies spatially across the continent and has changed dramatically over geological time and will change in the future. This worksheet introduces students to the Antarctic climate and provides them with a wide range of present and past climatic data to analyse and interpret. Students are asked to examine the evidence for current climate change in Antarctica and to forecast future changes due to global warming.

Model answers to tasks

Task 1 **Climate graphs for Amundsen-Scott, Vostok, Mawson, Rothera and Signy research stations**



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Summary of climate for Amundsen-Scott, Vostok, Mawson, Rothera and Signy research stations

	Amundsen-Scott (USA)	Vostok (Russia)	Mawson (Aus)	Rothera (UK)	Signy (UK)
Latitude	90°S: winter darkness between April–August	78.5°S: winter darkness between May–July	67.6°S: close to Antarctic Circle. Few days in June without daylight	67.5°S: close to Antarctic Circle. Few days in June without daylight	60.7°S: maritime sub-Antarctic. No days without daylight
Altitude	2800 m: high and very cold – average temperature -49°C	3488 m: very high and excessively cold – average temperature -55.3°C	16 m above sea level – average temperature -11.2°C. Steep coastline promotes strong katabatic winds	16 m above sea level – average temperature -5.2°C	16 m above sea level – average temperature -3.5°C
Distance to the sea	1300 km: dry with little precipitation. Total annual precipitation <70 mm	1300 km: dry with little precipitation	0 km: snow and rain with open water in summer	0 km: snow and rain with open water in summer, and often in winter too	0 km: surrounded by sea ice in winter. Cloudy and wet. Total annual precipitation 405 mm
Proximity to ocean currents	>3000 km in winter to edge of pack ice	>2500 km in winter to ice edge	> 1000 km to open water in winter	<<500 km to open water in winter	Can often be surrounded by pack ice in winter

The South Pole is not the coldest place in Antarctica because it is not the highest location, and is not at the centre of the continent.

Task 2 Ice cores can be dated and detailed records of past climate change deduced by carefully melting the ice and analysing the ratio of natural isotopes of oxygen and hydrogen in the water molecules.

BAS

A scientist working on an ice core in the ice chemistry laboratory at BAS, Cambridge

Summarised as a series of bullet points, the dating technique is as follows:

- Snow and ice are both forms of water (H_2O).
- Water can contain oxygen with different atomic weights; the technical term for the different forms is 'stable isotopes'. Ice core dating usually involves examination of two forms of oxygen – O^{16} and O^{18}. The most common form of oxygen in water is O^{16}.
- The ratio of O^{16} and O^{18} depends on the temperature of the snow when it fell. The lower the temperature, the fewer heavy molecules of O^{18} there are in the snow of the ice sheet.
- Analysis of the ratio of O^{16} and O^{18} can show if the snow fell in summer or winter. The ratio in the snow changes, with more heavy molecules in the summer than in the winter. This summer–winter variation allows annual layers in an ice core to be counted and the snow layers can be dated.
- The stable oxygen ratio of O^{16} to O^{18} can also be used to determine temperatures over hundreds of thousands of years. Oxygen isotope ratios rise when temperature falls.
- Minute shell organisms (Foraminifera) live in the sea. Oxygen atoms in the calcium carbonate of their shells mirror the isotopic ratio of the ocean water as the shells grow.
- When the Foraminifera die they fall to the bottom of the sea and build up in the sediment. The sediment can then be dated by analysing the Foraminifera shells. The isotopic composition of the shells reflects both the temperature of the ocean water and the amount of ice locked away in the ice caps.
- Thus by analysing ice and marine sediment cores it is possible to build up a climate record that should reflect the same major changes in global climate.

Ice ages have occurred roughly at 100,000 year intervals and are due to small changes in the Earth's orbit around the Sun. This periodicity results in either more or less solar radiation being received on the Earth's surface, which in turn triggers natural changes in the Earth's climate.

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Task 2 continued **Summary of the reasons for the astronomical cycles of ice ages**

Periodicity	Cause	Effect
21,000 years	**Wobble**	This affects the timing through the year of the closest approach by the Earth to the Sun. Currently the northern hemisphere is in winter at the closest approach to the Sun. The effect is to change seasonal patterns of temperature which are out of phase between the northern and southern hemisphere. In 10,000 years time the northern hemisphere will be closest to the Sun in summer (therefore hotter than today) and furthest away in the winter (therefore colder than today).
41,000 years	**Tilt or roll**	The greater the tilt the more pronounced the difference between winter and summer. Currently summers are becoming less extreme and cooler. Tilt varies from 21.8° to 24.4° in a cycle. Currently, it is 23.4°.
100,000 years	**Stretch of Earth orbit**	This varies the distribution of radiation from the Sun at the Earth's surface through the year. If the Earth's orbit is circular around the Sun the radiation at the Earth's surface is constant. However, the orbit varies from nearly circular to an elliptical shape. At maximum ellipticity the radiation at the Earth's surface may vary by 30% from its maximum (closest to the Sun) to its weakest (furthest from the Sun).

Task 3 The graph in Resource C3 shows that there is a very close correlation between local temperature change, CO_2 and methane as measured from the Vostok ice core.

In the last major ice age, 20,000–100,000 years ago, the Vostok ice core shows that local temperature and CO_2 and methane concentrations were all at very low levels. The core also shows that local temperature and CO_2 and methane concentrations all rose very quickly at the end of the last ice age. This information has led scientists to suggest that, while the start of ice ages may be astronomically controlled, rising concentrations of greenhouse gases accompany the end of ice ages and help to promote further warming. The ice core data also shows that current levels of CO_2 and methane are unprecedented, and are higher now than at any time in the past 420,000 years. The level of CO_2 during glacial periods was about 180 parts per million (ppm). During interglacials, this concentration rose rapidly to around 290 ppm. Today it stands at about 360 ppm.

Task 4 **Mean annual temperature (°C) and the standard deviation of the monthly temperatures each year at Faraday/Vernadsky station 1945–98**

Year	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954
Mean	-5.4	-4.4	-4.1	-5.9	-6.9	-5.3	-4.4	-5.0	-7.6	-5.8
SD	4.7	4.1	4.5	5.0	5.2	5.0	4.7	4.2	5.4	6.2
Year	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964
Mean	-3.5	-1.9	-4.8	-7.5	-8.1	-5.1	-4.6	-3.7	-5.2	-4.6
SD	2.9	2.4	5.8	7.4	6.3	4.4	4.8	3.2	5.1	5.0
Year	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
Mean	-4.3	-5.2	-4.4	-3.6	-5.0	-3.2	-1.9	-2.1	-3.5	-2.1
SD	4.8	5.2	3.5	3.5	4.5	3.1	2.2	3.1	3.4	3.1
Year	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
Mean	-3.3	-5.0	-5.1	-5.4	-4.4	-6.1	-4.8	-3.9	-2.3	-2.6
SD	3.6	5.7	6.2	5.3	4.0	5.7	4.3	4.3	2.3	2.9
Year	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
Mean	-1.9	-3.9	-5.7	-2.7	-1.2	-2.6	-3.6	-4.2	-2.9	-3.8
SD	2.8	4.6	6.7	3.1	2.1	3.1	3.3	4.3	2.8	4.5
Year	1995	1996	1997	1998						
Mean	-3.9	-2.2	-3.1	-1.5						
SD	4.4	2.9	3.5	2.3						

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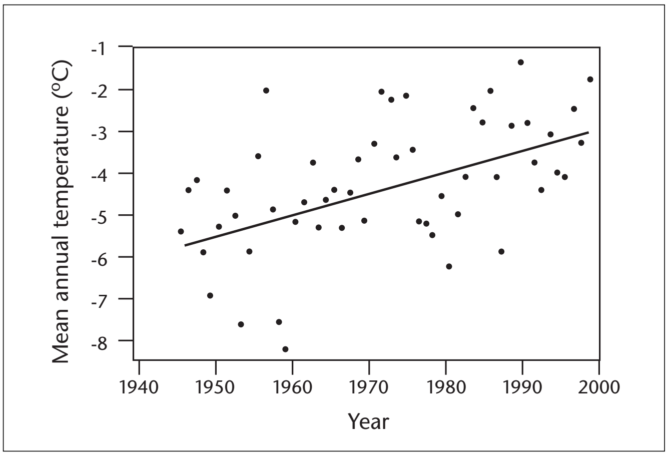
Task 4 continued **Mean temperature (°C), standard deviation, minimum and maximum temperature for each month at Faraday/Vernadsky between 1945–98.**

Month	Mean	Standard deviation	Minimum	Maximum
Jan	0.6	0.8	-1.4	2.3
Feb	0.4	1.1	-2.9	2.3
Mar	-0.7	1.2	-4.7	1.4
Apr	-2.9	2.6	-13.9	0.1
May	-5.1	2.8	-13.8	-1.4
Jun	-7.2	3.3	-17.2	-1.1
Jul	-9.6	4.6	-20.1	-2.6
Aug	-10.0	3.7	-17.3	-3.3
Sep	-7.8	3.0	-14.1	-2.1
Oct	-5.1	1.9	-9.5	-1.6
Nov	-2.4	1.4	-6.7	0.1
Dec	-0.2	0.6	-1.7	1.6

Plot of mean annual temperature at Faraday/Vernadsky between 1945–98



BAS

The variation in mean annual temperature is extremely large, mainly as a result of the severity of the winter. Such large variations from year to year make it difficult to pick up any long-term trend in the data.

Simple regression analysis can be used to see if there is a statistically significant trend in the data.

To fit a least squares linear regression we need to evaluate *a* and *b* in the equation:

$$y = a + bx$$

Calculate *b* by:

$$b = \frac{\sum_{1}^{n} (x - \overline{x})(y - \overline{y})}{\sum_{1}^{n} (x - \overline{x})^2}$$

where *x* is the year, *y* is the mean annual temperature and *n* is the sample size.

In this case:

$$b = \frac{687.09}{13118}$$

$$b = 0.0524$$

Rearrange the regression equation to find *a*:

$$a = \overline{y} - b\overline{x}$$
$$a = -4.1687 - 0.0524\ (1971.5)$$
$$a = -107.5$$

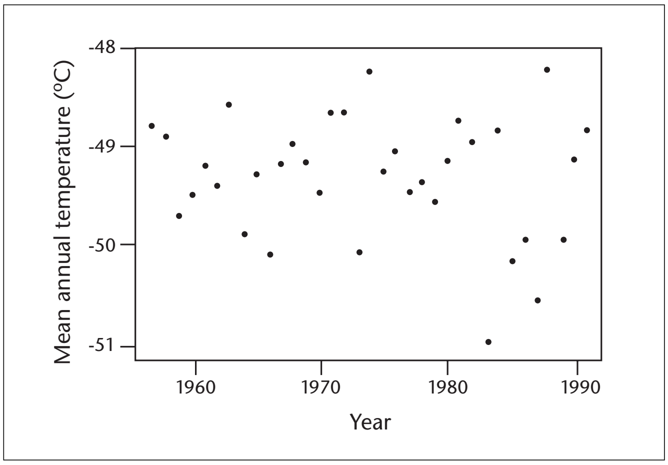
Thus the regression is:

$$y = -107.5 + 0.00524x$$

where *y* is mean annual temperature in °C and *x* is the year.

The regression line is also plotted on the graph of mean annual temperatures. This indicates that the temperature at Faraday/Vernadsky has been increasing by 0.052°C each year, giving an overall rise of about 2.5°C between 1945 and 1998. The increase is statistically significant (F variance ratio test with 1 and 52 degrees of freedom = 19.8, $P < 0.001$). The r^2 value (a measure of the degree of variation explained by the regression) is 28% which is rather low. This is due to the large dispersion of the data points around the regression line.

Plot of mean annual temperature at Amundsen-Scott station between 1957–91



BAS

A regression analysis indicates that there is no statistically significant change in mean annual temperature over time (F variance ratio test with 1 and 33 degrees of freedom = 0.97, $P = 0.33$). The r^2 value is only 3%. This indicates that a regression line has no value in predicting temperature change. The statistical analysis shows that there are no significant temperature trends in the South Pole data. This means that unlike Faraday/Vernadsky, there is no evidence of increasing mean annual temperatures at the South Pole.

The temperature trends at Amundsen-Scott are different to Faraday/Vernadsky because of the very different geographical locations of the stations.

Geographical differences between Amundsen-Scott and Faraday/Vernadsky stations

	Amundsen-Scott	Faraday/Vernadsky
Latitude	90°S	65°S
Altitude (m)	2800	sea-level
Distance to sea (km)	1300	0

Annual temperatures at the two stations vary with latitude, altitude and distance to the sea. Amundsen-Scott is very high and far from the sea. Its location at the South Pole means it is dark for six

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months of the year, and temperatures are highly dependent on the elevation of the Sun (see answer to Task 1). In contrast, Faraday/Vernadsky is at sea level on a small island on the Antarctic Peninsula. Its temperature, particularly in winter, is dominated by whether the wind comes off the Southern Ocean or from a cold southerly direction off the Antarctic continent, and how extensive the sea ice is around the station. Faraday also lies to the north of the Antarctic Circle so daylight is seen each day of the year.

Task 5 Since the early 1960s, rainfall and snowmelt have both increased during the austral summer months of December, January and February in the Marguerite Bay area of the Antarctic Peninsula. January is now the warmest and rainiest month, with around six days of rain and 25 days of snow melt occurring in the 1990s.

Rain is a very efficient means of transferring heat into snow or ice and therefore causes rapid snow melt.

Study of aerial photographs of northern Marguerite Bay has shown that there has been a significant decline in the extent of small coastal areas of snow and ice since the late 1950s. The decline appears to be continuous, as there is no evidence of re-advance at any site. The extent of the change is related to elevation and distance from the sea. Sites at higher elevations (>200m above sea level) and away from the coast have not seen increased snow or ice melt.

Aerial photography is an excellent technique with which to assess changes in small areas of snow or ice. This is because such areas are too small to be observed accurately from satellite imagery. Also, satellite images have only been readily available since the 1980s, whilst aerial photographs are available from the late 1950s giving a much longer historical record.

The changes in snow and ice cover in Marguerite Bay are characteristic of the Antarctic Peninsula as a whole. The BAS has documented that warming in the region has caused a temperature increase of about 2.5°C over the past 50 years, and the annual melt season to increase by two or three weeks over the last 20 years. However, the regional warming found in the Antarctic Peninsula has not been seen in other areas of Antarctica. Scientists do not yet know whether warming in the Peninsula is as a result of natural climate fluctuations or the first sign of global warming.

The overall conclusions that can be drawn from Resource C6 are:
- Low-lying coastal sites in the Marguerite Bay area have lost snow and ice cover.
- Local temperatures have increased during the summer.
- There is more summer rainfall at sea level and this has caused increased snowmelt.
- Sites at higher elevations and further from the sea, where temperatures remain below freezing throughout the year, remain more or less the same.

Task 6 The graphs of global CO_2, methane and nitrous oxide concentrations and global temperature all show increases since 1850. There have been rapid increases in CO_2, methane and nitrous oxide since the 1960s. The temperature graph shows some decades which have been cooler than the ones before. However, the 1980s and 1990s have been the warmest on record.

CO_2, methane and nitrous oxide are all 'greenhouse' gases. These gases allow solar radiation from the Sun to reach the Earth's surface, but absorb infra-red radiation emitted as heat from the Earth, so preventing infra-red radiation from escaping into space. The result is global warming. Just like glass in a greenhouse, the greenhouse gases trap heat in the Earth's atmosphere. Human activities have increased the concentrations of greenhouse gases. For example, CO_2 levels have risen by about 25% in the past 150 years. This is due to the increased burning of fossil fuels since the industrial revolution, and the burning of rainforests.

Task 7 Based on a likely doubling of atmospheric CO_2, the Intergovernmental Panel on Climate Change (IPCC) predicted in 1995 that there would be an increase in global mean surface air temperature relative to 1990 of about 2°C by 2100. However, the IPCC acknowledged that there was considerable uncertainty in this prediction and also gave a low estimate of a 1°C increase and a high estimate of a 3.5°C increase.

The IPCC also predicted that sea level would rise by about 50 cm by 2100, with a low estimate of 15 cm and a high estimate of 95 cm.

The other possible effects that the IPCC warned might result from global warming were:
- An increased variability in the weather, with extreme events (such as severe storms, floods and droughts) becoming more common.
- Major changes to oceanic circulation, especially in the North Atlantic.
- Increased pressure on water resources, particularly in arid regions such as Africa.

According to the IPCC, future changes to the Antarctic climate might include:
- Little warming over much of the Southern Ocean, associated with areas of deep ocean mixing.
- High warming over the sea ice zone reducing sea ice and snow cover.
- Increased precipitation over Antarctica, falling as snow in the interior.
- Increased rainfall and snow melt at low level coastal sites where some melting occurs today.
- Further disappearance of ice shelves in the Antarctic Peninsula as the region warms further.

At the periphery of Antarctica is the sea ice zone. Sea ice reflects most of the incoming solar radiation back into space. If sea ice cover is reduced by global warming then the incoming solar radiation will not be reflected but instead will be absorbed by the sea which will warm up. Also, heat can be more quickly transferred to the atmosphere from the ocean when sea ice is absent. Taken together these two processes create a positive feedback mechanism that will increase temperatures and bring about further loss of snow and sea ice. This is why temperature increases are expected to be the highest on the periphery of Antarctica.

Task 8 Predictions of the effects on Antarctica as the climate warms:
- More snow at the centre of Antarctica.
- More rain at the periphery of Antarctica.
- More melting of low-lying snow and ice on the Antarctic Peninsula.
- Collapse of further ice shelves along the Antarctic Peninsula.
- Less sea ice around the coast of Antarctica.
- Changes in the size and locations of the breeding populations of penguins and seals. Populations of Adélie penguins along the Antarctic Peninsula are declining, possibly because of less sea ice.
- Increasing populations of native flowering plants in Antarctica and colonisation of locations further south.

The ozone hole

Worksheet 9

Key ideas
- The nature of ozone and its occurrence
- Measuring ozone
- Discovery of the ozone hole over Antarctica
- Causes of ozone depletion
- The effects of ozone depletion
- International actions taken to combat the ozone hole

Key skills
- Summarising text and use of bullet points
- Diagram construction and labelling
- Diagram interpretation
- Satellite image interpretation
- Correlation analysis
- Map interpretation
- Table construction
- Production of time line sequence
- Working in pairs

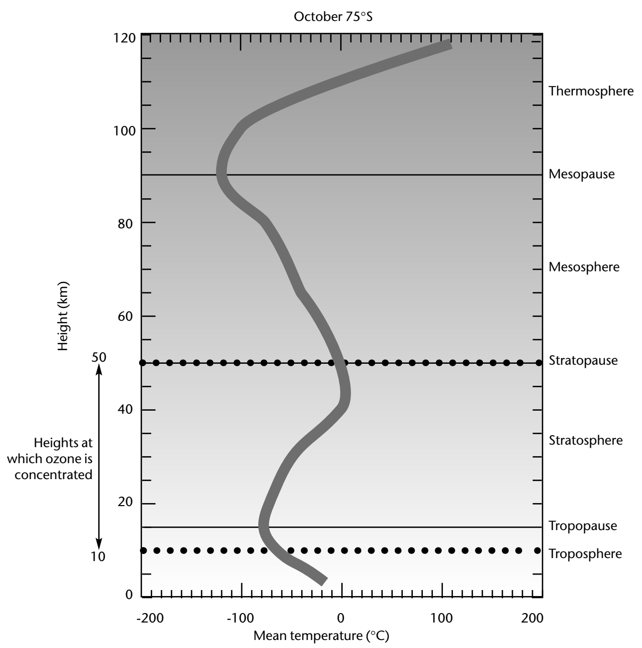
Ozone (O_3) is a form of oxygen comprising three oxygen atoms. Ozone is constantly being produced and broken down in the atmosphere as a result of a set of complex reactions involving the action of ultraviolet (UV) radiation on oxygen. The highest concentration of ozone is in the stratosphere, about 17–22 km above the Earth's surface. Here it forms a layer that shields life on Earth from harmful UV radiation produced by the Sun. In 1985, scientists at the British Antarctic Survey (BAS) discovered the ozone hole over Antarctica. They found that the amount of ozone above Halley Research Station during the Antarctic spring had decreased by 30% since the mid 1970s and linked this discovery to emissions of man-made chlorofluorocarbons (CFCs). The discovery of the ozone hole caused a major worldwide shift in the way people think about the environment, as it was the first real evidence of how mankind can cause global environmental impacts. This led to rapid international action to try and solve the problem. In 1987, 80 countries agreed the Montreal Protocol, which originally aimed to halve the use of CFCs by 1999. This worksheet introduces students to the nature of ozone. The discovery of the ozone hole is explained as are the effects of ozone depletion. Recent measurements of ozone taken at Halley Research Station are provided for students to analyse. The international response to the threat of ozone depletion is then discussed.

Model answers to tasks

Task 1 Ozone (O_3) is a form of oxygen. It is a bluish, toxic, oxidising gas, often formed by air pollution at the Earth's surface. Ozone is formed naturally in the stratosphere, about 20 km above the ground, by the action of solar ultraviolet (UV) light on oxygen molecules and by catalytic cycles involving trace gases. Ozone is therefore constantly being produced and destroyed naturally, but the overall level remains stable. This produces the ozone layer. Ozone is a rare gas, even in the ozone layer there is less than one ozone molecule for every 100,000 molecules of air.

Most ozone is created over the tropics where there is a greater incidence of solar radiation. Global atmospheric circulation then transports the ozone towards the poles. The highest levels of ozone are found in the mid-latitudes.

The stratosphere is where most ozone is found, with the highest concentrations occurring in the lower stratosphere (see graph opposite). In the Antarctic, this is between 10–50 km altitude, with a peak ozone concentration at around 17 km. Temperature in the atmosphere falls with height until the tropopause is reached, it then begins to rise in the stratosphere reaching a peak at the stratopause at about 40 km altitude. Ozone is the reason for this temperature increase because it absorbs solar energy, including virtually all UV radiation between the wavelengths 200–310 nm, and this warms the upper stratosphere.

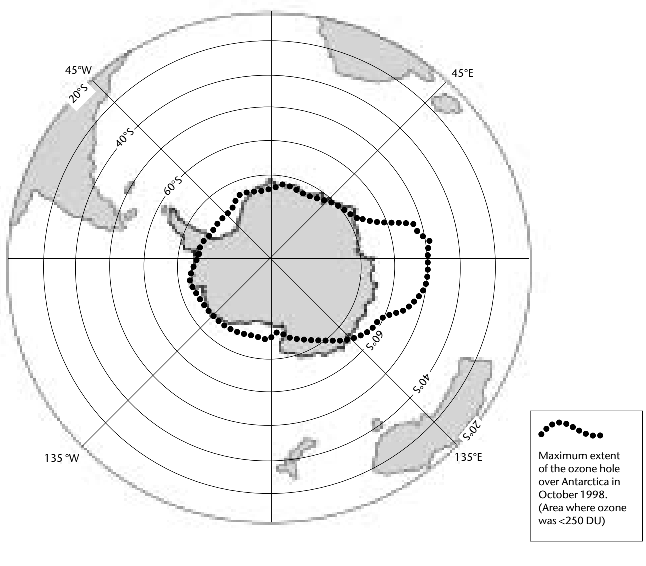


Generalised vertical temperature profile at 75°S during October

BAS

Ozone is usually formed by the action of UV light on oxygen molecules. Carbon dioxide (CO_2) is formed through respiration of living flora and fauna, dissolution of carbonates, burning of fossil fuels and from volcanic eruptions. CO_2 forms through a combination of physical and biological processes. Direct biological processes are not involved in ozone formation.

Task 2 The graphs in Resource OZ2 show ozone and other measurements taken at Halley Research Station. The green lines on the graphs show the historical mean and range of values recorded between 1957 and 1972. The period 1957–72 was before the ozone hole formed. The blue lines represent daily values recorded in 1997/98 and the red line is the running mean for the same year. Comparing the ozone measurements at Halley over the year 1997/98 and for the years 1957–72 shows that present day ozone levels are lower all year round, with major decreases in October and November. In the earlier period, ozone was typically around 300 Dobson Units (DU) through the winter until late October (spring in the Antarctic). The rapid spring warming of the Antarctic atmosphere caused by the return of the Sun caused ozone levels to rise rapidly to over 400 DU by the beginning of November and they then slowly fell back to 300 DU by March. Since the early 1980s, however, a seasonal decrease in ozone levels – the ozone hole – has appeared each spring. In 1997/98, ozone values fell from 240 DU in early September, reaching a minimum of just over 100 DU in early October. The spring warming does not result in increasing ozone levels until late November, and peak values in December only just reach 300 DU. Ozone values then slowly decline, reaching 280 DU in late autumn.



Sketch map of the ozone hole over Antarctica in October 1998

BAS

During the Antarctic winter a strong westerly circulation around the continent, known as the circumpolar vortex, builds up in the atmosphere. This effectively cuts off the interior and allows it to cool. Stratospheric temperatures at the height of the ozone layer (17 km altitude) can fall to below -80°C. When the Sun returns in the spring, the stratosphere begins to warm and temperatures increase rapidly in November and December. The circumpolar vortex then breaks down. Comparison of the ozone and stratospheric temperature measurements shows that there is a strong correlation between the temperature of the lower stratosphere and total ozone. Generally, when the lower stratospheric temperature rises, so too does the total ozone. However, a significant change between 1997/98 and 1957–72 is what happens to temperatures during the Antarctic spring. Today ozone values drop until early October, but the temperature remains fairly steady until the spring warming begins at the end of November. This is because virtually all the ozone is removed from the atmosphere between about 15 and 20 km altitude and thus there is no absorption of solar energy and heating of the lower stratosphere cannot take place despite the presence of sunlight.

Ozone is not confined to a narrow layer in the lower stratosphere, but is spread throughout the atmosphere, mostly between 10 and 50 km above the ground, with a peak at about 17 km. The August 15 1987 data from Halley shows a typical profile with an ozone concentration declining from the surface to a minimum (20 nbar) at the tropopause (10 km altitude). Ozone then rises rapidly to reach a maximum (170 nbar) at about 17 km. It then falls rapidly to about 60 nbar at 25 km altitude. The October 13, 1987 data show a very different profile. Ozone concentrations drop dramatically above 12 km to a minimum (< 10 nbar) at about 17 km altitude. There is virtually no ozone between 14 and 20 km.

The major changes that occur between August and October at Halley are that in early August the Sun has not risen above the horizon. This means that no photochemistry can take place and ozone is not destroyed. By mid October the Sun never sets on the stratosphere, photochemistry can take place 24 hours a day thus producing a very rapid loss of ozone.

Task 3 In October 1998 the maximum size of the ozone hole was about 26 million km^2, the biggest on record.

The shape of the ozone hole is defined by the circumpolar vortex and this changes shape in response to atmospheric dynamics. Sometimes the ozone hole is nearly circular; at others it is highly elliptical and very elongated. However, the hole cannot normally extend beyond 55°S. The NASA satellite image of the ozone hole over Antarctica in October 1998 also shows a high ozone concentration 'collar' surrounding the continent. In winter, the circumpolar vortex prevents transport of ozone to Antarctica and causes the build up of ozone in sub-Antarctic latitudes. As the ozone hole rotates, it may extend over the southern tip of South America and the Falkland Islands for a short while when it is very elongated. When this happens the intensity of UV light at the surface goes up, and this brings with it the immediate risk of severe sunburn. In the longer term, there is an increased risk of skin cancer and eye cataracts, particularly as the noonday Sun is high in the sky in southern South America during October and November. The ozone hole has not been observed to pass over New Zealand.

The October mean ozone at Halley has declined from about 300 DU in the 1950s to 130 DU in the 1990s, a decrease of 170 DU. This is a loss of about 57%, with the majority of this happening since the mid 1970s. If this decline continued there would be no ozone left in 2050. However, during the late 1990s the October mean ozone did not decrease significantly and values are now beginning to level out. It seems unlikely, therefore, that October 2050 will see mean monthly values below 100 DU. The main reason for this is that the photochemical process which destroys ozone has so far been confined to between 12 and 25 km altitude, probably because the air above and below is too warm for stratospheric clouds to form.

Task 4 Calculation of the Spearman rank correlation coefficient, r_s, for the ozone and CFC-11 data in Resource OZ3 requires students to:

- Rank the values in each column, averaging tied ranks
- Evaluate:

$$r_s = 1 - \frac{6\sum_{1}^{n}(R_1 - R_2)^2}{n\,(n^2 - 1)}$$

where R_1 and R_2 are the rank values and n is the sample size.

continued ➤

In this case:

$$r_s = 1 - \frac{6\sum_{1}^{37} 13225}{37(1368)}$$

$$= 1 - \frac{79350}{50616}$$

$$r_s = -0.57$$

This is statistically significant at the P < 0.001 level (> 99.9%).

In fact, for sample sizes greater than 30 the product moment correlation coefficient, r_α is normally calculated (this is sometimes known as the Pearson correlation coefficient in the literature). Evaluating:

$$r_\alpha = \frac{\sum_{1}^{n} (x - \bar{x})(y - \bar{y})}{(n-1)\, S_x S_y}$$

where $\alpha = n$-2, $\bar{x}$ and $\bar{y}$ are the means of x and y and S_x and S_y are the standard deviations of the two variates, x and y.

In this case:

$$r_{35} = -0.50,\ P = 0.002$$

which is almost identical to r_s.

Both coefficients are statistically significant and are negative indicating an inverse relationship. This means that as the amount of CFC-11 released increases the corresponding value of total ozone decreases.

Scientists agree that ozone is being destroyed because of the release of CFCs into the atmosphere. CFCs were used in fridges, air conditioning systems, foams and aerosols. They are very stable compounds and can persist in the atmosphere for more than a century. CFCs are only broken down high in the stratosphere, by UV light above the ozone layer. However, this reaction releases free chlorine atoms which react with ozone breaking it down much more rapidly than it can be replaced naturally.

Task 5 Summary of the processes involved in the destruction of ozone in the stratosphere:

- Ozone is destroyed naturally by photodecomposition by sunlight, and also by catalytic cycles involving trace gases in the atmosphere.
- Man-made CFCs and other ozone depleting gases (e.g. halons) are mostly released in the northern hemisphere. They have very long lifetimes and can remain in the atmosphere for over 100 years.
- CFCs and other ozone depleting gases are transported to the upper stratosphere, where they are broken up by UV radiation and release chlorine (and bromine).
- Chlorine reacts with ozone to form chlorine monoxide (ClO) and oxygen (O_2). The ozone is destroyed through a complex series of photochemical reactions. Similar reactions involving bromine instead of chlorine also take place.

Task 6 In the stratosphere, the winter wind circulation above Antarctica is predominantly westerly and is known as the circumpolar vortex.

At the South Pole (90°S) in winter there is no sunlight and temperatures fall by nearly 30°C compared to summer. The average surface temperature at the South Pole in June is -58.4°C. However, there is a very strong surface inversion and the temperature rises to -40°C in the lowest kilometre of the atmosphere (the boundary layer). The temperature falls above the boundary layer reaching below -80°C in the lower stratosphere.

At -80°C, water vapour and nitric acid in the lower stratosphere can condense to form thin clouds known as polar stratospheric clouds or mother-of-pearl clouds.

The polar stratospheric clouds allow complex chemical reactions to take place which promote springtime ozone depletion. The surfaces of the clouds absorb nitric acid and nitric acid trihydrate (HNO_3. $3(H_2O)$) crystals are formed. This prevents chlorine being locked up in an inactive form as chlorine nitrate (ClO NO_2) and thus preventing ozone catalysis. The concentration of chlorine monoxide (ClO) in the lower stratosphere becomes high and this can react in the presence of sunlight to destroy ozone. Bromine is able to take part in similar reactions. The ozone hole is therefore formed when the Sun rises above the horizon during the early spring.

When the stratosphere warms up again in late spring the circumpolar vortex breaks down, and rapid ozone destroying reactions finish. The ozone hole then disappears as ozone rich air is brought in from mid-latitudes.

Task 7

	Potential impacts of ozone depletion
Humans	Sun burn, cataracts, ageing of skin and skin disorders, skin cancer, suppression of immune system.
Plants	Damage to leaves, bleaching of chlorophyll, decreased photosynthesis, decreased resistance to disease, lower crop yields, DNA damage and mutations.
Marine ecosystems	Decreased photosynthesis by plankton, lower plankton productivity, decreased food supply to higher predators.
The man-made environment	Damage to painted surfaces, degradation of plastics, faster ageing of materials, bleaching of materials.
Climate	Cooling of the stratosphere, increased levels of CO_2 because of reduced carbon fixing by plants damaged by UV, greenhouse effect of ozone, greenhouse effect of CFCs and their replacements.

When the ozone hole forms over Antarctica and the Southern Ocean the intensity of UV radiation increases. People working on Antarctic research stations, or on board vessels in the Southern Ocean, are much more likely to get sunburnt and must take precautions by covering exposed skin or by applying sun block. Plants and animals also receive increased exposure to UV and must adapt, migrate or die. So far, no significant long-term changes have been observed in surface dwelling organisms.

Task 8 Time sequences of actions taken to combat ozone depletion:

1974 Role of CFCs identified.

↓

1975 World Meteorological Organisation (WMO) conducts first international assessment of the ozone layer.

↓

1985 Vienna Convention for the Protection of the Ozone Layer agreed.

↓

1985 BAS scientists publish the discovery of the ozone hole over Antarctica in the scientific journal *Nature.*

↓

1987 Montreal Protocol on Substances that Deplete the Ozone Layer agreed. Phase out of CFCs by 50% by 1999.

↓

1989 Montreal Protocol comes into force.

↓

1990 Second Meeting of the Parties to the Montreal Protocol. London amendment agreed. Agreement for developed countries to phase out CFCs, halons and carbon tetrachloride by 2000.

↓

1992 Fourth Meeting of the Parties to the Montreal Protocol. Copenhagen amendment agreed. Phase out of CFCs and carbon tetrachloride brought forward to 1996. Phase out of halons brought forward to 1994.

↓

1995 Seventh Meeting of the Parties to the Montreal Protocol. Agreement to phase out methyl bromide by 2010.

↓

1997 Ninth Meeting of the Parties to the Montreal Protocol. Phase out of methyl bromide by developed countries brought forward to 2005. Developing countries to phase out methyl bromide by 2015.

The graph in Resource OZ5 shows that provided the Montreal Protocol and its amendments are adhered to, the total chlorine loading should drop by the early 2000s. The concentration of some CFCs is no longer increasing, and the concentration of some other ozone depleting gases, such as carbon tetrachloride, has dropped rapidly. The decline in overall chlorine loading is not as rapid as predicted in the graph because developing countries were given more time to implement the provisions of the Montreal Protocol, and have until 2010 to phase out the production of CFCs and other ozone depleting gases.

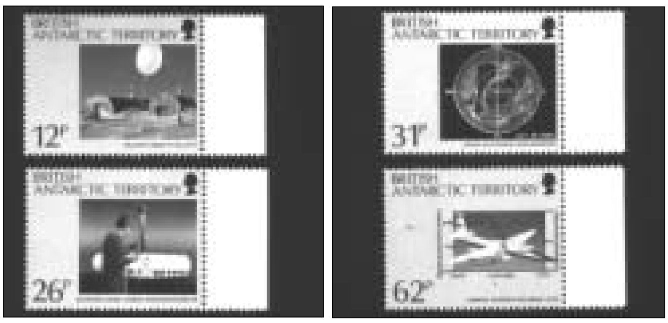
BAS

The Simpson building which houses the ozone laboratory at Halley Research Station. The people standing on the scaffolding are jacking the platform to stop it from being buried by drifting snow

Many developing countries, particularly China, have increased their production of CFCs and this has contributed to the development of the black market trade. This increased production and trade makes it unlikely that there will be any significant decrease in the Antarctic ozone hole for another decade or more, and could seriously undermine attempts by the international community to attain pre-1970 ozone levels by 2050.

Task 9 The key messages that emerge from the ozone hole problem are:

- High quality, long-term scientific monitoring has a major role to play in detecting global change.
- The global dimension of the problem – CFC emissions largely originate from the northern hemisphere but have created an ozone hole in the southern hemisphere.
- The long time-scale to solve the problem – as CFCs are such stable gases it will take at least 50 years for the ozone hole to disappear, even if CFC production were to halt immediately.
- The ozone hole is a warning to us that it is very easy for mankind to significantly alter the Earth's atmosphere.
- It is possible for governments to act quickly to make international agreements to address global environmental problems.
- International cooperation and action are needed to solve global environmental problems as the actions of any one country could wreck the good intentions of everyone else.
- Antarctica plays a significant part in the global atmospheric system.



BAS

A special set of British Antarctic Territory stamps were issued to mark the discovery of the ozone hole

Key ideas
- What is geospace?
- The solar wind
- Interactions of the solar wind with the Earth's magnetic field
- The aurora
- The impacts of space weather
- Space weather forecasts
- The importance of Antarctica to geospace science

Key skills
- Diagram interpretation and construction
- Data analysis and interpretation
- Satellite image and map interpretation
- Table construction and impact analysis
- Working in small groups
- Summarising text

Antarctica is one of the best places in the world to see the aurora – wonderful glowing curtains and sheets of green and reddish light rippling across the night sky. These amazing displays of light are the result of the solar wind, a stream of ions and electrons, coming from the Sun, colliding with hydrogen and oxygen atoms in the Earth's upper atmosphere. Auroras occur between 100 and 320 km above the Earth's surface, and in an oval-shaped ring about 14,000 km in circumference centred around the geomagnetic pole in each polar region. Auroras are concentrated at the poles because the Earth's magnetic field funnels the solar wind particles along magnetic field lines into these regions. Antarctica therefore provides an excellent observing platform to study the southern lights or aurora australis. This research is important as auroras can tell us a great deal about space weather, particularly magnetic storms which can disrupt modern satellite communication systems and cause power blackouts. Most students will know very little about geospace and the study of space weather. This worksheet introduces the basic concepts of geospace, and explains the solar wind. The effects of space weather on human activity are discussed. Finally, the importance of Antarctica as a place to study geospace is assessed.

Model answers to tasks

Task 1 The stream of ionised particles from the Sun forms an ellipsoidal shell around the Earth like the bowl of a wine glass. This can best be seen in the inset of Resource GS1. If you turn the image 90° anti-clockwise, the Sun appears as the base of the wine glass and the Earth sits inside the wine glass bowl. (Notes: An ellipsoid is three dimensional and the figure is a two-dimensional cut through it – an ellipse. The figure is not to scale.)

The ellipsoidal shell comes about because the magnetic outer atmosphere of the Earth (the magnetosphere) forms an obstacle to the stream of ionised particles from the Sun (the solar wind). The magnetosphere exerts a pressure on the solar wind that deflects it around the magnetosphere – like an aeroplane or bullet deflects air around it as it flies.


BAS

The aurora in winter over the Advanced Ionospheric Sounder at Halley Research Station

Task 2 The time taken for the solar wind to flow from the Sun to the Earth

Time = Distance / Velocity
= 150×10^6 km / 600 km/second
= 250,000 seconds
= 69.4 hours
= 2.9 days

Note: The solar wind speed is the average speed of a solar wind ion or electron. Some ions and electrons travel much faster, almost up to the speed of light (300,000 km/second)! Light takes only 500 seconds or 8 minutes to travel from the Sun to Earth.

Task 3 The key characteristics seen in Resource GS2 are annotated on the diagram on page 33.

Key characteristics which students should note are:
- Solar wind streamlines coming from the Sun are on the left of the figure. The flow direction is parallel to the streamlines and the flow speed is proportional to the streamline separation. Thus the figure shows a near-Earth solar wind that is uniform and flowing parallel to the Sun-Earth line, away from the Sun. These streamlines are a more detailed representation of the straight, radial streamlines coming from the Sun illustrated in the inset of Resource GS1.
- The magnetic structure of the Earth's outer atmosphere (the magnetosphere) is illustrated in the figure by the loop-like lines emanating from the Earth's surface. These are the Earth's magnetic field lines. They show the direction and strength of the Earth's magnetic field in the same way that a flow streamline shows the direction and strength of fluid flow: at any point, the direction of the Earth's magnetic field is parallel to the line of force and its strength is proportional to the separation between

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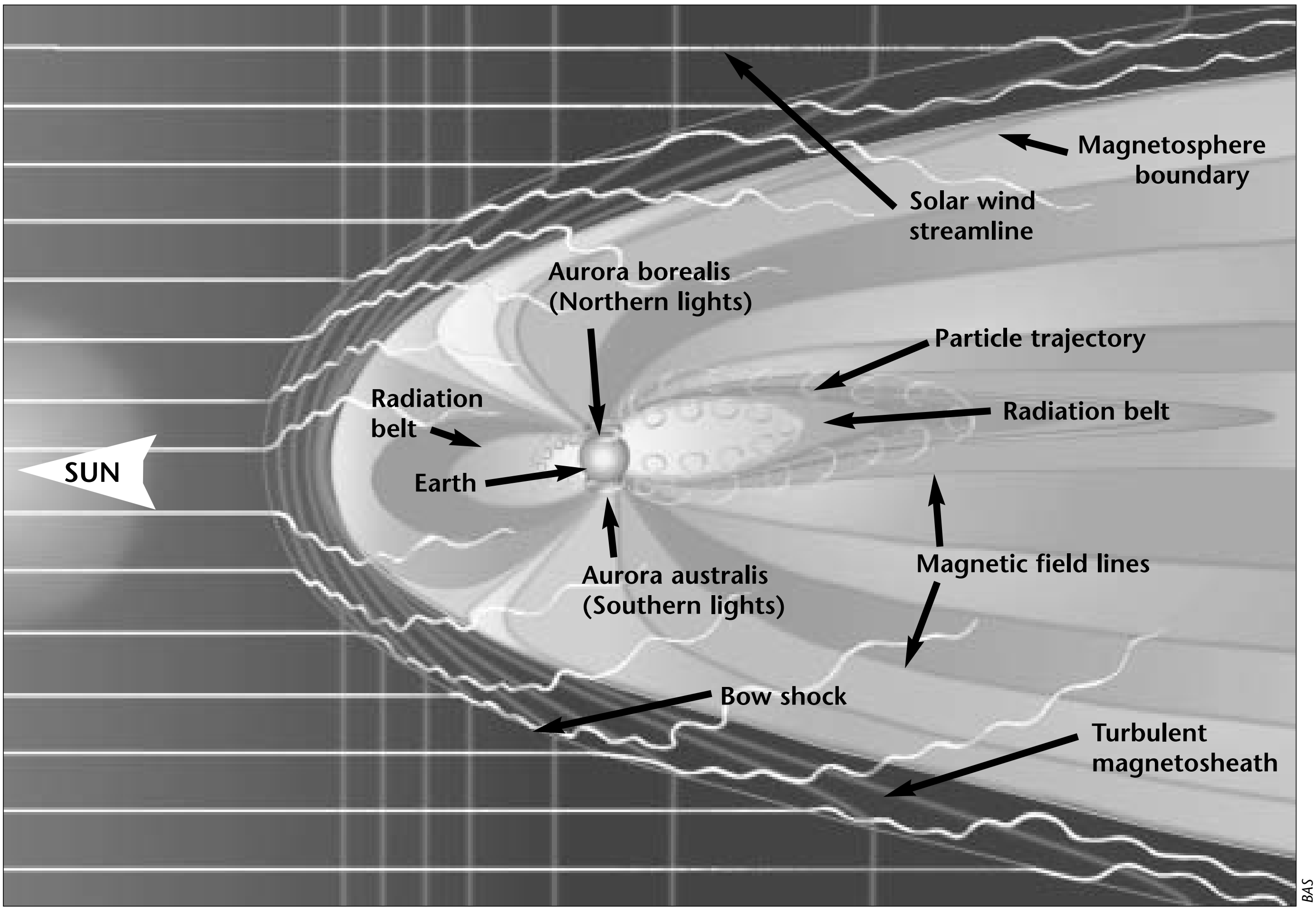


An annotated illustration of the interaction between the solar wind and the magnetosphere

neighbouring lines. The magnetic field lines on the sunward side of the Earth are squashed up to give a relatively strong magnetic field strength and magnetic pressure to resist the pressure of the oncoming solar wind, whereas on the opposite side the magnetic field lines are more stretched out. In the absence of the solar wind, the Earth's magnetic field lines would look like those of a bar magnet and be symmetrical.

- Solar wind streamlines are deflected by a bow shock wave and flow around the magnetosphere in a turbulent layer known as the magnetosheath.
- There is leakage of some of the solar wind plasma into the magnetosphere across magnetic field lines.
- Spiral trajectories of individual ionised particles along magnetic field lines. (Note: These trajectories show the motion of individual particles, whereas flow streamlines show the average net motion of a collection of particles. There may be no net motion along the magnetic field line because as many particles may be travelling in one direction along it as in the other direction.)
- Radiation belts in regions where ionised particles are trapped and bounce back and forth between northern and southern polar regions along magnetic field lines.
- Auroral ovals around the Earth's north and south magnetic poles caused by the precipitation of ionised particles into the atmosphere.

Task 4 The image in Resource GS3 shows a ring of auroral light around Antarctica. Comparing carefully with the map on Worksheet 10 shows that the poleward edge of this auroral ring can be seen to follow more closely the contours of constant geomagnetic latitude than those of constant geographic latitude. For example, compare the latitudes of the poleward edge of the aurora at South American and Australian geographic longitudes. This part of the edge is at similar geomagnetic latitudes but very different geographic latitudes.

The poleward edge of the aurora lies between 60° and 70°S geomagnetic latitude. Also, the centre of the dark area bounded by the poleward edge of the aurora can be found to lie at a position closer to the south geomagnetic pole than the south geographic pole.

The aurora are found mainly in the polar regions because ionised particles from the Sun follow the spiral trajectories along geomagnetic field lines as shown in Resource GS2. It can be seen that the magnetic field lines converge towards the Earth's magnetic poles. Consequently, most ionised particles moving along magnetic field lines eventually end up precipitating into the polar regions and this causes the aurora.

Task 5 The number of power stations with an output of Didcot 'A' needed to produce the electricity in a 10^{13} watt aurora:

Didcot 'A' produces 2000 megawatts = 2000 x 10^{6} watt

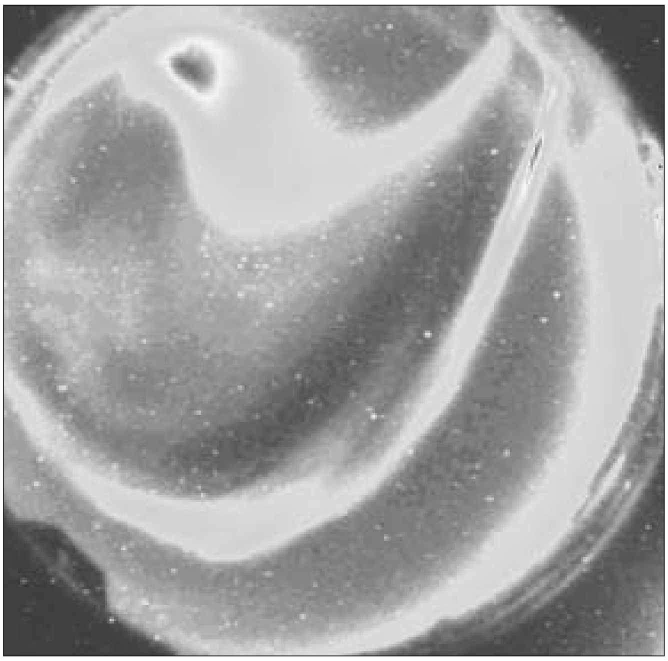
Number of power stations = Power output of aurora/ Power output of power station

= 10^{13} watt/2000 x 10^{6} watts

= 5000

Task 6 **Space weather impact table**

System under threat	Nature of hazard	Impact of hazard	Cost of impact	Measures to minimise impact
Satellites	Accumulated radiation dose. Electrical discharging. Atmospheric drag. Penetrating energetic particles.	Degradation of satellite components. 'Phantom commands' leading to satellite malfunction. Changes to satellite orbit. Corruption of binary-encoded information on satellite memory chips.	Possible loss of satellite services, such as communication links. Launch of replacement satellite. Possible boost of satellite orbit. Checking and resending of corrupted information.	Expensive protection for satellite components. Alternative satellite orbits to avoid worst radiation regions. Higher satellite orbits to reduce drag. Expensive protection for satellite chips. Better warning of impact to plan for alternative satellite service or replacement.
Power systems	Geomagnetically induced currents.	Damage to electrical transformers. Possible electricity supply failure.	Repair or replacement of transformer. Compensation payment to consumers.	Improved electrical protection. Plans for alternative electricity supply.
Pipelines	Geomagnetically induced currents.	Corrosion of pipeline joints.	Repair of pipeline and temporary loss of supply.	Regular pipeline inspection and prediction of hazard impact.
Communication systems	Modification of ionosphere by solar radiation and solar or auroral energetic particles.	Radio signal attenuation and noise.	Lost or impaired radio and radar service. Possible total communication blackout.	Alternative communications by cable or satellite. Improved noise reduction technology.
Navigation systems	Modification of ionosphere by solar radiation and solar or auroral energetic particles.	Errors in global positioning due to time delays in radio signal propagation.	Unnecessary deviations to journeys. Wrong positions given may lead to accidents to aircraft or ships.	Improved prediction of hazard in order to avoid or correct for impact.
Geomagnetic surveys	Geomagnetic perturbations due to space weather.	Errors in survey data. Erroneous identification of geological resources.	Rescheduling of geomagnetic surveys. Unnecessary test drilling.	Improved prediction of hazard for rescheduling of geomagnetic surveys.
Humans in space	Radiation exposure.	Human cancers.	Possible death of astronauts. Loss of space missions.	Avoidance of high radiation regions. Improved prediction of space weather to reschedule space activities.



Picture of the aurora taken by the all-sky digital imager at Halley Research Station. The imager is a special type of digital camera, which uses a fish-eye lens to view almost the whole night sky from horizon to horizon

Task 7 A magnetic storm on Earth is caused by a coronal mass ejection on the Sun that is carried to Earth by the solar wind. Thus, from Task 2, the maximum warning of an approaching magnetic storm is about 3 days (provided that the coronal mass ejection can be observed on the Sun). Mission Control should tell the astronauts not to do any space walks and to remain in a shielded shelter on the spacecraft until the magnetic storm has passed and it is safe to go outside again.

Military strategists can use space weather forecasts to predict when radio communications and radar systems are most likely to malfunction.

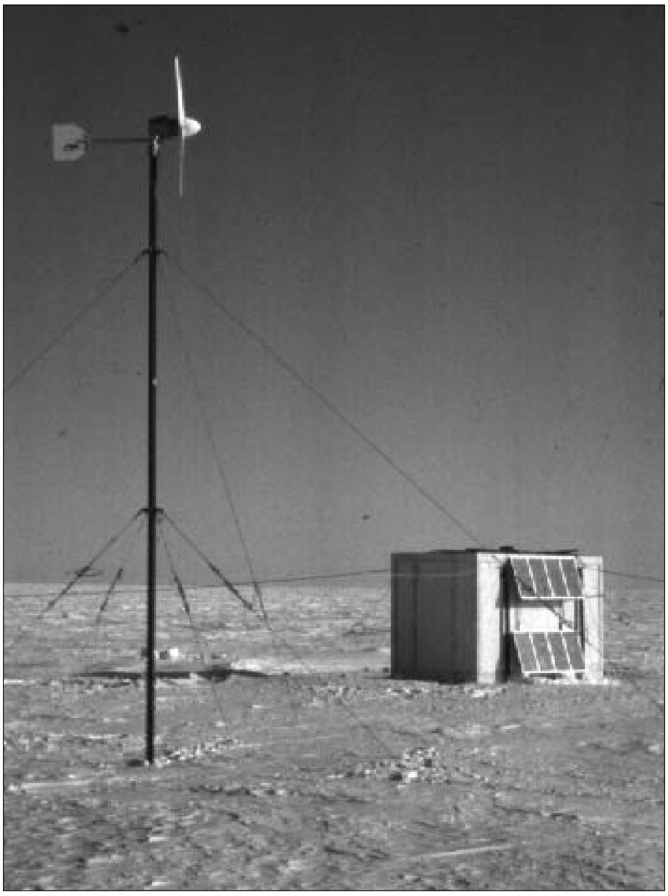
Task 8 This exercise should reveal whether students have grasped the basic physics of geospace, and appreciated the severe impacts that a magnetic storm might have. Key points that forecasts should cover are:

- The scale and intensity of the magnetic storm, which depends on the phase of the solar cycle. The solar magnetic field varies with the 'sunspot' cycle of 11 years. When there are many sunspots the Sun's magnetic field is very disorganised. Magnetic structures in the corona can cause mass ejections of plasma, which cause magnetic storms in geospace.
- The speed of the solar wind, and hence the time the weather will take to reach earth. During a coronal mass ejection plasma can be ejected at very high speed, and a magnetic storm could take only a few hours to reach Earth;
- Predictions for different types of human activities that might be impacted. Activities in space are now part of everybody's lives. Magnetic storms can severely disrupt satellite communication and navigation systems, and terrestrial power supplies. Forecasts should therefore be geared to the need of key users, as well as the general public.

Task 9 Geospace scientists use Antarctica primarily as a platform from which to remotely sense global-scale phenomena in regions above and beyond the continent. In contrast, geologists and biologists go to Antarctica to study the place itself, its rocks, and the organisms that live there.

Geospace science does not have a significant impact on the environment in that many of the scientific instruments used are passive – effectively just 'listening' to the natural environment – such as magnetometers, auroral imagers and radio receivers. Also, relatively few instruments are required to remotely sense huge volumes of geospace. In addition, many instruments are now automatic and use 'green' technologies, such as solar and wind power. Geospace scientists can therefore carry out much of their research in the comfort of their offices, needing only occasional visits to Antarctica to install, check and download equipment. The human 'footprint' of geospace science in Antarctica is small compared to other scientific disciplines.

The Antarctic Treaty System provides protection for geospace science by conserving the Antarctic environment and preventing light and radio pollution which would interfere with sensitive scientific measurements. In addition, the Treaty ensures freedom of scientific investigation and cooperation in Antarctica, requires the free exchange of scientific data and results, and promotes collaboration between scientists working in the region.



An unmanned BAS Automatic Geophysical Observatory (AGO) deployed in Coats Land. AGOs are powered by solar panels and wind turbines

Terrestrial and freshwater lake ecosystems — Worksheet 11

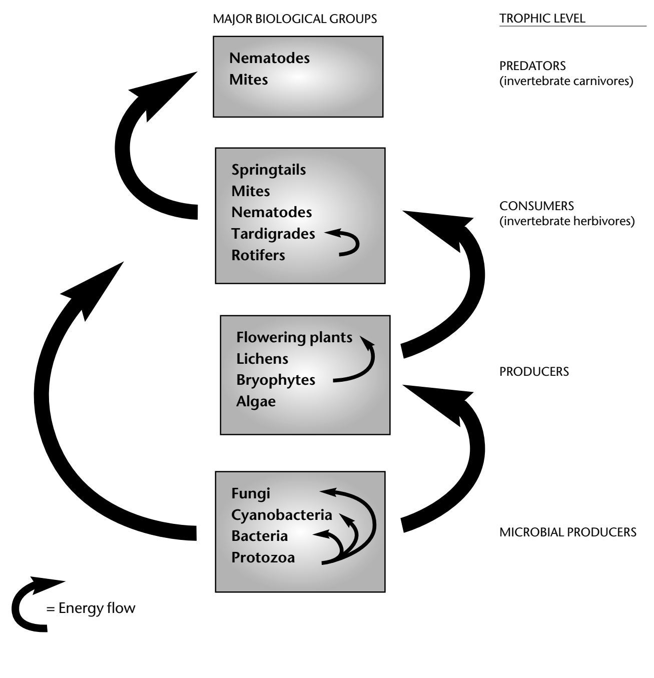
Key ideas
- Life on land
- Terrestrial plants
- Terrestrial animals
- Life in the lakes
- Lake Vostok
- Links between land and sea
- Ecological effects of increasing fur seal populations
- Lessons for management

Key skills
- Food web diagram construction and labelling
- Diagram interpretation
- Essay writing
- Impact analysis
- Class discussion
- Summarising text

The terrestrial and freshwater lake ecosystems in Antarctica are very simple as the extreme polar environment presents a hostile habitat for plants and animals. Land mammals, reptiles, freshwater fish, amphibians and trees are all absent. Terrestrial, and most freshwater, ecosystems are restricted to the 0.5% of Antarctica which is not permanently covered by ice. Moisture and temperature are major physical controls on land, whilst ice cover and light are the major influences on freshwater lakes. This worksheet provides a simple overview of Antarctic terrestrial and freshwater ecosystems. The recent discovery of Lake Vostok – a vast subglacial lake in the centre of Antarctica – is discussed. The exploration of Lake Vostok is one of today's greatest scientific challenges in Antarctica. However, this will have to be done with great care so as not to pollute the lake with chemicals or surface bacteria. Antarctic terrestrial and freshwater ecosystems are vulnerable to natural environmental changes and to local human impacts from research stations. Finally, the worksheet provides students with a case study of the ecological impact of the increasing fur seal population at Signy Island.

Model answers to tasks

Task 1 **The Antarctic terrestrial food web**



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Task 2 Key points that students should include in the essay are:

General
- The freezing of the surface layer of many lakes in Antarctica for all or part of the year is a major physical control on the character and development of the ecosystems within them. This is because the ice cover:
  – Stops the inflow and outflow of water. The lake below the ice effectively becomes a closed system, with few nutrients reaching the water.
  – Limits the amount of solar radiation entering the lake, which restricts the energy available for plant growth. The input of solar radiation can be reduced still further by snow accumulating on the ice surface.
  – Inhibits wind-induced turbulence within the lake preventing mixing of the water and producing a highly stable water column.
  – Insulates the water column and so helps to maintain constant and stable temperatures.
  – Prevents the exchange of gases between the lake and atmosphere. This allows gases produced in the lake to accumulate.
- The waters in permanently ice-covered lakes are therefore likely to be clear with very low nutrient levels.

Ecosystems in permanently frozen lakes
- Ecosystems in permanently frozen lakes are simple. There are few phytoplankton and overall biological productivity in the water column is very low. The sediment of such lakes, however, is often rich in nutrients and this can support mats of blue-green algae and diatoms. Small invertebrates such as tardigrades and nematodes browse or scavenge on the benthic mats.
- Some permanently frozen over lakes have highly stratified water columns. For example, Lake Vanda, in the Dry Valleys of Victoria Land, has a salty lower level, which is probably the remnants of a larger lake which has partly evaporated. This ancient saline layer is roughly four times more salty than sea water. On top of this is less dense freshwater which has drained into the lake from glacier melt-water streams. The lake surface is permanently frozen to a depth of 2-4 m. In Lake Vanda the lower salty level is virtually sterile. Algae are present in the upper layers beneath the ice but productivity is low even in summer.

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Ecosystems in seasonally frozen lakes

- Ecosystems in seasonally frozen lakes are more complex. This is because the melting of the ice in summer allows solar radiation to enter the water column and permits rapid photosynthesis by phytoplankton, benthic algae and moss. Nutrients and minerals are also brought in by melt-water streams during the summer thaw.
- Lakes which undergo seasonal freezing can be split into two types according to their nutrient content:
  – Oligotrophic (nutrient poor) lakes
  Oligotrophic lakes are often at high altitude and remote from the sea. Thus, they are distant from the Southern Ocean ecosystem which is rich in nutrients. In such lakes most of the plants and animals live on the lake bottom as it is here that nutrient levels are highest. There is usually a rich and dense benthic flora of perennial mosses and algae. Planktonic algae are scarce. The fauna consists of rotifers and crustaceans.
  – Eutrophic (nutrient rich) lakes
  Eutrophic lakes are found close to the sea. Nutrient levels are high because of wind blown input from the sea or from the excreta of seals and seabirds living nearby. Waters are clear under the ice in winter, but quickly become turbid in summer because of suspended organic material and sediment. Eutrophic lakes are rich in phytoplankton, particularly during summer. However, benthic plants are less abundant than in oligotrophic lakes. This is because the summer turbidity prevents light reaching the lake bottom and thus preventing plant growth. The fauna is dominated by planktonic crustaceans, and there are fewer invertebrates in the benthic algal mats.

Task 3 Environmental Impact Assessment (EIA) of the scientific investigation of Lake Vostok.

Resource EP5 shows the EIA carried out for the Rothera airstrip. This can be used as an example to help students plan the structure for the EIA of the Lake Vostok research proposal.

Key areas which the EIA should cover are:

- The proposal

The NASA proposal to explore Lake Vostok involves:

  – Using a hot water drill to melt a 3500 m long hole down into the ice sheet to within about 100 m of the lake surface.
  – A bullet-shaped probe – carrying a range of instruments, cameras and robotic submarines – being dropped down the drill hole. The probe would use a heated tip to melt its way through the remaining ice and unwind a fibre-optic cable behind it so that information could be relayed to the surface.
  – The sterilisation of the probe as it descends to ensure that no micro-organisms living or lying dormant on the probe or in the ice sheet could be transferred into the lake. Sterilisation would be done using a chemical, such as hydrogen peroxide, which would break down harmlessly to water and oxygen.
  – After penetrating the lake, the probe would release one or more tethered mini-robots – 'hydrobots'. The 'hydrobots' would search for living organisms, test the water and take pictures.
- Alternatives to the proposal
  – Using other, smaller, sub-glacial lakes in Antarctica rather than drilling into Lake Vostok. There are about 70 of these known to exist on the continent.
  – Not proceeding with the investigation of Lake Vostok at all, and instead stopping the ice drilling for 20–50 years until technology is such that the work can be done without risking contamination of the lake.
- The scientific benefits
  – Lake Vostok has been isolated from the outside world for millions of years and is possibly a unique ecosystem containing unknown micro-organisms.
  – If organisms exist they may have evolved along a separate evolutionary path, and in ways not considered possible before.
  – NASA sees an analogue between Lake Vostok and the ocean beneath the ice sheet on Europa, one of the moons of Jupiter. The investigation of Lake Vostok therefore offers a 'test-bed' which will help develop the technologies needed to search for extra-terrestrial life.
- The environmental impacts
  Very little is known about Lake Vostok. It is therefore very difficult to predict what environmental impacts the proposal might have.

  Possible impacts could include:
  – Contamination of the lake by toxic chemicals and fuel, which could change water chemistry and kill any lake micro-organisms.
  – Introduction of surface micro-organisms or micro-organisms contained in the ice-sheet, which could alter food-webs or predate native lake micro-organisms.
  – Wider cumulative effects on the Antarctic environment as the investigation of Lake Vostok would be one of the biggest scientific projects ever undertaken in Antarctica. For example, about 24 C-130 Hercules transport flights would be needed just to bring in the cargo and equipment needed for the hot-water drilling. Also, a new building will probably be required at Vostok for controlling the probe and hydrobots, and for analysing data.

Summary of reasons for and against exploring Lake Vostok

For	Against
Discover and study new life forms that have been cut off from the evolutionary paths seen elsewhere on Earth.	Lake Vostok is likely to be the oldest sub-glacial lake in Antarctica. It is unique and pristine.
New micro-organisms could yield promising new enzymes or antibiotics.	Risk of possible pollution by chemicals or fuels.
Provides a test-bed for the search for alien life in the frozen oceans thought to exist on Europa.	Risk of possible contamination by micro-organisms from the surface or ice sheet.
The water in Lake Vostok could have a unique chemical composition.	Other smaller sub-glacial lakes in Antarctica could be drilled.
Sediments at the bottom of Lake Vostok may contain a record of ancient climate conditions going back for millions of years.	Lake Vostok is too valuable to be used as a test-bed for unproven technology.

The major reasons for and against exploring Lake Vostok are given above. Students should be able to identify these reasons by reading Resource TL3 and by looking at their EIAs. An article describing the exploration of Lake Vostok was published in the *New Scientist* magazine on 4 December 1999, No. 2215, pp34–37.

Task 4 Reasons for the rapid increase in the fur seal population at Signy Island.

- Almost all the immigrant fur seals at Signy Island are immature males from South Georgia, where their breeding success and pup survival has been exceptionally high. Here the total population is about 3 million and has been increasing at about 17% per year since the early 1970s. Over-population around the coast of South Georgia causes an annual migration southwards.
- Increased food supply (krill and fish) resulting from the decline in whale stocks, which have not recovered significantly since the cessation of the Southern Ocean whaling industry in 1965.
- Although fur seals were hunted almost to extinction in the early 1800s, they were given Specially Protected Species status by the Agreed Measures for the Conservation of Antarctic Fauna and Flora adopted by the Antarctic Treaty Nations in 1964. This protection has been carried over to the Environmental Protocol (1998).
- The summer migration of fur seals to land sites further south is probably linked to the fact that the distribution of winter sea ice, and subsequently spring/summer pack ice, is not so great as it was in the early 1970s. Fur seals tend to avoid pack ice. In the bar histogram in Resource TL4, the low numbers of seals are due largely to heavy pack ice around Signy at the time when the annual seal census was made. Low numbers also occur when counts are made during high winds and driving snow, as the seals go back to the sea.
- Because of regional warming in the Antarctic Peninsula region, especially in summer, many low-lying coastal areas of Signy have become ice-free, providing new sites where the fur seals can come ashore.

Effects of fur seals on terrestrial and freshwater ecosystems

- Physical damage. Soil and, especially, the very sensitive vegetation (principally mosses and lichens), are severely affected by trampling by seals. This damages or kills the plants which are then removed by meltwater, rain or wind. Once the cover of vegetation has gone there is rapid erosion of the thin mantle of soil. This prevents recolonisation, except by green algae. The degree and rate of damage is exacerbated by the high density of seals.
- Chemical damage. Seal fur contains high concentrations of marine salts. This is washed out out during periods of rain or snow when the seals come ashore, or when they swim in lakes, considerably increasing the salinity of soil, moss peat and freshwater. Seal faeces contain toxic levels of some chemicals, especially ammonia, which quickly kills vegetation. Even away from direct contact with faeces, the dissolved chemicals leaching over, or through, the soil may still be too concentrated for many plant species, which soon die.
- Nutrient input. Many freshwater lakes and pools are favoured by fur seals for bathing. Large numbers of fur seals enter several of the lakes near the coast directly from the sea. Excreta enriches the water and sediment with nitrogen. Waters quickly become saline, turbid and nutrient rich. The lakes become eutrophic resulting in significant changes in the benthic vegetation, as well as in microbial and crustacean diversity and abundance.

Recovery of impacted ecosystems

- As yet, no heavily impacted area has seen a decline in fur seal numbers during the summer, so it is impossible to know if ecosystem or community recovery will ever occur. However, field experiments using seal-proof fences (exclosures) have shown that, if the damage is not too serious, or is stopped within a few years of the commencement of damage, the vegetation may recover to a small degree. In the long-term, recovery of the original plant community does not appear to occur. Certainly, where seals are excluded from a badly damaged area, there is no evidence of recovery. Lichens are particularly sensitive to both physical and chemical damage, as are many mosses. The Antarctic pearlwort cannot withstand physical damage, but the Antarctic hair grass appears to be one of the most tolerant plants and may resist trampling and nutrient enrichment for several years.
- Eutrophic lakes will recover to their original state only after the seal impact is removed, and even then it will probably take many years for the lakes to return to their former oligotrophic state. Much of the input from seals is organic material and may be sedimented out. Once in the sediments, it will enrich the lakes for many years.

Control measures to limit fur seal impact

- Fur seal impact on the terrestrial and freshwater ecosystems of Signy could be prevented by erecting strong fences around sensitive areas (e.g. those with well-developed vegetation, lakes, patterned ground). However, fences must be maintained, and this is costly in time and money. The cost effectiveness of this must be considered in terms of the importance of the values being protected (e.g. scientific research, nature conservation). It is not always practicable to fence large areas off.
- Control of the annual influx of fur seals to a relatively small island such as Signy could possibly be achieved by culling large numbers of the animals. However, first of all the fur seal would have to have its Specially Protected Species status removed, and culling would have to be agreed by all the Antarctic Treaty nations. It is highly unlikely that such a controversial option would ever get agreement. There is no doubt that environmental pressure groups, such as Greenpeace, would argue strongly for culling to be prohibited.
- Fur seals could be frightened off from haul-out sites by people walking around the island. However, the seals very quickly get used to people and noise, even young animals, and this option is not likely to work.
- Do nothing at all.

Students should appreciate that although there are a range of options available, there is in practice very little that can be done about the problem beyond monitoring the damage caused by the fur seals. The class debate should produce an appreciation of the very real problems that face decision-makers today in trying to manage and protect the Antarctic environment.

The fur seal population explosion at South Georgia is a natural phenomenon (albeit linked to the collapse of whale stocks caused by the whaling industry in the early 20th century). There are very few examples of a mammal species experiencing such success in modern times. Despite the damage they cause to terrestrial and freshwater ecosystems in the northern maritime Antarctic, their impact is extremely localised, in terms of the range of the animals. It is probably best to accept this natural change to the Signy Island environment and adapt scientific research to the new conditions the seals have created. There is much that can be learned about the seal's influence on the local environment and how individual plant or invertebrate species and terrestrial and freshwater ecosystems develop, tolerate, adapt or alter when they are disturbed. Lessons that may be learned from such a simple ecosystem, where the number of species are few and the cause of impact easy to assess, can then be applied to more complex systems elsewhere in the world.

Marine ecosystems

Key ideas
- The Southern Ocean environment
- Biological productivity
- Marine food webs
- Carbon and energy flow
- Distribution of species
- Interactions between predators and prey
- Adaptions of marine organisms
- Human impacts

Key skills
- Text interpretation
- Diagram and chart construction
- Diagram annotation and interpretation
- Data analysis and interpretation
- Table construction
- Impact analysis

Antarctica is entirely surrounded by the Southern Ocean. The water is extremely cold. Surface water temperatures range from 3.5°C at the Antarctic Polar Front, which marks the northern boundary of the Southern Ocean, to -1.8°C near the continent. Despite the low temperatures, the seas around Antarctica are rich in marine life. This is because the cold water south of the Polar Front contains large supplies of oxygen and nutrients. Sea ice plays a crucial role in determining the dynamics of the marine ecosystem. When the sea ice melts there is a sudden bloom of microscopic algae – phytoplankton – the primary producers of the food chain. The most important consumer of phytoplankton is the Antarctic krill, *Euphausia superba*, and this 6 cm-long shrimp-like creature is the key organism in the marine food web. This worksheet sets out the basic features of the Southern Ocean ecosystem. It examines the environmental controls which affect the ecosystem, concentrating on those factors which determine the growth of phytoplankton. The Southern Ocean food web is introduced and an assessment is made as to how carbon and energy flow through it. The distribution of marine organisms and their various adaptions to the cold environment are described. Finally, the impact of human activity, particularly fishing, on the Southern Ocean ecosystem is considered.

Model answers to tasks

Task 1 The physical factors which control the amount of light available to phytoplankton in the Southern Ocean operate over a range of space- and time-scales. Starting at the largest scale, these can be summarised as:

- Latitudinal variation in daily amount of solar radiation at the sea surface (see figure in Resource M1) – at high latitudes day length is short in winter, and solar illumination is weak
- Sea ice. At its maximum extent in late winter, ice covers around 20 million km^2. Sea ice, and its overlying snow cover, reflects or absorbs much of the sunlight at the surface. Reduction in underwater illumination under sea ice amplifies the seasonal changes at high latitudes.
- Wind mixing. When wind-mixing is vigorous, phytoplankton are mixed deep into the water column. This takes them into regions where light is insufficient to support growth, so the average light regime is sub-optimal. In contrast, a stable surface layer, such as that produced by meltwater from melting sea ice in spring, allows algae to remain at high light intensity.
- Turbidity. Water itself is relatively transparent, but suspended particles can absorb or reflect light. Mineral particles and other detritus are important close to the coast, but in the open ocean it is the phytoplankton themselves which cause most of the turbidity.

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Crabeater seals swimming under pack ice

Task 2 Students are asked to address the HNLC paradox. They should be able to identify from Resource M1 the major controls on phytoplankton growth, which in turn lead to failure to use all nutrients during the growth season. These controls should include:

- Light (including an appreciation of the effects of vertical mixing) – refer to the items in Task 1. Argument for: Wind-mixing is demonstrated to be important in reducing production. Argument against: Note from the figure in Resource M1 that solar radiation over the Southern Ocean in summer is similar to that at lower latitudes.
- Low temperature. Argument for: Most biological processes are slower at low temperatures. Argument against: Growth rates and biomass in Southern Ocean phytoplankton can be as high as found at lower latitudes.
- Aspects of nutrient availability. Argument for: The section in Resource M1 on the nitrogen cycle indicates that high concentrations are not always indicative of high availability. Argument against: Nutrients such as nitrogen and silicon are present at high levels.
- The importance of trace elements. Argument for: Experiments suggest that trace elements limit production (Resource M1). Argument against: It is difficult to explain areas of high phytoplankton production solely on the basis of trace element availability.

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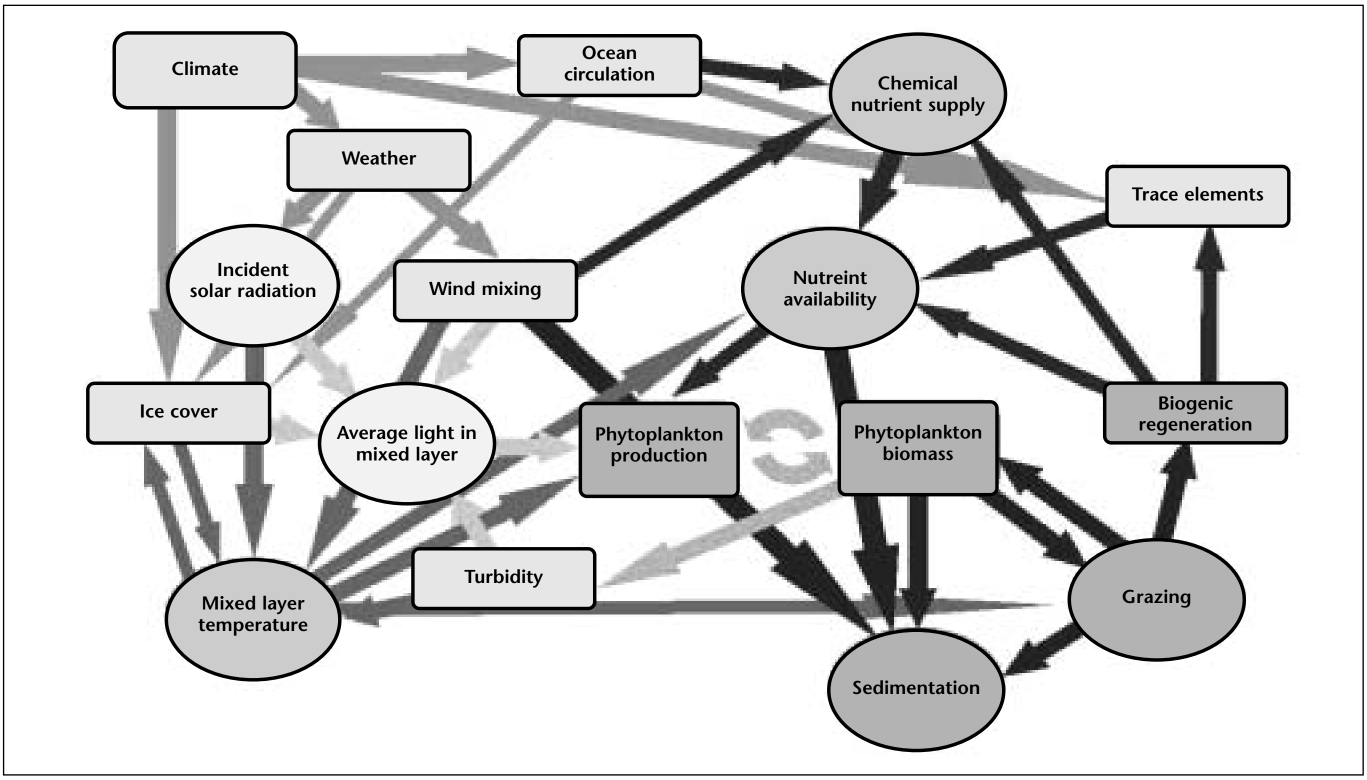
Task 2 continued **Controls of phytoplankton growth**



J. Priddle/BAS

- Grazing control. This is probably the most equivocal control, and cannot be set simply in terms of 'pros and cons'. Documented grazing rates vary from a few per cent of daily phytoplankton production to more than the available biomass.

These controls are summarised in the diagram above. It is most unlikely that students will include all of the possible interactions. This diagram is complex, and contains nearly all of the controls and feedbacks involved in determining the growth of phytoplankton and the accumulation of biomass. It also includes a number of simple and complex feedback relationships. Two instances are worthy of note. The first is the relatively simple linkage between phytoplankton biomass and water column illumination. Thus dense blooms of phytoplankton can become self regulating, and the depth over which they can grow becomes more and more shallow. The second feedback is more complex and involves the interaction between phytoplankton and grazers. Grazing is itself density-dependent, so is controlled by abundance of both phyto- and zoo-plankton. Grazing regenerates nutrients, which not only makes elements like nitrogen available for further phytoplankton growth but may also influence the way these elements are taken up by phytoplankton.

Task 3 Resource M3 contains an unlabelled simple food web diagram. When completing this diagram, students should examine Resource M2. This is a food web with five trophic levels, the key species of which are labelled along the bottom right side of the main figure. The simplified web in Resource M3 is divided into the microbial, grazer and predator components only.

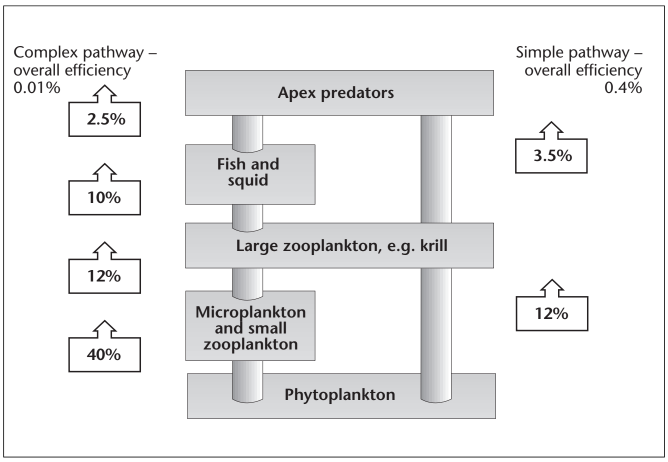
The birds and seals are linked to the land, where they breed (some penguins and seals breed on sea ice). Whales are warm-blooded and air-breathing, but spend all of their lives in the water.

Krill is a key species in the Southern Ocean food web. Krill is an important grazer, feeding on small microbes and also forms the food supply of most of the predators in the Southern Ocean, including the largest whales. Dependent predators are affected by natural variability in krill abundance, and would also be susceptible to any reduction in krill numbers through over-fishing.

Task 4 There are five levels in the food web, therefore four transfers of energy take place between the lowest (microbial community) and highest (killer whales). Since only 10% of the carbon is transferred for growth, and the starting point is 50 tonnes, the amount of growth, as tonnes of carbon, available to killer whales is 0.005 tonnes (or 5 kg) of carbon. This calculation shows that for top predators to survive they require considerable primary production to occur at the bottom of the food web.

This simple calculation could be repeated with some more realistic values (some are given in the worksheet and a complete set is given below). Students should appreciate that short food chains are more 'efficient' than long ones, and that top predators are very 'expensive to run'.

Conceptual model of carbon flow in the Southern Ocean ecosystem



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The diagram shows a very simple conceptual model of carbon flow in the Southern Ocean ecosystem. On the right, carbon is passed along the 'classic' diatom → krill → whale pathway, with about 0.4% of diatom carbon appearing as whale tissue. On the left is a pathway with more stages, and one where a much smaller fraction of the algal carbon appears at the top of the food-chain.

Weddell seals have a thick layer of fat and blubber to help retain their body heat

Task 5 The distribution of the predators is linked to the distribution of their main prey – krill – which in turn is often determined by physical environmental factors. In general, krill are most numerous where there is an abundance of phytoplankton. However, the relationship between krill and higher predators is more complex. Although many species feed on the krill swarms which are concentrated in the seasonal pack ice zone, others respond directly to their environment. For instance, crabeater seals live and breed in the pack ice zone, fur seals typically breed on sub-antarctic islands and avoid pack ice, while minke whales breed in subtropical waters, and migrate south to feed in the pack ice in summer. So the distributions shown in the chart in Resource M3 reflect the interaction between food supply and habitat preference.

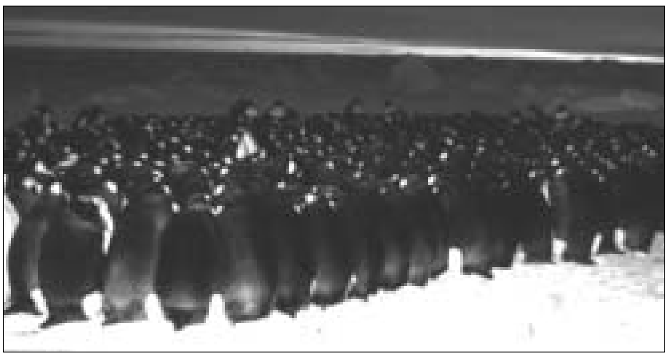
Task 6 **Table of adaptive mechanisms**

	Adaptive mechanism	Function	Examples
1. Biochemistry and physiology	Slow growth Production of antifreeze proteins Loss of red blood cells and haemoglobin	Reduces energy demand Prevents freezing Reduces energy consumption in circulation and synthesis	Most cold-blooded animals Pelagic fish living close to ice Ice fish
2. Body structure and feeding	Insulation – fur, feathers Insulation – fat and blubber High energy diet for young	Conserves body heat Conserves body heat Rapid growth increases survival	Birds, some seals incl. pups Seals and whales Seals and baleen whales
3. Life cycle and breeding	Seasonal reproductive strategies Migration Social behaviour such as crèche formation	Utilise summer food supply Avoid cold in winter Find food sources Conserve body heat	Benthic animals Many birds and mammals Penguin chicks

Task 7 Human activity can affect the South Georgia marine ecosystem directly through overfishing of mackerel icefish leading to a collapse of the stock. Icefish is part of the diet of several predators, such as penguins, seals and seabirds. Over-exploitation of icefish could therefore have wider effects on the marine ecosystem. Also, icefish feed on krill, and in years when krill abundance is low the icefish are in poor breeding condition. They may also be subject to heavier predation from large animals such as fur seals, which switch to this prey to make up for the lack of krill. This shows that fishing can have both a direct effect on the population of mackerel icefish and an indirect effect on dependent species.

In Resource M5 the direct effects of fishing on the target species of mackerel icefish appears to be closely controlled. Regulation of the fishery sets limits on catches. These limits are based on a scientific assessment of the various properties of the fish population, including the number of individuals, and the size and age composition of the fish. The indirect effects on dependent species appear not to be closely controlled. However, fishing in the South Georgia area is regulated by the Convention for the Conservation on Antarctic Marine Living Resources (CCAMLR) agreed under the Antarctic Treaty. This has established internationally-agreed catch levels for mackerel icefish which are based not simply on maintaining the population of the commercial species, but also on minimising the impact on dependent species as well.

At a global level, several impacts of human activities also have the capacity to affect the Southern Ocean ecosystem. These include fallout of persistent organic pollutants, such as pesticides, increased levels of UV radiation resulting from ozone depletion and global warming which could change ocean circulation and sea ice extent.



Emperor penguins huddling to keep warm

Management and conservation of marine species — Worksheet 13

Key ideas
- The importance of krill in the Southern Ocean ecosystem
- The krill fishery
- The ecosystem approach to calculating fishing limits
- Illegal fishing of Patagonian toothfish
- Seabird entanglement in long lines
- The exploitation of whale stocks

Key skills
- Map interpretation
- Data analysis and interpretation
- Graph construction and interpretation
- Comparing texts
- Writing a short newspaper article
- Class debate

The Southern Ocean is rich in marine living resources, such as krill, fish, squid, seals and whales. Several of these resources have been over-exploited. Huge numbers of seals were killed in the early 1800s. In the 1900s, most species of the great whales were hunted until stocks were exhausted. Today, fishing fleets from Chile, Japan, Spain, Russia and Korea all work in the Southern Ocean catching fin fish, squid and krill. The krill fishery began in the early 1980s. This caused widespread concern since krill is one of the key species in the Southern Ocean ecosystem, and a large uncontrolled fishery could have a very damaging environmental impact. This led to the Antarctic Treaty nations adopting the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) in 1982. CCAMLR is based on the 'ecosystem approach' whereby commercial fishing takes account not only of the impact on the targeted species, but also on the prey and predators of that species. At present, there is no large-scale fishing for krill and stocks are not threatened. However, there are problems with other fisheries, particularly that for Patagonian toothfish. This worksheet explains the importance of the ecosystem approach in fisheries management by examining the exploitation of krill in the Southern Ocean. The major problems faced by CCAMLR in controlling the illegal fishing of Patagonian toothfish are discussed. Finally, the impacts of whaling are assessed. Students are asked to debate whether sustainable whaling in Antarctica should be permitted.

Model answers to tasks

Task 1 The life history of krill:
- Krill is a shrimp-like crustacean which may live for 6–7 years and grow to 6 cm in length.
- Krill spawn during the austral summer at 80–200 m depth. Mature females can spawn 3–9 times a season and lay about 1400 eggs each time.
- The eggs sink and hatch into larvae at depths of 750 m.
- The larvae slowly rise through the water column taking 2–3 weeks to reach the surface. They take 2–3 years to become mature.
- In summer, adult krill can form dense 'swarms' which may be hundreds of metres across and contain millions of animals. Such swarms can colour the surface water pink and extend from the sea surface to depths of 40–50 m.
- Krill stocks are very large. It is estimated that the Southern Ocean contains around 200–800 million tonnes of krill.

In order of importance, krill feeds on protozoa, phytoplankton and copepods. In winter, there is less food available and krill shrink and will even eat other krill.

Species that are directly dependent on krill are seals (e.g. crabeater seals and fur seals), penguins (e.g. macaroni, Adélie and chinstrap penguins) and other birds (e.g. black-browed albatross), baleen whales (e.g. humpback and minke whales), fish and squid. Crabeater seals are thought to be the single biggest consumers of krill, taking some 63 million tonnes of krill a year. The crabeater seal is the world's most abundant seal.

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I. Everson/BAS

Tinned krill products

Krill prefer cold water and are not found to the north of the Antarctic Polar Front. They are distributed all round Antarctica, carried by the circumpolar current which goes from west to east all around the continent. Several areas show major concentrations of krill (see map shown in Resource MC1) corresponding generally to gyres and eddies along the boundary zone of the Antarctic Coastal Current. The largest concentration of krill is found in the Weddell Gyre. Dense concentrations are often located close to continental shelf breaks, such as off South Georgia, where deep water rich in nutrients upwells to the surface.

The uses of krill as food for humans include:
- peeled krill tail meat
- krill protein reconstituted as 'sticks'
- krill sausage

The uses of krill as food for farmed animals include:
- Aquaculture – krill meal fed to farmed fish. The pink coloration of krill also helps to colour the meat of farmed salmon.
- Poultry and pig farming – krill meal used as an animal feed.

Task 2 The key conservation principles of CCAMLR are to:
- Safeguard individual harvested species in the long-term by preventing a decrease in the size of the harvested population to levels below which stable recruitment cannot be ensured.
- Apply an ecosystem approach which maintains the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and ensures depleted populations are restored.
- Ensure the sustained conservation of Antarctic marine living resources by using the precautionary principle. This sets out to prevent changes, or the risk of changes, to the marine ecosystem which cannot be reversed over two to three decades.

This approach is more important for krill quotas than for tuna quotas because of the position of krill in the food chain compared to that of tuna. More species are dependent on krill than are dependent on tuna. Task 1 showed that krill is the main prey for a large number of different predators in the Southern Ocean. In contrast, in tropical waters tuna are near the top of the food chain so fewer species are dependent upon it.

Task 3 **Krill consumption, percentage uptake of krill, and foraging ranges for a range of predator species breeding on South Georgia.**

Predator species	Krill consumption (million tonnes)	Percentage uptake	Foraging range (kilometres)
Macaroni penguin	3.87	39.7%	123
Antarctic prion	1.35	13.8%	244
White-chinned petrel	0.21	2.2%	1218
Diving petrel	0.18	1.8%	243
Other birds	0.10	1.0%	–
Fur seal	4.05	41.5%	150
Total	9.76	100.0%	

The total krill consumption by predators foraging in the waters around South Georgia is at least 9.76 million tonnes. Note that this figure does not include consumption by whales, which are another major predator.

The range of the white-chinned petrel is less significant than that of other species because its foraging range is very large (1218 km). Thus, its area of exploitation is also very large and spread a long way from South Georgia.

The instantaneous standing stock at South Georgia (CCAMLR Statistical Subarea 48.3) is:

$$B = PT\,(M^2 + V(M))/M^3$$

where:

P = Predator krill consumption
T = Krill retention time
M = Krill natural mortality rate
V(M) = Variance of M

therefore:

$$B = (9.76 \times 0.5\,(0.6^2 + 0.1))\ /\ 0.6^3$$
$$= 10.4 \text{ million tonnes}$$

The potential yield of krill from South Georgia (Subarea 48.3) is:

$$Y = \lambda B_o$$

where:

λ = discount factor
B_o = total standing stock (biomass)

therefore:

$$Y = 0.116 \times 10.4$$
$$= 1.2 \text{ million tonnes}$$

Over-fishing of krill would remove a major food source for seals, birds, whales, fish and squid living in the Southern Ocean. If higher predators were unable to find alternatives to krill, their populations would decline.

It is difficult to know how long it might take for the effects of krill over-fishing to be felt as many predators are long-lived with slow reproductive cycles (e.g. whales). Evidence of reductions in the breeding populations of dependent species may take some time to become apparent by which time they could be under serious threat. Fast growing dependent species which reproduce at an early age (e.g. fish) would be affected earlier by over-fishing.

Task 4 The total allowable catch (TAC) for krill set by CCAMLR for the South Atlantic sector is 1.5 million tonnes. Currently, the actual catch in the South Atlantic is less than 100,000 tonnes (see bar graph in Resource MC2). The actual catch is therefore very much lower than the TAC.

Catches have declined because the former Soviet Union, which was the major fishing nation until 1992, no longer fishes for krill. Fishing has declined because of the economic difficulties in the former Soviet Union which has prevented many of their factory trawlers from sailing to the Southern Ocean. There have also been problems in processing and marketing krill products. Japan, the other major krill fishing nation, has concentrated on high-value, low-volume products such as tail meat. This is expensive and difficult to do as krill enzymes rapidly break down body tissues after death. Krill for human consumption must therefore be processed within three hours of catching.

Task 5 The reports by CCAMLR and ASOC both concern illegal, unreported and unregulated fishing in the Southern Ocean. The CCAMLR report is extracted from the report of the sixteenth meeting of the Commission. This is a text which has to be agreed by all Commission members before it can be released and is therefore a sober and accurate reflection of the information that was put forward and the debate that occurred. The CCAMLR report calls for a collective effort by its members, measures by Flag States and Coastal States, and further steps to ensure enforcement

continued ➤


C. Goss/BAS

Adult Patagonian toothfish (*Dissostichus eleginoides*) caught off South Georgia

and compliance with agreed CCAMLR conservation measures. The ASOC report has been written by the environmental pressure group to try and influence delegates and media attending the Antarctic Treaty Consultative Meeting in 1998. It uses information contained in scientific reports and extrapolates them to predict the extreme effects illegal and unregulated fishing might have. The language used is highly emotive, because it is designed to make political capital out of the problem and to press home ASOC's views in a very direct way. Both CCAMLR and ASOC consider illegal, unreported and unregulated fishing a very serious issue, which merits strong action. CCAMLR seeks to do this by agreeing conservation measures which member states apply to the fishing activities of their nationals, whilst ASOC seeks to raise media and public awareness to exert political pressure on CCAMLR.

Fishing companies might want to fish illegally or not report their catches because:

- Their catches are significantly higher than that allowed by CCAMLR.
- They do not want to pay for a licence to fish legally as it increases costs and lowers profit margins.
- They do not want to comply with CCAMLR conservation measures, such as taking on board international fisheries observers, as it would interfere with their illegal fishing activities.
- They consider that Illegal fishing is very profitable with little risk of being caught.

Longlining for Patagonian toothfish has been concentrated on the continental shelf break around South Georgia, Iles Kerguelen, Prince Edward Islands and Heard and McDonald Islands. It is easy therefore to work out where vessels might be fishing. Also, it is not hard to identify fishing fleets using high resolution satellite imagery. However, it is very difficult to identify individual fishing vessels and prove that they are fishing illegally. This needs information which can only be obtained by patrolling fisheries protection vessels or aircraft. Policing of the fishing grounds is expensive and cannot be done on any substantial scale because of the huge and remote sea areas involved. Once vessels have been identified as fishing illegally they can then be 'black listed' so that they cannot land their catches or obtain licences to fish.

In 1999, CCAMLR agreed a catch documentation scheme for the toothfish fishery. This requires every toothfish shipment to have its own unique export documentation, which can be used to trace the fishing vessel that caught the fish, and the date and place legal fishing took place. This scheme will put a premium on legally caught fish and so will significantly reduce the amount of illegal fishing.

Students should use a range of different sources when writing their article examining the problem of illegal fishing for toothfish in the Southern Ocean. Sources they should use are Resources MC3 and MC4 as well as the text on page 2 of Worksheet 13. Students should be encouraged to search the internet for the latest news and to look at past stories on the subject on newspaper or TV news web sites. Students should discover that toothfish is currently worth about £3000 per tonne. In 1997–98, nearly 70,000 tonnes of toothfish were traded, much of it illegally caught. The stock of this long-lived and slow-growing fish is in grave danger of being over-exploited. Also the longline hooks used to catch toothfish entangle tens of thousands of seabirds every year. This is causing significant declines in albatross populations on many sub-Antarctic islands. The differing views of governments, scientists, the fishing industry and environmental pressure groups should all be taken into account by students.

Task 6 Entanglement of birds in longlines could be prevented by:

- Restricting the setting of longlines to hours of darkness so that birds cannot see the baits going over the side.
- Frightening the birds away from the lines as they are being set by using brightly coloured streamers.

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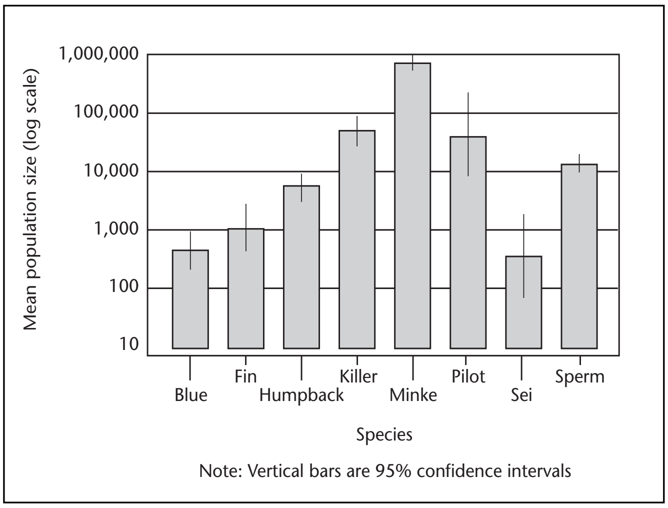
- Ensuring baited lines sink quickly by weighting them correctly.
- Not discharging fish waste and offal into the sea, as this attracts birds.
- Using minimal lighting around the stern of the ship when setting longlines (although lack of lighting makes it more dangerous for fishermen setting the lines).
- Setting longlines under the water surface by using special equipment attached to the ship.
- Finding another way of catching toothfish which reduces incidental seabird mortality.

Task 7 The succession of species caught was: humpback, blue, fin and sperm, sei, and minke.

Humpback whales were caught first by the whalers in the early 1900s as they were the easiest to catch and were found in large numbers close to land around the whaling stations on South Georgia. As the numbers of humpbacks were reduced and whaling technology improved during the 1920s, the industry was able to move offshore and target the largest and most profitable species – the blue whale. This whale was taken primarily for its oil, which was used in the production of soap and margarine, especially in the years after the First World War. The oil produced by one blue whale equalled two fin, three humpback and five sei whales. Whaling virtually stopped during the Second World War and catches of all species of whale were greatly reduced. By the early 1950s, the stocks of blue whales had been exhausted and the whaling fleets switched to fin whales. Eventually, fin whale stocks collapsed in the early 1960s, and large numbers of the smaller sei and minke whales were taken. Whaling became increasingly unprofitable. The last of the whaling stations on South Georgia closed on 15 December 1965. In 1982, the International Whaling Commission (IWC) introduced a worldwide ban on commercial whaling. Both Japan and the former USSR continued commercial whaling in Antarctica 'under objection' to the IWC until the end of the 1986/87 season. Now only Japan continues to kill whales in the Southern Ocean, taking about 300 minke whales a year for scientific purposes.

Estimated stocks of Antarctic whales



BAS

It is extremely difficult to make accurate population counts of whales. This is because whales are now so rare and widely dispersed. Attempts have been made to estimate populations, directly from whale watching cruises, or indirectly using mark and recapture methods. However, these different counting methods have major difficulties and since 1991 the IWC has ceased to produce population estimates because of doubts about their accuracy. For example, sighting whales is highly dependent on sea state and light levels, and the mark and recapture of individual whales is very difficult to do as whales can travel very long distances.

Task 8 The killing of more than 1.3 million whales, representing a biomass of around 70 million tonnes, by commercial whaling activities is the single largest human impact to the Southern Ocean ecosystem. The massive reduction in the stock of whales is popularly thought to have produced an enormous krill surplus which would be available to other predators. However, no one really knows if this is the case. This is because there was no measure of krill biomass before the period of whale exploitation. Also, any surplus is probably illusory since any extra krill was probably quickly taken up by other predators. Fast growing species, such as crabeater seals and fur seals, have greatly expanded their numbers and range since the 1950s and this may be as a result of increased krill availability.

Task 9 Students should consider the following points during their class debate as to whether sustainable whaling should be permitted:

- Whale meat is high grade protein which is suitable for human consumption. Is it a marine living resource that should be harvested?
- Is the population of minke whales in Antarctica so large (760,000) that a sustainable catch might be feasible?
- It is very difficult to estimate whale populations, so should whaling be allowed when the total number of whales in the targeted stock is not accurately known?
- Is it ethical to kill whales?
- Can whales be killed humanely?
- Is it more profitable to take tourists to watch whales or to hunt them and sell their meat?
- Are whales highly intelligent and thus special species which need to be protected?

I. Everson/BAS

The Falkland Islands Government fishery patrol vessel M/V *Cordella* policing the waters around South Georgia

Environmental protection of Antarctica — Worksheet 14

Key ideas
- Types of human impacts affecting Antarctica
- Major pollution incidents – The *Bahia Paraiso* marine fuel spill
- The Environmental Protocol
- The response of the UK to the Protocol
- Waste management in the British Antarctic Survey (BAS)
- Clean-up of the old British stations
- Environmental Impact Assessment (EIA) – the Rothera airstrip

Key skills
- Analysing and summarising text
- Producing lists
- Table construction
- Working in small groups or pairs
- Using bullet points
- Report writing
- Flow diagram construction
- Environmental impact analysis

International concern over the conservation of Antarctica led to the Antarctic Treaty nations agreeing the Protocol on Environmental Protection, which came into force in 1998. However, the most significant impacts in Antarctica are not caused by human activities on the continent but by people elsewhere on the planet. The ozone hole is the greatest human impact at present and now covers an area of more than 26 million km^2 around the South Pole each southern spring. The hole is created because ozone is destroyed by man-made ozone depleting chemicals, such as CFCs and halons, released mostly in the northern hemisphere and taken to Antarctica by long-range atmospheric transport. In comparison, the impacts from human activities within Antarctica are local and small-scale. Physical disturbance around a research station, for instance, is likely to be less than 3 km^2. Most research stations are built on flat, ice-free areas near the coast. However, such sites are also often important for breeding wildlife. This worksheet identifies the various types of human impacts affecting Antarctica. Case studies of the *Bahia Paraiso* marine fuel spill and the construction of the Rothera airstrip are provided for students to assess. Information is given on the environmental management of British Antarctic Survey (BAS) activities in Antarctica. This demonstrates how seriously Antarctic operators now try to limit their environmental effects.

Model answers to tasks

Task 1 List of human impacts affecting Antarctica

Impact	Worksheet	Resource
Climate change	1, 4, 7, 8, 12	N5, S5, ICE5, C3, C5
Sealing	2, 5	TL4
Whaling	2, 12, 13	D5, TL4, ML5
Research stations and scientific projects	2, 3, 5, 10, 11, 14	LW6, S5, ATS5, TL3, EP3–EP5
Vessel operations	5, 14	ATS5, EP2
Fishing	5, 12, 13	ATS3, M5, MC1–MC4, EP3
Tourism	5, 15	ATS5, EP3, T4
Ozone depletion	9, 12, 14	OZ1
Global pollution	12	

The only worksheet which does not mention human impacts affecting Antarctica is Worksheet 6 – Geology in Antarctica. However, this worksheet does examine mineral occurrences in the Antarctic and the controversial issue of mining on the continent. Mining has the potential to cause significant adverse environmental impacts, but has never taken place due to a lack of knowledge of mineral resources, hazardous environmental conditions, logistical and technical problems and major political and environmental concerns. Moreover, the Environmental Protocol now prohibits any activity relating to mineral resources, other than scientific research, in Antarctica. All the worksheets therefore raise environmental issues in some way.

List of the United Nations' main findings on the state of the Antarctic environment

Subject	Finding
Tourism	A rapidly growing industry. Long-term impacts are largely unknown.
Fishing	Commercial fishing levels for most fish are below total allowable catch levels set by CCAMLR. There are problems with illegal fishing and bird entanglement in longlines.
Global pollution	Pollutants are being released from activities in industrialised and populated areas of the world and are being transported in the atmosphere and oceans to Antarctica. Levels in Antarctica are, however, very low. Therefore, it is important for Antarctica not to be contaminated by local sources otherwise its value for baseline global pollution will be ruined.
Ozone depletion	The ozone hole is expected to occur over Antarctica each spring for many decades to come. International agreements – the Vienna Convention and Montreal Protocol – now control emissions of ozone depleting substances.

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Subject	Finding
Sea ice	Analysis of satellite images has not detected any significant overall change in sea ice cover in Antarctica, although there have been fluctuations in the length of the sea ice season and maximum extent of sea ice.
Mass balance of the Antarctic ice sheet	There are major uncertainties in the estimation of the mass balance of the Antarctic ice sheet. Scientists are unsure as to what might happen to the West Antarctic Ice Sheet in the future as a result of global warming.

Both the students' own lists and their list of the United Nations' main findings should identify ozone depletion, global pollution, fishing and tourism as human impacts affecting Antarctica. Students should find that their own lists contain more impacts than those reported by the United Nations. This is because Resource EP1 is a summary of the United Nations' report and so sets out their views on the most important issues affecting the state of the Antarctic environment. Surprisingly, the United Nations summary makes little mention of the impacts caused by scientific research and associated logistical operations, despite science being the major activity currently undertaken in Antarctica. The United Nations also only looked at the current state of the Antarctic environment and did not examine the historical impacts of sealing and whaling. It is unlikely that students will have listed changes in either sea ice or the mass balance of the Antarctic ice sheet. However, they should have identified climate change. Climate change could cause changes in sea ice extent and increase the melting of the ice sheet, although there is considerable scientific uncertainty as to the extent and magnitude of these impacts.

Task 2 **Human impacts on Antarctica**

Impact	Cause	Extent	Damage	Action	Significance
Climate change	Emissions of greenhouse gases	Global	Likely to be high	Convention on Climate Change (1994) Kyoto Protocol (1997)	1
Ozone depletion	Emissions of CFCs and other ozone depleting chemicals	Global	Likely to be high. Worldwide, most zone lost over Antarctica	Vienna Convention (1985) Montreal Protocol (1989)	2
Whaling	Hunting of the great whales for oil and meat	Regional. Southern hemisphere oceans	High. Little or no recovery in whale populations since commercial whaling finished in the 1960s	Convention for the Regulation of Whaling (1946) Moratorium on Commercial Whaling (1982) Southern Ocean Whale Sanctuary (1994)	3
Sealing	Hunting of fur seals for pelts and elephant seals for oil	Regional. Southern Ocean and South Atlantic Ocean	Medium. Full recovery of fur and elephant seal populations since sealing finished in the late 1800s	Agreed Measures (1964) Convention on the Conservation of Antarctic Seals (1972)	4
Fishing	Fishing for finfish, squid, krill	Regional. Southern Ocean. Major fisheries on continental shelf break areas	Medium. No recovery of badly depleted stocks. Incidental mortality of seabirds	Convention on the Conservation of Antarctic Marine Living Resources (1982)	5
Research stations and projects	Scientific research and associated logistical support	Impacts local. Antarctic coastline and offshore islands	Low	Agreed Measures (1964) Environmental Protocol (1998)	6
Vessel operations	Logistical support for scientists and tourists. Support for fishing operations	Impacts local. Antarctic Peninsula and offshore islands. South Georgia	Low	International Convention for the Prevention of Pollution from Ships (1973) Antarctic Special Area (1992) Environmental Protocol (1998)	7
Tourism	Tourists going ashore from tour ships	Impacts local. Antarctic Peninsula and offshore islands. South Georgia	Low	Agreed Measures (1964) Antarctic Treaty Visitor Guidelines (1994) Environmental Protocol (1998)	8
Global pollution (particulates)	Emissions of heavy metals and organic pollutants	Global	Likely to be very low in Antarctica	Environmental Protocol (1998) for activities in Antarctica. Draft UN protocols to control emissions of heavy metals and persistent organic pollutants worldwide	9

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The most significant environmental issues affecting Antarctica are climate change and ozone depletion. These impacts are global problems and have continental scale effects on Antarctica. For example, the ozone hole now covers an area of more than 26 million km^2, nearly twice the size of Antarctica, by the end of each southern spring. Impacts that are the result of activities within Antarctica, such as research stations and tourism, are direct, but highly localised. The physical disturbance around a research station, for instance, is likely to be less than 3 km^2. However, the significance of such local impacts may be greater than the small area affected suggests. This is because most research stations are built within the 0.5% of the land area of Antarctica that is ice-free. The best sites for stations are flat, ice-free areas near the coast which are also often important natural habitats and breeding areas for seals, penguins and other birds.

The management of major global environmental issues, such as climate change, requires international action to tackle the problem. No single country, or group of countries, can solve such global impacts alone. For example, international action has been taken to protect the ozone layer through the Vienna Convention and Montreal Protocol. These agreements are phasing out the production and use of man-made ozone depleting chemicals, such as CFCs and halons. In Antarctica, localised environmental impacts, for instance from waste disposal or fuel spills, are now subject to stringent controls through the regulations contained in the Environmental Protocol. Nations working in Antarctica have placed a high priority on compliance with the Protocol and this has significantly reduced local impacts.

Task 3 **Oil spill report – Palmer Station**

- To: Operations Director, US National Science Foundation
- Date: 29/01/89
- Time: 1100 hrs (local)
- Quality and type of fuel spilled: Unknown, likely to be > 100,000 litres of diesel fuel and other fuel products.
- Source and cause: Spill caused by the grounding of the Argentine Navy resupply vessel *Bahia Paraiso* about 2 km away from Palmer Station. An underwater ledge has ripped a 30 m long gash in the hull which has allowed fuel to leak out.
- Location, size and movement of spill: Initially, a 1 km^2 fuel slick was seen next to the grounded vessel. After 4 hours, the slick spread into Arthur Harbour and near the vicinity of the station. At present, the spill remains fairly concentrated in this area.
- Weather conditions: Good. Winds slight.
- Response action: Station personnel have responded to a request for emergency assistance from the Captain of the *Bahia Paraiso*. Inflatable boats have been used to ferry the passengers and crew to Palmer. There has been no loss of life. Total of 81 passengers and 235 crew have been rescued and are being housed in emergency accommodation on the station.
- Resources at risk and environmental impact: All scientific research programmes at Palmer have been cancelled in order to cope with the emergency. The fuel spill presents a grave threat to the local environment, particularly the coastline and penguin colonies, and to ongoing scientific research.
- Assistance requested: The station cannot carry out a major clean-up as we lack the necessary equipment. Please organise an international oil spill response team to help us as a top priority. We also need assistance in monitoring the environmental impact of the spill.
- Additional comments: We have contacted two tour ships operating nearby. They have altered course and are on their way to Palmer to evacuate the tourists and some of the ship's crew. Please alert other national programmes and tour operators to this emergency and request immediate ship assistance.

Initial forecasts by environmentalists suggested that the spill could damage Antarctic marine ecosystems for a century as they believed the fuel would degrade only very slowly in the cold environment. However, the results of long-term environmental monitoring showed that damage was far less than expected. Several factors helped to minimise the impacts of the fuel spill, including the high volatility of the fuel, the relatively small amount of fuel lost and natural dispersion of the fuel in the high-energy wave environment.

The lessons that can be learnt from the *Bahia Paraiso* fuel spill are:

- Despite the use of ice-strengthened ships and modern navigation technology, vessel operations in Antarctica remain hazardous and major accidents are a real risk.
- International cooperation and collaboration is vital in the event of a major marine accident in Antarctica. No one nation operating in the region has the local resources available to carry out a large-scale rescue, contain and remove fuel, and monitor the environmental impacts.

Major spills could be prevented by:

- Ensuring vessels sailing in Antarctic waters are ice-strengthened and have on board modern navigation and ice-detection equipment.
- Training officers and crew to work safely in Antarctic waters, and requiring them to carry out regular pollution response exercises.
- Ships continuing to use light refined fuels (e.g. diesel fuel) in Antarctica. Heavy fuel oil is used by only a handful of ships operating in the area. Spills of heavy fuel oil products are likely to have much more long-lasting impacts as they do not evaporate or disperse as easily as refined fuels.
- Preparing oil spill contingency plans for station and ship operations in Antarctica.

The Antarctic Treaty nations are currently discussing an Annex to the Environmental Protocol which will cover liability for environmental damage arising from activities in Antarctica. This will establish who will pay for cleaning up oil spills. The negotiations are proving to be very complex and difficult, and it may be several years before the new Annex is agreed. In the meantime, it is likely that the clean-up after any major spill will require an international effort, utilising the resources of several nations, as the response to the *Bahia Paraiso* demonstrated.

Task 4 In general, there are considerable similarities between the Environmental Protocol and the World Park concept. The main objective of both is to ensure the comprehensive protection of the Antarctic environment. They both set out to protect the intrinsic value of Antarctica as the world's last great wilderness and its value as a globally important area for scientific research. Also, under both approaches Antarctica remains a continent for peace, free of nuclear weapons and military activities. However, there is one major difference between the two approaches. Under the World Park concept, protection of the Antarctic environment is given 'paramount consideration' when evaluating all human activities. There has been concern among some scientists that this policy would be very restrictive and interfere with important scientific research. In contrast, the Environmental Protocol gives priority to scientific research against other human activities. Thus, the Protocol adopts a twin track approach protecting both the Antarctic environment and Antarctic science.

Improvements that could be made to the Environmental Protocol:

- Agreement of a new Annex to the Environmental Protocol setting out a liability regime for environmental damage in Antarctica.
- Production of guidelines for ship operations in Antarctica

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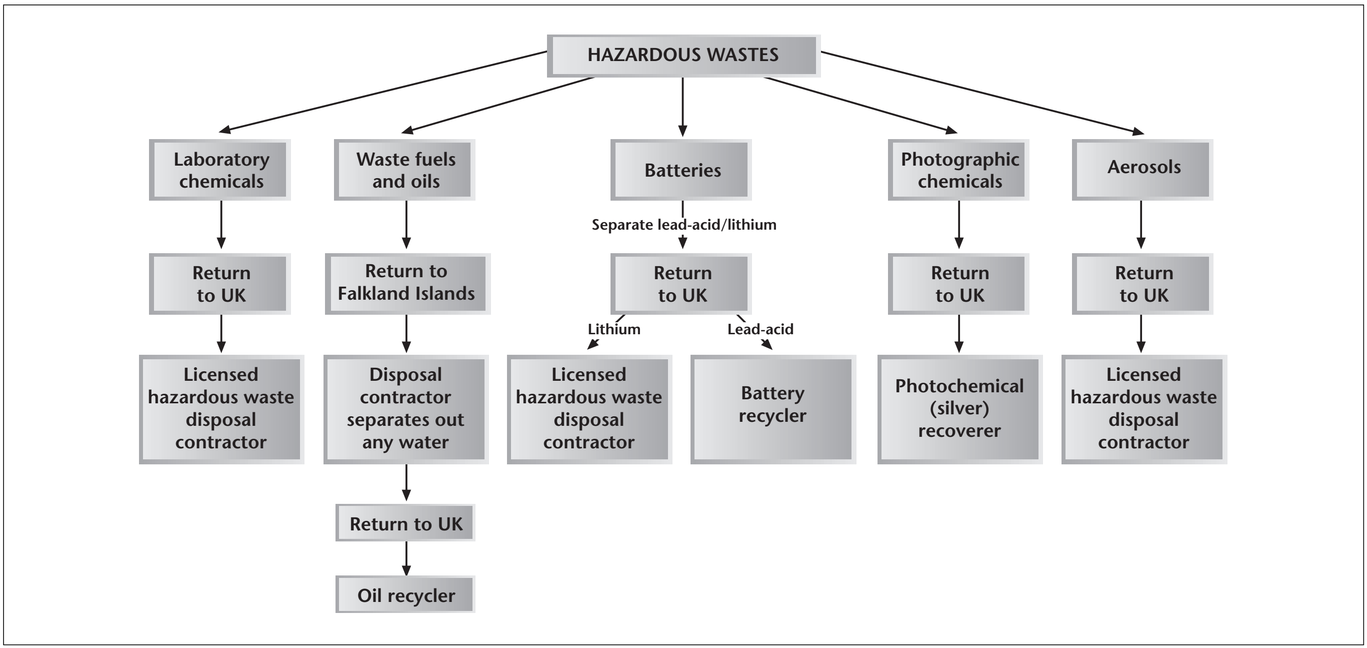
recommending measures to be taken in the design, construction, operation, manning and equipment of ships.

- Revision of the list of Specially Protected Species contained in Annex II of the Protocol. This has not been reassessed since the list was originally agreed as part of the Agreed Measures in 1964.
- Some students might discover that environmental pressure groups such as Greenpeace have argued that the Protocol should be policed by an independent Antarctic Environmental Protection Agency. It would have the power to monitor the impacts of human activities and set stronger environmental controls if necessary.

Task 5 **Flow diagrams showing the disposal routes taken by different types of waste produced by BAS in Antarctica.**



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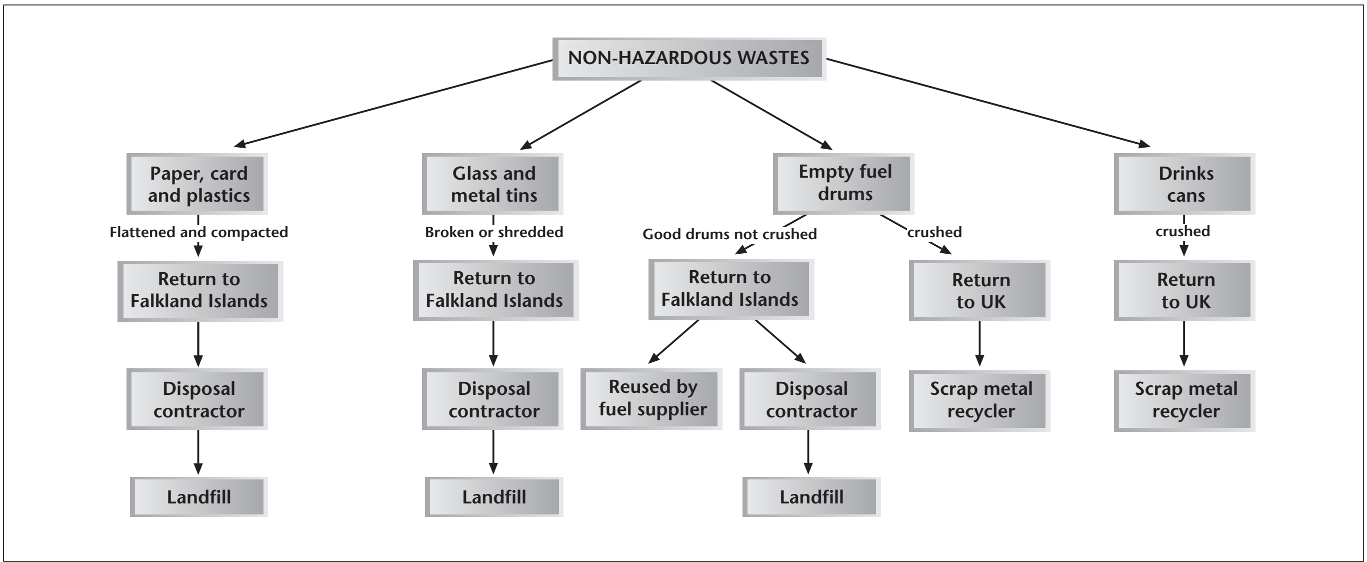

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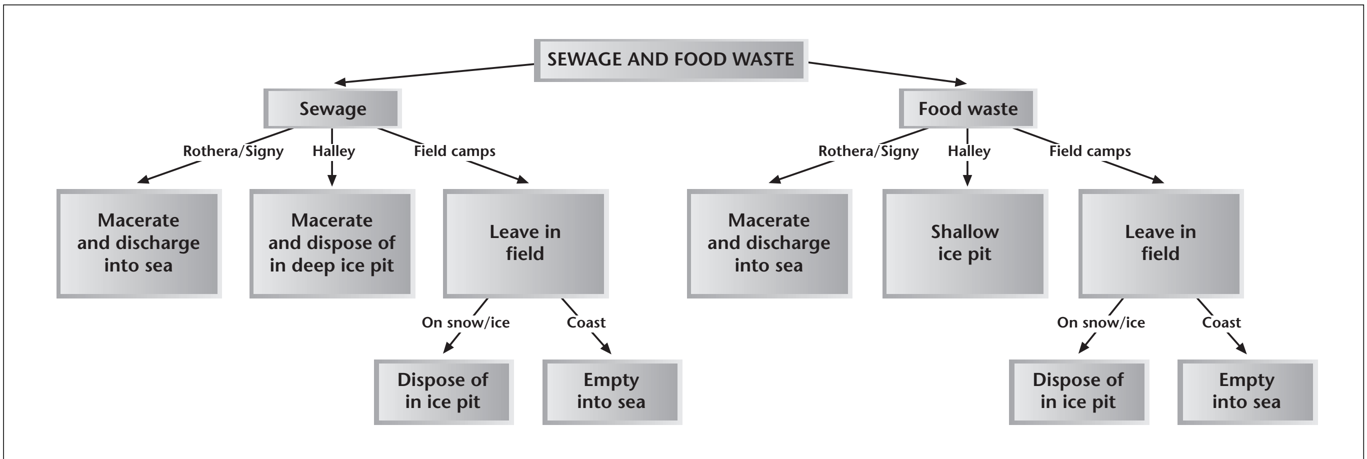

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Major improvements that could be made to the BAS waste disposal methods are:

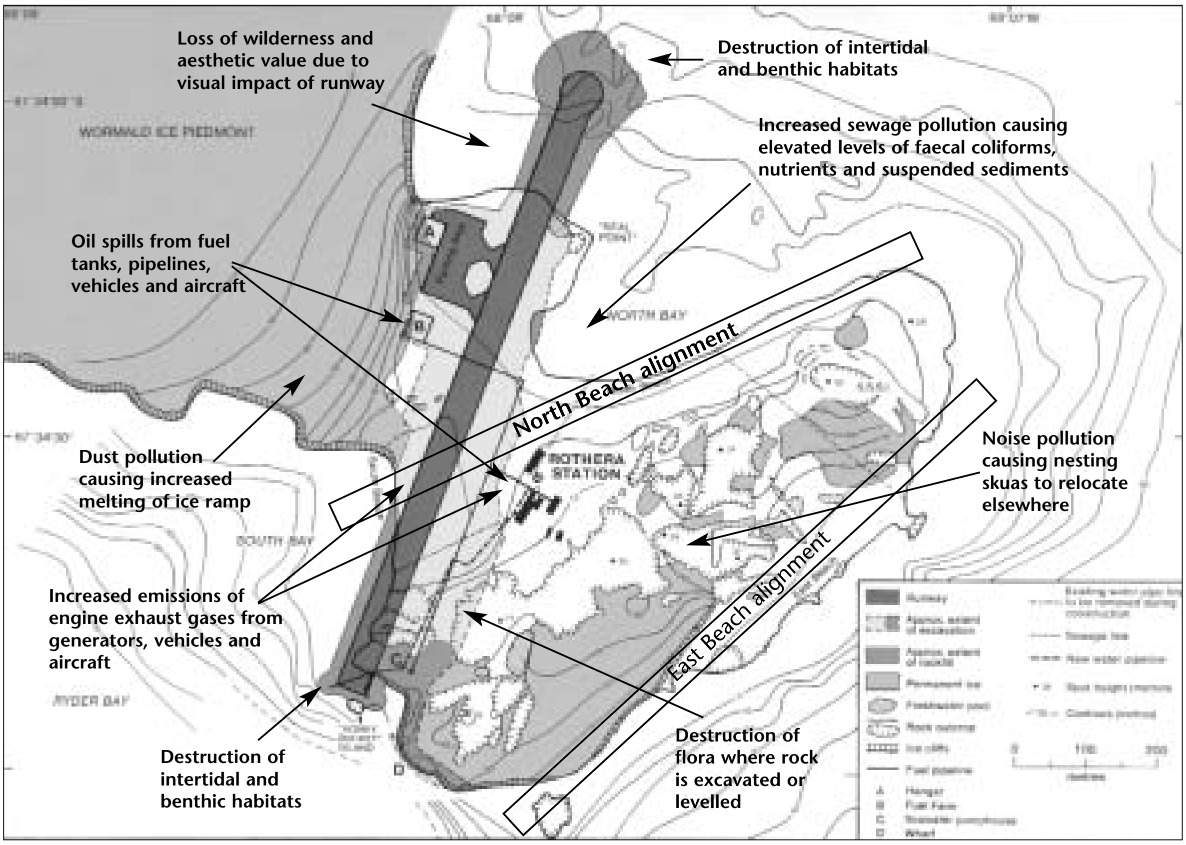
- Sewage treatment
  Sewage and food waste are not treated on the BAS research stations before disposal in Antarctica. Treatment was not considered necessary in the past as equipment costs and ongoing maintenance were considerable and impacts on the environment were found to be minor or negligible. However, the installation of a sewage treatment plant is planned at Rothera. This will significantly reduce pollution of the local environment by faecal coliforms and thus protect the health and safety of station scientists and support staff. The treatment plant will produce sewage sludge and this material will have to be removed from Rothera for disposal outside Antarctica.
- Increased recycling
  Most categories of non-hazardous wastes (e.g. paper, card, plastics, glass, and most metals) are not recycled. It is very difficult to separate out such wastes on large and busy research stations. Furthermore, there are no recyclers on the Falkland Islands and prices for recyclables, such as paper and glass, in UK are very low. Currently, the most cost-effective option for BAS is to minimise waste production and dispose of most non-hazardous wastes to landfill in the Falkland Islands.

The BAS has nine old British stations that it is responsible for in Antarctica. These stations are spread along about 1000 km of the Antarctic Peninsula.

Options taken by the BAS to deal with the old British stations are:

- Conservation as Historic Monuments
  The bases at Port Lockroy, Argentine Islands, Horseshoe Island and Stonington Island have been cleared up and conserved as Historic Monuments. This was done after these four bases had been identified as having the most historical interest by an independent survey of all the old British stations carried out by the UK Antarctic Heritage Trust (UKAHT) in 1994.
- Maintenance as visitor centres
  Port Lockroy has been operated as a visitor centre since 1997. A two person team from the UKAHT run the station each summer. They maintain and conserve the buildings, guide tourists around the site, monitor human impact on the local breeding colony of gentoo penguins, and run a small Post Office and shop. Visits to historic sites like Port Lockroy are an important and very popular part of many tour ship cruises in the Antarctic. However, opening up other historic British bases to visitors is not practical. The Argentine Islands base is near the Ukranian station Vernadsky and large numbers of visitors could disrupt scientific research. Horseshoe Island and Stonington Island are below the Antarctic Circle (66.5°S). This is too far for most tour ships to reach in a one or two week cruise from South America. Both bases are also frequently inaccessible to ships because of sea ice.
- Maintenance as refuges
  Most of the old bases are maintained as refuges for use by scientific field parties or in case of emergencies. Horseshoe Island is near to Rothera Research Station and is often used by BAS field parties. The old station at Cape Geddes is used as a bird observatory by personnel from the Argentine station Orcados on Laurie Island, South Orkney Islands.
- Dismantling and complete removal
  Hazardous wastes, fuel and rubbish have been removed from all the old British stations. Currently, BAS is looking at options to remove the nine remaining old bases. Dismantling and complete removal is very expensive and highly complex and raises difficult management issues. For example, the old British base at Deception Island was destroyed by volcanic mudflows in 1969. Geologists have argued that the ruined buildings should stay untouched as they are an unique example of the power of volcanic eruptions.

Task 6 **Possible environmental impacts of the construction of the Rothera airstrip as forecast by the Environmental Impact Assessment carried out in 1989**



Source: NERC/BAS

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Task 6 continued **Cost benefit analysis of the Rothera airstrip project**

Costs	Scale	Significance	Benefits	Scale	Significance
Environmental impact around Rothera Research Station: – noise pollution – dust pollution – destruction of terrestrial and marine habitats in areas where construction takes place – fuel spills and leaks	Local	High	Increased logistical support for high quality BAS scientific research: – air bridge to the Falkland Islands from Rothera – longer range and better mobility for aircraft operations – air link to Halley Research Station	International	Very high
Cumulative environmental impacts around Rothera Point: – increase in both summer and wintering staff – addition of further facilities to enhance science or logistics (e.g. laboratories, accommodation blocks, power station)	Local	High	Increased international scientific collaboration and cooperation – direct continental air links encourages foreign scientists to carry out research at Rothera	International	High
Loss of wilderness and aesthetic value in the vicinity of Rothera Point: – visual impact of runway, fuel tanks and buildings – noise from aircraft, vehicles, and generators	Local	Low	Improved and increased safety for BAS aircraft operations: – better weather at sea level for aircraft flights – less hazardous maintenance and refuelling of aircraft	Regional	High
Wider environmental impacts along the Antarctic Peninsula: – pollution from emissions from BAS aircraft engines spread over a wider area – increase in number of field parties and fuel depots, with some being located in areas which were previously inaccessible to BAS	Regional	Medium	Reduced risk of a major fuel spill at Rothera Research Station: – new and improved fuel storage with tanks fully bunded – improved pipelines and bunkering facilities	Local	High

The final decision on the construction of the Rothera airstrip was made by BAS's parent body the Natural Environment Research Council (NERC) in September 1989. NERC decided that the construction of the airstrip was justified and necessary, as its value in supporting global science objectives outweighed the minor and local environmental impacts at Rothera Point. The airstrip was constructed during the 1989/90 and 1990/91 seasons and came into full operation at the start of the 1991/92 season.

Environmental monitoring at Rothera Research Station has shown that the actual local impacts have been less serious than predicted. Noise pollution has not had an impact on bird and seal populations. The local breeding population of skuas has stayed very stable and has not decreased. Dust pollution from the airstrip has probably not been a major contributory factor in the melting of the ice ramp leading up to the Wormald Ice Piedmont. It is now thought that the ramp has melted back due to the regional warming which is affecting the whole of the Antarctic Peninsula.

Monitoring of heavy metals in lichens found on Rothera Point has shown that lead and zinc levels show a significant decrease with distance away from the station and airstrip. The background levels of lead and zinc are now found 1 km away from the station. The major local sources of lead and zinc pollution are likely to be the combustion of fuel in generators, vehicles and aircraft, particularly leaded petrol in snowmobiles.

All activities undertaken in the Antarctic, including scientific research, have some form of environmental impact. Thus, there has to be a balance between the sometimes conflicting demands of science and environmental protection. The evidence shows that the Rothera airstrip has provided a vital logistical facility which has greatly improved BAS's abilities to carry out high quality research in Antarctica. The airstrip has had an environmental impact but this is limited, local and not as adverse as first predicted. In this instance, the scientific and logistical benefits the airstrip has brought outweigh the minor and local environmental costs.

Tourism in Antarctica

Worksheet 15

Key ideas
- Reasons for visiting Antarctica
- Models of tourist motivation
- The development of Antarctic tourism
- Cruise ship tourism
- Adventure tourism
- Overflights
- The environmental impacts of tourism
- The management of tourism in Antarctica

Key skills
- Carrying out a survey
- Data analysis
- Graph and pie chart construction
- Text analysis
- Summarising text using bullet points
- Table construction

Antarctica may seem an unlikely holiday destination, yet 10,000 tourists visit each summer. Modern transport and the availability of low-cost, ice-strengthened ships from Russia has made the continent more accessible and cheaper to get to. Nearly all tourism is ship-borne. The favoured location is the Antarctic Peninsula, as it is the part of the continent closest to the major ports in South America from where most tour ships depart. The majority of tourists come from the USA and many tour operators are based in North America. Not all tourists visit Antarctica by tour ship. About 150 people a year sail to Antarctica on private and chartered yachts, and a further 130 fly to the continent to undertake land-based activities such as mountaineering and skiing. The environmental impact of tourism has been a major concern of the Antarctic Treaty nations, and in 1994, they agreed visitor guidelines to try and minimise disturbance to wildlife. This worksheet examines the factors which motivate people to go to the Antarctic. Data on the tourist industry is provided for students to analyse and discuss. Evidence of the environmental impact of tourism is presented. Finally, students are asked to consider how tourism should be managed in the future.

Model answers to tasks

Task 1 The aims of this task are to get students to think about where most British people go on holiday and to frame this in the context of tourism in Antarctica. A detailed understanding of holiday destinations requires consideration of the factors most likely to influence holiday choice. Some of these factors are listed in the task, but there may be others (e.g. abundance of natural wildlife, wilderness experience). The factors are unlikely to have equal weighting, and for many people the most important determinants of where they go on holiday are probably destination, price and availability. The final part of the task is an attempt to separate the constraints on holiday choice from the ideal. Many people have somewhere they have always dreamed of visiting, or some type of special holiday they have always wanted to undertake. Some examples are a cruise around the world, visiting Disney World or going to a luxury beach resort in the Caribbean. Visiting Antarctica, the seventh and least known continent, also falls into this category for some people.

Task 2 The motivation of Antarctic tourists is examined by students looking at two theoretical models of tourist behaviour. In Crompton's model it might be expected that motives of escape (1) and self-exploration (2) might rate highly, while regression (5) might rate lowly. In Iso-Ahola's model a visit to Antarctica either on a cruise or adventure holiday would be both an 'escape from everyday environment' and a 'search for something new'. Climbing the Vinson Massif would be undertaken by a small group of mountaineers who would be taken up the mountain by a highly experienced guide. There would be less extensive interpersonal interaction on a mountaineering expedition compared to a ship cruise as a climber would meet far fewer people. The experience would thus be highly personal (Box 1). A cruise would probably be different. Initially, at the start of a cruise a tourist would see the holiday on a personal level (Box 1). However, by the end of the cruise the tourist would have made many new friends, many of whom would probably share the same desires and goals. The motivation of the tourist would probably change to that of the wider group and the experience would be highly interpersonal (Box 4).

Based on discussions by British Antarctic Survey (BAS) staff with tourists on cruise ships in Antarctica, several common themes emerge regarding the motivations of visitors. Most are interested in natural history and wildlife and want to see and photograph the amazing Antarctic wildlife and scenery. Some want to set foot on the seventh and most remote continent (many richer visitors have already 'ticked off' the other six!). Concern for the global environment motivates others who want to see for themselves the last wilderness left on Earth.

Task 3 The bar graph in Resource T2 (upper left) shows that more people visited Antarctica during the 1990s than previously, yet 10,000 visitors per year currently represents the maximum number. Compared with Madam Tussaud's, which is Britain's most popular tourist attraction with 2.7 million visitors annually, the scale of Antarctic tourism is still very small. Regarding trends in visitor numbers, some points to note are that although the first recorded tourism visit was in 1957/58, regular commercial tourism did not begin until the end of the 1960s. Until the late 1980s, Antarctic tourism was an expensive niche market attracting less than 2000 visitors annually. However, since about 1987, the number of visitors has been increasing because of the availability of cheap ice-strengthened passenger ships from the former Soviet Union. Nevertheless, the International Association of Antarctic Tour Operators (IAATO) currently believes that: 'Antarctica is likely to remain a specialised and relatively expensive niche destination offered by a limited number of experienced operators focusing on educational voyages to areas of natural and wilderness value'. The number of tourists is projected to increase slightly over the

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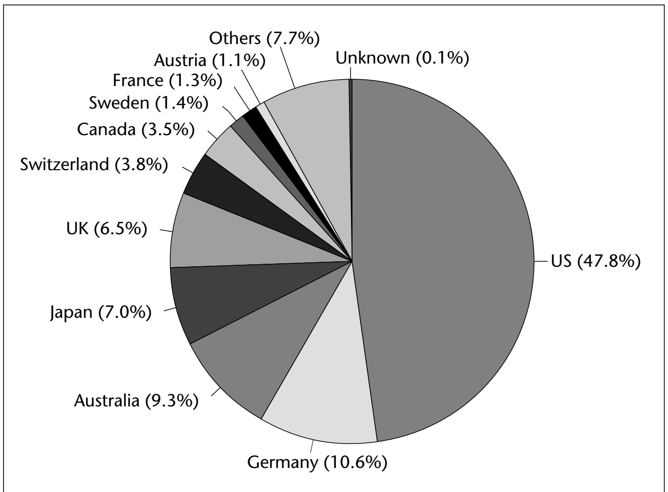
Millennium as people are likely to use the date as a reason for taking their holiday of a lifetime.

The table of nationalities (Resource T2, bottom right) indicates the predominance of US citizens, and this undoubtedly reflects their greater affluence, especially in the retirement age category, which dominates cruise ship tourism in Antarctica. A pie chart showing the numbers of visitors from different countries is shown below. There are probably cultural influences also, with elderly Americans being particularly adventurous in their choice of holiday and Germans very keen on exotic cruise ship destinations. Many of the Australians are young backpackers travelling through South America who arrive in Ushuaia, the departure port for many cruise ships, and discover the possibility of reduced fare trips offered by companies keen to fill empty berths. The marketing strategy of tourist companies also influences nationality with Australian, Canadian and German companies advertising heavily in their own countries.

Nationality of Antarctic tourists 1996/97 season



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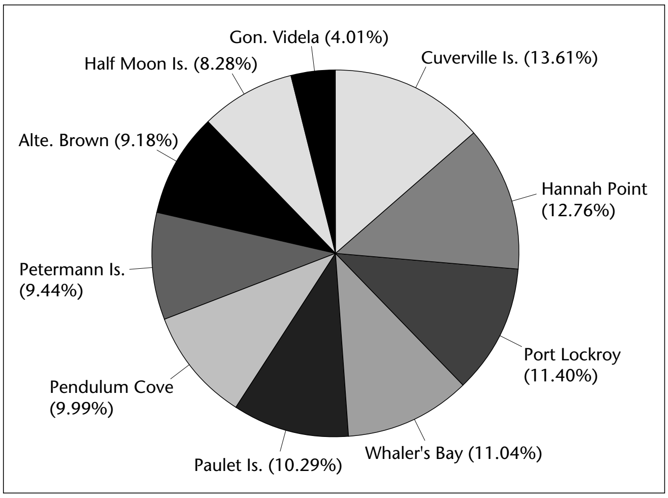
Task 4 The table in Resource T2 (bottom left) gives details of the major vessels involved in Antarctic tourism in 1997/98. The four Russian flagged ships shown in the table underline the point made in Task 3 concerning the availability of numerous cheap, ice-strengthened passenger vessels from the former Soviet Union. The *Disko* is flagged in Denmark, another nation which has many ice-strengthened vessels on its shipping register. The remainder all use 'flags of convenience', such as Liberia and Panama. Flagging out to these countries by vessel owners is done to reduce operating and crew costs. This is because 'flags of convenience' are frequently not party to international maritime regulations concerning vessel manning levels, pollution control, safety or liability in case of accidents. The three ships making the most visits are *Akademik Shuleykin*, *Akademik Iloffe* and *Disko*. They are all used by Marine Expeditions. The discrepancy between the maximum passenger capacity of the *Marco Polo* (800) and the actual number it carried (465) is because of a voluntary self-imposed passenger restriction set by the charter company, Orient Lines, to avoid excessive visitor impact during landings. However, this restriction still exceeds the 400 person maximum stipulated by IAATO and has prevented Orient Lines from joining the organisation.

Ushuaia is in Argentina, situated on the southern coast of Tierra del Fuego on the Beagle Channel. It is a large coastal city (population 40,000) with an international airport, large hotels and a commercial port capable of handling ocean-going cruise ships. Its southerly location makes it the closest port to the Antarctic Peninsula. Cruise ships normally take two days to sail from Ushuaia to the South Shetland Islands, whereas it takes three days to get to this location from other nearby 'gateway' ports, such as Punta Arenas in Chile or Stanley in the Falkland Islands.

Task 5 **Proportion of visitors going to each tourist destination on the Antarctic Peninsula 1996/97 season**



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The reasons for each site's popularity are:

- Deception Island (Whaler's Bay and Pendulum Cove) – sunken volcanic caldera providing excellent natural harbour for large vessels, remains of historic whaling station, opportunity to bathe in geothermally heated water, large penguin colonies.
- Hannah Point – excellent scenery, wildlife concentrations including one of the most southerly breeding localities of macaroni penguins, fossils.
- Port Lockroy – good anchorage for large ships, beautiful mountain and glacier scenery, remains of whaling industry, historic base with artifacts, guides providing interpretation, Post Office/shop, large concentrations of breeding gentoo penguins.
- Cuverville Island – large concentrations of breeding gentoo penguins and other birds and seals, moss banks, island set in impressive iceberg-choked fjord, frequent whale and seal sightings during zodiac cruising (trips in small inflatable boats) around the island.
- Half Moon Island – one of the first safe landing sites available after the two days spent crossing the rough Drake Passage, large chinstrap penguin colonies, beautiful scenery.
- Paulet Island – large Adélie penguin rookery, historic base containing artifacts from the Swedish Antarctic Expedition (1901–04).
- Petermann Island – furthest south for most cruise ships, historic connections with French Antarctic Expedition which over-wintered here in 1909, most southerly gentoo penguin colony.
- Almirante Brown and Gonzalez Videla stations – these stations (Argentine and Chilean respectively) give visitors the opportunity to set foot on the mainland of Antarctica. All the other sites mentioned above are islands.

Task 6 Usually two days are spent by a cruise ship crossing the Drake Passage between Ushuaia and the first landfall in the Antarctic Peninsula, which is often Half Moon Island or somewhere else in the South Shetland Islands. Thus, about 50% of an eight day cruise to the Antarctic Peninsula is taken up by ocean sailing, during which time lectures are given to passengers and seabird and whale watching from the bridge of the ship is organised. Based on discussions by BAS staff with cruise ship passengers, different people enjoy different aspects of a cruise. Most visitors are

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Orient Lines

Marco Polo sailing in the Ross Sea, Antarctica

Task 6 continued
apprehensive about the crossing of the Drake Passage, which has a fearsome reputation for storms, but once in the calmer waters of the Antarctic Peninsula most are overawed by the spectacular glacial and mountain scenery, the opportunity to watch whales at close quarters and the abundant concentrations of tame wildlife. At Port Lockroy, in addition to the scenery and wildlife, there is the added attraction of talking to the two person team from the UK Antarctic Heritage Trust (UKAHT) who maintain the station during the summer months, guide visitors, run a Post Office and small shop and monitor the local gentoo penguin population. The ability to post a card home is very popular with visitors.

Task 7 Fewer tourists are involved in adventure tourism in Antarctica compared to tour ship tourism. According to IAATO, in the 1997–98 season 95 people visited Antarctica on chartered yachts and Adventure Network International (ANI) supported 131 land-based visitors. About another 50 people visited on private yachts. Fewer people take part in adventure tourism because of the high costs (the cost of a tourist skiing trip to the geographic South Pole is about £35,000) and the amount of time needed in case the schedule gets delayed by bad weather or problems with logistics. Delays caused by bad weather of up to two weeks in getting in or out of ANI's Antarctic summer base at Patriot Hills are not uncommon. The strenuous nature of these trips confine this type of tourism mainly to very affluent, young, physically fit people who have flexible work arrangements and few commitments.

Task 8 Overflights to Antarctica were suspended for many years following the Air New Zealand DC-10 crash into the side of Mount Erebus, Ross Island on 28 November 1979. All 257 people on board were killed, and despite the crash site being near Scott and McMurdo research stations, recovery of all the wreckage and bodies proved impossible. It was the greatest peace-time disaster in New Zealand history. This incident highlighted the major problems of operating passenger jets in the hostile environment of Antarctica, including the practical difficulties of search and rescue in the event of an accident and the legal problems (e.g. liability) associated with the non-sovereign status of Antarctica. The environmental impacts of overflights and accidents are also of concern. Jet engine noise pollution could disturb birds and seals and exhaust emissions could pollute the atmosphere. Currently, only the Australian airline Qantas runs sightseeing overflights and carries out about 15 flights during each austral summer. These flights use commercial Boeing 747 aircraft departing from and returning to Melbourne, Australia. Overflights are lengthy because of the large distances involved and the round trip takes about 12 hours, of which only 2.5 hours are actually spent over Antarctica. Qantas overflights operate no lower than 3050 m above ground level to ensure aircraft safety and minimise noise pollution on the ground.

Task 9 The main findings of the research at Port Lockroy are:

- Since the 1950s, the numbers of breeding gentoo penguins have increased at similar rates at both Alice Creek, which has many visitors, and at Damoy Point, which has few visitors.
- At Alice Creek, visitor pressure is unevenly distributed because of topography and distance. Fewer people go to Lécuyer Point compared with Jougla Point, but over a nine year period the numbers of breeding gentoo penguins have increased at similar rates at both sites.
- On Goudier Island over 4000 visitors landed in the 1996/97 summer season, and visitors were restricted to particular gentoo penguin breeding colonies.
- The breeding performance of the visited and unvisited colonies were compared and showed no differences in the numbers of breeding pairs, hatching success or brood size (number of chicks per pair).
- The clutch size (number of eggs laid) was smaller in visited colonies compared with unvisited colonies, but this was attributed to the colony position (low lying) and the high amount of snow cover at these colonies rather than effects of visitors.
- A comparison of chicks at a visited and unvisited colony found no differences in growth rate, and a similar survival rate up to the age at which they left the nest (crèching).
- The overall productivity of gentoo penguins on Goudier Island is similar to that found in other studies of gentoo penguins at sites in Antarctica not visited by tourists.
- The overall conclusion is that, so far, there have been no detectable effects of visitor disturbance in any of the penguin colonies studied at Port Lockroy.

The main findings of the research at Palmer Station are:

- Cruise ship tourism has increased in this area since 1975.
- Lichfield Island became a Specially Protected Area in 1978, placing it off limits to tourists. In contrast, Torgersen Island continued to attract tourists, and their numbers have increased.
- Both islands have breeding Adélie penguins and their numbers have decreased between 1975 and 1992.
- The overall decrease in numbers of Adélie penguins on Lichfield Island (no tourists) was 43%, but on Torgersen Island (tourists) it was 19%.
- The data suggests that any adverse effects of tourism and research are negligible relative to long-term changes in other environmental variables.

Task 10 **Possible impacts of Antarctic tourism**

Potential impacts	Part of the environment at risk	Ways to minimise impact
Disturbance of wildlife	Breeding birds, hauled out seals	Impose minimum approach distances to wildlife. Educate visitors to behave responsibly
Litter, waste	Terrestrial habitats. Marine wildlife, particularly seals and birds, becoming entangled	Ensure visitors bring all waste back to ship. Retain waste on ship until back in port
Oil pollution	Marine/inshore marine	Ensure ship operation conforms to international maritime standards. Ensure ships are ice-strengthened and have modern ice navigation equipment. Limit size of tourist vessels entering Antarctic waters. Ensure ship has an oil spill response plan in case of an accident. Oil spill equipment available and crew trained in cleanup techniques
Environmental degradation (e.g. trampling)	Moss banks, fossils, patterned ground	Limit numbers going ashore. Avoid sensitive areas. Brief tourists before arrival
Removing historic artifacts, fossils, bones	Historic sites, fossils	Tell tourists not to collect souvenirs. Brief tourists before arrival
Disruption to important scientific research	Research stations, field study sites	Allow only a few tourist visits per season. Brief tourists before arrival. Guide tourists around station

Task 11 The advantages and disadvantages of the self-regulation of the Antarctic tour industry through IAATO are:

Advantages of IAATO
- Fosters cooperation and exchange of information between tour operators.
- Promotes the importance of safety and environmental protection within the tour industry.
- Helps to establish and agree environmental and safety guidelines which have the backing of the major tour operators.
- Able to react quickly to changes in a rapidly moving industry.
- Provides a central contact point for national Antarctic research programmes, environmental pressure groups, tourists and the general public.
- Has expert status at Antarctic Treaty meetings and so can represent the interests of tour operators at the highest political level.

Disadvantages of IAATO
- Cannot oblige tour operators to become members. Membership is voluntary.
- Has no way of enforcing its environmental and safety guidelines, apart from asking a member who breaks them to leave the organisation.
- Unable to control the activities of private yachts or private adventure expeditions.
- Has no independent regulator of its activities. Tour companies are commercial profit making companies. Profits may therefore come before safety or environmental protection.
- By establishing its own environmental and safety guidelines IAATO has made it difficult for the Antarctic Treaty nations to agree stricter regulations to control the industry.

Tour companies which are not IAATO members can be regulated by individual Antarctic Treaty nations. For example, ANI is not currently a member of IAATO. ANI has its main offices in the UK and its activities are regulated by the UK Government through the Foreign & Commonwealth Office (FCO). To operate in Antarctica, ANI must first obtain a permit to do so from the FCO under the

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A party of tourists listen to their expedition leader at Deception Island

N Cobley/BAS

A private ocean going yacht moored off Goudier Island

Protocol in UK law. Before issuing a permit the FCO needs to be satisfied that ANI has full insurance to cover any accidents, will be able to operate safely, and can comply with the provisions of the Protocol. However, there remains the difficulty of regulating tour operators who are not IAATO members and also organise their activities in countries which are not Antarctic Treaty Consultative Parties.

It is rare for tourists to infringe either the Antarctic Treaty visitor guidelines or the IAATO guidelines. This is because tourist visits ashore are strictly controlled by expedition leaders, and the vast majority of tourists willingly accept the regulations imposed. The action that could be taken if a tourist deliberately infringed the guidelines might include a verbal or written warning from the expedition leader or sending the person back to the ship. Some countries, such as New Zealand and Australia, employ official government observers aboard Antarctic tour ships operated by tour companies based in, or operating from, those countries. This gives a greater on-the-spot oversight of visits. In the worst case, a tourist infringing the guidelines could be reported to such an official observer.

Overall it is useful for the Antarctic tour industry to be represented by IAATO. The organisation has worked hard to pull the major tour operators together and requires its members to work within the framework of the Antarctic Treaty and the Environmental Protocol. IAATO has implemented its own set of guidelines for tourist operators. It also represents the Antarctic tourist industry at Antarctic Treaty meetings. However, as the tourist industry grows and larger passenger vessels enter Antarctic waters there will be severe strains on IAATO. Already there is pressure for IAATO to revise upwards its voluntary limits on the size of vessels being used (no more than 400 passengers) and numbers of tourists going ashore at any one time (no more than 100 people).

Task 12 One of the objectives of IAATO, shown in Resource T5, is to: ‘Create a corps of ambassadors for the continued protection of Antarctica by offering the opportunity to experience the continent first hand’.

On their return home tourists are potentially influential advocates able to lobby for the conservation of Antarctica and for scientific research. This can lead to tourists writing to politicians or government officials about Antarctic issues they consider to be important. Such pressure has been credited with shaming some national Antarctic programmes to begin cleaning up abandoned research stations. Although the influence of tourists in fostering wide public support for the protection of the Antarctic environment and Antarctic science is difficult to determine, it is clear that they have an important role to play and have undoubtedly contributed to the growing public awareness of Antarctica.